CHARACTERIZATION AND SIMULATION OF THE SHADING
INDUCED HOT SPOT RELIABILITY PROBLEM IN SILICON
PHOTOVOLTAIC SOLAR MODULES

by

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Characterization and Simulation of the Shading Induced Hot Spot Reliability Problem in Silicon Photovoltaic Solar Modules

Thesis directed by Professor Carlos paz de Araujo, and Associate Professor Rebecca N. Webb

ABSTRACT

The formation of a damaging hot spot on a solar cell in a non-uniformly illuminated solar photovoltaic module was characterized and simulated. Hot spot power is the product of reverse bias voltage and current through the hot spot region, and is predominantly dissipated as heat. Results were presented of monocrystalline and polycrystalline silicon photovoltaic solar cells tested in the lab under a solar simulator or in the dark. FLIR E60 infrared camera hot spot thermal images, one at 368 °C, along with thermocouple temperature measurements confirmed literature that a hot spot can cause permanent damage.

Several test equipment modules were built and described. In addition to indoor lab tests, thermal and electrical measurements were recorded outside on a polycrystalline silicon solar PV module test setup, when it was being fully illuminated by solar radiation and then non-uniformly illuminated (shaded). The output current versus output voltage (I-V) graph was recorded as load resistance was increased to show how shade decreased the output power and distorted the graph. Electrical measurements of the bypass diode in parallel with the partially shaded PV submodule showed when the diode turned on allowing current to bypass the submodule solar cells.

National Instruments Multisim 14.0 software was used to model and simulate the output current, voltage, and power in a silicon PV solar cell, and in a silicon PV module, in order to produce I-V and P-V curves. Shaded and unshaded PV module I-V and P-V curves were compared to outdoor measurements. COMSOL MULTIPHYSICS 4.4 software was used to
model and run simulations of the hot spot temperature on a horizontal solar cell in air for a range of spot diameters, power, location on the solar cell, and solar cell thickness. Simulation results showed hot spots over 400 °C for 15 watts of reverse bias input power, in a 3.0 mm diameter cylindrical spot on a 125 mm square solar cell. Temperature reached 90% of final value in 13 seconds. When the solar cell is encapsulated in a PV module, heat flow and temperatures will change. Lab and outdoor tests were compared to thermal simulations.
DEDICATION

This thesis is dedicated to former United States President, Georgia Governor, Nobel Peace Prize Laureate, author, Georgia Tech student (US Naval Academy graduate), and fellow Georgian Jimmy Carter. When he was President, his administration established the Department of Energy, and a national energy policy that encouraged the change “to strict conservation and to the use of coal and permanent renewable energy sources, like solar power.”[1] Thirty six years after leaving office, at the age of 92, he once again demonstrated his support for renewable energy by having 3,852 solar PV modules installed on 10 acres of his property in Plains, Georgia.

In loving memory of my father

George C. Lundquist

1930 - 1966

In loving memory of my mother

Ruth Shenk Lundquist

1921 - 1980
ACKNOWLEDGEMENTS

I would like to thank my thesis committee members Dr. Carlos Paz de Araujo, Dr. Rebecca Webb, and Dr. T.S. Kalkur for their generous time, discussions, patience, and encouragement throughout this project. My thesis co-advisor Dr. Carlos Paz de Araujo provided a grand view of semiconductor physics and solar cell technology in his classes, suggested the outline of my thesis, and with Dr. Rebecca Webb helped acquire the IR camera. My thesis co-advisor Dr. Rebecca Webb (now at Oregon State University) taught an excellent course on heat transfer, provided lab space and basic equipment for my use in the SECanT (Sustainable Energy Collection and Transport) Lab she managed in the MAE department, frequently discussed solar topics with me, and kept her group meetings lively with her humor and energy.

I thank Ron Wilkinson for his help and guidance in the MAE machine shop when I made test equipment, Dr. Jacob Graul for his suggestions and help on formatting a thesis, and Eva Wynhorst for help on submitting my M.S.E.E degree administrative paperwork. I appreciate the conversations I had with my lab colleagues Tom, Corbin, Colin, Bashir, Sam, Salim, and Roser.

I thank Dr. Steve Hegedus from IEC at Univ. of Delaware who at the 39th IEEE PV Specialist Conference suggested I research solar cell thermal issues for my thesis.

I acknowledge the contributions of the mathematicians, scientist, and engineers, who throughout history have advanced our knowledge of the world and created beneficial products.

I gratefully acknowledge my wife Teresa, son Vlad, and daughter Jen for their patience and encouragement as I spent years studying and working on this solar energy thesis.

I am thankful for the grace of almighty God providing my health, endurance, and the people I met during my studies at UCCS. I am in awe of the life sustaining power of the sun and the incredible scale of the universe from the subatomic particle to the distant galaxies.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>antireflection (coating)</td>
</tr>
<tr>
<td>$\vec{B}$</td>
<td>magnetic field [T], [Wb/m$^2$], (1 tesla, T = 10,000 gauss, G)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>heat capacity at constant pressure [J/m$^3$K]</td>
</tr>
<tr>
<td>$\vec{D}$</td>
<td>electricity flux density [C/m$^2$]</td>
</tr>
<tr>
<td>$D_n$</td>
<td>diffusion coefficient for electrons [cm$^2$/s]</td>
</tr>
<tr>
<td>$D_p$</td>
<td>diffusion coefficient for holes [cm$^2$/s]</td>
</tr>
<tr>
<td>DC</td>
<td>direct current [A]</td>
</tr>
<tr>
<td>$\vec{E}$</td>
<td>electric field [V/m] or [N/C]</td>
</tr>
<tr>
<td>$E$</td>
<td>energy [eV] or [J]</td>
</tr>
<tr>
<td>$E_g$</td>
<td>bandgap energy [eV]</td>
</tr>
<tr>
<td>EHP</td>
<td>electron-hole pair</td>
</tr>
<tr>
<td>$\vec{F}$</td>
<td>force [N]</td>
</tr>
<tr>
<td>$G_n$</td>
<td>generation rate of electron concentration [1/cm$^3$·s]</td>
</tr>
<tr>
<td>$G_p$</td>
<td>generation rate of hole concentration [1/cm$^3$·s]</td>
</tr>
<tr>
<td>GWh</td>
<td>gigawatt hours of energy [J]</td>
</tr>
<tr>
<td>$\vec{H}$</td>
<td>magnetic field intensity [A/m]</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz [cycles/s]</td>
</tr>
<tr>
<td>I</td>
<td>current [A]</td>
</tr>
<tr>
<td>$I_0$</td>
<td>reverse saturation current [A]</td>
</tr>
<tr>
<td>$I_{MPP}$</td>
<td>current at maximum power point [A]</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>current short circuit [A]</td>
</tr>
<tr>
<td>$I_{sh}$</td>
<td>shunt current [A]</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>photocurrent [A]</td>
</tr>
<tr>
<td>IR</td>
<td>infrared electromagnetic radiation</td>
</tr>
<tr>
<td>I-V</td>
<td>current voltage graph</td>
</tr>
<tr>
<td>$\bar{J}$</td>
<td>current density [mA/cm$^2$]</td>
</tr>
<tr>
<td>$L_n$</td>
<td>electron diffusion length [cm]</td>
</tr>
<tr>
<td>$L_p$</td>
<td>hole diffusion length [cm]</td>
</tr>
<tr>
<td>MW</td>
<td>megawatts [$10^6$ watts]</td>
</tr>
<tr>
<td>N</td>
<td>number of samples</td>
</tr>
<tr>
<td>$N_A$</td>
<td>acceptor concentration [1/cm$^3$]</td>
</tr>
</tbody>
</table>
$N_D = \text{donor concentration} \ [1/cm^3]$

$N(E) = \text{density of energy states at a specific energy}$

$P = \text{power} \ [W]$

$P = \text{probability}$

$P_{MPP} = \text{power at maximum power point} \ [W]$

$P_S = \text{incident solar power} \ [W]$

$\text{P-V} = \text{power voltage graph}$

$Q = \text{quantity of heat} \ [J]$

$R = \text{resistance} \ [\text{ohms}]$

$R_s = \text{series resistance} \ [\text{ohms}]$

$R_{sh} = \text{shunt resistance} \ [\text{ohms}]$

$T = \text{temperature} \ [\text{K or °C}]$

$TW = \text{terawatts} \ [10^{12} \text{ watts}]$

$U_n = \text{recombination rate of electron concentration} \ [1/cm^3 \cdot \text{s}]$

$U_p = \text{recombination rate of hole concentration} \ [1/cm^3 \cdot \text{s}]$

$UV = \text{ultraviolet light electromagnetic radiation}$

$V = \text{voltage} \ [V]$

$V_{MPP} = \text{voltage at maximum power point} \ [V]$

$V_{oc} = \text{voltage open circuit} \ [V]$

$\alpha = \text{absorptivity of a surface}$

$eV = \text{electron volt energy} \ [1.60218 \times 10^{-19} \text{ J}]$

$f = \text{frequency} \ [\text{Hz}]$

$f(E) = \text{Fermi-Dirac distribution function}$

$h = \text{heat transfer coefficient} \ [\text{W/m}^2 \cdot \text{K}]$

$h^+ = \text{hole with elementary charge} \ [1.60218 \times 10^{-19} \text{ C}]$

$k = 2\pi/\lambda \ [\text{rad/m}]$

$\vec{k} = \text{k-space wave vector}$

$k = \text{thermal conductivity} \ [\text{W/m-K}]$

$l = \text{length} \ [\text{m}]$

$m = \text{mass} \ [\text{kg}]$

$m^* = \text{effective mass} \ [\text{kg}]$

$n = \text{concentration of electrons in the conduction band} \ [1/cm^3]$

$n_i = \text{intrinsic carrier concentration} \ [1/cm^3]$

$\vec{n} = \text{vector normal to surface}$
\[ p \quad = \quad \text{momentum [kg}\cdot\text{m/s]} \]
\[ p \quad = \quad \text{concentration of holes in the valence band [1/cm}^3]\]
\[ p-n \quad = \quad \text{p-type n-type (junction)} \]
\[ q \quad = \quad \text{rate of heat flow [W]} \]
\[ q'' \quad = \quad \text{heat flux [W/m}^2\]}
\[ t \quad = \quad \text{time [s]} \]
\[ \tau \quad = \quad \text{transmissivity of a surface} \]
\[ \tau_n \quad = \quad \text{electron recombination lifetime [s]} \]
\[ \tau_p \quad = \quad \text{hole recombination lifetime [s]} \]
\[ \nu \quad = \quad \text{velocity [m/s]} \]
\[ c \quad = \quad \text{speed of light [2.9979 \times 10^{8} \text{ m/s]} } \]
\[ e^- \quad = \quad \text{electron with elementary charge [-1.60218 \times 10^{-19} \text{ C}]} \]
\[ \varepsilon \quad = \quad \text{permittivity of the material [F/m]} \]
\[ \varepsilon_0 \quad = \quad \text{permittivity of free space, vacuum [8.854 \times 10^{-12} \text{ F/m]} } \]
\[ h \quad = \quad \text{Planck’s constant [6.6261 \times 10^{-34} \text{ J}\cdot\text{s}], or [4.1357 \times 10^{-15} \text{ eV}\cdot\text{s}]} \]
\[ h \quad = \quad h/2\pi \text{ [1.0546 \times 10^{-34} \text{ J}\cdot\text{s}], [6.5822 \times 10^{-16} \text{ eV}\cdot\text{s}]} \]
\[ k_B \quad = \quad \text{Boltzmann constant [1.38 \times 10^{-23} \text{ J/K}], or [8.62 \times 10^{-5} \text{ eV/K}]} \]
\[ \eta \quad = \quad \text{solar cell efficiency [%]} \]
\[ q \quad = \quad \text{elementary charge [1.60218 \times 10^{-19} \text{ C}]} \]
\[ \bar{q} \quad = \quad \text{electric charge density [C/m}^3\]}
\[ \rho \quad = \quad \text{reflectivity of a surface} \]
\[ \rho \quad = \quad \text{mass density [kg/m}^3\]}
\[ \lambda \quad = \quad \text{wavelength of incident light [nm]} \]
\[ \sigma \quad = \quad \text{Stefan-Boltzmann constant [5.670 \times 10^{-8} \text{ W}/\text{m}^2\cdot\text{K}^4]} \]
\[ \sigma \quad = \quad \text{electrical conductivity of the material [1/\Omega\cdot\text{m}]} \]
\[ \mu \quad = \quad \text{permeability of the material [H/m]} \]
\[ \mu_0 \quad = \quad \text{permeability of free space, vacuum [1.257 \times 10^{-6} \text{ H/m}]} \]
\[ \mu_n \quad = \quad \text{electron mobility [cm}^2/\text{V}\cdot\text{s}] \]
\[ \mu_p \quad = \quad \text{hole mobility [cm}^2/\text{V}\cdot\text{s}] \]
\[ \nu \quad = \quad \text{temporal frequency [Hz]} \]
CHAPTER I

INTRODUCTION

A. The Reliable Supply of Energy is the Motivation

“Our decision about energy will test the character of the American people and the ability of the President and the Congress to govern. This difficult effort will be the "moral equivalent of war" -- except that we will be uniting our efforts to build and not destroy.”[1][Appendix A] This is one of President Jimmy Carter’s most famous quotes delivered three months after becoming president on April 18, 1977 during his televised address to the nation about his proposed energy policy, “World consumption of oil is still going up. If it were possible to keep it rising during the 1970s and 1980s by 5 percent a year as it has in the past, we could use up all the proven reserves of oil in the entire world by the end of the next decade.”[1][Appendix A]

Figure 1: Cars wait in long lines during the gas shortage [2].
“Because we are now running out of gas and oil, we must prepare quickly for a third change, to strict conservation and to the use of coal and permanent renewable energy sources, like solar power.”[1][Appendix A] During the Organization of Petroleum Exporting Countries (OPEC) oil embargo against the United States, the Netherlands, and several other countries, which lasted from October 1973 till March 1974, the price of a barrel of oil jumped from $3 to $12. This raised the price of all products containing oil. OPEC cut off the oil supplies because President Richard Nixon directed the United States to support Israel during the Arab-Israeli War. This energy crisis caused rationing and long lines to purchase gasoline as shown in Figure 1. The world was consuming about 60 million barrels (barrel = 42 gallons) of oil per day [1][Appendix A]. Many Americans, including the author, believed that the world would run out of oil before the year 2000, and therefore drove their cars less, walked, carpooled, or used mass transit to conserve oil. Conservation of energy from better insulation of homes, to design of more efficient engines for cars and planes became a high priority, which created many engineering jobs. The Carter administration created the Department of Energy from a number of government agencies. The use of coal was increased to replace the use of oil where possible.

In 1979 the Iranian Revolution decreased oil output and caused the second energy crisis, which reinforced the oil shortage concerns. On the other hand, many people thought that oil companies and oil cartels created the oil shortages to increase the price of oil, and their profits.

Today in 2017, the world has not run out of oil! The price of oil hit a monthly average high of $126 per barrel in June 2008 and then decreased. The large rise in the price of a barrel of oil increased exploration, which greatly increased the proven oil and natural gas reserves compared to the 1970s. The widespread use of hydraulic fracturing (fracking) increased the amount of oil and natural gas produced by a well. The world now consumes 97 million barrels of oil per day [3] at $52 per barrel for a cost of over $5.0 billion per day, $1.8 trillion per year. Once the oil is refined, distributed, and taxed the retail price to the consumer is much higher. An
excellent book about the history and politics of oil is Daniel Yergin’s “The Prize the Epic Quest for Oil, Money & Power” [4]. Coal power plants are being replaced by new natural gas power plants, which can change the output power quicker, run cleaner, and produce less CO₂.

CO₂ green house gas is one cause of climate change and global warming [5]. One problem resulting from global warming is the melting of polar ice caps, which adds water to oceans. Add in the expansion of ocean water volume as the temperature increases, and the result is higher ocean levels and more coastal flooding worldwide during storms endangering millions of people. The National Flood Insurance Program (NFIP), managed by FEMA, is part of the federal government’s efforts to limit the damage and financial effect of floods. As of March 2016, it has borrowed from the U.S. Treasury $23 billion to cover flooding disaster expenses [6]. Renewable energy sources can reduce the production of CO₂, and slow down the global warming process and related problems. President Carter called for “permanent renewable energy source, like solar power”. The well known renewable energy sources are hydroelectric power plants, wind turbines, geothermal power plants, ethanol fuels, passive solar heating, solar thermal modules (panels), and solar PV modules.

Solar photovoltaic (PV) rooftops and power plants have increased rapidly worldwide, giving rise to the following statistics for 2015 [7].

- U.S. compound annual PV growth rate from 2005 to 2015 was 59.9%
- Solar PV electricity power grid connected capacity expanded to 25,599 megawatts dc (MWdc) which is changed by inverters into 19,711 MWac in the U.S., an increase of 7,260 MWdc, 39.6% from 2014.
- Solar PV electricity energy generation in the U.S was 40,365 gigawatt hours (GWh). This was an increase of 11,448 GWh or 39.6% over 2014 and was 1.0% of total U.S. electricity generation.
With increased manufacturing volumes of PV system parts, their cost has dropped for years. The average U.S. residential solar PV system is rated at 5 kilowatts (kW) of electricity. The National Renewable Energy Lab (NREL) calculated these installed solar PV system (no battery storage) costs, “Based on our bottom-up modeling, the Q1 2016 PV cost benchmarks are:

- $2.93 per watt DC (Wdc) for residential systems (3-10 kW)
- $2.13/Wdc for commercial systems (10 kW-2MW)
- $1.42/Wdc (or $1.99 per watt AC [Wac]) for fixed-tilt utility-scale systems (>2MW)
- $1.49/Wdc (or $1.79/Wac) for one-axis-tracking utility-scale systems (>2MW).”[8]

The installed price for a customer for a PV system includes the above costs with installer profits added and federal, state, and utility subsidies subtracted. The time to pay off the PV solar system in terms of the savings on electricity not purchased from a utility company depends on the initial PV system price, the utility’s price of electricity, financing costs, and solar radiation incident on the PV system. It takes 10 to 20 years to pay off the price of a solar PV system. It takes 3 to 4 years to pay back energy and CO₂ pollution that went into making the PV system [9].

Solar PV modules (panels) typically have a 25 year warranty. A PV array is made by connecting multiple PV modules in series or parallel to an inverter to generate electrical power. When a bank loans money for a PV power plant project, it is expected that the solar PV arrays will generate a certain amount of electrical energy per year, to produce money to pay the bank loan. Reliability must be excellent on solar PV systems to make sure that the expected energy per year is produced. PV solar modules are exposed to sunlight, rain, snow, hail, dust, and high winds in climates with a range of humidity and temperature. The output power and reliability of a PV module and a PV array of modules is diminished if some of the solar cells are partially or fully shaded, which causes a non-uniform solar irradiance. The non-uniform illumination on a solar module can cause a hot spot to form on the shaded solar cell.
B. Hot Spot Reliability Problem Definition

The PV module shown in Figure 2 is made of 36 rectangular polycrystalline silicon (polycrystalline silicon (poly-Si)) solar cells in a 4 column by 9 row configuration, see Appendix C. For this module, the specified normal operating cell temperature (NOCT) is 45°C ± 2°C. NOCT conditions for any PV module are 800 W/m² irradiance, 20°C (68°F) air temperature, 1 m/s wind velocity, open circuit no electrical load, open space on back side.

Figure 2: Solar PV module containing 36 polycrystalline silicon solar cells. [APPENDIX C]

Any cells experiencing shading produce less current, voltage, and power than the other cells in series with them. This non-uniform illumination can be due to obstruction shading or direct shading [10]. Obstruction shading is produced by an object such as a tree or chimney casting a shadow across part of the modules in a PV array. This shadow moves across the array as the sun moves across the sky. Direct shading is produced by an object very close or on the front of a solar cell, such as sand from a sandstorm, or a branch of leaves casting a shadow, which has very minimal movement as the sun moves across the sky.
Figure 3: Schematic of solar PV module showing 36 solar cells and 2 bypass diodes
A solar PV module is composed of typically 32 to 80 solar cells electrically connected in series. The PV module typically is made up of 2 to 4 submodules. A submodule usually has 16 to 20 solar cells electrically connected in series, which are in parallel with a bypass diode. Figure 3 displays the schematic of the PV module shown in Figure 2. The schematic shows that the PV module has 36 polycrystalline silicon solar cells labeled SC1 to SC36 contained in 2 submodules. Submodule 1 has 18 solar cells, SC1 to SC18, in the first two columns, with a bypass diode D1 in parallel with the 18 cells. Submodule 2 is similarly constructed. When one or more cells in a submodule are shaded, the electrical current flowing through the solar cells in that submodule is greatly reduced. The bypass diode turns on with about 0.3 volts forward bias and allows the current from the other submodule and other modules in series with this module to bypass the shaded submodule solar cells. In the partially shaded submodule, the cells in full sunlight can each produce up to 0.6 volts DC. Suppose solar cell number SC1 is shaded and producing no current or voltage, and has a shunt resistance of 30 ohms. (Shunt resistance is the cell resistance between the + and - voltage outputs.) The 17 solar cells in full sunlight can produce an output voltage of 17 x 0.6 volts equal to 10.2 volts. The circuit for submodule 1 now looks like Figure 4.

![Figure 4: Equivalent circuit for PV module with solar cell SC1 shaded.](image-url)
The voltage across solar cell SC1 is 0.3 volts from diode D1 + 10.2 volts from solar cells S2 to SC18 for a combined voltage of 10.5 volts. This voltage is opposite to the polarity of solar cell SC1 and is called a reverse bias voltage. This reverse bias voltage causes the 200 um thick solar cell to electrically conduct current through the shunt resistance (also called parallel resistance). The power dissipated in the solar cell is the product of the reverse bias voltage and the current, and can heat up the solar cell. In worse case, the solar cell may electrically breakdown due to the reverse bias voltage stress, which can result in a high current density and ironically a high temperature area, referred to as a hot spot! If the bypass diode D1 were to fail as an open circuit, then the power from the other submodule, and other PV modules in series with this PV module could create a much higher reverse bias voltage across the shaded cell(s) and create even higher temperature hot spots.

Hot spots have been recognized as a potential problem for many years. A team at the Jet Propulsion Laboratory (JPL) in Pasadena, CA in a 1982 report [11] said this about hot spots.

“Hot-spot heating is caused when the operating current level exceeds the reduced short-circuit current capability of an individual cell or group of cells in an array circuit. The reduced short-circuit current fault condition can be the result of a variety of causes including non-uniform illumination (local shadowing), individual cell degradation due to cracking or soiling, or loss of a portion of a series-parallel circuit due to individual interconnect or cell open circuits. Under one or more of these conditions the cell(s) carrying the excess current dissipate power equal to the product of the current and the reversed voltage that develops across the cell(s), which can heat the cell(s) to elevated temperatures.”

In 1984, another Jet Propulsion Laboratory team report [12] discussed using bypass diodes in PV modules to decrease the hot spot problem.

“Without the introduction of bypass diodes, this reverse voltage is only limited by the system voltage itself. However, with the introduction of bypass diodes, the maximum reverse voltage is limited to that generated by the number of series cells per diode.”

“Significant hot-spot heating occurs when shadows are large enough to cause the diode to conduct, and when there are cell strings with one or two shadowed cells.”
“In the tests described, with one diode per 24 cells, stressful heating was obtained without current imbalance and severe heating with imbalance. When one diode per 12 series cells was used, acceptable heating levels were achieved.”

A hot spot can permanently degrade the shaded cell power performance, crack the PV module glass, and destroy the encapsulation material. If the encapsulation material has a hole burned through it, then moisture can penetrate and corrode the module. Worst case, the hot spot could ignite flammable materials touching the cell.

If there is not an electrical load connected to the PV module, an open circuit, then a shaded cell will not form a hot spot because there is not any current flowing through the bypass diode. The exception would be if the diode is shorted out, then a hot spot could form.

C. Literature Survey Background

In addition to what was mentioned in the previous hot spot definition section, the Jet Propulsion Laboratory (JPL) in Pasadena, CA developed a test in which 3 cells in a PV module were instrumented and subjected to a cyclic hot-spot heating for 100 hours total on time.

“This test is intended to evaluate the ability of a module to endure the long-term effects of periodic hot-spot heating associated with common fault conditions such as severely cracked or mismatched cells, single-point open circuit failures, or non-uniform illumination.”[11]

Ronald G. Ross Jr., one of the coauthors of the 2 JPL reports [11], [12] from the 1980s discussed the hot spot reliability problem again 32 years later as one of many topics in a paper PV Reliability Development Lessons From JPL’s Flat Plate Solar Array Project, [13]

“Operating temperature also shares the top of the list by having an accelerating influence on nearly every failure mechanism including voltage isolation, corrosion, hot-spot heating, photo-thermal degradation of encapsulants, delamination, interconnect fatigue, and cell cracking.

The National Renewable Energy Lab (NREL) in Golden, Colorado published a technical report [10] in May 2012 in which two side-by-side PV identical arrays were used. The reference
PV array was connected to a standard string inverter to convert the PV array DC output power to 60 Hz AC power. The second PV array was connected to an inverter under test. Its output power was measured and compared to the standard inverter for numerous direct shading configurations. The shading was achieved by using fabric to cover part of the solar module. Several pieces of fabric, each with a different opacity from 7% to 50% were used one at a time. “For two-string PV systems in which one string is shaded and the other is unshaded, as little as 25% opacity shade on a single cell could be enough to cause that module’s bypass diode to begin conducting.”[10], [14].

In “Standard Test Method for Hot Spot Protection Testing of Photovoltaic Modules” in appendix B, figures 1 and 2 show the power which gets dissipated as heat in the reverse biased shaded cell as a rectangular area in the second quadrant of the I-V curve. The effect of one cell being shaded on the I-V curve is shown in Figure 3.

Unlike monocrystalline silicon solar cells, multicrystalline (polycrystalline) silicon solar cells instead of being a single crystal substrate have crystal grains of various sizes and orientations. Defects occur at the grain boundaries. A key point of the 2015 article “Combined Thermography and Luminescence Imaging to Characterize the Spatial Performance of Multicrystalline Si Wafer Solar Cells” [15] is on page 106 under Diode Breakdown Images. It discusses spatially resolved breakdown voltage images obtained in the reverse bias voltage operation using DLIT, dark lock-in thermography. There are three groups of breakdown voltages:

1. -16 to -17 volts is the most common breakdown type due to avalanche breakdown, which is due to a geometrically induced increase in the local electrical field.
2. -19 volts breakdown is due to metallic impurity elements and their associated energy levels.
3. -10 to -12 volts breakdown is correlated with regions of high diffusion current densities due to recombination active defects.

The article mentions hot spots.

“The device presented was irreversibly destroyed due to a large heating caused under reverse-bias. Imprecise edge isolation of this device is hypothesized to have imposed a large current flow through a small region (<1 mm<sup>2</sup>) of the device. For this reason, a low ohmic shunt path crossing the p-n junction appears in the cell … Similar cell breakdown incidents were observed with other solar cells studied, which means that the variation in the spatial conduction of a device leads to large current flows through small defects when a PV device is under reverse bias. It was observed that regions of concentrated reverse-current-generated hot spots would melt metallic paste through the p-n junction and contact the front grid to the back plate of the cell causing irreversible destruction of the device. Thus, a reverse-bias may lead to irreversible destruction of a solar cell where defects may cause concentrated current flows through the cell edges or the p-n junction.” [15]

The 17 solar cells in an 18 cell submodule shown in Figure 4 were previously calculated to produce up to -10.5 volts DC across a shaded solar cell. Some modules have 20 cell strings which by a similar calculation could produce a reverse bias voltage up to -11.7 to -12 volts DC. The higher the shunt (parallel) resistance of the solar cell, the higher the reverse bias voltage can be. Hence, the reverse bias voltage can reach one of the solar cell breakdown voltages.

The topic of solar module shading and the reduction in output power is discussed in the textbook “Renewable and Efficient Electric Power Systems” by G. Masters[16]. Calculations and graphs show the effect on the I-V curve for one cell being shaded and then for 2 cells being shaded. Example 8.6 shows that a 36 cell PV module which was producing 41.5 watts of output power had that drop to 10.1 watts when one cell was shaded, with 30.2 watts being dissipated as heat in the shaded cell. If 30 watts of power is dissipated in a small region, it can produce a hot spot. Hot spot simulations as a function of dissipated power are shown in Section IV.D Thermal Modeling and Simulations.

There are many additional papers on shading of solar cells and the potential for hot spot formation in a PV module, a few are listed in the REFERENCE section [17]-[23].
D. The Study of Hot Spot Formation

In the following chapters, the interactions taking place to create a hot spot on a solar cell in a non-uniformly illuminated solar PV module are explored. The results of monocrystalline and polycrystalline silicon photovoltaic solar cells tested in the lab under a solar simulator or in the dark are presented. FLIR infrared camera [24] hot spot thermal images and thermocouple (TC) measurements demonstrate that a hot spot can form when a solar cell is subjected to a reverse bias voltage.

Several pieces of test equipment were built to perform the tests. They are described along with the off the shelf test equipment and software that was used. In addition to the indoor lab tests, outdoor tests were performed on a PV module illuminated by sunshine. A key question is what pattern of shading of solar cells in a submodule has a high potential for creating a hot spot? Boards painted white were clamped to the PV module to create shading patterns. Thermal and electrical measurements were recorded outside in the sunshine on a polycrystalline silicon solar PV module test setup. IR images and thermocouples recorded the temperature of several solar cells and ambient while the PV module was being fully illuminated by solar radiation and then non-uniformly illuminated (shaded). Simultaneously, the output current versus output voltage (I-V) curve was recorded as the load resistance was increased to show the effect of full illumination or shade. Electrical measurements of the bypass diode in parallel with the partially shaded PV submodule were taken to show when the diode was turned off, and when it was turned on allowing current to bypass the solar cells in the submodule. A National Instruments Multisim [25] model and simulation was used to create an I-V curve. The lab and outdoor tests were compared to COMSOL MULTIPHYSICS [26] thermal simulations of hot spot power, diameter, and location.
CHAPTER II

PHYSICS OF A SOLAR CELL

The following sections will briefly discuss the solar radiation received at the earth, how a photovoltaic solar cell generates electricity and heat from the absorbed solar radiation, and the state of the art of commercially available solar cells.

A. Basic Physics of Solar Radiation

There are many benefits of using solar radiation as a source of power. The sun is:

- An incredible 865,000 mile (1.39 x 10⁶ km) diameter black body radiator with a surface temperature of 5760 K
- A stable radiator of 3.8 x 10²⁰ MW of electromagnetic power into the vacuum of space
- Powered by clean H₂ to He nuclear fusion, with no shortage of fuel
- A nuclear power source a safe 93 million miles (155 million km) away
- Immune to political embargos or price manipulation
- Immune to terrorist physical attack or cyber attack
- A provider of free solar energy delivered everyday around the earth

The solar intensity, also called irradiance, which is incident on the earth’s surface (also called insolation for incident solar radiation) is measured in watts per square meter (W/m²). On average the surface of the earth receives 174,000 TW (terawatts) of solar radiation power, or 174 x 10¹⁵ joules/sec in terms of energy per second. In comparison, the world energy consumption used by all of human civilization in terms of average power consumption was 12.3 TW in 2013[7](World energy consumption). Hence, the solar power received at the earth’s surface is about 14,000 times more than the power used by civilization. This demonstrates the benefit of
using free abundant solar energy as much as possible in place of costly fossil fuels to save money, reduce pollution, green house gases, and climate change.

It is common knowledge that the sun’s observed path across the sky varies with the time of day and day of the year. The angle of the sun above the horizon is known as its altitude. The azimuth angle of the sun is the angle with 0° being north and increasing in a clockwise manner. Thus 90° is east, 180° is south, and 270° is west. UCCS is located at latitude 38.89° N, longitude 104.80° W, and an elevation of about 1880 meters. Due to the UCCS latitude of 38.89° N, the sun varies within the altitude and azimuth angles shown in Table 1, which captures the extremes of the winter solstice typically December 21, and the summer solstice typically June 21. The solar noon altitude difference between maximum and minimum equals 74.6° - 27.7° = 46.9° as expected, which is twice the tilt of the earth’s spin axis with respect to the ecliptic plane. The ecliptic plane is the plane the earth moves in as it orbits the sun. A solar module which is at a fixed tilt position will have a wide range of angles for the incident solar radiation, which may affect the reflection and absorption of the solar radiation.

Table 1: Range of altitude and azimuth angles of incident direct beam solar radiation [27]

<table>
<thead>
<tr>
<th>Date</th>
<th>Sunrise</th>
<th></th>
<th>Solar Noon</th>
<th></th>
<th>Sunset</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Altitude</td>
<td>Azimuth</td>
<td>Altitude</td>
<td>Azimuth</td>
<td>Altitude</td>
<td>Azimuth</td>
</tr>
<tr>
<td>Winter solstice</td>
<td>0°</td>
<td>120°</td>
<td>27.7°</td>
<td>180°</td>
<td>0°</td>
<td>240°</td>
</tr>
<tr>
<td>Summer solstice</td>
<td>0°</td>
<td>59°</td>
<td>74.6°</td>
<td>180°</td>
<td>0°</td>
<td>301°</td>
</tr>
</tbody>
</table>

The solar radiation at the earth’s surface is a combination of direct beam, diffuse, and reflected radiation. Diffuse refers to the radiation which was scattered by molecules and aerosols (dust, smoke) in the atmosphere. Reflected refers to the radiation which bounces off the ground or other surfaces. Hence, on a cloudy day a lot of the direct beam radiation is converted into
diffuse radiation before it reaches the earth’s surface. The diffuse radiation is incident on the earth’s surface from any point in the sky, hence all altitude and azimuth angles. The top layer of a solar cell is typically an antireflection coating which is designed to minimize the reflectance, hence maximize the solar cell’s sunlight absorption, for the range of the solar radiation incident angles. The location of bluffs and mountains will block the sunlight at sunrise and sunset.

The solar irradiance in outer space at the edge of the earth’s atmosphere is greater than on the earth’s surface. The solar constant is defined as the direct solar irradiance measured at the top of the atmosphere on a surface perpendicular to the sun’s incident radiation. The solar constant has an average value of 1,366 W/m², and throughout the year varies from 1,412 W/m² in early January to 1,321 W/m² in early July due to the earth’s elliptical orbit around the sun. Sunspot activity can increase the solar irradiance by about 1.5%. To take into account the effect of the atmosphere on the attenuation of the direct solar beam electromagnetic radiation, airmass ratio numbers were developed. At the top of the atmosphere on the edge of outer space, the airmass ratio number is zero, abbreviated AM 0. The solar irradiance at AM 0 equals the solar constant of 1,366 W/m². Figure 5 shows when the sun is directly overhead at sea level the irradiance path length is one atmosphere thick and is called airmass ratio 1.0 or AM 1.0, with solar irradiance of 1040 W/m², which includes both direct and diffuse radiation.

\[
\text{air mass ratio} = \frac{\text{path length through atmosphere to a spot on earth's surface}}{\text{path length through atmosphere with sun directly overhead to a spot on surface}}
\]

An equivalent formula is airmass ratio (AM) = 1/(sin(\(\beta\))) where \(\beta\) is the altitude angle of the sun above the horizon. In Figure 5, \(\beta = 90° - 60° = 30°\), airmass ratio AM = 1/sin (30°) = 2. The airmass ratio changes as the sun moves through the sky. \(\beta = 41.8°\) for AM 1.5, which is often used as an average solar spectrum at the earth’s surface for the continental USA, with solar irradiance of 970 W/m².
Figure 5: As the air mass ratio (AM) increases, the atmospheric attenuation increases for solar radiation incident on a solar PV module [28].

The atmosphere absorbs solar radiation depending on its wavelength. Figure 6 shows the solar radiation spectrum of spectral irradiance as a function of photon electromagnetic wavelength, and marks the UV, visible, and infrared regions. The sunlight at the top of the atmosphere spectrum (AM 0) has the greatest magnitude as expected. The radiation at sea level spectrum is attenuated and has dips where O$_3$, H$_2$O and CO$_2$ in the atmosphere absorb certain wavelengths. At AM 1.5 the solar radiation spectrum consists of 2% in the UV range, 54% in the visible range, and 44% in the infrared range. Near sunrise and sunset, the airmass increases beyond 20 as the solar radiation travels through a lot more atmosphere. This increases attenuation of the solar radiation. Since the shorter wavelengths are attenuated more than the longer wavelengths, this shifts the solar radiation spectrum towards the longer wavelengths making the sky look red. Clouds also attenuate the solar radiation and shift the spectrum.
Figure 6: Solar radiation spectrum range is from 250 nm to 2,500 nm [28]

The National Renewable Energy Laboratory (NREL) located in Golden, Colorado considers optical radiation to range from 250 nm to 2,500 nm; it includes the ultraviolet (250-400 nm), visible (400-750 nm), near infrared (750-1,100 nm), and shortwave infrared (1,100-2,500 nm) ranges. These ranges include almost all of the solar radiation.

In Table 2 the energy (E) of solar radiation electromagnetic wave photons are listed for several optical wavelengths λ in nm and can be computed using equation (1) where h is Planck’s constant of $4.1357 \times 10^{-15} \text{eV} \cdot \text{s}$, c is the speed of light of $2.9979 \times 10^8 \text{m/s}$, and $\nu$ is the frequency of the electromagnetic wave in Hz.

$$E = h\nu = hc/\lambda = 1,239.8 \text{ eV nm}/\lambda \quad (1)$$
The photon energies range by a factor of 10 from 0.50 eV to almost 5.0 eV. Ultraviolet (UV) radiation photons have the most energy and infrared (IR) photons have the least. This is just a small section of the electromagnetic wave spectrum which include frequencies < 3 Hz for geophysical prospecting to > $10^{22}$ Hz for cosmic rays. In between in increasing frequency are AC power, AM radio, FM radio, TV channels, radar, infrared, visible, ultraviolet, x-rays, γ-rays, and cosmic rays. The electromagnetic spectrum has been extensively studied.

Table 2: Photon energy computed for several solar radiation wavelengths.

<table>
<thead>
<tr>
<th>Electromagnetic Wave</th>
<th>Wavelength Range</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet</td>
<td>250 nm to 400 nm</td>
<td>4.96 eV to 3.10 eV</td>
</tr>
<tr>
<td>Visible</td>
<td>400 nm to 750 nm</td>
<td>3.10 eV to 1.65 eV</td>
</tr>
<tr>
<td>Near Infrared</td>
<td>750 nm to 1,100 nm</td>
<td>1.65 eV to 1.13 eV</td>
</tr>
<tr>
<td>Shortwave Infrared</td>
<td>1,100 nm to 2,500 nm</td>
<td>1.13 eV to 0.50 eV</td>
</tr>
</tbody>
</table>

The wavelength $\lambda_{\text{max}}$ at which the monochromatic blackbody emissive power $E_{\text{b}\lambda}$ (W/m$^3$) is at a maximum for a black body radiator at a temperature $T$ can be calculated using Wien’s displacement law, see equation (2).

$$\lambda_{\text{max}} T = 2898 \text{ um K}$$  \hspace{1cm} (2)

Using this equation, the sun at 5,760 K would therefore emit the most power $E_{\text{b}\lambda}$ at

$$\lambda_{\text{max}} = \frac{2898 \text{ um K}}{T} = \frac{2898 \text{ um K}}{5,760K} = 0.503 \text{ um} = 503 \text{ nm}$$  \hspace{1cm} (3)

The calculated emissive power peak at 503 nm agrees with the wavelength for the peak spectral irradiance of the solar radiation spectrum in Figure 6.
B. Photovoltaic Generation of Electricity

This section gives a brief history and discussion of how optical photons interact with a photovoltaic material to produce electricity. Each of the mentioned topics has been discussed extensively in numerous physics, material science, chemistry, and electrical engineering books, several of which are mentioned in the Bibliography.

The first observation of the photovoltaic effect was credited to Edmund Becquerel, who in 1839 observed that in the presence of light a silver coated platinum electrode immersed in an acidic solution produced an electric voltage and current. In a solar cell, the photovoltaic effect occurs in a solid state device. The first silicon p-n junction solar cell was developed at Bell Telephone Laboratories, Inc. in Murray Hill, New Jersey in 1954 by D. M. Chapin, C. S. Fuller, G. L. Pearson, and M. B. Prince. It had an efficiency of 6% for converting solar radiation into electricity. The photovoltaic effect should not be confused with the photoelectric effect.

In 1905 Albert Einstein published a theoretical paper about the photoelectric effect explaining experimental data that UV light incident on a metal surface caused an electron to leave the surface. He concluded that light consists of individual particles called photons. Each photon has an energy \( E = h \nu = hc/\lambda \) as previously discussed for equation 1. Einstein was awarded the Nobel Prize in physics in 1921.

Maxwell’s set of 4 equations (4-7) describe classical electromagnetism, electromagnetic radiation such as light and radio waves, and electrical circuits.

\[
\begin{align*}
\text{Faraday's law of induction:} & \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (4) \\
\text{Gauss’s law for electricity:} & \quad \nabla \cdot \vec{D} = \rho \quad (5) \\
\text{Generalized Ampere’s law:} & \quad \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (6) \\
\text{Gauss’s law for magnetism:} & \quad \nabla \cdot \vec{B} = 0 \quad (7)
\end{align*}
\]
The vectors are defined as: $\vec{E}$ is electric field, $\vec{D}$ is electric flux density, $\vec{B}$ is magnetic field, $\vec{H}$ is magnetic field intensity, $\vec{J}$ is electric current density, and $\vec{p}$ is electric charge density.

Lorentz force law $^8$ describes the force on a charge in an electric field or moving with a velocity $\vec{v}$ through a magnetic field.

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$  \hspace{1cm} (8)

The constitutive relations $^9$-$^{11}$ relate the fields in the presence of a material media, without polarization or magnetization. The material medium has these properties: $\varepsilon$ is the permittivity, $\mu$ is the permeability, and $\sigma$ is the electrical conductivity.

$$\vec{D} = \varepsilon \vec{E}$$  \hspace{1cm} (9)

$$\vec{H} = \frac{1}{\mu} \vec{B}$$  \hspace{1cm} (10)

$$\vec{J} = \sigma \vec{E}$$  \hspace{1cm} (11)

A photon, electron, or other elementary particle in some situations has to be described as a wave, in other situations as a particle, and in the remaining situations as either a wave or a particle. Many physicists and mathematicians worked on this problem, and arrived at the wave-particle duality concept to explain electrons, photons, and other elementary particles behavior.

Quantum mechanics is used to study the behavior of elementary particles. The following 4 key equations $^{12}$-$^{15}$ are some of the equations used in its calculations. The De Broglie equation $^{12}$ is used to find the wavelength $\lambda$ of a particle with momentum $p$. This wavelength is not an electromagnetic wave. Prince Louis-Victor de Broglie was awarded the Nobel Prize in physics in 1929.

$$\lambda = \frac{h}{p} \therefore p = \frac{h}{\lambda} = \frac{h}{2\pi} \frac{2\pi}{\lambda} = \hbar, \text{ where } \hbar = \frac{h}{2\pi}, \text{ and } k = \frac{2\pi}{\lambda}$$  \hspace{1cm} (12)
Electrons orbit a nucleus so quickly that there is uncertainty in their location and momentum. The Heisenberg uncertainty principle inequality (13) states the measurement limit $\frac{\hbar}{2}$ for simultaneously knowing the standard deviation of position $\sigma_x$, and the standard deviation of momentum $\sigma_p$. If the product of position $\sigma_x$ and momentum $\sigma_p$ is almost $\frac{\hbar}{2}$, then improving the position measurement certainty, (its standard deviation decreases), is at the expense of the momentum measurement certainty, (its standard deviation must increase). Werner Heisenberg was awarded the Nobel Prize in physics in 1932.

$$\sigma_x \sigma_p > \frac{\hbar}{2}$$  \hspace{1cm} (13)

The wave function $\Psi(x, y, z, t)$ of a particle is found from the Schrödinger equation (14) where $V$ is the potential energy, $m$ is the mass of the particle, and $i = \sqrt{-1}$. In quantum theory, the state of a system is represented by its wave function. Erwin Schrödinger and Paul Dirac were awarded the Nobel Prize in physics in 1933.

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right) + V\psi(x, y, z, t)$$  \hspace{1cm} (14)

The probability $P$ of finding the particle between points $a$ and $b$ at time $t$ is given by Max Born’s statistical interpretation of the wave function, which is given in equation (15) for 1D. Inside the integral, the complex conjugate of the wave function is multiplied by the wave function for doing the calculation. Max Born was awarded the Nobel Prize in physics in 1954.

$$P = \int_a^b |\psi(x, t)|^2 \, dx = \int_a^b \psi^*(x, t) \psi(x, t) \, dx$$  \hspace{1cm} (15)

Silicon Si is a semiconductor used in solar cells, with an atomic number of 14, and an atomic mass of 28.09 u. It has 14 electrons orbiting the nucleus, which contains 14 protons and 14 neutrons for the predominant mass 28 isotope. Quantum mechanics has rules for assigning 4 quantum numbers to an atom, which for silicon have the following ranges:
Each of the 14 electrons orbiting the silicon atom has its unique set of quantum numbers. For the silicon atom, the discrete energy levels and electron probabilities can then be calculated and the 5 orbital shells visualized. Orbital shells are labeled with n and l quantum numbers: 1s, 2s, 2p, 3s, and 3p. Each of the 14 electrons orbits the nucleus at high velocity; its orbital shell shows the region outside the nucleus in space where the electron is located. The electrons configuration tells the number of electrons in each of the silicon atom’s 5 orbitals. 1s (orbital) has 2 (electrons), 2s has 2, 2p has 6, 3s has 2, and 3p has 2. The 3p orbital has room for 4 more electrons. The 1s orbital electrons are closest to the silicon nucleus. The 3s and 3p orbital electrons are furthest from the silicon nucleus, and are called the valence electrons.

The valence electrons can make covalent bonds with other atoms. Crystalline silicon material has a diamond cubic lattice structure with 5 x 10^{22} silicon atoms /cm³. Figure 7 (a) shows a silicon atom using its 4 valence electrons to form 4 covalent bonds with 4 adjacent silicon atoms in a tetrahedral formation. The 3s and the 3p orbitals hybridize to form 4 tetrahedral sp³ orbitals. Each covalent bond has 2 valence electrons, 1 from each of the 2 bonded silicon atoms. This sharing of electrons allows each silicon atom to fill its outer shell of sp³ orbitals with 8 electrons. Filling each atom's outer shell makes intrinsic (pure) silicon into an electrical insulator, with a free electron concentration of 1.5 x 10^{10}/cm³ at 300 K. The small free electron concentration is due to thermal energy breaking some covalent bonds. These bonds are strong giving silicon a melting point of 1415 °C. In Figure (b) the unit cell is outlined by black lines with a lattice constant of 0.54 nm (length of cube edge) and a distance of 0.235 nm between neighboring atoms. The unit cell repeats to fill the silicon crystal volume.
There is a higher energy band above the valence band called the conduction band. The minimum energy between the valence band energy $E_v$ and the conduction band energy $E_c$ is called the band gap energy $E_g$. Hence $E_g = E_c - E_v$. Silicon has an $E_g = 1.11$ eV at a room temperature of 300 K, that rises to 1.16 eV at 0 K. When sunlight (solar radiation) is incident on the front of a solar cell, an interaction between the solar radiation photon and the silicon of the solar cell may occur. If the energy of the photon is $> 1.11$ eV ($E_g$), corresponding to a wavelength $< 1117$ nm, then an electron in the silicon atom can gain this photon energy and be promoted from the valence band to the conduction band. Once in the conduction band the electron is free to move around the silicon lattice. The silicon atom which lost an electron now has a net (+) charge called a hole with symbol $h^+$ in its valence band. This interaction of the photon with the silicon atom is said to have created an electron-hole pair (EHP). When free electrons created in this manner are collected, they create the output current of the solar cell.

Every crystal structure can be represented by 2 lattices, the crystal lattice and the reciprocal lattice. Crystals can be studied by looking at the diffraction pattern of photons, electrons, or neutrons. The diffraction pattern of a crystal is a map of the crystal’s reciprocal lattice, which has dimensions of 1/length. In quantum mechanics wave vectors $\vec{k}$ are always drawn in this reciprocal space, sometimes called k-space. There are 3 orthogonal axis in k-space:
\( k_x, k_y, \text{ and } k_z \). The first Brillouin zone of a lattice is the region in \( \vec{k} \) space between \(-\pi/a\) and \(+\pi/a\), where \( a \) is the spacing between planes of atoms in a given direction.

The atoms in a crystal have a periodic structure, which makes the potential energy periodic. When there is a periodic potential energy, the Bloch theorem can be applied to the Schrödinger equation (14) to give a solution for the wave function in the form of a Bloch function. An electron is affected by the periodic potential energy from the other atoms in the silicon lattice. The potential energy also depends on the direction in the lattice. The electron energy is no longer limited to discrete energy levels, because they become split to form bands, the valence band or the conduction band. The electron and the hole also have an effective mass \( m^* \) which can be greater or less than their rest mass, due to the lattice interactions. The effective mass \( m_e^* \) of an electron near the minimum of the conduction band, and \( m_h^* \) of a hole near the maximum of the valence band [31] are given in equation (16).

\[
\frac{1}{m_e^*} = \frac{1}{\hbar^2} \frac{\partial^2 E_e(k)}{\partial k^2}, \quad \frac{1}{m_h^*} = -\frac{1}{\hbar^2} \frac{\partial^2 E_h(k)}{\partial k^2}
\]

(16)

The parabolic relationship for a free electron in space between energy \( E \) and momentum \( p \) is given by equation (17).

\[
E(k) = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}, \quad \text{where } p = \hbar k, \quad \text{and } k = \frac{2\pi}{\lambda}
\]

(17)

In a crystal, a slightly different parabolic relationship exists, where the effective mass and a momentum offset \( p_0 \) are used due to the periodic force of the lattice atoms [32]. For electrons near the conduction band minimum \( E_c \), the relationship is given by equation (18).

\[
E(k) - E_c = \frac{(p - p_{0c})^2}{2m_e^*} = \frac{\hbar^2 (k - k_{0c})^2}{2m_e^*}
\]

(18)

For holes near the valence band maximum energy \( E_v \), the relationship is given by equation (19).
An important diagram to use for looking at the conduction and valence bands is the energy vs. k wave vector (E vs. k) graph shown in Figure 8. This graph was created by using the first Brillouin zone in reciprocal space. Since the electron crystal momentum $p$ is related to $k$, the E vs. k graph is also called the energy vs. crystal momentum graph. Figure 8 depicts the bandgap $E_g$ on a rough sketch of the E vs. k diagram. As mentioned previously, the bandgap energy $E_g = E_c - E_v = 1.11$ eV for silicon at a room temperature of 300 K. Silicon is an indirect bandgap material, which means that the lowest energy at the bottom of the conduction band has a momentum offset from the highest energy at the top of the valence band. Hence, in equations (18) and (19), $p_{0c} \neq p_{0v}$, and this indirect bandgap offset is shown in Figure 8. The (-) signs represent electrons in the conduction band. The (+) signs represent holes in the valence band. Germanium Ge is another important indirect bandgap semiconductor.

\[
E_v - E(k) = \frac{(p - p_{0v})^2}{2m_h^*} \quad \text{(19)}
\]

Figure 8: Silicon indirect band gap between valence band and conduction band
An infrared IR photon with $\lambda = 1117$ and energy of 1.11 eV can promote an electron from the top of the valence band to the bottom of the conduction band as shown by the dashed arrow for path B in Figure 8. The momentum $p$ of a photon is very small, $p = E/c$. Due to the indirect bandgap, a phonon (lattice vibration of ~ 0.01 to 0.03 eV) is needed to give the required momentum needed to make up for the horizontal offset in k-space. If a phonon of the needed momentum is not available, then the photon does not create an EHP. Hence, this photon may on average have to travel up to 100 microns into the silicon crystal before it can interact with a phonon with the needed momentum to create an EHP. This is why silicon solar cells are made 200 um or thicker in order to capture the photons and make EHP. Photons with less than the 1.11 eV bandgap energy cannot promote an electron from the valence band to the conduction band. These photons if absorbed in the silicon or in impurities in the silicon will have their energy converted into heat.

An ultraviolet UV photon with $\lambda = 300$ nm and energy of 4.13 eV can easily promote an electron from the valence band to the conduction band as shown by the dashed arrow for path A. It has enough energy that whatever phonon it interacts with, it will make it into the conduction band. Hence, UV photons do not travel far into the silicon to be absorbed. Since they are frequently absorbed near the silicon surface, the conductance band electron produced is frequently captured by defects at the surface interface. This can lead to recombination of the electron with a hole, and prevent that electron, also called a charge carrier, from being part of the solar cell output current. If the electron does not suffer recombination, then it will undergo thermalization where it gives up some of its energy as heat and settles near the lower energy level of the conduction band.

A direct bandgap material such as GaAs, CdTe, or CIGS does not have an offset in momentum between the bottom of the conduction band and the top of the valence band. Direct bandgap materials absorb light easily since a phonon is not involved. Solar cells made of these
materials can then be made as thin films about 10 microns thick, which is deposited typically on a glass substrate. Direct bandgap materials are also used for making LEDs, since an injected electron can move from the conduction band to combine with a hole in the valence band without needing a phonon, and give off a visible light photon.

The number of electrons which can be promoted across the bandgap in a volume $V$ is determined by the density of energy states, also called density of states DOS. The calculation for the conduction band DOS concentration $N(E)$ as a function of energy is given by equation (20). For silicon at 300K, the effective density of states in the conduction band is $2.8 \times 10^{19}/\text{cm}^3$, and in the valence band is $2.65 \times 10^{19}/\text{cm}^3$.

$$N(E) = \frac{V}{4\pi^2} \left(\frac{2m}{\hbar^2}\right)^{3/2} E^{1/2}$$

(20)

The Fermi-Dirac distribution function $f(E)$ is the probability that a certain energy state is occupied by electrons, and is calculated by equation (21). Enrico Fermi was awarded the Nobel Prize in Physics in 1938. $E_F$ is the Fermi energy. When $f(E)$ is evaluated at the Fermi energy, $f(E_F) = \frac{1}{2}$. For intrinsic silicon, the Fermi energy is half way between the valence band and the conduction band because there are the same number of electrons in the conduction band as holes in the valence band. At $T = 0.01K$, $f(E) = 0$ for $E > E_F$, and $f(E) = 1$ for $E < E_F$, which shows that at a temperature at almost 0 K, there are not any electrons in the conduction band.

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{k_B T}\right) + 1}$$

(21)

Any energy state in the conduction band can hold 0, 1, or 2 electrons. If there are 2 electrons in an energy state, then the Pauli Exclusion Principle requires that one electron have positive spin and the other electron must have negative spin. The energy gap $E_g$ between $E_V$ and $E_C$ is the forbidden region, which contains no energy states. The concentration of electrons in the conduction band at a given energy is the product of the Fermi-Dirac distribution function $f(E)$, the
density of states $N(E)$ at that energy, and a multiplier of 2 electrons per energy state due to the Pauli Exclusion Principle. The total concentration of electrons $n$ in the conduction band is given by equation (22).

$$n = \int_{E_c}^{\infty} 2f(E)N(E)dE$$

At equilibrium, the concentration of electrons $n$, and holes $p$ is related to the intrinsic carrier concentration $n_i$ ($9.65 \times 10^9 \text{[1/cm}^3\text{]}$ at 300 K) by the law of mass action in equation (23).

$$np = n_i^2$$

Pure intrinsic silicon is an electrical insulator. To make silicon into a semiconductor it is doped typically with boron, phosphorus or arsenic to increase its electrical conductivity. P-type silicon is doped with boron, which has 3 electrons in its valence band, to increase the hole concentration $p$, which are the majority carriers, and decrease the electron concentration $n$, which are the minority carriers. Boron is an electron acceptor atom, which ionizes. In p-type material the majority carrier hole concentration $p$ almost equals the boron concentration $N_A$. Equation (23) can be used to find the minority carrier electron concentration $n$ shown in equation (24).

$$n = n_i^2/N_A, \quad p \approx N_A$$

Similarly, for solar cells, n-type silicon is doped with phosphorus, which has 5 electrons in its valence band, to increase the electron concentration $n$, which are the majority carriers, and decrease the hole concentration $p$, which are the minority carriers. Phosphorus is an electron donor atom, which ionizes. In n-type material the majority carrier electron concentration $n$ almost equals the phosphorus concentration $N_D$. Equation (23) can be used to find the minority carrier hole concentration $p$ shown in equation (25).

$$p = n_i^2/N_D, \quad n \approx N_D$$
Figure 9 shows a diagram of a cross section view of an illuminated silicon photovoltaic solar cell. The absorbed light enters across the entire front surface area and creates electron hole pairs EHPs for photons with energy > 1.11 eV, the bandgap energy $E_g$. The electron hole pairs inject carriers: electrons to the conduction band and holes to the valence band, and increase their concentration above their equilibrium values. The solar cell is designed with a p-n junction to separate electrons from holes, transport electrons through the n-type emitter to the busbar grid negative voltage terminal, and transport holes through the p-type base to the positive voltage terminal.

The p-type Si base on the bottom is 200 um thick. It has a boron doping concentration near $1 \times 10^{16}$ /cm$^3$. The much thinner n-type Si emitter above the base is 0.5 um thick. It has a phosphorus high doping concentration near $1 \times 10^{19}$ /cm$^3$. At the semiconductor junction between the base and emitter, the electron concentration $n$ is equal to the hole concentration $p$.

Figure 9: Solar cell diagram with solar radiation illumination (drawing not to scale)
See section III A. for more info on process steps to make a solar cell. Above and below the junction is the depletion region, also called the space charge region, with a depletion width (thickness) $W_d$ calculated by equation (27). The space charge was formed by the diffusion and drift of charge carriers, calculated by equations (28) and (29). Electrons diffuse from their high concentration in the emitter to the lower concentration in the base. Likewise, holes diffuse from their high concentration in the base to the lower concentration in the emitter. When an electron leaves its donor phosphorus atom on the emitter side, the phosphorus atom then has a fixed (+) charge. Likewise, when a hole leaves its boron acceptor atom on the base side, the boron atom then has a fixed (−) charge. Figure 9 shows the fixed charges in the depletion region which created the electric field and the built in voltage $V_{bi}$ barrier, calculated by equation (26). The electric field causes electrons to drift from the base to the emitter, which is opposite to the electron diffusion current. Similarly, holes drift from the emitter to the base, which is opposite to the hole diffusion current. Hence the drift current balances out the diffusion current to establish equilibrium. In equilibrium the depletion region is depleted of mobile charge carriers.

The built in voltage $V_{bi}$ potential across the depletion region is given by equation (26).

$$V_{bi} = \frac{k_B T}{q} \ln \left( \frac{N_D N_A}{n_i^2} \right) \quad (26)$$

The depletion width $W_d$ of the space charge region is given by equation (27).

$$W_d = \sqrt{\frac{2\varepsilon_{Sl}}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) V_{bi}} \quad (27)$$

The current density $J_n$ due to electron drift and diffusion is given by equation (28) where $\mu_n$ is the electron mobility, and $D_n$ is the electron diffusion coefficient.

$$\vec{J}_n = q n \mu_n \vec{E} + q D_n \nabla n \quad (28)$$
The current density $J_p$ due to hole drift and diffusion is given by equation (29) where $\mu_p$ is the hole mobility, and $D_p$ is the hole diffusion coefficient.

$$J_p = q\mu_p E - qD_p \nabla p,$$  \hspace{1cm} (29)

The current density $J$ due to drift and diffusion of electrons and holes is given by equation (30) which combines equations (28) and (29). For one dimension, $J$ is given by equation (31)

$$j = \sigma E + qD_n \nabla n - qD_p \nabla p,$$ \hspace{1cm} where $\sigma = qn\mu_n + qp\mu_p$ \hspace{1cm} (30)

$$\dot{j} = \sigma \dot{E} + qD_n \frac{dn}{dx} - qD_p \frac{dp}{dx}$$ \hspace{1cm} (31)

Diffusion and drift both make charge carriers move, and it turns out are related to each other for nondegenerate semiconductors by the Einstein relation given in equation (32).

$$\frac{D_n}{\mu_n} = \frac{kT}{q}, \text{electrons;} \quad \frac{D_p}{\mu_p} = \frac{kT}{q}, \text{holes;} \quad \frac{kT}{q} = 0.026 \text{ volts at 300 K}$$ \hspace{1cm} (32)

Using equation (32) to substitute for the diffusion coefficients in equation (31) creates equation (33) which includes temperature. Electron and hole diffusion currents increase in magnitude with temperature, changing the net current density $J$ with temperature.

$$\dot{j} = \sigma \dot{E} + \mu_n kT \frac{dn}{dx} - \mu_p kT \frac{dp}{dx}$$ \hspace{1cm} (33)

Recall that the higher energy photons can be absorbed by silicon easier than low energy ones. Hence in Figure 9, the UV photons will create EHPs in the emitter, while IR photons will create EHPs near the bottom of the base. Photons with energy $< 1.11$ eV bandgap energy, will not make EHP pairs, but will generate heat if absorbed. When EHP created electrons and holes diffuse towards the depletion region, minority charge carriers will be swept across by the electric field, while majority charge carriers will be blocked by the electric field. Hence electrons and holes are separated from each other. Electrons go to the n-type emitter. Holes go to the p-type
base. If there is an electrical load connected to the solar cell, as shown in Figure 9, then the illuminated solar cell becomes a current source and pushes electrons out of the (-) negative terminal, through the load, and back to the (+) terminal of the solar cell where they recombine with holes in the p-type base. The most current flows through a short circuit (0 ohm) electrical load. If the load resistance is increased, then the output voltage will increase from 0 volts. As this voltage increases, the p-n junction of the solar cell, which is a diode becomes forward biased and conducts an internal current, which reduces the available output current. If the load is removed, then the solar cell produces the maximum output voltage called open circuit voltage $V_{oc}$ with no output current; all of the current produced by the solar cell is being conducted across the p-n junction diode inside the solar cell. This load effect produces the I-V curve graph discussed in section III-4.

For light incident on a surface, the sum of its absorptivity $\alpha$, reflectivity $\rho$, and transmissivity $\tau$ must equal 1 as shown in equation (34). Reducing the reflection from the surface of the solar cell by using an antireflection coating, and making the solar cell thickness large enough to avoid transmission through the solar cell, increases the absorption of solar radiation. A solar cell is a large area diode. The larger the surface area, the more solar radiation can be captured and electricity produced. Minimizing the size of the electrical current finger and busbar grid on the front surface allows more light to be absorbed by the solar cell.

$$\alpha + \rho + \tau = 1$$  \hspace{1cm} (34)

The continuity equations for electrons (35) and holes (36) are used to look at the time dependent phenomena affecting charge carriers, such as generation $G$ of electron hole pairs by optical photons, recombination $U$, and net electrical current in and out of the solar cell.

$$\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q} \nabla \cdot \vec{j}_n$$  \hspace{1cm} (35)
The generation of charge carriers in silicon in the dark is from thermal energy breaking bonds and creating electron hole pairs. This is the basis of the equilibrium concentration of electrons \( n \) and holes \( p \) in intrinsic silicon with a low carrier concentration \( n_i \) of \( 9.65 \times 10^9 \) \([1/cm^3]\) at 300 K. Illuminated silicon can produce an EHP for each photon which has energy greater than the 1.11 eV bandgap energy. Sunlight, solar radiation, has approximately \( 10^{19} \) photons for an irradiance of 1000 W/m\(^2\). The quantum efficiency is the probability that a photon will deliver an electron to the solar cell external load. The EHP generated electrons and holes have a lifetime \( \tau \) of about 2 us in poly c-Si and 10 us in mono c-Si solar cells. The lifetime is shorter in poly c-Si due to recombination of electrons and holes at grain boundaries.

In indirect bandgap silicon, when an electron descends from the conduction band to the valence band it recombines with a hole and releases energy as heat. In comparison, in direct bandgap GaAs, when the electron descends from the conduction band to recombine with a hole in the valence band the energy is released as a photon in a process called radiative recombination. This process is used by LEDs to produce visible light. Other recombination processes that occur in silicon are auger recombination, recombination at traps, and recombination at surfaces. Traps are defects in the silicon due to broken bonds at the surface interface or at grain boundaries in poly c-Si. Impurities can collect at the trap sites and cause an electron to recombine with a hole. 

\[ \frac{\partial p}{\partial t} = G_p - U_p + \frac{1}{q} \mathbf{v} \cdot \mathbf{J}_p \]  

(36)

\( \text{SiO}_2 \) is grown on the front surface of silicon to decrease surface defects compared to bare silicon. This reduces dangling bonds and decreases recombination. Four important parameters when dealing with recombination are: the minority carrier lifetimes \( \tau_n \) for electrons and \( \tau_p \) for holes, with units of seconds, and the carrier diffusion length \( L_n \) for electrons, and \( L_p \) for holes with units of cm. The minority carrier lifetime is the exponential decay time of recombination of minority carriers. The diffusion length is the average distance a carrier diffuses before recombining. The calculation of diffusion length is given in equation (37).
A silicon solar PV cell is a large area diode; therefore, understanding the diode equation is very useful. The ideal diode equation, also called the Shockley equation is given in equation (38) in terms of current $I$, or current density $J$. $I_0$, $J_0$ are the reverse saturation current in a p-n junction. The ideality factor $n$ determines the deviation from the ideal diode performance, and can take on any value in the range of 1 to 2. For an ideal diode, $n = 1.0$. Figure 10 shows a typical looking graph of the diode equation. Five different values were chosen for $n$: 1.90, 1.92, 1.94, 1.96, and 2.00. The forward bias current decreases as the ideality factor $n$ increases as expected, since a higher value of $n$ could indicate a higher recombination rate. For a given bias voltage, the diode current depends on the values chosen for $I_0$ and $n$ per equation (38).

$$I = I_0 \left( e^{qV/nkT} - 1 \right), \text{ or } J = J_0 \left( e^{qV/nkT} - 1 \right)$$  

\[ L_n = \sqrt{D_n \tau_n}, \; L_p = \sqrt{D_p \tau_p} \]  

(37)

Figure 10: Diode curve simulation for a forward bias voltage with $I_0 = 10 \text{ ua}$, and $n$ varied.
The reverse saturation current $I_0$ for a typical diode may be 1 nA. $I_0$ was picked to be 10 uA since the solar cell area may be 10,000 times a diode junction area, which would probably increase the reverse saturation current by a factor of 10,000. From equation (38) it can be seen that for a given bias voltage, the diode current depends on the values chosen for $I_0$ and $n$. For a reverse bias voltage, the diode current saturates at $-I_0$, or $-J_0$. In a solar cell, shunt resistance from the front of the solar cell to the back will cause the diode current to become more negative as the reverse bias voltage is increased. The generation and recombination of charge carriers in the depletion region can affect the value of $I_0$. A detailed equation for the reverse current density $J_R$ is given in equation (39), which is from page 97 of a book by S. M. Sze, and K. K. Ng listed in the bibliography. The term $\tau_g$ is the generation lifetime

$$J_R = q \frac{\frac{D_p}{\tau_p} \frac{n_i^2}{N_D} + \frac{q n_i W_D}{\tau_g}}$$  \hfill (39)

A basic schematic model for a solar cell is shown in Figure 11. It is called the single diode model. Sunlight absorbed by the solar cell creates the photocurrent $I_{ph}$, which is represented as current source $I_1$. The p-n junction is represented by diode $D1$. The shunt resistance $R_{sh}$ is between the (+) and (-) voltage terminals on the solar cell; it can drain some of the power and reduce the efficiency of the solar cell. The series resistance $R_s$, from the p and n junctions to their output terminals, drops the voltage and reduces the solar cell efficiency. The design tries to minimize $R_s$. The load resistance $R_L$ receives the output power from the solar cell. The electrical load resistance could be for example a battery charger, an LED light, etc. The output current equation for the single diode model for the solar cell shown in figure 11 is given in equation (40). Please refer to section IV.C. which has numerous discussions and electrical model simulations of solar cells and solar modules.

$$I = I_{sc} - I_0 \left( e^{\frac{q(V+I \cdot R_s)}{n k T}} - 1 \right) - \left( \frac{V+I \cdot R_s}{R_{sh}} \right)$$  \hfill (40)
Figure 11: Solar cell single diode model

A shaded solar cell in a solar PV module may have a reverse bias voltage applied to it by solar cells illuminated by sunlight in its submodule. Figure 12 is a diagram of this reverse bias voltage, which as previously mentioned could easily be over 10 volts DC, being applied across the solar cell. Breakdown results measured on a poly c-Si solar cell are given in section IV.A.

Figure 12: Reverse bias voltage stress may cause a voltage breakdown during shading.
The efficiency $\eta$ is a very critical measurement of the performance of a solar cell and a solar module. The efficiency is the ratio of the maximum output electrical power $P_{\text{mpp}}$ divided by the incident solar radiation power $P_s$, expressed as a percentage. In 1961 William Shockley and Hans-Joachim Queisser at Shockley semiconductor calculated that the maximum theoretical efficiency of a solar cell using one p-n junction at standard test conditions STC is 33.7% at a bandgap of 1.34 eV. The standard test conditions use an AM 1.5 solar spectrum. This famous calculation is referred to as the Shockley – Queisser limit. For silicon, the maximum theoretical efficiency is about 29% due to its bandgap energy of 1.11 eV. The lost energy is converted to heat as discussed in the next section II.C. The efficiency calculation is given in equation (41). Figure 27 has a graph which shows what the various terms like $I_{\text{MPP}}$, etc. mean.

$$\eta = \frac{P_{\text{mpp}}}{P_s} = \frac{I_{\text{MPP}}}{I_{\text{SPP}}} = \frac{I_{\text{SCV}_{\text{OCFF}}}}{P_s}, \text{where fill factor } FF = \frac{I_{\text{MPP}}}{I_{\text{SCV}_{\text{OC}}}} \quad (41)$$

Another efficiency term is called quantum efficiency, which is the probability that a photon of a given wavelength will deliver an electron to the solar cell output. It is measured for each wavelength of the solar spectrum.

C. Generation of Heat

There are many sources of heat generation in an operating silicon solar PV module. Refer back to the Figure 6 solar radiation spectrum with a range from 250 nm to 2,500 nm. If the energy of the photon is $> 1.11$ eV ($E_g$), corresponding to a wavelength $< 1117$ nm, then an electron in the silicon atom can gain this photon energy and be promoted from the valence band to the conduction band, and an electron hole pair EHP is created. On the other hand, all of the solar radiation photons with wavelengths from 1,118 to 2,500 nm do not create an EHP, but generate heat when absorbed, amounting to 23% of the incident solar radiation power.
Since silicon is an indirect bandgap semiconductor, most electrons which fall in energy to recombine with holes in the valence band give up that energy as heat.

Figure 13 shows the electrons in the conduction band with energy greater than the band gap energy is scattered to a lower energy state near the conduction band edge above 1.11 eV ($E_g$). This energy loss to thermalization generates heat. A similar process happens with holes falling back to their valence band gap edge. The total thermalization of holes and electrons to their band edge generates heat amounting to 33% of the incident solar radiation power.

![Wave vector (crystal momentum)](image)

**Figure 13: Thermalization of electrons with energy greater than $E_g$ to the conduction band edge.**

Electrical current $I$ flowing through the series resistance $R_s$ of the solar cell fingers and busbar grid, and backside electrical connections loose power $I^2R_s$, which generates heat. Similarly, electrical current $I$ flowing through the shunt resistance $R_{sh}$ of the solar cell between the fingers and busbar grid, and the backside electrical connections loose power $I^2R_{sh}$, which generates heat. When a solar cell is shaded, the other cells in series with it in the submodule push
electrical current through the reverse voltage biased solar cell and loose power which generates heat. Sometimes a hot spot forms due to a breakdown in the silicon when the solar cell is reverse voltage biased.

This loss of energy and power to heat is at the cost of electrical power which does not get produced. Hence, for a typical solar PV module only 17% to 20% of the incident solar radiation power is converted to electricity, the rest is converted to heat. Please refer to section IV.D. which has numerous discussions and thermal model simulations of solar cells and solar modules.

D. State of the Art of Commercial Solar Cells

The photovoltaic industry is developing new technologies quickly, many of which become commercial products. Increasing the solar cell efficiency is always important. The efficiency is the percent of the solar power incident on the solar cell which is converted into electrical power. Higher efficiency solar cells give more electrical power from a fixed area, like a rooftop. Since 1976 the National Renewable Energy Lab (NREL) located in Golden, Colorado has recorded on their “Best Research-Cell Efficiencies” chart shown in Figure 14 when a new efficiency record is achieved for any of the 24 PV solar cell technologies. The chart shows that the efficiency record for mono c-Si is 25%. If the light is concentrated to several suns, then the efficiency increases to 27.6%. Silicon is not a good material for concentrated light because efficiency decreases with increasing temperature. The record for multi c-Si is 21.3%, which is less than the 25% for mono c-Si. The grain boundaries of poly c-Si cause recombination of the electron hole pair resulting in lower current and efficiency. Single crystal GaAs has a record efficiency of 27.5%, which under concentrated light increases to 29.1%.

The thin-film technologies of CIGS (copper indium gallium selenide), CdTe (cadmium telluride), and a-Si (amorphous silicon) are materials applied as thin layers on a glass or plastic substrate. Only a 4 um thickness of CIGS or CdTe material is needed to absorb the sunlight. A
flexible solar cell can be made by applying any of these thin-film materials to a flexible substrate. Figure 14 shows that CIGS and CdTe have achieved efficiencies of 22.3% and 22.1% respectively, while a-Si is much lower at 13.6%.

Figure 14: NREL research solar cell record efficiencies over past 40 years [33].
In terms of global PV module MW production in 2015, CIGS was 2%, CdTe was 3%, and a-Si was 3%. The emerging PV technologies on the NREL chart are not in production, but have potential. Perovskite cell efficiency improved in the last 3 years from 14% to 22.1%!

By incorporating multiple junctions in a solar cell, the efficiency can be increased. There are two, three, and four junction solar cells. The highest efficiency at 46.0% is from a four-junction solar cell under concentrated light, developed by Soitec and CEA-Leti, France, together with the Fraunhofer Institute for Solar Energy Systems ISE, Germany, and was announced on December 1, 2014. The four junctions are stacked one on top of the other. Each junction converts one quarter of the incoming photons into electricity, for the photon wavelength range of 300 to 1750 nm. Each junction needs to produce the same number of electrons to flow to the next junction or the load, because the current output of the solar cell is limited by the junction which produces the least current. To match the 4 junctions, each one is carefully made at a precise thickness of a different III-V compound semiconductor material, with its own bandgap energy which responds to a specific part of the spectrum. The record 46.0% efficiency was achieved by placing the solar cell beneath a Fresnel lens, with light concentrated to 508 suns.

The I-V curve shown in Figure 15 lists the electrical and temperature measurements. Since the 4 junctions are in series, the output voltage equals the sum of the 4 junction voltages. The open circuit voltage Voc equal to 4.227 volts is 6.7 times that of a single junction silicon solar cell! This small 4 junction solar cell is only 5.20 mm², with a maximum power of 1.215 watts.
Commercial PV modules range in output power, voltage, current, efficiency, cell number, cell size, cell technology, size, weight, frame, and price. For instance, a small 50 watt PV module at standard test conditions (STC) has a maximum power point at 17.5 volts and 2.86 amps DC, 12.5% efficiency, thirty six 156 mm x 60 mm poly c-Si solar cells, 26” x 24” aluminum frame, 11 lbs weight, and $60 price online.

This compares to a very large 350 watt PV module at STC has a maximum power point at 38.2 volts and 9.10 amps DC, 17.3% efficiency, seventy two 156 mm x 156 mm mono c-Si solar cells, 78.5” x 39.4” aluminum frame, 48 lbs weight, and $274 price online.

A typical solar PV module manufacturer’s warranty has

- 10 year limited product warranty on materials and workmanship.
- 25 year warranty on > 80% power output, and 10 year warranty on > 90% power output.
CHAPTER III

EXPERIMENTAL APPROACH

A. Mono Crystalline vs. Poly Crystalline Silicon Solar Cells

There are 3 silicon based solar cells that are commercially available: mono crystalline silicon, polycrystalline silicon, and amorphous silicon. Monocrystalline silicon abbreviated as mono c-Si is the most expensive and has the highest efficiency. Polycrystalline silicon abbreviated as poly c-Si is cheaper and less efficient than mono c-Si, but the material used the most. Multicrystalline silicon abbreviated multi c-Si is another name for poly c-Si. Amorphous silicon abbreviated as a-Si is the cheapest and least efficient silicon based material. Global photovoltaic manufacturing data for 2015 [5] of these 3 types of solar cells is shown in Table 3.

Table 3: Silicon based solar cell manufacturing data for 2015

<table>
<thead>
<tr>
<th>Material Technology</th>
<th>Percentage of Production</th>
<th>MWdc (megawatts dc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>poly c-Si</td>
<td>69</td>
<td>73,012</td>
</tr>
<tr>
<td>mono c-Si</td>
<td>24</td>
<td>25,096</td>
</tr>
<tr>
<td>a-Si</td>
<td>3</td>
<td>2,861</td>
</tr>
<tr>
<td>total</td>
<td>96</td>
<td>101,969</td>
</tr>
</tbody>
</table>

Table 3 shows that 96% of the solar cells manufactured in 2015 were silicon based. It is desirable to make solar cells have a large surface area to absorb as much solar radiation as possible. Solar cells are designed to minimize the thickness to decrease the weight and amount of material required, while keeping enough thickness to absorb most of the solar radiation and thereby minimize transmission through the solar cell. Putting an antireflective coating on the surface helps to decrease reflection and also increase absorption of solar radiation.
A monocrystalline silicon solar cell is the most expensive and has the highest efficiency because the silicon is a single crystal. It is manufactured by the Czochralski process starting with a small seed crystal of silicon in a furnace of molten purified silicon. The molten silicon grows on the surface of the seed crystal and maintains the crystal grain structure. To make the bulk silicon into a p-type material, boron is added as the dopant to the molten silicon. To make it n-type, phosphorous is added as the dopant. The seed is slowly pulled out of the molten silicon forming a long ingot of silicon. Impurities are reduced in the silicon by additional thermal processes. A large cylindrical ingot could be up to 6 feet long and 9 inches in diameter. The ingot is sawed into thin slices of single crystal silicon about 200 to 250 microns thick. Unfortunately, the sawing process wastes about 50% of the ingot creating silicon dust. The surface of the thin slice of silicon is polished. To make the p-n junction, n-type phosphorus is diffused into the front surface of silicon slices which have p-type bulk silicon. Likewise, p-type boron is diffused into the front surface of silicon slices which have n-type bulk silicon. When this material is exposed to sunlight, the p-type side will generate a positive voltage relative to the n-type side.

A bare silicon surface can reflect up to 30% of the solar radiation incident on it. A dielectric antireflective (AR) coating and texturing is added to the front surface to minimize the reflection of light from the solar cell, and increase the absorption of light into the solar cell. The AR coating thickness is made to be about a quarter wavelength of the peak power wavelength of visible light, which is near 600 nm. Hence the AR thickness is about 150 nm made of silicon nitride $\text{Si}_3\text{N}_4$ or titanium oxide $\text{TiO}_2$. To finish manufacturing the solar cell, the back side is coated with aluminum to collect the electrical current flow. The front side has a screen printed thick film silver metallization grid of busbars and fingers as shown in Figure 16 to pick up the electrical current flow. The area of this grid blocks light and decreases the solar cell efficiency. Hence, the design of the grid is to maximize the collection of electrical current while minimizing the blockage of light to the solar cell.
A poly crystalline silicon solar cell is cheaper and less efficient than mono c-Si due to the large number of grain boundaries in the silicon. The less expensive manufacturing process starts with melting chunks of purified silicon. The silicon is cooled to form a block, but no effort is made to create a single crystal. Instead, a lot of small randomly shaped crystals form, with grain boundaries between crystals. Grain boundaries attract impurities when the material cools from molten silicon. Defects in the crystal structure also occur at the grain boundaries. The impurities and the crystal defects diminish the electrical properties of the silicon like electron or hole carrier lifetime, which reduces the solar cell efficiency compared to mono c-Si. Hot spots are more likely to form on poly c-Si due to the grain boundaries. The remaining processing steps to make a solar cell are similar to the ones discussed for mono c-Si.

![Solar cell front surface](image)

**Figure 16: Solar cell front surface busbars and fingers pick up current but block light.**

An amorphous silicon solar cell is the cheapest and least efficient because it does not have a crystal structure. The amorphous silicon is typically deposited as a thin film on a surface instead of being produced from a molten silicon melt and then sawed into solar cell starting material. Hence, a-Si solar cells are called thin film solar cells. Since, a-Si material can be
deposited on a flexible material, this gives it applications which brittle mono c-Si and poly c-Si do not have.

B. Test Equipment

A lot of time was spent designing and building several pieces of equipment for testing solar cells and solar modules (panels). This included selecting parts required by the design, purchasing, machining, and assembling the parts, and then downloading and configuring data collection software. Once that was completed the equipment could then be used to test solar cells and solar modules. It was an iterative process, when testing solar cells and modules one then realized that some parts of the test equipment had to be modified. The benefit of spending so much time on hardware and software for testing was the hands on experience gained with real hardware such as PV solar cells, PV solar modules, LED lamps, infrared camera, power resistance loads, and automated data acquisition hardware and software. These measurements were recorded: voltage, current, light intensity, temperature, thermal images and visible images. Each piece of test equipment is described in the following sections.

1. Solar Cell Tester

The solar cell tester shown in Figure 17 was made to safely test solar cells which might develop high temperature hot spots. Non flammable materials were used. The base is a large beige ceramic tile, with nylon runners underneath to protect the table, and to allow sliding it beneath the solar simulator (section 3B2). The solar cell rests on a G10 material printed circuit board. The standoffs supporting the G10 board and the electrical connections are made of metal. The insulators are ceramic. Electrical wiring connects to the solar cell to allow for current flow up to 10 amps, and voltage measurement. The black square painted on the tile is for aligning the infrared shield (section 3B6) to the solar cell tester.
2. Solar Simulator

The solar simulator was designed, parts purchased, built, and tested. It was created after trying many configurations of the number, placement, and type of lamps. The first solar simulator tried belonged to the SECanT Lab and had one 1000 watt 60 Hz AC powered halogen lamp. It had been used by previous students for heat transfer studies of radiant light absorption on aluminum micro structured surfaces. Since a halogen bulb spectrum has a high percentage of power in the infrared it overheated the solar cell which hit 100 °C quickly. A photovoltaic silicon solar cell only converts to electricity electromagnetic wave photons which have energy greater than the silicon bandgap energy of 1.11 eV. This corresponds to a wavelength less than 1,117 nm. The halogen lamp spectral content contained a large percentage of photons with energy less than the silicon bandgap, which when absorbed into the silicon gave the undesirable result of producing too much heat and not enough electricity. Lower wattage halogen lamps were tried, but still had too high a percentage of heat produced. In Figure 18, the halogen lamp spectrum
makes it clear that a large percentage of the emitted photons (radiant flux) are at wavelengths greater than 1,117 nm. As the lamp temperature is decreased, the percentage of photons below the 1.11 eV bandgap energy increases, which results in more heat produced in the solar cell and less electricity produced by the solar cell. For a silicon solar cell, as its temperature increases its output power changes by about -0.45% / °C. Hence, efficiency is lost as the temperature of the solar cell increases.

Figure 18: A typical halogen lamp spectrum [35].

Several LED lamps were tried since most of their photon emission is in the visible light range, which makes them very efficient for lighting applications, and lets the solar cell generate electricity without overheating it. The design requirement was to find a full spectrum LED lamp with a 5000 K correlated color temperature to better replicate the solar spectrum, and a beam angle between 9° to 15° to focus the light on the solar cell. The LED lamp spectrum shown in Figure 19 has minimal infrared and a lot of blue light. The LED lamps are manufactured by SORAA with these specs: PAR 30L, 1050 lumens, 5000K color temperature, 18.5 watt, 9° beam
angle, 95 CRI (color rendering index), 100 - 120 volts AC, and fancy heat sink (pn SP30L-18-09D-950-03).

### Spectroradiometric Parameters

![Spectroradiometric Parameters Graph]

**Figure 19:** Soraa LED lamp full spectrum range: 380 – 780 nm with a peak wavelength of 413.8 nm, radiant flux of 4.341 W, and a correlated color temperature of 5026 K [36].

The lower wattage LED lamps were not able to produce enough electrical power output from the solar cell. A combination of LED lamps and halogen lamps decreased the percentage of heat produced and increased the percentage of electricity produced! By adding the LED spectrum to the halogen lamp spectrum a spectrum closer to the solar radiation spectrum of Figure 6 was achieved. After trying numerous LED lamps with halogen lamps, the final design of the solar simulator shown in Figure 20 was achieved. For best light intensity, uniformity, spectral quality, and solar cell electrical power output, the solar simulator was configured with 4 LED lamps and 4 halogen lamps. There is a power switch for each lamp on its electrical box. An electrically grounded metal wire 3 shelf storage unit was modified and the shelf height adjusted to support the
lamps at a distance from the solar cell for a beam spot size optimized for light intensity uniformity and power on the solar cell.

Figure 20: Solar simulator is part of the PV solar cell test stand in the SECanT Lab.

The halogen lamps are manufactured by GE with these specs: MR16, 725 lumens, 3050K color temperature, 50 watt, 15° beam angle, 100 CRI, Constant Color Coating, UV protection, and 12 volts AC or DC (pn 20872).

In the previous design of the solar simulator, the lamps were powered by 120 volts 60 Hz AC, which produced a 120 Hz fluctuation of the light intensity (flicker) in LED lamps and 60 Hz flicker in halogen lamps. The 120 Hz flicker as seen in Figure 21 was due to the 60 Hz AC signal being rectified to 120 Hz by the AC to DC converter inside each LED lamp. The filtering leaves a lot of 120 Hz ripple; less expensive filters give more ripple. The flicker is over 50%! (Does this cause eye strain?) The halogen lamps light intensity fluctuates at 60 Hz because the filament temperature and radiated light increases and decreases with the 60 Hz power. The halogen lamp
percent flicker is less than the LED lamp, because the thermal response time is much slower for
the halogen lamp, than the electrical response time for the LED lamp.

Figure 21: 120 volts AC power causes flicker on SORAA LED PAR 30L lamp.

In Figure 21, the dimmer was set for maximum output power. The solar cell output
current (top graph), output voltage (middle graph), and apogee pyranometer output voltage
(bottom graph) all show over 50% variation due to flicker.

By powering the SORAA with 120 volts DC the flicker goes away as shown in Figure
22. SORAA Corp. said it is OK to run their lamp with 120 volts DC. The 120 volts DC was
produced by connecting 4 Agilent / HP E3611A power supplies in series, and setting each power
supply to 30.0 volts as shown to right of solar simulator in Figure 20. Similarly, the halogen
lamp flicker is eliminated when it is powered by 12 volts DC. 12 volts DC was used due to a lack
of power supplies to produce 120 volts DC for the halogen lamps. Also it is much safer to run
with 12 volts DC, than potentially lethal 120 volts DC. The 12 volt DC MR16 halogen lamps
actually put out a better quality beam spot than the 120 volt halogen lamps, because at the lower
voltage, the filament geometry can be made smaller to give a smaller beam spot size. A 50 watt lamp running on 12 volts DC needs 4.17 amps! At OEM Parts near campus 2 used Microsoft Xbox 360 console AC adapters were purchased (benefit of having a son who plays video games). Each one can put out 16 amps at 12 volts DC. Each AC adapter connector was modified to power two halogen lamps at 12 volts and 8.33 amps DC output, half of the power supply’s maximum current spec.

Figure 22: 117 volt DC power makes SORAA LED PAR 30L lamp light stable as sunlight.

Solar cell output current (top graph), output voltage (middle graph), and apogee pyranometer output voltage (bottom graph) each show a constant value with minimum noise.

One disadvantage of powering the SORAA LED lamps with a DC voltage is that an AC dimmer cannot be used with them. If the DC voltage is lowered, then the DC converter inside the lamp pulls more current, which could potentially burn out the lamp. A DC voltage constant current LED would dim, by decreasing the input current. One was tried, but its specifications list only half as much light output.
The next step was to adjust the lamps on the solar cell plane to achieve uniform light intensity across the solar cell that is intense enough to produce near specification power from the solar cells being tested.

3. Light Intensity Profiler

The light intensity profiler was designed, parts purchased, built, and tested. It is shown in Figure 20 measuring the light intensity versus position beneath the solar simulator at the solar cell plane. The profiler performs two very important measurements. First, it can measure the light intensity spot size at the solar cell plane for each lamp. Second, with all of the LED and halogen lamps on, it can measure the uniformity of the light intensity across the plane of the solar cell.

A linear actuator was purchased. An Apogee Instruments, Inc. solar pyranometer was attached to the linear actuator as shown in Figure 23. On the left of the picture, the dark green Microsoft Xbox 360 console AC adapter was modified to produce 12 volts DC to power the linear actuator. The Agilent power supply is set for 10.0 volts for use on the potentiometer position feedback on the linear actuator. Light Intensity Linear Profiler Control Box has a switch to extend or retract the linear actuator arm. The box also has wiring connections between the power supplies, the linear actuator, and the National Instruments data acquisition module.

The constant speed of the linear profiler over its range of travel is shown in Figure 24. A profile of the light intensity beam spot size from one halogen lamp in the solar simulator is shown in Figure 25. A profile of the light intensity over the x-y solar cell plane from a series of 17 profiles when all 8 lamps are on is shown in Figure 26. The goal is to have intense uniform light over the solar cell to simulate sunlight.
Figure 23: Linear actuator system for precise movement of the solar pyranometer

Figure 24: Linear actuator arm extension and retraction
On the Light Intensity Linear Profiler Control Box the control switch is moved from Off to Extend. Once the arm has extended to its maximum travel of 203 mm (8.0 inches) it stops. The control switch is then moved to Retract. Once the arm has retracted to 0 mm it stops. The control switch is then set to its center OFF position. Potentiometer wiper feedback voltage is shown in Figure 24 as the linear actuator arm extends 8.0 inches (203 mm). The linear graph shows that the arm is extending and later retracting at a constant velocity.

![Linear profiler measurements of halogen lamp light intensity and position](image)

Figure 25: Linear profiler measurements of halogen lamp light intensity and position

The linear profiler measured the light intensity profile of the halogen lamp located at lamp position L8 on the solar simulator. The 3 graphs shown in Figure 25 are: light intensity (from pyranometer voltage) vs. time (top graph), position in mm vs. time (middle graph), and profile of light intensity vs. position in mm (bottom graph). These are clean graphs due to use of the DC powered solar simulator and linear profiler.
Figure 26: Profile of light intensity from the solar simulator's 4 LED and 4 halogen lamps measured at solar cell plane.

A square on the solar cell plane represents a 156mm x 156mm solar cell in Figure 26. Light intensity of approximately 750 watts / m² was measured over most of the solar cell. The light intensity uniformity is acceptable over the solar cell, and drops off beyond its edge. Thanks to Corbin Spells who wrote a MATLAB program to create the 3D figure from the 17 profiles.

4. PV Variable Resistance Load Box

A high power variable resistance load module for connecting to either the solar cell under test, or an entire solar PV module (panel) was designed, parts purchased, built, and tested. By varying the load resistance, the illuminated solar cell or solar PV module output current I and the output voltage V can be measured. The output current I is computed from the voltage across the
0.005 Ω current shunt by the relationship that 1.0 mV equals 0.20 A. One of the most important and displayed graphs for looking at the performance of a solar cell or solar PV module is the I-V chart shown in Figure 27. It shows the short circuit current I_{sc}, open circuit voltage V_{oc}, maximum power point voltage V_{mpp}, maximum power point current I_{mpp}, and maximum power.

For a solar cell the load resistance R_{LMP} at the maximum power point is

\[
R_{LMP} = \frac{V_{MPP}}{I_{MPP}}
\]

Inserting typical values gives

\[
R_{LMP} = 0.5 \text{ volts} / 5 \text{ amps} = 0.10 \text{ ohm for a 125 mm x 125 mm solar cell}
\]

\[
R_{LMP} = 0.5 \text{ volts} / 8 \text{ amps} = 0.062 \text{ ohm for a 156 mm x 156 mm solar cell}
\]

Figure 27: I-V curve and P-V curve simulation for a solar cell showing Isc, Voc, I_{MPP}, V_{MPP}, and Maximum Power, similar to Fig. 67.
For a solar module with 32 solar cells, the load resistance would be about 32 times that of a single solar cell. $R_{LMP}$ equals 3.2 ohms for a solar module with 32 solar cells of 125 mm x 125 mm, and 2.0 ohms for a solar module with 32 solar cells of 156 mm x 156 mm. Some solar modules have 96 solar cells giving an even higher value for $R_{LMP}$. Points on the I-V graph which are to the left of the maximum power point have a lower $R_L$ than $R_{LMP}$. Points on the right of the maximum power point have a higher $R_L$ than $R_{LMP}$.

Pictures of the PV variable resistance load box are shown in Figure 28 and Figure 29, and the schematic in Figure 30. Solid Works software was used to carefully lay out the parts mounted on the box top. The box has connectors on it to connect either to the solar cell tester or to a solar PV module. In the Figure 28 front view, the 4 rheostat knobs, 6 power resistors, 2 switches, and one jumper are seen. Switch 1 selects either input from the solar PV panel connectors or the solar PV cell connectors, and switch 2 connects lower current handling rheostats 3 and 4 to the circuit, once rheostats 1 and 2 are at their maximum resistance.

The 4 rheostats connected in series are used to vary the resistance for testing solar cells or solar panels from 0.1 to 13.5 ohms. A rheostat becomes a variable resistor when wires are connected to a fixed terminal and the wiper which can be rotated from 0 to 300 degrees, with no connection to the third terminal. (If wires are connected to all 3 terminals, then it behaves as a potentiometer.) The rheostats are manufactured by Ohmite. Their specs are in Table 4. The six 50 watt power resistors with a total resistance of 2.9 ohms fastened on top of the module are connected in series with the rheostats only when a solar panel is connected, since the maximum power point is at a higher $R_{LMP}$ value. The 2 jumpers allows bypassing some of these power resistors in a make before break connection technique to give more data points on the I-V power curve graph.
Figure 28: PV Resistance Load Box with jumpers connected to resistors 1 and 2

Figure 29: View inside the PV Resistance Load Box showing 4 power rheostats, 2 switches, terminal strip, electrical wiring, current shunt, connecting cables.
Table 4: Ohmite rheostat specs

<table>
<thead>
<tr>
<th>Rheostat part number</th>
<th>Resistance +/- 10%</th>
<th>Power</th>
<th>Max Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>RJSR50E</td>
<td>0+ to 0.5 ohms</td>
<td>50 watts</td>
<td>10 amps</td>
</tr>
<tr>
<td>RKS1R0E</td>
<td>0+ to 1.0 ohms</td>
<td>100 watts</td>
<td>10 amps</td>
</tr>
<tr>
<td>RKS2R0E</td>
<td>0+ to 2.0 ohms</td>
<td>100 watts</td>
<td>7.07 amps</td>
</tr>
<tr>
<td>RKS10RE</td>
<td>0+ to 10.0 ohms</td>
<td>100 watts</td>
<td>3.16 amps</td>
</tr>
</tbody>
</table>

Figure 30: Schematic for PV Resistance Load Box
It was found that the minimum resistance was 70 milliohms due mainly to the contact resistance of the rheostat wiper. Some of the resistance is in the connecting cable. It was necessary to design, purchase parts, build, and test a PV solar cell milliohm load module shown in Figure 31. It has sixteen 5 milliohm 2 watt resistors manufactured by ohmite p/n 12FR005E. The resistors are connected in series by terminal strips. By using 2 jumpers in a make before break technique to short out some of the resistors, resistance values can be selected from 0 to 80 milliohms in 5 milliohm steps when making the I-V curve. Then the PV resistance load box can be used to increase the resistance up to 13.5 ohms, and switch S1 flipped to go to open circuit. In industry or research labs, an expensive electronic load would be used to vary the resistance to the solar cell or to a solar panel, and record the data automatically.

Figure 31: PV solar cell milliohm load module has sixteen 0.005 ohm, 2 watt resistors
5. Infrared (IR) Camera

The UCCS Engineering Department acquired a very useful FLIR E60 infrared camera, shown in Figure 32, to use on this project, and future student projects, for viewing thermal images. The 3.5" color LCD display has a matrix of 320 x 240 pixels, which give a thermal 2D image of an object. Colors are automatically assigned to the temperature range of the object, so one can see a thermal image of the object. Each IR detector measures the power received from a small section of the object being viewed to compute temperature by the Stefan-Boltzmann radiation law:

\[ E(T) = \varepsilon \sigma A T^4 \quad , \quad T = \frac{4 E(T)}{\varepsilon \sigma A} \tag{43} \]

- \( E(T) \) is the power emitted in watts as a function of temperature \( T \) (K).
- The Stefan-Boltzmann constant \( \sigma = 5.670 \times 10^{-8} \text{ W/(m}^2 \text{K}^4) \).
- The surface emissivity \( \varepsilon \) depends on the material and surface finish, \( 0 < \varepsilon < 1 \). If \( \varepsilon \) varies from 1 to 0.01 then \( T \) is multiplied by a factor of 3.16. Determine \( \varepsilon \) correct value!
- The symbol \( A \) is the area on the surface of the object being studied in \( \text{m}^2 \).

The computed temperature is then converted to a color and displayed on the pixel corresponding to the IR detector. The matrix of 76,800 pixels gives the thermal image.

Some of the IR camera’s specifications are:

- Temperature range: -20 to 650 °C (-4 to 1202°F)
- Detector type is focal plane array: 320 x 240 pixels = 76,800 pixels
- Spectral range: 7.5 to 13 um (sensitive to IR from 1 to 15 um)
- Field of view / Focus: 25° x 19° / Manual (minimum focus distance 1.3ft, 0.4m)
- Video visible light camera: 3.1 MP, LED lamp, laser pointer, Frame rate: 60 Hz
Figure 32: FLIR infrared camera model E60 [24].

Figure 33 contains a visible picture and a thermal image, taken simultaneously by the FLIR E60 IR camera, of the PV solar array located on the roof of the UCCS Centennial Hall building. It is a 25 kilowatt fixed tilt solar PV system that was installed in December 2010. In the thermal image, the temperature scale on the right side shows a range from 16.4 °C, with a blue color, to 41.9 °C with a yellow color. The solar cells have an orange color. The cross hairs for spots 1 to 3 indicate a temperature of 26.1 °C for each of the solar cells. The blue dots are areas not covered by a solar cell. The dots could be a different color than the solar cells because either they are cooler, or they have a different emissivity than the solar cells, or a combination of both reasons. On the right side of each module is a brighter yellow area indicating the location of the warmer electrical junction box on the back of the solar PV module. Emissivity was set to 0.80. From the visible picture, one can see the solar cells more clearly and the tilt of the solar PV modules.
Figure 33: Thermal (bottom) and visible (top) images taken simultaneously by the FLIR E60 IR camera of the PV solar array on the UCCS Centennial Hall classroom building roof.

6. Infrared (IR) Shield

It was noticed that IR radiation from the power supplies, digital multimeters, and author was being reflected from the solar cell surface and interfering with the IR camera image, see Figures 34 and 35. An IR shield was made by cutting out the bottom of a black nylon trash can. The bottom of the IR shield was positioned around the solar cell as shown in Figures 36. The FLIR infrared camera was positioned at the top of the IR shield as seen in Figure 37 to capture the solar cell IR image seen in Figure 38.
Figure 34: IR from power supplies and digital multimeters can interfere with measurements.

Figure 35: Infrared camera image shows reflection of hand off of solar cell.
Figure 36: View of solar cell tester surrounded by infrared shield with cover removed.

Figure 37: Infrared camera used to take image of solar cell inside infrared shield
Figure 38: IR image of a poly c-Si solar cell with the IR shield in place.

For the IR image in Figure 38, the emissivity ($\varepsilon$) setting on the FLIR IR camera was set to 0.80. The silicon on the solar cell and the metal busbars are actually at the same temperature. The metal busbars and fingers appears cooler because they has a much lower emissivity near .05 compared to the silicon with an antireflective coating emissivity of approximately 0.80. The maximum temperature of $88.3^\circ$C was located by the crosshair inside the rectangular box. The pattern of the polysilicon large grains is quite visible. The test stand support board beneath the solar cell has heated up.

7. National Instruments Data Acquisition Modules

National Instruments Corp. (NI) makes a product line of data acquisition modules (DAQs) which connect by a USB port to a computer. The USB port powers the DAQ, and exchanges data between the computer and the DAQ. Each DAQ used for experiments had several analog inputs which could measure a voltage between -10 volts to 10 volts. The measurement data was transmitted to the computer and recorded using a project created with NI Signal Express 2015 software. The following (quantity) and DAQ models were used (1) NI
USB-6002, (2) NI USB-6210, and (1) NI USB-6229. The NI USB-6229 had a separate power supply due to its large size, and its 16 differential (32 single ended) analog inputs. Each analog input was converted by an analog to digital converter to a value with a 16 bit ($2^{16} = 65,536$) resolution. The NI USB-6210 measures at a sampling rate up to 250 kS/s.

The graph in Figure 39 shows large temperature swings from 23 °C to 47 °C in 4 seconds for a part in thermal equilibrium. After viewing the graph, electrical noise problems were first looked for, and metal shielding was tried, but did not help. The NI USB-6002 16 bit DAQ has only one input range of +/- 10 V, and therefore a resolution of $20V / 2^{16} = 0.31$ mV. For a K-type thermocouple, there is a temperature range of 0 °C to 1260 °C causing an output voltage range of 0 to 50.990 mV. Thus, a resolution of 0.31 mV would correspond to a resolution of 7.66 °C, which is not good enough when looking for temperature changes of a few degrees C.

Figure 39: Thermocouple resolution is 8 °C when using the NI USB-6002 DAQ

Better resolution was obtained by using the NI USB-6210 DAQ which has 4 input ranges: +/- 10 V, +/- 5 V, +/- 1 V, and +/- 0.2 V. On the +/- 0.2 V input range, it has a resolution of 0.0061 mV corresponding to a resolution of 0.15 °C, which is 50 times better than the NI USB-
6902 DAQ. All temperature measurements were then done with the NI USB-6210 or the NI USB-6229 DAQs, which each has 4 input ranges: +/-10 V, +/-5 V, +/-1 V, and +/-0.2 V, giving a resolution of 0.15 °C.

The National Instruments NI USB-6210 DAQ module has an input impedance of over 10 Gȍ in parallel with 100 pF on each analog input. If only thermocouples are connected to the DAQ in the recommended differential mode, then the displayed measured temperature can become very unstable as shown in Figure 40 by over 70 °C even though the temperature is stable. In differential mode, one TC lead is connected to an analog (+) input and the other lead to an analog (-) input. This instability occurs because the electrical signal picks up stray charge and starts to float around due to the TC connected to two 10 Gȍ input impedance analog inputs. One month of time was lost trying to troubleshoot these two TC problems of resolution and electrically floating inputs. Solution was found for the floating inputs on the NI website.

![Thermocouple displayed temperature dropped by over 70 °C due to 1 GΩ high input impedance of DAQ module analog inputs.](image)

Figure 40: Thermocouple displayed temperature dropped by over 70 °C due to 1 GΩ high input impedance of DAQ module analog inputs.
The National Instruments published cure was to add a bias resistor between each of the TC analog inputs and the analog ground terminal as shown for differential inputs in Figure 41; see the NI white paper in Appendix D. Pick a bias resistor value between 10 kȍ and 100 kȍ, which will not load down the voltage being measured.

If there are analog ground referenced signals connected to other analog inputs on the DAQ, then the bias resistor may not be necessary, since a ground reference is available to discharge the stray charge as the DAQ is switched between analog inputs for measurement. By using bias resistors when needed, the TC measurements became stable as displayed on the computer monitor using NI Signal Express software to take the DAQ data and make the 10 minute stability test chart shown in Figure 42. The 6 TCs are measuring 21.5 ± 1 °C!
**Table 1. Analog Input Connections**

Figure 41: National Instruments recommended use of bias resistors for differential floating signal sources. See more of report in Appendix D.
The 6 thermocouple measurements were 21.5 ± 1 °C!


When downloaded from www.ni.com in May 2016, the NI Signal Express 2015 free software would not work with the Windows 10 Operating System. NI Signal Express 2015 worked well on a used computer purchased with Windows 7. The DAQ module measurements were transmitted by USB cable to the computer and recorded. Signal Express software on the computer used the DAQ measurements in a user created project to create display screens like the one shown in Figure 42. There are a lot of excellent features one can select with the software. The DAQ hardware, and NI Signal Express 2015 were used to record and display temperature, voltage, current, position, and light intensity measurements. The number and frequency of measurements can be selected. Several graphs can be displayed on the monitor screen simultaneously, as shown in Figure 43. The display can be captured and saved as a file, or the data can be exported to an Excel spreadsheet for further analysis and graphing.
9. Solar PV Module GS-STAR-100W

The Grape Solar Company sells solar panels (modules) through online sites like Home Depot. Their poly crystalline silicon PV module model GS-STAR-100W was purchased for outdoor testing as shown in Figure 44. The PV module front view is shown in Figure 2, and the schematic is shown in Figure 3. The drawing and specifications for this module are in Appendix C: Grape Solar Model GS-STAR-100W Solar PV Module Specs. It costs about $100.

10. Solar Cell Test Stand

Figure 43: A solar cell was connected to solar cell tester beneath solar simulator with partial shade from white board on the solar cell test stand.

The solar cell test stand is shown in Figure 43. Many of the assemblies which made it up have already been described. It consisted of the solar cell tester which supported the solar cell and its electrical connections, the solar simulator and its associated DC power supplies, white boards for producing shadows, the light intensity profiler, the PV variable resistance load box, the FLIR E60 infrared camera, the infrared shield, the NI USB-6229 data acquisition module, the
desktop computer loaded with NI Signal Express 2015 software, a FLUKE thermometer 52 II with 2 thermocouples, and 2 FLUKE DMMs.

With this system the solar cell was tested to produce: the illuminated I-V graph, the forward bias voltage dark current graph, the reverse bias voltage dark current graph, and the illuminated reverse bias voltage partial shade (25%, 50%, and 75%) graphs. 125 mm x 125 mm solar cells and 156 mm x 156 mm solar cells could be connected to the solar cell tester. A 50 mV at 10 amp current shunt was connected to measure the output current from the solar cell. The NI USB-6229 measured voltages from the current shunt, solar cell, pyranometer, and thermocouples and stored the data on the desktop computer for display by the NI Signal Express software. Refer Section 3. C. Technique for Testing Solar Cells for the test procedure.

11. PV Module Outdoor Solar Test Stand

The PV module outdoor solar test stand is shown in Figures 44 and 45. A Grape Solar 100 watt PV module model GS-STAR-100W (see Appendix C) was used. It has 36 polycrystalline solar cells in 4 columns by 9 rows. Three busbars are visible on each rectangular solar cell. In Figure 44 the front of this PV module had a white board clamped to it to shade the first column of 9 solar cells SC1 to SC9. The PV module was attached to two long boards to support it at a 45 tilt angle from horizontal. The two boards were fastened to a wooden support rail connected to the top rail of a 3 step stepstool. Positioning the PV module at this height made it easier to work on, and is closer to the height of a PV module in a PV field array. The floor is a level concrete patio. This area is exposed to the afternoon sun. The instrumentation cart was located to the left of the PV module. The black mesh below the PV module with the 3 red tape stripes improved visibility and helped prevent people from tripping on the wooden legs. A solar pyranometer and a UV pyranometer were attached near the top of the right wooden leg. The
pyranometers pointed in the same direction as the PV module. The windows in the background reflected some light (glare) and heat towards the back of the PV module.

![PV module outdoor solar test stand front view](image)

**Figure 44:** PV module outdoor solar test stand front view shows one column of 9 solar cells shaded by a board clamped to PV module.

The back of the PV module and the measurement instruments are seen in Figure 45. The 2 output power cables from the PV module are seen connected to the PV resistance load box, which is on the step ladder top step. The current shunt on the PV resistance load box measured the PV module output current, and produced a voltage which the NI USB-6210 DAQ measured at 2 analog inputs in differential mode. There were 12 thermocouples (TCs) which are seen connected to the back side of the PV module. Each TC was centered on one of the 12 solar cells.
to measure its temperature. Two other TCs measured the ambient temperature on the back side, and the aluminum chassis frame temperature. The 14 TCs were run through holes drilled in the side of the aluminum chassis frame to support the wires and then connected in differential mode to the analog inputs of the 2 NI USB-6210 DAQ modules, and two NI-USB TC01 modules. These DAQ modules are the white modules seen to the left of the laptop on the top shelf of the instrumentation cart. The DAQs were connected by USB cables to the COMPAQ laptop computer, which ran Microsoft Windows 7 operating system, and was loaded with NI Signal Express 2015 software for recording the measurement data. The 2 pyranometer cables, along with voltage divider wires from the PV modules also were connected to the DAQs.

Figure 45: PV module outdoor solar test setup back view shows measurement instruments.
The FLIR E60 infrared camera is visible on the bottom shelf on top of a notebook. A FLUKE 52 II thermometer with 2 thermocouple probes, one FLUKE 179 digital multimeter (DMM), and a Southwire 21050T 400 A AC/DC clamp on meter were on the cart for temperature, voltage, and current manual measurements. A carpet covered the top front area of the cart to keep the laptop and NI DAQs out of the sunlight, and to keep them from overheating. Glare from the windows is seen reflecting off the back of the PV module and the laptop screen. To cut down on glare, so the laptop screen could be read easily, an umbrella was sometimes used on a sunny day as shown in Figure 46.

![Figure 46: PV module testing outside required umbrella to shield from glare.](image)

The aluminum chassis of the PV module had several holes drilled in it to mount 4 terminal strips, and a current shunt as seen in Figure 47. Three of the terminal strips had resistors connected to them to make voltage dividers, which are necessary to keep the voltages measured by the NI DAQs between -10 to +10 volts. The PV module junction box was opened and wires
connected to it to measure the bypass diode current, and voltages as shown in Figure 47, and schematic in Figure 48. AC power was supplied to power the laptop computer and to provide an earth ground which was fastened to the aluminum solar panel chassis.

Figure 47: Voltage dividers and current shunt are fastened to PV module to measure junction box bypass diode current and voltages
It typically took 2 hours to pack this system in the SECanT Lab, take it outside, set it up, and check its operation before taking data. It was important to watch the weather forecast. On very cloudy or windy days it was not used. Because lawns are watered and mowed, they were not used as a setup location. It is best to pick a spot with minimal people walking by, who might momentarily block the sun to the PV module. The location was only illuminated by the afternoon sun. These factors restricted the PV module solar test setup use. Between tests, it could be moved to track the sun, as the sun’s position in the sky changed during the afternoon. It then took 2 hours to disconnect wires, move the system back to the SECanT Lab and put things away.

With this system the PV module was tested to produce the illuminated I-V graph, and the non-uniformly illuminated (shaded) I-V graph. Several different size boards were made and painted white to cover from 1 to 9 solar cells. Temperatures of the shaded and fully illuminated solar cells were measured. The FLIR E60 IR camera was used to view the temperature and its uniformity across the back or front of the PV module, and to look for hot spots. The voltage across and the current through the bypass diode D1 was measured to see if it was bypassing current when shading occurred. The pyranometers gave a measurement of the solar irradiance during the tests. Refer to Section 3.D. Technique for Testing Solar Modules for the test procedure.
C. Technique for Testing Solar Cells

The following 4 solar cell characterization tests were performed inside in the lab:

- Test 1. Applied forward bias voltage (FBV) diode curve in the dark
- Test 2. Applied reverse bias voltage (RBV) diode curve in the dark
- Test 3. Current versus voltage (I-V) output performance curve with illumination
- Test 4. Current versus applied reverse bias voltage (RBV) with illumination and partial shading of 25%, 50%, 75%, and 90%

The four solar cell characterization tests used the solar cell test stand, (section III B.10). If a hot spot problem formed on a solar cell, it would be expected to occur on the reverse bias voltage tests because more voltage and power was available to stress the p-n junction. The RBV was varied from 0 to -20 VDC compared to the FBV was varied from 0 to 0.65 VDC. Initially, the measurements were recorded manually for some tests. Then the NI USB-6229 DAQ and NI Signal Express software were connected to automatically record the data. If during Test 2 the reverse bias voltage stress caused a hot spot to form and damage the solar cell, then this could degrade the Test 3 I-V output performance curve. The characterization steps for each solar cell test using the solar cell test stand with automatic data recording are listed below.

1. The forward bias voltage (FBV) dark current test used the solar cell tester, FLIR E60 IR camera, IR shield, Omega TCs, NI USB-6229 data acquisition module (DAQ) and NI Signal Express software. The test was performed by applying a voltage with 3 HP E3610A DC power supplies connected in parallel, which could produce 0 to 8 V, at 0 to 9 A DC. The IR shield was placed around the solar cell to keep it in the dark. If this test were done in room light, then a small PV current would be produced and interfere with the measurements.
a. Current I and voltage V are measured and recorded by the NI DAQ and Signal Express software as the bias voltage is increased from 0 volts to approximately 0.65 volts DC until the current equals the spec short circuit current $I_{sc}$. Wait 5 minutes for thermal stability.

b. Use the FLIR E60 IR camera to take an IR image at dark current equal to $I_{sc}$. If a hot spot is seen, then measure and record its temperature with a TC.

c. Measure and record the temperature at center of solar cell with a thermocouple.

2. The applied reverse bias voltage (RBV) diode test used the solar cell tester, FLIR E60 IR camera, IR shield, Omega TCs, NI USB-6229 data acquisition module (DAQ) and NI Signal Express software. The test was performed by applying a negative voltage from 3 HP E3611A DC power supplies connected in parallel, which could produce from 0 to -20 V, at 0 to 4.5 ADC. The IR shield was placed around the solar cell to keep it in the dark (100% shading). If this test were done in room light, then a small PV current would be produced and interfere with the measurements.

a. Current I and voltage V are measured and recorded by the NI DAQ and Signal Express software as the reverse bias stress voltage is increased in one minute from 0 to -20 volts on monocrystalline and from 0 to -12 volts on multicrystalline solar cells in the dark. The solar cell may breakdown before it reaches the maximum reverse bias stress voltage. Wait 5 minutes for thermal stability.

b. Use the FLIR E60 IR camera to take an IR image and look for hot spot(s). If a hot spot is seen then measure and record its temperature with a TC.

c. Measure and record the temperature at center of solar cell with a thermocouple.

3. Illuminated I-V curve test used the solar cell tester, solar simulator, variable resistance load, FLIR E60 IR camera, Omega TCs, apogee pyranometer, NI USB-6229 data acquisition module (DAQ) and NI Signal Express software. The solar cell tester was centered beneath the solar simulator.
a. Turn on the solar simulator and let it stabilize for 5 minutes. It will then illuminate the solar cell area with an intensity of about 750 watts/meter$^2$.

b. Manually increase the load resistance from about 0 ohms to open circuit, which causes the output current I to decrease and the output voltage V to increase. I and V are measured and recorded by the NI DAQ and Signal Express software.

c. Use the FLIR E60 IR camera to take an IR image at approximate maximum power point Pmpp, which is the desired production operation point. If a hot spot is seen then measure and record its temperature with a thermocouple (TC).

d. At approximate maximum power point Pmpp, measure and record the temperature at the center of the solar cell with a thermocouple.

e. At approximate maximum power point Pmpp, measure and record the light intensity at the center of the solar cell with the apogee pyranometer.

4. The partial shade reverse bias stress voltage (RBV) current test used the solar cell tester, solar simulator, FLIR E60 IR camera, Omega TCs, apogee pyranometer, white shading boards, NI USB-6229 data acquisition module (DAQ) and NI Signal Express software. The solar cell tester was centered beneath the solar simulator. A white board was placed on the solar simulator lower shelf to shade 25%, 50%, 75%, and 90% of the solar cell from the light as shown in Figure 43.

a. Place the white board on the solar simulator shelf to shade starting at the front edge of the solar cell 25% or its surface area.

b. Turn on the solar simulator and let it stabilize for 5 minutes. It will then illuminate the solar cell area with an intensity of about 750 watts/meter$^2$.

c. Current I and voltage V are measured and recorded by the NI DAQ and Signal Express software as the reverse bias stress voltage is increased in 1 minute from 0 volts to -20 volts on monocrystalline and from 0 to -12 volts on multicrystalline
solar cells. The solar cell may breakdown before it reaches the maximum reverse bias stress voltage. Wait 5 minutes for thermal stability.

d. Use the FLIR E60 IR camera to take an IR image and to look for hot spot(s). If a hot spot is seen then measure and record its temperature with a TC.

e. Measure and record the temperature at center of solar cell with a thermocouple.

f. Measure and record the light intensity at center of solar cell with the apogee pyranometer. Move the white board if needed.

g. Move the white board on the solar simulator shelf to shade starting at the front edge of the solar cell 50% of its surface area. Repeat steps c. to f.

h. Move the white board on the solar simulator shelf to shade starting at the front edge of the solar cell 75% of its surface area. Repeat steps c. to f.

i. Move the white board on the solar simulator shelf to shade starting at the front edge of the solar cell 90% of its surface area. Repeat steps c. to f.

5. Remove the white board from the solar simulator shelf. Repeat test 1 to check if the I-V curve is still the same.

6. For polycrystalline solar cells which have survived the above testing, repeat test 3 but increase the reverse bias voltage all the way to -20 volts, unless voltage breakdown occurs at a lower voltage.

D. Technique for Testing Solar Modules

Using the PV module outdoor solar test stand (refer to Section III.B.11), the PV module proposed tests are listed in the test procedure provided and explained below. In Section 1.B. Hot Spot Reliability Problem Definition the purpose of the bypass diode in parallel with a submodule was discussed. A solar module can be partially shaded in many different ways. The concern is what pattern of shading of solar cells in a submodule has a high potential for creating a hot spot? A PV module is typically installed in portrait or landscape position. A PV module in portrait
position, when shaded by a vertical object could have a column of cells shaded, like column 1
cells SC1 to SC9 of Figure 3 and Figure 48 schematic, or part of the column. This could cause a
potential hot spot problem in submodule 1. If columns 3 or 4 were shaded, this could cause a
potential hot spot problem in submodule 2. If the PV module were shaded by a horizontal object,
then a row of cells could be shaded, like row 9 with cells SC9, SC10, SC27, and SC28. This
could cause a potential hot spot problem in submodules 1 and 2. If the PV module is in landscape
configuration, then a vertical shadow could potentially cause a hot spot in submodules 1 and 2,
and a horizontal shadow could potentially cause a hot spot in one of the submodules 1 or 2.

Is it a worse problem to have a few cells shaded or many? Table 5 has calculations for
reverse bias voltage and power available to dissipate per shaded cell. Consider first, when this
PV module is irradiated by 1000 W/m$^2$ each 156 mm x 104 mm solar cell receives 16.2 watts of
solar radiation. If 95% of the sunlight is absorbed, 5% reflected, and 0% transmitted (these
percentages must total 100), then the solar cell captured 15.4 watts. When a cell is shaded, it does
not receive that power from the sun, and will of course be at a lower temperature than the cells in
the sunlight. Table 5 shows that when 9 cells in a submodule are shaded, then the remaining 9
cells are illuminated by solar radiation, and can produce up to 5.7 volts (0.6 volts per cell + 0.3
volts from D1) and 25.0 watts (2.78 watts per cell). Since the shaded cells are off and not
producing power, a reverse bias voltage of 5.7 volts can be created across them by the illuminated
cells. This would average only 0.63 volts of reverse bias voltage and 2.78 watts per shaded cell
and not cause a problem. The table shows the greatest reverse bias stress voltage occurs when
only one solar cell is shaded in the submodule. It would be reverse bias stressed by up to 10.5
volts and could have up to 47.2 watts of power dissipated in it. If most of that power flows
through a breakdown region in the solar cell, then it could produce a high temperature hot spot as
discusses in section IV. D. Thermal Modeling and Simulations. The test procedure was designed
to take measurements on the PV module outdoor solar test stand with the white boards clamped
on the PV module to shade 9 cells, then 3, 2, and last the worst case 1 solar cell in column 1 with the PV module in portrait position. Shading can also be done on part of a solar cell.

**Table 5: Ratio of Shaded to Illuminated Solar Cells in PV Submodule**

<table>
<thead>
<tr>
<th>18 cells in submodule</th>
<th>ratio of illuminated cells to shaded cells</th>
<th>maximum reverse bias voltage (volts)</th>
<th>average reverse bias per shaded cell (volts)</th>
<th>maximum electrical power from illuminated cells (watts)</th>
<th>average power dissipated per shaded cell (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>shaded cells</td>
<td>illuminated cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1.00</td>
<td>5.7</td>
<td>0.63</td>
<td>25.00</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>1.25</td>
<td>6.3</td>
<td>0.79</td>
<td>27.78</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>1.57</td>
<td>6.9</td>
<td>0.99</td>
<td>30.56</td>
</tr>
<tr>
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<td>12</td>
<td>2.00</td>
<td>7.5</td>
<td>1.25</td>
<td>33.33</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>2.60</td>
<td>8.1</td>
<td>1.62</td>
<td>36.11</td>
</tr>
<tr>
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<td>14</td>
<td>3.50</td>
<td>8.7</td>
<td>2.18</td>
<td>38.89</td>
</tr>
<tr>
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<td>15</td>
<td>5.00</td>
<td>9.3</td>
<td>3.10</td>
<td>41.67</td>
</tr>
<tr>
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<td>16</td>
<td>8.00</td>
<td>9.9</td>
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</tr>
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<td>17.00</td>
<td>10.5</td>
<td>10.50</td>
<td>47.22</td>
</tr>
</tbody>
</table>

Figure 48 shows on the schematic for the modified Grape Solar GS-Star-100W PV module the location where these parts were attached: 14 thermocouples (TCs), 3 voltage dividers to sense voltage, and current shunt2 to sense current through bypass diode D1. The PV variable resistance load box was connected to the PV module. The detailed schematic for the PV variable resistance load box is in section 3.4. By increasing the load resistance, data for the I-V curve was obtained. A switch on the box disconnects the load for the open circuit voltage V_{oc} measurements. The temperatures, voltages, currents, and solar irradiance were measured with the NI USB-6210 and NI USB-6002 modules and displayed with the NI Signal Express software. The chassis ground was supplied from an electrical outlet.
Figure 48: Schematic of modified PV module and PV Resistance Load Box
In the test procedure shown below, the configuration for each test of the PV module outdoor solar test stand is listed. For most of the tests, temperatures of several shaded and fully illuminated solar cells were measured with TCs. A 5 minute $V_{oc}$ stability test let the PV module heat up since there was not an electrical load to dump power into. The FLIR E60 IR camera was used to view the temperature and its uniformity across the back or front of the PV module, and to look for hot spots. A picture with visible light was also taken. The voltage across and the current through the bypass diode D1 was measured to see if it was bypassing current when shading occurred. The pyranometers gave a measurement of the solar irradiance during the tests. Here are the general configurations.

In Part 1, an outline of setting up the test stand, along with warming up the NI DAQs, and doing temperature calibrations was given.

In Part 2A, a flexible 5/16” thick grey plastic cover was fastened over the front of the PV module (100% shading). Current and voltage produced by reflected light absorbed into the back of the module was measured by an I-V curve test.

In Part 2B, the baseline performance of the PV module with no shading was measured. A 5 minute $V_{oc}$ stability test, an I-V curve test, a 5 minute stability test at the maximum power point, and taking FLIR IR camera images and visible light pictures were part of the test.

In Part 2C, the partial shade tests were done. Several different size boards were made and painted white to be clamped onto the PV module to cover from 1 to 9 solar cells, or ¼, ½, or ¾ of one or more solar cells. A 5 minute $V_{oc}$ stability test, an I-V curve test, a 5 minute stability test at the maximum power point, and taking FLIR IR camera images and visible light pictures were part of the test.
Test Procedure for Characterization of Thermal and Electrical Properties of a Polycrystalline
Silicon PV Module in Direct Sunshine as Shade is Increased

Test Date: ________________

Part 1: Outdoor Setup of PV Module Solar Test Stand

The PV module model GS-STAR-100W manufactured by Grape Solar is the unit under test.

Move the PV module test equipment to a sunny level location outside near 120 volt AC power.

Install the flexible 5/16” thick grey plastic cover over front of the PV module to block sunlight.

Connect equipment mechanically and electrically. Plug in DAQs later. Remove plastic covers from both apogee pyranometers.

Turn on COMPAQ notebook laptop. Once Windows 7 is fully running, then plug the DAQs into the USB ports and start warm up of NI USB DAQ modules. Time = ___: ___

Start National Instruments software programs NI MAX, NI Signal Express, and for the 2 NI USB TC01s click on the Launcher.exe program.

Run temperature calibration on the NI USB-6210s after a 15-minute warm up. Record the current device temp. for USB 6210-A _____ °C, and USB 6210-B _____ °C. Time = ___: ___

Use the FLUKE 52 II Thermometer to measure at NI DAQs ambient (air) temperature _____ °C.

On the NI Signal Express set both NI USB-6210s TC CJC value = air temp + 3°C. Time = __: __

Note wind conditions: _____________________________________________________________

Comments: ____________________________________________________________________

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Part 2: Measurements for Partial Shadowing Test Configurations

Open NI Signal Express project named “Shadowing Test PV Module GS-STAR-100W.seproj”.

2A. Measurements due to Light on PV Back: The flexible 5/16” thick grey plastic cover should still be over the front of the PV module. The following measurements record the short circuit current ($I_{sc}$), the maximum power point power ($P_{mpp}$), and the open circuit voltage ($V_{oc}$) produced from light reflecting off the white concrete patio, the building windows and metal trim into the PV module back. Do not stand in front of the reflected light incident on the back of the PV module.

Record the measurements and the completion time for each step in the space provided.

I-V Power curve settings are 301 samples at 5 Hz for a 60-second test.

Stability test settings are 301 samples at 1 Hz for a 300 second (5 minute) test.

Use the FLUKE 52 II Thermometer to measure at NI DAQs ambient (air) temperature ______℃.

___ : ___ Run the I-V Power curve. Record in the space provided these measurements

$I_{mpp}$ = _______ amps DC, $V_{mpp}$ = _______ volts DC,

$I_{sc}$ = _______ amps DC, $V_{oc}$ = _______ volts DC

Compute: $P_{mpp}$ = _______ watts, $R_{LMP}$ = _______ohms

___ : ___ Take FLIR E60 infrared camera IR images with simultaneous visible pictures of front and back of the PV module, FLIR image numbers: _______, _______.

FLIR settings: emissivity = _______, distance = _______ meters

___ : ___ Take Nikon Coolpix P610 pictures of the setup area.
**2B. Baseline:** Remove thick grey plastic cover from the PV module.

Record the measurements and the completion time for each step in the space provided.

I-V Power curve settings are 301 samples at 5 Hz for a 60-second test.

Stability test settings are 301 samples at 1 Hz for a 300 second (5 minute) test

Use the FLUKE 52 II Thermometer to measure at NI DAQs ambient (air) temperature _____°C.

___ : ___ Switch to $V_{oc}$ test setup and wait 5 minutes for temperatures to stabilize.

___ : ___ Run the $V_{oc}$ stability test for 5 minutes. $V_{oc} = _______ $ volts DC.

___ : ___ Take IR picture of front and back, FLIR image numbers: _______, _______.

___ : ___ Run the I-V Power curve. Record in the space provided these measurements

$I_{mpp} = _______ $ amps DC, $V_{mpp} = _______ $ volts DC,

$I_{sc} = _______ $ amps DC, $V_{oc} = _______ $ volts DC

Compute: $P_{mpp} = _______ $ watts, $R_{LMPP} = _______ $ohms

___ : ___ Setup to the $P_{mpp}$ setup and wait 5 minutes for temperatures to stabilize.

___ : ___ Run the $P_{mpp}$ stability test for 5 minutes.

$I_{mpp} = _______ $ amps DC, $V_{mpp} = _______ $ volts DC

___ : ___ Take IR picture of front and back, FLIR image numbers: _______, _______.

Take Nikon Coolpix P610 pictures of the front and back: _______, _______.
2C. Partial Shade Tests:

Record the measurements and the completion time for each step in the space provided.

I-V Power curve settings are 301 samples at 5 Hz for a 60-second test.

Stability test settings are 301 samples at 1 Hz for a 300 second (5 minute) test

Shade front of first column of 9 solar cells numbered SC1 to SC9 with board.

Use the FLUKE 52 II Thermometer to measure at NI DAQs ambient (air) temperature ______ °C.

___ : ___ Switch to \( V_{oc} \) test setup and wait 5 minutes for temperatures to stabilize.

___ : ___ Run the \( V_{oc} \) stability test for 5 minutes. \( V_{oc} = \) ______ volts DC.

___ : ___ Take IR picture of front and back, FLIR image numbers: _______, ________.

___ : ___ Run the I-V Power curve. Record in the space provided these measurements

\[ I_{mpp} = \] ______ amps DC, \( V_{mpp} = \) ______ volts DC,

\[ I_{sc} = \] ______ amps DC, \( V_{oc} = \) ______ volts DC

Compute: \( P_{mpp} = \) ______ watts, \( R_{L\text{MPP}} = \) ______ ohms

___ : ___ Setup to the \( P_{mpp} \) setup and wait 5 minutes for temperatures to stabilize.

___ : ___ Run the \( P_{mpp} \) stability test for 5 minutes.

\[ I_{mpp} = \] ______ amps DC, \( V_{mpp} = \) ______ volts DC

___ : ___ Take IR picture of front and back, FLIR image numbers: _______, ________.

Take Nikon Coolpix P610 pictures of the front and back: _______, ________.
Repeat the 2C. Partial Shade Test and record the data for each one of these shade configurations:

Shade ¾ of front of first column of 9 solar cells numbered SC1 to SC9 with board.

Shade ½ of front of first column of 9 solar cells numbered SC1 to SC9 with board.

Shade ¼ of front of first column of 9 solar cells numbered SC1 to SC9 with board.

Shade front of 3 solar cells numbered SC7 to SC9 with board.

Shade front of 2 solar cells numbered SC8 and SC9 with board.

Shade front of 1 solar cell numbered SC9 with board.

Shade ¾ of front of 1 solar cell numbered SC9 with board

Shade ½ of front of 1 solar cell numbered SC9 with board

Shade ¼ of front of 1 solar cell numbered SC9 with board

Note to run the I-V Power curve, start test with PV Resistance Load Box switch set to solar panel and minimal resistance selected for short circuit current ($I_{sc}$). Increase the resistance until maximum. Then set the PV Resistance Load Box switch to solar cell for open circuit voltage ($V_{oc}$).

Note the $V_{oc}$ test, besides the voltages and currents measured, records the solar cell temperatures when there is not any current flowing through the solar cell substring. Hence, there should not be any hot spot formation.
CHAPTER IV
EXPERIMENTAL RESULTS VS THEORY

A. Solar Cell Experimental Results and Analysis

These comparison tests between mono c-SI and poly c-Si solar cells were performed as outlined in section III C. Technique for Testing Solar Cells:

- Test 1. Applied forward bias voltage (FBV) diode curve in the dark
- Test 2. Applied reverse bias voltage (RBV) diode curve in the dark
- Test 3. Current versus voltage I-V output performance curve with illumination
- Test 4. Current versus applied reverse bias voltage (RBV) with illumination and partial shading of 25%, 50%, 75%, 90%, 95%, and 98%

The solar cells dimensions were 125 mm x 125 mm x 200 um thick. Each solar cell had a p-type silicon base, and an n-type silicon emitter. The front electrical contact grid consisted of 2 busbars and fingers. Tabbing wires were soldered to the busbars on the front and to the pads on the back. The tabbing wires were connected to the solar cell tester (section III B.1) electrical power bars, with the front of the solar cell facing up. For the tests in the dark, the solar cell was surrounded with the large volume IR shield (section III B.6). HP E3610A and E3611A power supplies were connected to the solar cell tester to provide the required bias voltages. A FLUKE 45 and a FLUKE 179 digital multimeter were used to measure the solar cell voltage and current. The solar cells were purchased online. The manufacturer specifications are listed in Table 6.

<table>
<thead>
<tr>
<th>Solar cell</th>
<th>Efficiency</th>
<th>Pmpp watts</th>
<th>Vmpp volts</th>
<th>Impp amps</th>
<th>Voc volts</th>
<th>Isc amps</th>
<th>Antireflection Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono c-Si</td>
<td>17.6%</td>
<td>2.7</td>
<td>0.52</td>
<td>5.22</td>
<td>0.63</td>
<td>5.58</td>
<td>SiN</td>
</tr>
<tr>
<td>Poly c-Si</td>
<td>15.7%</td>
<td>2.4</td>
<td>0.50</td>
<td>4.8</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
For test 1, the applied forward bias voltage was supplied by 2 HP E3610A power supplies in parallel, which could provide 0 to 8 volts and 0 to 6 amps. The (+) voltage lead was electrically connected to the solar cell p-type silicon back side, while the (-) voltage lead was electrically connected to the n-type silicon front side. The IR shield was installed around the solar cell tester to block out light for this dark measurement. The voltage was slowly increased in 0.03 volt increments from 0 to 0.63 volts to let the temperature stabilize. The FLIR IR camera emissivity was set equal to 0.80 for all measurements. A more accurate diode equation (44) includes the series resistance $R_s$, and the shunt resistance $R_{sh}$ shown in the solar cell model in section II.B. Figure 11, with the current source I1 off for this dark test. Current I is going in the opposite direction due to the applied bias voltage.

$$I = I_0 \left( e^{q(V-I R_s)/n k T} - 1 \right) + \frac{V-I R_s}{R_{sh}} \quad (44)$$

The graphs in Figures 49 and 50 show the forward bias voltage curves look very similar for mono c-Si and poly c-Si solar cells. The curves have the typical appearance of a p-n junction diode, which was plotted in section II.B. Figure 10 for the diode equation (38). In Figure 49, on the mono c-Si solar cell number MONO1, the current rose to 5.58 amps, which is Isc spec, at an applied voltage of 0.637 volts, producing 3.55 watts of heat. The FLIR IR thermal image shows 5 spots which average 39.1 °C ± .5% giving uniform heating across the solar cell. In Figure 50, the test was run 4 times on the poly c-Si solar cell number PS2. The forward bias voltage curves for runs 3 and 4 occurred after the reverse bias voltage breakdown event, and have slightly more current than runs 1 and 2, most likely due to reduced shunt resistance $R_{sh}$, but fortunately still perform well. The current rose to 5.80 amps at an applied voltage of 0.634 volts, producing 3.67 watts of heat. The FLIR IR thermal image lists the temperature at 5 spots across the solar cell, which average 35.1 °C ± 2.3%. The poly c-Si large grain pattern is visible as different colors. The solar cell busbar temperature rose 21 °C, from the room temperature of 22 to 43 °C, as measured with a TEGAM 850 Calibrator Thermometer thermocouple with a K-type bead TC.
Figure 49: Forward bias voltage curve for mono c-Si 125 mm solar PV cell, with IR thermal image. TC soldered to right side of lower busbar.
Figure 50: Forward bias voltage curve for poly c-Si 125 mm solar PV cell. IR thermal image shows the large grain pattern. TC soldered to right side of lower busbar.
In Figure 51, the data from Figure 49 mono c-Si solar cell MONO1 was plotted using a semi-log scale in order to see the behavior of the low currents better. Similarly, in Figure 52 the data from Figure 50 poly c-Si solar cell PS2 was plotted using a semi-log scale. PS2 runs 1 and 2 look similar to MONO1. The FBV curves for runs 3 and 4 occurred after the RBV breakdown event, and have more current than runs 1 and 2, most likely due to reduced shunt resistance $R_{sh}$.

**Figure 51: Forward bias voltage curve for mono c-Si 125 mm solar PV cell, semi-log**

**Figure 52: Forward bias voltage curve for poly c-Si 125 mm solar PV cell, semi-log**
For test 2, an HP E3611A power supply capable of 0 to 20V at 0 to 1.5 A supplied the reverse bias voltage (RBV) which was increased from 0 to -20 volts, while the leakage current was measured. The power supply output leads were switched to reverse the applied voltage polarity to the solar cell. The (-) voltage lead was electrically connected to the solar cell p-type silicon base back side, while the (+) voltage lead was electrically connected to the n-type silicon emitter front side. A TEGAM 850 Calibrator Thermometer with an exposed bead K-type thermocouple was connected to the solar cell busbar to measure its temperature. The IR shield was installed around the solar cell tester for the dark measurement, so stray light from the room would not be absorbed by the solar cell and interfere with the measurement. The reverse bias voltage was slowly increased from 0 to -20 V in 1 V increments to let the temperature stabilize, while the leakage current was measured. Figures 53 and 54 show the RBV curves look very different when comparing the mono c-Si and poly c-Si solar cells.

In Figure 53, on the mono c-Si solar cell labeled MONO1, for run 1 as the applied RBV was increased from 0 to -16 V, the leakage current increased from 0 to -28.3 mA, producing only 0.45 W of heat. For run 2 as the applied RBV was increased from 0 to -20 V, the leakage current increased from 0 to -33.3 mA, producing only 0.67 W of heat. This result was the expected performance. Runs 1 and 2 were repeatable, and within 2 mA of each other. The thermal image had one warm spot in the lower right corner at 35.2 °C, which may be a lower shunt resistance at that point. Spots 1 to 4 averaged 26.9 °C ± 1.6%.
Figure 53: Leakage current due to reverse bias voltage on the mono c-Si 125 mm solar cell, with IR thermal image. TC soldered to right side of lower busbar.
In Figure 54, the reverse bias voltage test was run 8 times on the poly c-Si solar cell numbered PS2. The 8 RBV curves show repeatability in the measurement. For run 1, as the reverse bias voltage was increased from 0 to -10 V, the current increased in magnitude from 0 to -458 mA producing 4.58 W of heat. Already it was obvious that the performance was much worse than the mono c-Si solar cell. At -15.00 V the current was -1.384 A producing 20.76 W of heat. The TC temperature measurement had increased 39.8 °C from 23.1°C at the start to 62.9 °C. The 1.5 A current limit of the power supply was reached at -15.5 V, and -1.57 A giving 24.3 W of heat; see Figure 54 FLIR thermal image for run 1. Spots 1 to 5 averaged 73.7 °C ± 7.5%.

An HY3002D-3 power supply capable of supplying 0 to 4 A was used in place of the HP 3611A power supply. Run 2 followed the curve of run 1. At a RBV of -16.0 V there was -1.92 A producing 30.7 W of heat at 70 °C.

Thermal image of reverse bias voltage test run 1 producing 24.3 W of heat
Figure 54: Leakage current due to reverse bias voltage on the poly c-Si 125 mm solar cell, with IR thermal image. The voltage stress caused a breakdown and hot spot.

Figure 54 shows that run 3 followed the curves for runs 1 and 2. The voltage was increased beyond -16 V to see if -20 V could be obtained, like it was for mono c-Si. Before a RBV of -17 V was obtained, the solar cell went into thermal runaway. At −17 V the leakage current was 3.048 A, producing 51.8 W at 122 °C! The current increased to 4.08 A causing the voltage to drop to 2.27 V generating 9.27 W of heat. On the remaining runs 4 to 8 done on different days,
once the applied voltage was increased to about – 5 V, and -1.2 A producing 6 W of heat, then there would be a voltage breakdown in the solar cell and the voltage would drop back to -2.5 V at -4.8 A producing about 12 W of heat. The reverse bias voltage curve was permanently degraded. For run 8, the HY3002D-3 power supply was replaced by 2 HP E3610A DC power supplies connected in parallel to provide 0 to 8 volts at 0 to 6 amps for more power. On run 8, with more current available from the power supply, the voltage dropped back to -2.32 volts at -5.17 A.

Figure 55: Hot spot seen in IR thermal image had a maximum temperature of 368 °C, after a reverse bias voltage breakdown produced 12 W. Solar cell is poly c-Si, 125 mm.
The FLIR E60 IR camera thermal image of the hot spot is shown in Figure 55, along with a solar cell picture. The FLIR IR camera reported 7 minutes after the hot spot formed, a hot spot temperature of 368 °C, for an emissivity ε setting of 0.80, and a refl. temp. of 20 °C! The following temperatures were measured at these distances from the hot spot: 128.3 °C at 1 cm (Sp1), 88.1 °C at 2cm (Sp2), and 59.2 °C at 3cm (Sp3). This produced a 240 °C/cm temperature gradient between the hotspot and measurement spot 1 (Sp1). The TC showed that the center of the solar cell 7 cm away was at 42 °C. The hotspot occurred near the edge of the solar cell very close to the busbar, which provided plenty of current to fuel the hotspot.

The FBV curve of test 1 was permanently slightly altered for low currents shown in Figure 52 as mentioned previously, but looked typical in Figure 50 for a FBV above 0.57 volts.

The k-type thermocouple was soldered to the busbar about 9 cm away from the hotspot. The TC showed a temperature increase for runs 4 to 7 as the voltage was increased from 0 to -5 V at -1.2 A producing 6 W and 30 °C. When the solar cell broke down to -2.5 V at -4.8 A producing 12 W (twice the power before breakdown) the TC dropped to 20 °C, when it should have gone up! Turning off the power supply, the TC immediately read 36 °C. The hotspot affected the TC measurement. The fix was to unsolder the TC from the busbar. Then, put a square cm of electrical tape on the solar cell front center for electrical insulation. Fasten the TC to the electrical tape using heat sink compound for thermal conduction. This caused the TC to measure a temperature of 43 °C during the voltage breakdown. The temperature did not suddenly jump when the power supply was turned off, but slowly decreased and was normal.

Conclusion for test 2: The reverse bias voltage breakdown permanently degraded the solar cell and for a RBV greater than 5 volts a hotspot forms that can reach 335 °C.
For test 3, the I-V performance curve measurements were made as discussed in section III B.4 for the mono c-Si solar cell labeled MONO2, and for the poly c-Si solar cell labeled PS2. The solar cell I-V power curves shown in Figures 56 and 57 were generated by the following technique. The PV solar cell milliohm load module and then the PV resistance load box were connected one at a time to the solar cell tester – green wire to chassis ground, black wire to solar cell (+) output, and white wire to solar cell (-) output. The solar simulator was set to its maximum light intensity output of about 750 W/m$^2$ over the solar cell area. The IR shield was not used for this test. Each resistance load was manually increased from its minimum resistance to an open circuit in less than 30 seconds while the solar cell output voltage and current were measured and stored by the NI USB-6229 DAQ hardware and the NI Signal Express software. The data from the two resistance loads were combined to make an I-V graph.

Figure 56 shows the I-V performance graph for the mono c-Si solar cell labeled MONO2. The graph had the typical curve produced by a high quality solar cell. Figure 57 shows the I-V graph for the poly c-Si solar cell labeled PS2. The graph did not have the typical curve produced by a high quality solar cell; there was probably hot spot permanent damage to the shunt resistance of the solar cell. The drop off in the current with voltage indicates a lower shunt (parallel) resistance than MONO2. The short circuit current $I_{sc}$ was extrapolated for both graphs. The data is listed in Table 7. Based on this data, MONO2 looked like a better solar cell than PS2. If the solar simulator light intensity could be increased, then the solar cell output current and voltage would have increased to be closer to the specification values of Table 6.

<table>
<thead>
<tr>
<th>Solar cell</th>
<th>Label</th>
<th>$P_{mpp}$ watts</th>
<th>$V_{mpp}$ volts</th>
<th>$I_{mpp}$ amps</th>
<th>$V_{oc}$ volts</th>
<th>$I_{sc}$ amps</th>
<th>$R_{LMP}$ milliohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono c-Si</td>
<td>Grade A</td>
<td>MONO2</td>
<td>1.63</td>
<td>0.427</td>
<td>3.83</td>
<td>0.55</td>
<td>4.3</td>
</tr>
<tr>
<td>Poly c-Si</td>
<td>PS2</td>
<td>0.99</td>
<td>0.378</td>
<td>2.61</td>
<td>0.50</td>
<td>3.8</td>
<td>145</td>
</tr>
</tbody>
</table>
Figure 56: I-V performance curve of illuminated mono c-Si 125 mm solar PV cell

Figure 57: I-V performance curve of illuminated poly c-Si 125 mm solar PV cell
For test 4, the reverse bias voltage current tests were performed beneath the solar simulator in partial shade, of 25%, 50%, 75%, 90%, 95%, and 98% shade. A white painted board was suspended about 5 inches above the solar cell to provide the shade. Mono c-Si solar cell labeled MONO2 replaced MONO1 which broke. Poly c-Si solar cell labeled PS3, replaced PS2 which had hot spot damage resulting from the thermal runaway voltage breakdown of the RBV test. The test procedure was discussed in section outlined in section III C. Technique for Testing Solar Cells. The part of the solar cell which was not shaded had electrical carriers produced by the solar radiation, making that area more conductive to the reverse bias voltage. The power dissipated into the solar cell as heat was the product of voltage and current. Looking at Figure 58 for mono c-Si, and Figure 59 for poly c-Si, the 25% shade runs generated the most heat, 45 W and 47 W respectively. Comparing the results, Figure 58 graph of the MONO2 results appeared linear, which is similar to the RBV mono c-Si test in the dark; whereas Figure 59 graph of the PS3 results curved down at larger RBV, which is similar to the RBV poly c-Si test in the dark.

In Figure 58, the FLIR E60 IR camera thermal image and picture are shown with the graph for MONO2. The picture shows the location of the board relative to the solar cell for 25% shading. The thermal image lists a maximum temperature of 178.9 °C at the red triangle near the busbar. The part of the solar cell which is shaded appears cooler on the thermal image and as measured by spots 1, 2, and 3: 83.1 °C, 86.3 °C, and 75.6 °C.

In Figure 59, the FLIR E60 IR camera thermal image and picture are shown with the graph for PS3. The picture shows the location of the board relative to the solar cell for 25% shading. The thermal image lists a maximum temperature of 200.2 °C at the red triangle near the busbar, and about the same place as the hot spot on the previous solar cell labeled PS2. The part of the solar cell which is shaded appears cooler on the thermal image. Spots 1, 2, and 3 descend in temperature maybe due to a temperature gradient from the hottest spot.
Figure 58: Reverse bias voltage with partial shade on mono c-Si. Thermal image and picture had 25% shade, and generated 45 W of heat. SP1 to SP3 were shaded.
Figure 59: Reverse bias voltage with partial shade on poly c-Si. Thermal image and picture had 25% shade, and generated 47 W of heat. SP1 to SP3 were illuminated.
B. Solar PV Module Experimental Results and Analysis

A few of the tests outlined in section III.D, Technique for Testing Solar Modules, were performed. Each day testing was done required 2 hours of equipment setup outside, and then 2 hours to bring it inside and put it away. Only part of the test plan was done. National Instruments Signal Express was used with data acquisition modules to collect much of the data as explained in section III.

Table 8: Measurements from 12 Thermocouples on PV Module

<table>
<thead>
<tr>
<th>Data Record:</th>
<th>Baseline Voc Stability 10/27/2016 3:25:29 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_Unit_Label</td>
<td>Temperature (deg C)</td>
</tr>
<tr>
<td>X_Dimension</td>
<td>Time (s)</td>
</tr>
<tr>
<td>Delta_X</td>
<td>1 second</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X_Value:</th>
<th>TCs: 1-6 - Dev2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Acq. Module:</td>
<td>NI-USB-6210 #A</td>
</tr>
<tr>
<td>Analog Input:</td>
<td>ai1 ai2 ai3 ai4 ai5 ai6</td>
</tr>
<tr>
<td>Thermocouple #:</td>
<td>TC1 TC2 TC3 TC4 TC5 TC6</td>
</tr>
<tr>
<td>TC Measures:</td>
<td>SC1 SC2 SC3 SC4 SC5 Chassis</td>
</tr>
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</table>

<table>
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<th>Statistical Results:</th>
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<td>Measurements: N</td>
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<tr>
<td>Average: °C</td>
</tr>
<tr>
<td>Standard Deviation:</td>
</tr>
<tr>
<td>Std. Dev./Avg.: %</td>
</tr>
<tr>
<td>Slope: °C/s</td>
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<table>
<thead>
<tr>
<th>X_Value:</th>
<th>TCs: 7-10, 13, 14 - Dev3</th>
</tr>
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<tbody>
<tr>
<td>Data Acq. Module:</td>
<td>NI-USB-6210 #B</td>
</tr>
<tr>
<td>Analog Input:</td>
<td>ai1 ai2 ai3 ai4 ai5 ai6</td>
</tr>
<tr>
<td>Thermocouple #:</td>
<td>TC7 TC8 TC9 TC10 TC13 TC14</td>
</tr>
<tr>
<td>TC Measures:</td>
<td>SC6 SC7 SC8 SC14 SC23 Air</td>
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<table>
<thead>
<tr>
<th>Statistical Results:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements: N</td>
</tr>
<tr>
<td>Average: °C</td>
</tr>
<tr>
<td>Standard Deviation:</td>
</tr>
<tr>
<td>Std. Dev./Avg.: %</td>
</tr>
<tr>
<td>Slope: °C/s</td>
</tr>
</tbody>
</table>
Data was collected from the outdoor PV module baseline Voc (voltage open circuit, no load) setup without shading. None of the 12 thermocouples, TCs, were in direct sunlight. This was a 5 minute stability test with 300 measurements per TC, to see how closely the TCs measured temperature and how repeatable they were. Refer to Figure 48 for TC locations. In Figure 60 the National Instruments Signal Express screen showed the 5 minute TC stability test. Table 10 gives the statistics on the TC measurements. In the table, SC1 stands for solar cell 1, etc.; chassis is the double walled metal frame on the solar module, air is for an ambient measurement on back of solar module. The air temperature, ambient, was cooler than the chassis, which was cooler than the solar cells. The (one sigma standard deviation / average) % was calculated for each TC. It ranged from 1.39 % to 3.12%. for the solar cell TCs. To decrease the range of these 10 TCs may involve using surface TCs instead of bead TCs for better contact. The solar cells could have slightly different temperatures depending on how well their electrical parameters are matched. The slight wind seen in the variation of the ambient, bottom trace, may also add some variability.

Figure 60: Stability test of 12 thermocouples for 5 minute baseline in Voc setup on the Grape Solar GS-START-100W PV module.
Figure 61: Typical I-V power curve with no shade (top). Bypass diode D1 conducts current due to shade (bottom)

Look at the graphs displayed on the N.I. Signal Express screens of Figure 61. The top screen shows a normal I-V curve, colored in blue, for a power test on the 100 W solar PV module as the
external Variable Resistance Load Box is increased in resistance. The green curve shows that no current is going through the bypass diode D1.

To prepare for the partial shading test, a board was clamped as shown in figure 44 onto the front of the solar module over solar cells number 1 to 9. The bottom screen green curve is the current through bypass diode 1, versus output voltage, and proves that the bypass diode conducts when some of the cells in its submodule are shaded and turned off. This graph agrees with the graph in Figure 3 “Module I-V Characteristics with Different Cells Totally Shadowed” from Appendix B, “Standard Test Method for Hot Spot Protection Testing of Photovoltaic Modules”. The I-V curve started to drop off at an output voltage of 8 volts because the shaded solar cells were not producing electrical power. Similar curves are seen in section III-C Electrical Modeling and Simulations, Figures 72 and 73 for simulation of I-V, P-V, and bypass diode current curves for a 36 cell PV module with one cell shaded and $R_p$ equal to 70 ohms and then 10 ohms. Since D1 is conducting, and solar cells 10 to 18 are not shaded, therefore the shaded solar cells 1 to 9 are reverse biased by the voltage produce by solar cells 10 to 18.
C. Electrical Modeling and Simulations

National Instruments Multisim 14.0 software was used to model and simulate the current, voltage, and power in a silicon photovoltaic solar cell. In Figure 62, the constant current source I1 with a 6.13 amp DC output simulated the photovoltaic current produced by a solar cell in a PV module from STC incident solar radiation. STC stands for standard test conditions which is 1,000 W/m$^2$ (100mW/cm$^2$) irradiance, at 25 °C, and AM = 1.5 (air mass ratio). The solar cell “single diode” pn junction was modeled by diode D1, which was an MUR805G diode modified with N the emission coefficient changed [37] from 1.63481 to 1.16 to give Voc of 0.632 volts. The MUR805G diode was in the NI Multisim 14.0 software component database. $R_{sh}$ (sometimes called $R_p$) was the 70.0 Ω parallel resistance between the front (-) voltage and the back (+) voltage for this p-type substrate, 156 mm x 104 mm, 2 busbar solar cell. The series resistance $R_s$ equal to 0.005 Ω was due mainly to the resistance of the metal busbar and finger grid system on the front of the solar cell for collecting electron current. $R_L$ was the load resistance set to 0 Ω for a short circuit current $I_{sc}$ configuration. The simulation output was 6.13 amps DC at 0 volts, which was the specification for a solar cell in the GS-STAR-100W PV module, which was tested outside as discussed in Chapter IV section C.

V: 0 V
V(p-p): 0 V
V(rms): 0 V
V(dc): 0 V
V(freq): --

I: 6.13 A
I(p-p): 0 A
I(rms): 0 A
I(dc): 6.13 A
I(freq): --

D1 diode was an MUR805G diode modified with N the emission coefficient changed from 1.63481 to 1.16 to give Voc of 0.632 volts.

Figure 62: Model and simulation of short circuit configuration with $I_{sc} = 6.13$ A for a 156 mm x 104 mm poly c-Si solar cell.
To measure the open circuit voltage for this model, the load resistance was changed to 1 TΩ as shown in Figure 63. The simulation computed the output open circuit voltage $V_{oc}$ to be equal to 632 mV DC at 0 amps, which is a typical value for a quality solar cell.

$V_{oc}$

The $I_{sc}$ and $V_{oc}$ data demonstrated the solar cell maximum and minimum values for the range of load resistance. Figure 64 was created by a device parameter sweep, where load resistance was the parameter varied from 1 mΩ to 10 Ω logarithmically. The output voltage, output current, and output power were plotted as a function of the load resistance log scale. During this load resistance sweep, the current source stayed constant at 6.13 A. As expected, the output current decreased and the output voltage rose as the load resistance increased. As the load resistance increased, the power increased to its maximum power point $P_{MPP}$ of 2.65 watts for 86 mΩ load resistance, and then decreased. The $P_{MPP}$ of 2.65 watts was 4.7% less than the real solar cell spec maximum power of 2.78 watts. The simulation values were close enough for later shading simulations. The data for this simulation was exported to a Microsoft Excel spreadsheet.

Figure 63: Model and simulation of open circuit configuration with $V_{oc} = 632$ mV for a 156 mm x 104 mm poly c-Si solar cell.

D1 diode was an MUR805G diode modified with the emission coefficient changed from 1.63481 to 1.16 to give Voc of 0.632 volts.
Figure 64: Simulation of output current, voltage, and power as the load resistance is swept from 1 mΩ to 10 Ω, for a 156 mm x 104 mm poly c-Si solar cell.

The simulation data in the spreadsheet was used to create the I-V and the P-V curves shown in Figure 65. The importance of the I-V curve was previously discussed in Chapter 3 section B. 4 on the Variable Resistance PV Load Box. The I-V curve looked typical with the output current slightly decreasing until the output voltage reached 0.4 volts DC, where the diode current conduction greatly increased and made less current available at the output. The graph showed for a current of 0 A, the open circuit voltage \( V_{oc} \) was 0.63 volts. The rectangular area under any point on the I-V curve represents the output power equal to output voltage multiplied by output current at that point. The I-V and P-V graphs show the location of the maximum power point values \( V_{MPP} \), \( I_{MPP} \), and \( P_{MPP} \). \( P_{MPP} \) was 2.65 watts, \( V_{MPP} \) was 0.477 volts which is 4.6% less than the 0.50 volts real solar cell spec. \( I_{MPP} \) was 5.56 amps which is the same as the real solar cell spec. If the more detailed 2 diode model were used, then the difference between the simulation and a real solar PV cell may decrease.
Figure 65: Simulation of the I-V and P-V curves of a 156 mm x 104 mm poly c-Si solar cell

The simulation for the GS-STAR-100W PV module was performed by using the concept of the “single diode model” to represent each one of the 36 solar cells. Figure 66 shows that 36 diodes labeled D1 to D36 were used to represent the pn junctions of the 36 solar cells. These diodes were modified from a MUR805G diode, with N the emission coefficient changed from 1.63481 to 1.16. In submodule 1 the series connected 18 diodes are in parallel with a Schottky bypass diode D\textsubscript{bypass1} like in the PV module. Instead of showing 18 series resistors of 0.005 Ω, a simplification was made by combining them into R\textsubscript{s1} of 0.1Ω. Since in the sunlight a small percentage of current flows through each solar cell parallel resistance, to simplify things the parallel resistors were left out except for R\textsubscript{p1}. D1 is shown in parallel with R\textsubscript{p1} equal to 70 Ω. The parallel resistance becomes very important when the solar cell is shadowed. Since the same current flows through all 18 solar cells in series, therefore one current source is used.
Model of PV Module, $P_{\text{max}} = 95.2$ watts, $V_{\text{oc}} = 22.75$ volts, $I_{\text{sc}} = 6.13$ amps
Diodes D1 to D38 were modified from a MUR805G diode, with $N$ the emission coefficient changed from 1.63481 to 1.16.

Figure 66: Model of PV module connected to a variable resistance external load
Submodule 2 is designed similar to submodule 1. The two submodules are in series with their output connected to the variable resistance external load. Voltage probe 1 (VPR1) measures the output voltage relative to chassis ground, which is also the voltage across the load resistance. The output current and output power are measured at the variable resistance external load. Current probe 2 (APR2) measures the current through the bypass diode D\textsubscript{bypass1}.

Figure 67 was created by a device parameter sweep, where load resistance was the parameter varied from 10 m\text{\textOmega} to 1 k\text{\textOmega} logarithmically, with 30 points per decade. The output voltage, output current, and output power were plotted as a function of the load resistance log scale. During this load resistance sweep, the current source stayed constant at 6.13 A. As expected, the output current decreased and the output voltage rose as the load resistance increased. As the load resistance increased, the power peaked at 95.2 watts for a 2.93 \text{\textOmega} load resistance, and then decreased. The bypass diode current was 0 amps because the solar cells were not shaded. The data for this simulation was exported to a Microsoft Excel spreadsheet.

![Device Parameter Sweep](image)

**Figure 67**: Simulation of output current, voltage, power, and bypass diode current as the load resistance is swept from 10 m\text{\textOmega} to 1 k\text{\textOmega}, for a PV module with 36 poly c-Si solar cells.
The I-V and the P-V curves shown in Figure 68 were created from the spreadsheet simulation data. The importance of the I-V curve was discussed in Chapter 3 section B.4 on the Variable Resistance PV Load Box. The I-V curve looked typical with the output current slightly decreasing until the output voltage reached 14 volts DC, at which point the diodes current conduction greatly increased and made less current available at the output. The graph shows for a current of 0 A, the open circuit voltage $V_{oc}$ was 22.75 volts. The I-V and P-V graphs show where $V_{MPP}$, $I_{MPP}$, and the maximum power point $P_{MPP}$ equal to 95.2 watts occurred. $P_{MPP}$ was 4.8% less than the real solar cell maximum power spec of 100 watts. $V_{MPP}$ was 16.70 volts which was 7.2% less than the 18.0 volts of the real PV module spec. $I_{MPP}$ was 5.70 amps which was 2.5% more than the 5.56 amps of the real solar cell spec. These values are close enough for the following shading simulations.

Figure 68: Simulation of PV module with $P_{max} = 95.2 \text{ W}$, $V_{oc} = 22.75 \text{ V}$ and $I_{sc} = 6.13 \text{ A}$
The model for the GS-STAR-100W PV module was modified to simulate one solar cell being 100% shaded. Figure 69 shows that diode labeled D1 was removed because solar cell SC1 was 100% shaded, does not produce any current, and now has a reverse bias voltage stress across it. Resistor $R_{p1}$ equal to 70 $\Omega$ was the parallel resistance of the solar cell and remained in the model. Resistor $R_{p1}$ was moved to be in series with the current source. The value of this parallel resistance can be changed to simulate its effect on the PV module performance.

Figures 70 and 71 were created by a device parameter sweep, where load resistance was the parameter varied from 10 m$\Omega$ to 1 k$\Omega$ logarithmically, with 30 points per decade, like previously done. For Figure 70 $R_{p1}$ was equal to 70 $\Omega$. For Figure 71 $R_{p1}$ was equal to 10 $\Omega$. The output voltage, output current, output power, and current through the bypass diode were plotted as a function of the load resistance log scale. During each load resistance sweep, the current source stayed constant at 6.13 A. The graphs show that the shaded cell caused a large effect on how the output current decreased and the output voltage rose as the load resistance increased. As the load resistance increased, the power peaked at 45 watts about at a 1.47 $\Omega$ load resistance, and then decreased. The power and load resistance are about half of the values for an unshaded PV module. The bypass diode $D_{bypass1}$ current was slightly less than the output current when $R_{p1}$ was equal to 70 $\Omega$ showing that most of the current produced by submodule 2 passed through the bypass diode of submodule 1 because solar cell SC1 was 100% shaded. When $R_{p1}$ was equal to 10 $\Omega$, then the bypass diode $D_{bypass1}$ current was about 1 amp less than the output current, because some of the current flowed through the 100% shaded solar cell SC1. There is also a small amount of additional power and voltage available for higher load resistance when $R_{p1}$ was equal to 10 $\Omega$, than when it was equal to 70 $\Omega$. The data for these simulations was exported to a Microsoft Excel spreadsheet. Figures 72 and 73 show the large effect of 100% shading of one solar cell on the I-V and P-V graphs. These graphs resemble the I-V curve on the shaded PV module measured outside, and Figure 3 of APPENDIX B.
Model of PV Module, $P_{\text{max}} = 44.9$ watts, $V_{\text{oc}} = 20.67$ volts, $I_{\text{sc}} = 6.13$ amps
Diodes D2 to D38 were modified from a MUR805G diode, with N the emission coefficient changed from 1.63481 to 1.16. Rp1 represents the shaded cell.

Figure 69: Model of PV module which has one solar cell shaded represented by Rp1
Figure 70: Simulation of output current, voltage, power, and bypass diode current as load resistance was swept from 10 mΩ to 1 kΩ, for 36 cell PV module with one cell shaded and $R_p$ equal to 70 ohms.

Figure 71: Simulation of output current, voltage, power, and bypass diode current as load resistance was swept from 10 mΩ to 1 kΩ, for 36 cell PV module with one cell shaded and $R_p$ equal to 10 ohms.
Figure 72: Simulation of I-V, P-V, and bypass diode current curves for a 36 cell PV module with one cell shaded and $R_p$ equal to 70 ohms.

Figure 73: Simulation of I-V, P-V, and bypass diode current curves for a 36 cell PV module with one cell shaded and $R_p$ equal to 10 ohms.
D. Thermal Modeling and Simulations

COMSOL MULTIPHYSICS 4.4 software was used to model and simulate the formation of a hot spot on a silicon photovoltaic solar cell. The model of the solar cell and its hot spot included the geometry, material properties, heat generated, and heat transfer by conduction, convection, and radiation. Finite element analysis (FEA) was used for computing numerical simulations for several configurations. The FEA applied a tetrahedral mesh to the finite element discretization of the solar cell. These thermal simulations were for a cylindrical hot spot in a horizontal solar cell in air, before it was packaged into a solar PV module (panel). The reverse bias voltage multiplied by the current flowing through the hot spot region created the power generated to form the hot spot. This energy was mainly dissipated as heat. Since the solar cell was shaded from sunlight, no solar radiation was added. The simulation steady state temperature results across the silicon surface were displayed in two-dimensional plots. Several simulations were run varying the hot spot: diameter, power generated, location, and substrate thickness. Graphs of temperature vs. time were also generated for the time dependent simulations. Model details, tabulated results, and several thermal plots and graphs are discussed next.

Model values for solar cell geometry and materials:

- Solar cell substrate dimensions: 125 mm x 125 mm x 0.25 mm
- Hot spot cylinder dimensions: diameter = 3.0 mm, height = 0.25 mm
- Hot spot center base location: x = 30.0 mm, y = 12.5 mm, z = 0.0 mm
- Material of substrate and hot spot: silicon
  - Density $\rho = 2,329 \text{ kg/m}^3$
  - Heat capacity at constant pressure $C_p = 700 \text{ J/(kg*K)}$
  - Thermal conductivity $k = 130 \text{ W/(m*K)}$
  - Front emissivity $\varepsilon = 0.9$ represented a 100 nm thick antireflection coating.
Back emissivity $\varepsilon = 0.3$ represented a 0.002 mm thick aluminum coating.

Antireflection coating and aluminum coating were not created on COMSOL.

- Solar cell busbar dimensions: 1.4 mm x 125 mm x 0.2 mm
- Busbar locations: centerlines at $x = 30$ mm for busbar 1, and $x = 95$ mm for busbar 2
- Busbar material: silver
  - Density $\rho = 10,500$ kg/m$^3$
  - Heat capacity at constant pressure $C_p = 235$ J/(kg*K)
  - Thermal conductivity $k = 429$ W/(m*K)
  - Emissivity $\varepsilon = 0.1$

Model of solar cell heat transfer, initial conditions, and surface boundary conditions:

- Initial value for solar cell temperature $T = 293.15$ K = 20 °C
- Ambient temperature was constant at $T_{ext} = 293.15$ K = 20 °C
- There were no surfaces with thermal insulation.
- Heat Source $Q$ [W/m$^3$] from hot spot generation total power $P_{tot} = 15$ watts, $Q = P_{tot} / \text{Volume}$
- Heat Transfer in Solids: Fourier’s law of conduction equates the heat flux $q''$ [W/m$^2$] to the thermal conductivity $k$ [W/(m*K)] and the temperature gradient $\nabla T$ [K/m] by this equation $q'' = -k\nabla T$. The temperature $T$ [K] and heat flux $q''$ [W/m$^2$] were calculated in the solar cell model by this equation
  \[
  \rho C_p \frac{dT}{dt} = \nabla \cdot (q'') + Q = \nabla \cdot (-k\nabla T) + Q = -k\nabla^2 T + Q \quad (45)
  \]
- Heat Flux 1: Newton’s law of cooling (convection) was used with the estimated air heat transfer coefficient $h = 8$ W/(m$^2$K) inward on entire front solar cell horizontal top surface. Heat flux $q''$ [W/m$^2$] was calculated by this equation
  \[
  q'' = -\vec{n} \cdot (-k \nabla T) = h(T_{ext} - T) \quad (46)
  \]
• Heat Flux 2: like Heat Flux 1 calculation, but now used the estimated air heat transfer coefficient \( h = 3 \text{ W/(m}^2\text{K)} \) inward on entire back solar cell horizontal bottom surface.

• Surface-to-Ambient Radiation 1, the Stefan-Boltzmann law of radiation was used with the emissivity \( \varepsilon = 0.9 \) to represent 100 nm thick anti reflection coating on silicon substrate front and edges. The Stefan-Boltzmann constant is \( 5.670 \times 10^{-8} \text{ [W/(m}^2\text{K}^4]} \)

Surface-to-ambient radiation into the solar cell surface is given by this equation

\[
q'' = -\vec{n} \cdot (-k \nabla T) = \varepsilon \sigma (T_{amb}^4 - T^4)
\]  

(47)

• Surface-to-Ambient Radiation 2, like Surface-to-Ambient Radiation 1 calculation, but now the emissivity \( \varepsilon = 0.3 \) to represent the 0.002 mm thick aluminum coating on silicon substrate back,

• Surface-to-Ambient Radiation 3, like Surface-to-Ambient Radiation 1 calculation, but now the emissivity = 0.1 for 2 silver busbars and edges

Figure 74 shows the solar cell surface temperature simulation plot for a 3 mm diameter hot spot formed by 15 watts of power generated by the product of reverse bias voltage and current. The hot spot was represented as being cylindrical to simplify the calculations. In reality, it could be a random shape for the electrical conduction path between the solar cell front side (−) potential and the back side (+) potential for a p-type silicon solar cell. The hot spot had a maximum temperature of 320 °C, and was located at \( x = 30.0 \text{ mm}, y = 12.5 \text{ mm} \), centered beneath a busbar. Either busbar can provide electrical power with minimum resistance, and can produce a more powerful hot spot, compared to locations further away from a busbar, which would have a longer conduction path with more electrical resistance. The silver busbar conducted some heat away from the hot spot. The far corner at \( x = 125 \text{ mm}, y = 125 \text{ mm} \) was the coolest spot about 31 °C. Figure 75 shows the corresponding plot of lines of isosurface temperature, and hence the temperature gradient, along with the arrows pointing in the direction of heat flux flow.
Figure 74: Simulation of surface temperature for a 3 mm diameter, 15 watt hot spot

Figure 75: Simulation of isosurface temperature and heat flux flow for a 3 mm diameter, 15 watt hot spot
Model parameters were varied next to see their effect on hot spot temperature, and heat flux. The following simulation sets list the range a parameter was varied from the starting model.

1. Diameter of hot spot in mm: 2, 3, 4, 5, 6, 10, 15, and 20
2. Power generated in hot spot in watts: 10, 15, 20, 25, 30, 35, and 40
3. Location of hot spot: 5 different places including the center
4. Thickness of solar cell silicon substrate in mm: 0.20, 0.25, 0.30, 0.40, and 0.50

In addition to the above parameter data, the finite element analysis mesh degrees of freedom, and the simulation time were included. Results were summarized in the following tables and graphs.

In Table 9 and Figure 76, hot spot temperature decreased by 100 °C from 334 °C to 234 °C as the spot diameter was increased from 2.0 mm to 20.0 mm. Hot spot power was 15 watts, which was dissipated as heat centered beneath the busbar. Temperature decreased with increasing hot spot diameter because the 15 watts of heat generation was spread out over a larger hot spot volume resulting in a lower maximum temperature. Figure 77 shows the solar cell surface temperature plot for the 20.0 cm diameter hot spot. Figure 78 shows the corresponding plot of lines of isosurface temperature, with the arrows pointing in the direction of heat flux flow, which is opposite to the direction of the temperature gradient.

Table 9: Simulation of Hot Spot Temperature as a Function of Hot Spot Diameter

<table>
<thead>
<tr>
<th>Input 15 watt hot spot at x = 30.0 mm, y = 12.5 mm diameter, mm</th>
<th>Results</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature maximum, °C</td>
<td>Mesh degrees of freedom</td>
</tr>
<tr>
<td>2.0</td>
<td>334</td>
<td>154,731</td>
</tr>
<tr>
<td>3.0</td>
<td>320</td>
<td>155,173</td>
</tr>
<tr>
<td>4.0</td>
<td>309</td>
<td>155,632</td>
</tr>
<tr>
<td>5.0</td>
<td>300</td>
<td>155,976</td>
</tr>
<tr>
<td>6.0</td>
<td>292</td>
<td>154,956</td>
</tr>
<tr>
<td>10.0</td>
<td>268</td>
<td>155,529</td>
</tr>
<tr>
<td>15.0</td>
<td>248</td>
<td>155,266</td>
</tr>
<tr>
<td>20.0</td>
<td>234</td>
<td>156,174</td>
</tr>
</tbody>
</table>
Figure 76: Simulation shows hot spot temperature decreased as diameter increased.

Figure 77: Simulation of surface temperature for a 20 mm diameter, 15 watt hot spot
In Table 10 and Figure 79, the solar cell hot spot temperature increased almost linearly by 486 °C from 227 °C to 713 °C as the hot spot power was increased from 10 watts to 40 watts and dissipated as heat, for the 3.0 mm diameter hot spot centered beneath the busbar. At steady state, the hot spot temperature increased with power. Near ambient temperatures, most of the heat was dissipated by conduction and convection. As the hot spot power increased, the temperature $T$ rose above the 20 °C ambient. The amount of heat leaving the solar cell by radiation increased according to the Stefan-Boltzmann law by a factor of $\sigma(T^4 - 293.15^4)$. Assuming the same hot spot area, the radiated heat at 700 °C is about 74 times the radiated heat at 100 °C. Figure 80 shows the solar cell surface temperature plot for the 40.0 watt hot spot. Figure 81 shows the corresponding plot of lines of isosurface temperature, with the arrows pointing in the direction of heat flux flow, which is opposite to the direction of the temperature gradient.
Table 10: Simulation of Hot Spot Temperature as a Function of Power Dissipated as Heat

<table>
<thead>
<tr>
<th>Input hot spot at x = 30.0 mm, y = 12.5 mm</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>power, W</td>
<td>Temperature maximum</td>
</tr>
<tr>
<td>10</td>
<td>227 °C</td>
</tr>
<tr>
<td>15</td>
<td>320 °C</td>
</tr>
<tr>
<td>20</td>
<td>408 °C</td>
</tr>
<tr>
<td>25</td>
<td>491 °C</td>
</tr>
<tr>
<td>30</td>
<td>569 °C</td>
</tr>
<tr>
<td>35</td>
<td>643 °C</td>
</tr>
<tr>
<td>40</td>
<td>713 °C</td>
</tr>
</tbody>
</table>

Figure 79: Hot spot temperature increased as power dissipated as heat increased.
Figure 80: Simulation of surface temperature, for a 40 watt, 3 mm diameter hot spot with a maximum temperature of 713 °C

Figure 81: Simulation of isosurface temperature and heat flux flow for a 40 watt, 3 mm diameter hot spot
In Table 11 and Figure 82, the hot spot was located at 5 different spots on the solar cell. A simulation was run for each location of the hot spot. The hot spot temperature varied with its location on the solar cell. Each simulation took less than 45 seconds to run with a fine mesh setting that used about 155,000 degrees of freedom in the calculation. If a finer mesh setting were used for higher resolution and accuracy, then the number of mesh elements and degrees of freedom would increase and the calculation would take longer. Worst case, the computer would run out of memory and the COMSOL MULTIPHYSICS software would abort the calculation. In Figure 82, the 5 simulated hot spots are plotted on a 125 mm x 125 mm square which represents the solar cell front surface. The steady state maximum temperature is listed next to each hot spot, which was simulated with a 3 mm diameter, and 15 watts of power dissipated as heat. The hotspot in the bottom left corner had the highest temperature of 409 °C, because there was little silicon substrate nearby to conduct the heat away. The hotspots beneath the busbars were cooler because the silver busbar conducted heat. The 284 °C hotspot beneath the busbar was cooler than the 312 °C center. Without the busbars, the center would have been the coolest location for a hot spot due to all of the silicon substrate around it to conduct the heat away. Figure 83 shows the solar cell surface temperature plot for the 409 °C hot spot centered at x = 12.5 mm, and y = 12.5 mm. Figure 84 shows the corresponding plot of lines of isosurface temperature, with the arrows pointing in the direction of heat flux flow, which is opposite to the direction of the temperature gradient.

<table>
<thead>
<tr>
<th>Input 15 watt hot spot diameter = 3.0 mm at x, mm</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>y, mm</td>
<td>Temperature maximum</td>
</tr>
<tr>
<td>30.0</td>
<td>320 °C</td>
</tr>
<tr>
<td>12.5</td>
<td>368 °C</td>
</tr>
<tr>
<td>12.5</td>
<td>409 °C</td>
</tr>
<tr>
<td>30.0</td>
<td>284 °C</td>
</tr>
<tr>
<td>62.5</td>
<td>312 °C</td>
</tr>
</tbody>
</table>
Figure 82: Five simulations of surface temperatures (°C) for a 3 mm diameter, 15 watt hot spot at 5 different locations are plotted on the solar cell model.

Figure 83: Simulation of surface temperature for a 15 watt, 3 mm diameter hot spot near corner with a maximum temperature of 409 °C
Figure 84: Simulation of isosurface temperature with a 15 watt, 3 mm diameter hot spot

The time dependence of the hot spot temperature and its effect on the solar cell temperature were next studied. The previously mentioned 409 °C, 15 watt, 3 mm diameter hot spot located at x = 12.5 mm, and y = 12.5 mm was measured by Probe2 for 60 seconds at 1 second intervals from the time it started to generate heat. Four other probes measured the temperature time dependence at four other locations on the solar cell. The rise time from the starting temperature of 20 °C to 90% of the final temperature change was measured. Figure 85 shows a simulation plot of the 5 probe measurement locations, and lists for each spot the probe number, the temperature at 60 seconds, the rise time, and its (x, y) coordinates in mm. As would be expected, the farther away from the hot spot, the cooler the temperature. The rise time was longer the farther away from the hot spot because heat was being absorbed by all of the solar cell material, and took time to propagate across the solar cell. The temperature gradients produced in the solar cell by the hot spot might stress and cause micro crack damage in the silicon substrate.
Figure 85: Simulation of surface temperature for a 15 watt, 3 mm diameter hot spot was measured by Probe2. For each of the 5 probe measurement locations, the temperature at 60 seconds, the rise time, and the location (x, y) in mm are shown.

In Figure 86 the simulation plot of temperature vs. time shows for the 5 solar cell locations each measured by a probe how quickly the temperature rose during 60 seconds from the initial temperature of 20 °C. The hot spot reached its steady state temperature of 409 °C by 60 seconds, whereas the farthest point away measured by Probe5 was still increasing in temperature. The (x, y, z) coordinates in mm had the same z value of 0.25 mm which was on the top surface of the silicon but beneath the silver of the busbar.
Figure 86: Simulation of the 15 watt, 3 mm diameter hot spot at (12.5mm, 12.5mm) showed a rise time of 13 seconds that reached a steady state temperature of 409°C. Probes measured the temperature time dependence at 4 additional locations on solar cell.

In Table 12 and Figure 87, the hot spot temperature decreased by 133 °C from 357 °C to 224 °C as the solar cell silicon substrate thickness was increased from 200 nm (0.2 mm) to 500 nm (0.5 mm). The hot spot had a 3.0 mm diameter, with 15 watts of power dissipated as heat and centered beneath the busbar at (30, 12.5). As the silicon substrate thickness increased, more heat was conducted away from the hot spot, causing a decreased temperature. The thickness of commercial solar cells is typically minimized to decrease the material cost. However, this can increase the temperature of a hot spot, and may increase the probability of a hot spot since the thinner silicon may break down easier in reverse bias. Figure 88 shows the solar cell surface temperature plot for the 0.5 mm thick substrate. Figure 89 shows the corresponding plot of lines
of isosurface temperature, with the arrows pointing in the direction of heat flux flow, which is opposite to the direction of the temperature gradient.

Table 12: Simulation of Hot Spot Temperature as a Function of Silicon Substrate Thickness

<table>
<thead>
<tr>
<th>Input 15 watt hot spot at x = 30.0 mm, y = 12.5 mm</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness, mm</td>
<td>radius, mm</td>
</tr>
<tr>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>0.25</td>
<td>1.5</td>
</tr>
<tr>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>0.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 87: Simulation results show the hot spot temperature decreased as the silicon substrate thickness increased for a 3 mm diameter, 15 watt hot spot
Figure 88: Simulation of surface temperature for a 0.50 mm silicon substrate thickness with a 3 mm diameter, 15 watt hot spot

Isosurface: Temperature (degC)  Arrow Volume: Total heat flux

Figure 89: Simulation of isosurface temperature for a 0.50 mm silicon substrate thickness with a 3 mm diameter, 15 watt hot spot
The previous simulations suggest that the following combination of parameters would create a high temperature hot spot on the solar cell: a thin 0.20 mm silicon substrate thickness, with a small 2.0 mm diameter, high power 40 watt hot spot centered near the edge and beneath the busbar at \( x = 30 \text{ mm} \), and \( y = 5 \text{ mm} \). Figure 90 shows the solar cell surface temperature plot had a maximum temperature of 941 °C. The melting points of several solar cell materials are: aluminum 660 °C, silver 961 °C, copper 1,084 °C, and silicon 1,411 °C. Aluminum could melt on the back side of the solar cell, or if used in the front side busbars. The solder connecting the back side pads, and the front side busbars to the tabbing wires could melt and degrade the electrical connection to the solar cell from the adjacent solar cell(s). The linear thermal expansion coefficients of these materials are: aluminum \( 24 \times 10^{-6} \text{ [m/(m*K)]} \), silver \( 19 \times 10^{-6} \text{ [m/(m*K)]} \), copper \( 16 \times 10^{-6} \text{ [m/(m*K)]} \), which are much higher than silicon \( 5 \times 10^{-6} \text{ [m/(m*K)]} \). This expansion might fracture and crack the aluminum, the silicon substrate, and the busbars.

![Surface Temperature (degC)](image)

Figure 90: Simulation of surface temperature for a 941 °C, 2 mm diameter, 40 watt hot spot located at \( x = 30 \text{ mm} \), \( y = 5 \text{ mm} \), in a 0.20 mm thick silicon substrate
Figure 91 shows the corresponding plot of lines of isosurface temperature, with the arrows pointing in the direction of heat flux flow, which is opposite to the direction of the temperature gradient.

![Isosurface Temperature Arrow Volume Heat Flux](image.png)

**Figure 91: Simulation of isosurface temperature for a 941 °C, 2 mm diameter, 40 watt hot spot located at x = 30 mm, y = 5 mm, in a 0.20 mm thick silicon substrate**

The vertical axis through the 2 mm diameter cylindrical hot spot and busbar has a 9.6 °C variation as shown in Table 13. The highest temperature was at the silicon bottom, and the lowest at the silver busbar top, because the silver conducted away the heat better than the silicon.

**Table 13: Simulation of Temperature versus Vertical Position on Hot Spot Axis**

<table>
<thead>
<tr>
<th>Description</th>
<th>Z axis position</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>busbar top</td>
<td>0.40 mm</td>
<td>931.2 °C</td>
</tr>
<tr>
<td>busbar center</td>
<td>0.30 mm</td>
<td>931.7 °C</td>
</tr>
<tr>
<td>hot spot top, busbar bottom</td>
<td>0.20 mm</td>
<td>933.4 °C</td>
</tr>
<tr>
<td>hot spot center</td>
<td>0.10 mm</td>
<td>939.0 °C</td>
</tr>
<tr>
<td>hot spot bottom</td>
<td>0.00 mm</td>
<td>940.8 °C</td>
</tr>
</tbody>
</table>
The hot spot simulations show that there are many factors which can affect the hot spot temperature such as the diameter, power, and location of the hot spot along with the thickness of the solar cell substrate. How the silicon substrate breaks down under a reverse bias voltage will determine the diameter, power, and location of the hot spot. The maximum power available is the product of the reverse bias voltage and the current available from the unshaded solar cells. For these simulations each hot spot was cylindrical in shape for simplicity. In a real solar cell, the shape of the hot spot depends on the voltage breakdown path and is probably irregularly shaped. The silicon substrate can deteriorate over time due to partial damage from surface impacts from hail stones, or other objects. Sometimes when a hot spot occurs, it can permanently decrease the performance of the solar cell.

All of the simulations were done for a hot spot on a horizontal silicon solar cell in air, before it is packaged into a solar PV module (panel). This solar cell model in many respects was like a solar cell tested on the solar cell test stand. In the solar PV module, the solar cell is electrically connected to other cells. It is then encapsulated and packaged with the back sheet, front glass plate, and metal frame. The dimensions, contact, and properties of these PV module materials, which are combined with the solar cell in the solar PV module will affect the heat flow and temperatures of the solar cell. The PV module designer can take those factors into account in order to create a thermal model, which dissipates as much heat as possible to minimize the hot spot temperature, and possible damage to the solar cell and PV module.

E. Comparison of Experimental Results to Theoretical Modeling Results

An approximately 368 °C 12 watt hot spot was measured near the solar cell busbar with an IR camera on a reverse voltage biased poly c-Si solar cell. The COMSOL thermal simulations on solar cells not encapsulated in a module showed that this temperature could occur. One
simulation example is for a 15 W 3 mm diameter 368 °C hot spot located at x = 12.5 mm, y = 30 mm on the solar cell.

Steep thermal gradients were seen around hot spots on solar cells in the lab with the FLIR IR camera. In the COMSOL thermal simulations of the surface temperature and the isosurface temperature around a hot spot there were also steep thermal gradients seen.

The I-V curve to find the maximum power point was measured in the lab on a solar cell illuminated by the solar simulator see Figures 56 and 57. A similar I-V curve for a solar cell was simulated with National Instruments Multisim software in Figure 65.

The typical I-V curve of Figure 61 top graph was measured on a 100 watt solar PV module outside. A similar I-V curve for a solar PV module was simulated with National Instruments Multisim software in Figure 68.

Figure 61 bottom graph showed the bypass diode conducting current on a 100 watt solar PV module outside, which dropped off above an output of 8 volts. A similar graph for a bypass diode on a solar PV module was simulated with National Instruments Multisim software in Figures 72 and 73.

The simulations and the measured data agreed.
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The characterization and simulation of the formation of a hot spot on a shaded silicon solar cell in a PV module was studied. A solar cell by itself connected to a load does not develop a hot spot due to being shaded. Once a solar cell is installed in a PV module it can develop a hot spot if it becomes shaded and suffers a reverse bias stress voltage from the illuminated cells in its submodule. An infrared camera is a key tool to quickly find hot spots. The hot spot on a solar cell not encapsulated in a PV module reached about 368 °C in a reverse bias stress voltage test in the lab. PV module failures of melted materials and cracked glass have been reported due to hot spots. Situations which can increase the likelihood of a hot spot forming are:

1. Only one cell is fully or partially shaded. Then all of the other cells in the submodule generate the highest reverse bias stress voltage with the most power available to be dissipated in the shaded cell.

2. Solar cell silicon substrates are not as high a quality as silicon wafers used to make integrated circuits. A weak spot in the silicon which breaks down under a few volts of reverse bias could form a hot spot. Poly c-Si substrates have grain boundaries which can have higher leakage currents than mono c-Si. The hot spot dissipated power is the product of the reverse bias stress voltage and the leakage current. This power is dissipated as heat which can permanently damage the solar cell.

3. A thermal model of a solar cell silicon substrate was used to produce hot spot simulations. The hot spot temperature increased with: increasing dissipated power, decreasing hot spot leakage current path diameter or volume, decreasing silicon substrate thickness, and the closer the hot spot location was to the solar cell edge. The hot spot
temperature can be decreased by designing the materials around the solar cell to maximize heat flow away from the silicon substrate. The thermal conductivity, thickness, and contact resistance of the materials which are in the PV module could be optimized for heat flow.

4. Making the solar cell thinner to save material unfortunately, can make the hot spot temperature higher.

A bypass diode on each solar cell would eliminate the problem, but increase the PV module manufacturing cost. Having a low price is a major selling point for solar PV systems.

Shaded solar cells on the real PV module and the simulated PV model caused the bypass diode in parallel with its submodule to turn on and conduct the current. This indicates that the shaded cells were receiving a reverse bias stress voltage, and that the submodule is producing minimal power.

If an electrical load is not connected to the PV module, then there is no current flowing and a shaded cell will not develop a hot spot, unless the bypass diode has failed and shorted out. Then the submodule has a short circuit as its load, and the shaded cell can develop a hot spot.

It has been reported in literature, that if the bypass diode fails by becoming an open circuit, and part of the submodule is shaded, then the bypass diode trying to pass power from other modules can have a DC arc which is extremely hot and can melt or burn anything next to it. If the bypass diode does not have a DC arc, then high voltage from all of the other PV modules in the string can reverse bias the shaded cell or cells and cause hot spots.

Future work would be to continue the outdoor testing of the solar PV module as outlined in section III.D. It should be located at a permanent location to avoid having to set the equipment up and take it down for each day of testing.
Former President Jimmy Carter, in February 2017, 36 years after leaving office, at the age of 92, once again demonstrated his support for renewable energy by having 3,852 solar PV panels installed on 10 acres of his property in Plains, Georgia. The single axis tracking solar PV system generates up to 1.3 MW of electrical power, and supplies power to the small town of Plains, GA. Congratulations former President Carter!
REFERENCES


BIBLIOGRAPHY


APPENDIX A: “The President’s Proposed Energy Policy”

Jimmy Carter’s televised speech on April 18, 1977.

Tonight I want to have an unpleasant talk with you about a problem unprecedented in our history. With the exception of preventing war, this is the greatest challenge our country will face during our lifetimes. The energy crisis has not yet overwhelmed us, but it will if we do not act quickly.

It is a problem we will not solve in the next few years, and it is likely to get progressively worse through the rest of this century.

We must not be selfish or timid if we hope to have a decent world for our children and grandchildren.

We simply must balance our demand for energy with our rapidly shrinking resources. By acting now, we can control our future instead of letting the future control us.

Two days from now, I will present my energy proposals to the Congress. Its members will be my partners and they have already given me a great deal of valuable advice. Many of these proposals will be unpopular. Some will cause you to put up with inconveniences and to make sacrifices.

The most important thing about these proposals is that the alternative may be a national catastrophe. Further delay can affect our strength and our power as a nation.

Our decision about energy will test the character of the American people and the ability of the President and the Congress to govern. This difficult effort will be the "moral equivalent of war" -- except that we will be uniting our efforts to build and not destroy.

I know that some of you may doubt that we face real energy shortages. The 1973 gasoline lines are gone, and our homes are warm again. But our energy problem is worse tonight than it was in 1973 or a few weeks ago in the dead of winter. It is worse because more waste has occurred, and
more time has passed by without our planning for the future. And it will get worse every day until we act.

The oil and natural gas we rely on for 75 percent of our energy are running out. In spite of increased effort, domestic production has been dropping steadily at about six percent a year. Imports have doubled in the last five years. Our nation's independence of economic and political action is becoming increasingly constrained. Unless profound changes are made to lower oil consumption, we now believe that early in the 1980s the world will be demanding more oil that it can produce.

The world now uses about 60 million barrels of oil a day and demand increases each year about five percent. This means that just to stay even we need the production of a new Texas every year, an Alaskan North Slope every nine months, or a new Saudi Arabia every three years. Obviously, this cannot continue.

We must look back in history to understand our energy problem. Twice in the last several hundred years there has been a transition in the way people use energy.

The first was about 200 years ago, away from wood -- which had provided about 90 percent of all fuel -- to coal, which was more efficient. This change became the basis of the Industrial Revolution.

The second change took place in this century, with the growing use of oil and natural gas. They were more convenient and cheaper than coal, and the supply seemed to be almost without limit. They made possible the age of automobile and airplane travel. Nearly everyone who is alive today grew up during this age and we have never known anything different.
Because we are now running out of gas and oil, we must prepare quickly for a third change, to strict conservation and to the use of coal and permanent renewable energy sources, like solar power.

The world has not prepared for the future. During the 1950s, people used twice as much oil as during the 1940s. During the 1960s, we used twice as much as during the 1950s. And in each of those decades, more oil was consumed than in all of mankind's previous history.

World consumption of oil is still going up. If it were possible to keep it rising during the 1970s and 1980s by 5 percent a year as it has in the past, we could use up all the proven reserves of oil in the entire world by the end of the next decade.

I know that many of you have suspected that some supplies of oil and gas are being withheld. You may be right, but suspicions about oil companies cannot change the fact that we are running out of petroleum.

All of us have heard about the large oil fields on Alaska's North Slope. In a few years when the North Slope is producing fully, its total output will be just about equal to two years' increase in our nation's energy demand.

Each new inventory of world oil reserves has been more disturbing than the last. World oil production can probably keep going up for another six or eight years. But some time in the 1980s it can't go up much more. Demand will overtake production. We have no choice about that.

But we do have a choice about how we will spend the next few years. Each American uses the energy equivalent of 60 barrels of oil per person each year. Ours is the most wasteful nation on earth. We waste more energy than we import. With about the same standard of living, we use twice as much energy per person as do other countries like Germany, Japan, and Sweden.
One choice is to continue doing what we have been doing before. We can drift along for a few more years.

Our consumption of oil would keep going up every year. Our cars would continue to be too large and inefficient. Three-quarters of them would continue to carry only one person -- the driver -- while our public transportation system continues to decline. We can delay insulating our houses, and they will continue to lose about 50 percent of their heat in waste.

We can continue using scarce oil and natural [gas] to generate electricity, and continue wasting two-thirds of their fuel value in the process.

If we do not act, then by 1985 we will be using 33 percent more energy than we do today.

We can't substantially increase our domestic production, so we would need to import twice as much oil as we do now. Supplies will be uncertain. The cost will keep going up. Six years ago, we paid $3.7 billion for imported oil. Last year we spent $37 billion -- nearly ten times as much -- and this year we may spend over $45 billion.

Unless we act, we will spend more than $550 billion for imported oil by 1985 -- more than $2,500 a year for every man, woman, and child in America. Along with that money we will continue losing American jobs and becoming increasingly vulnerable to supply interruptions.

Now we have a choice. But if we wait, we will live in fear of embargoes. We could endanger our freedom as a sovereign nation to act in foreign affairs. Within ten years we would not be able to import enough oil -- from any country, at any acceptable price.

If we wait, and do not act, then our factories will not be able to keep our people on the job with reduced supplies of fuel. Too few of our utilities will have switched to coal, our most abundant energy source.
We will not be ready to keep our transportation system running with smaller, more efficient cars and a better network of buses, trains and public transportation.

We will feel mounting pressure to plunder the environment. We will have a crash program to build more nuclear plants, strip-mine and burn more coal, and drill more offshore wells than we will need if we begin to conserve now. Inflation will soar, production will go down, people will lose their jobs. Intense competition will build up among nations and among the different regions within our own country.

If we fail to act soon, we will face an economic, social and political crisis that will threaten our free institutions.

But we still have another choice. We can begin to prepare right now. We can decide to act while there is time.

That is the concept of the energy policy we will present on Wednesday. Our national energy plan is based on ten fundamental principles.

The first principle is that we can have an effective and comprehensive energy policy only if the government takes responsibility for it and if the people understand the seriousness of the challenge and are willing to make sacrifices.

The second principle is that healthy economic growth must continue. Only by saving energy can we maintain our standard of living and keep our people at work. An effective conservation program will create hundreds of thousands of new jobs.

The third principle is that we must protect the environment. Our energy problems have the same cause as our environmental problems -- wasteful use of resources. Conservation helps us solve both at once.
The fourth principle is that we must reduce our vulnerability to potentially devastating embargoes. We can protect ourselves from uncertain supplies by reducing our demand for oil, making the most of our abundant resources such as coal, and developing a strategic petroleum reserve.

The fifth principle is that we must be fair. Our solutions must ask equal sacrifices from every region, every class of people, every interest group. Industry will have to do its part to conserve, just as the consumers will. The energy producers deserve fair treatment, but we will not let the oil companies profiteer.

The sixth principle, and the cornerstone of our policy, is to reduce the demand through conservation. Our emphasis on conservation is a clear difference between this plan and others which merely encouraged crash production efforts. Conservation is the quickest, cheapest, most practical source of energy. Conservation is the only way we can buy a barrel of oil for a few dollars. It costs about $13 to waste it.

The seventh principle is that prices should generally reflect the true replacement costs of energy. We are only cheating ourselves if we make energy artificially cheap and use more than we can really afford.

The eighth principle is that government policies must be predictable and certain. Both consumers and producers need policies they can count on so they can plan ahead. This is one reason I am working with the Congress to create a new Department of Energy, to replace more than 50 different agencies that now have some control over energy.

The ninth principle is that we must conserve the fuels that are scarcest and make the most of those that are more plentiful. We can’t continue to use oil and gas for 75 percent of our consumption when they make up seven percent of our domestic reserves. We need to shift to
plentiful coal while taking care to protect the environment, and to apply stricter safety standards to nuclear energy.

The tenth principle is that we must start now to develop the new, unconventional sources of energy we will rely on in the next century.

These ten principles have guided the development of the policy I would describe to you and the Congress on Wednesday.

Our energy plan will also include a number of specific goals, to measure our progress toward a stable energy system.

These are the goals we set for 1985:

-Reduce the annual growth rate in our energy demand to less than two percent.

-Reduce gasoline consumption by ten percent below its current level.

-Cut in half the portion of United States oil which is imported, from a potential level of 16 million barrels to six million barrels a day.

-Establish a strategic petroleum reserve of one billion barrels, more than six months' supply.

-Increase our coal production by about two thirds to more than 1 billion tons a year.

-Insulate 90 percent of American homes and all new buildings.

-Use solar energy in more than two and one-half million houses.

We will monitor our progress toward these goals year by year. Our plan will call for stricter conservation measures if we fall behind.
I can't tell you that these measures will be easy, nor will they be popular. But I think most of you realize that a policy which does not ask for changes or sacrifices would not be an effective policy.

This plan is essential to protect our jobs, our environment, our standard of living, and our future.

Whether this plan truly makes a difference will be decided not here in Washington, but in every town and every factory, in every home and on every highway and every farm.

I believe this can be a positive challenge. There is something especially American in the kinds of changes we have to make. We have been proud, through our history of being efficient people.

We have been proud of our leadership in the world. Now we have a chance again to give the world a positive example.

And we have been proud of our vision of the future. We have always wanted to give our children and grandchildren a world richer in possibilities than we've had. They are the ones we must provide for now. They are the ones who will suffer most if we don't act.

I've given you some of the principles of the plan.

I am sure each of you will find something you don't like about the specifics of our proposal. It will demand that we make sacrifices and changes in our lives. To some degree, the sacrifices will be painful -- but so is any meaningful sacrifice. It will lead to some higher costs, and to some greater inconveniences for everyone.

But the sacrifices will be gradual, realistic and necessary. Above all, they will be fair. No one will gain an unfair advantage through this plan. No one will be asked to bear an unfair burden. We will monitor the accuracy of data from the oil and natural gas companies, so that we will know their true production, supplies, reserves, and profits.
The citizens who insist on driving large, unnecessarily powerful cars must expect to pay more for that luxury.

We can be sure that all the special interest groups in the country will attack the part of this plan that affects them directly. They will say that sacrifice is fine, as long as other people do it, but that their sacrifice is unreasonable, or unfair, or harmful to the country. If they succeed, then the burden on the ordinary citizen, who is not organized into an interest group, would be crushing.

There should be only one test for this program: whether it will help our country.

Other generation of Americans have faced and mastered great challenges. I have faith that meeting this challenge will make our own lives even richer. If you will join me so that we can work together with patriotism and courage, we will again prove that our great nation can lead the world into an age of peace, independence and freedom.

Significance and Use

4.1 The design of a photovoltaic module or system intended to provide safe conversion of the sun's radiant energy into useful electricity must take into consideration the possibility of partial shadowing of the module(s) during operation. This test method describes a procedure for verifying that the design and construction of the module provides adequate protection against the potential harmful effects of hot spots during normal installation and use.

4.2 This test method describes a procedure for determining the ability of the module to provide protection from internal defects which could cause loss of electrical insulation or combustion hazards.

4.3 Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current (Isc) of a shadowed or faulty cell or group of cells. When such a condition occurs, the affected cell or group of cells is forced into reverse bias and must dissipate power, which can cause overheating.

NOTE 1—The correct use of bypass diodes can prevent hot spot damage from occurring.

4.4 Fig. 1 illustrates the hot-spot effect in a module of a series string of cells, one of which, cell Y, is partially shadowed. The amount of electrical power dissipated in Y is equal to the product of the module current and the reverse voltage developed across Y. For any irradiance level, when the reverse voltage across Y is equal to the voltage generated by the remaining (s-1) cells in the module, power dissipation is at a maximum when the module is short-circuited. This is shown in Fig. 1 by the shaded rectangle constructed at the intersection of the reverse I-V characteristic of Y with the image of the forward I-V characteristic of the (s-1) cells.
4.5 By-pass diodes, if present, as shown in Fig. 2, begin conducting when a series-connected string in a module is in reverse bias, thereby limiting the power dissipation in the reduced-output cell.

4.6 The reverse characteristics of solar cells can vary considerably. Cells can have either high shunt resistance where the reverse performance is voltage-limited or have low shunt resistance where the reverse performance is current-limited. Each of these types of cells can suffer hot spot problems, but in different ways.

4.6.1 Low-Shunt Resistance Cells:

4.6.1.1 The worst case shadowing conditions occur when the whole cell (or a large fraction) is shadowed.

4.6.1.2 Often low shunt resistance cells are this way because of localized shunts. In this case hot spot heating occurs because a large amount of current flows in a small area. Because this is a localized phenomenon, there is a great deal of scatter in performance of this type of cell. Cells
with the lowest shunt resistance have a high likelihood of operating at excessively high temperatures when reverse biased.

4.6.1.3 Because the heating is localized, hot spot failures of low shunt resistance cells occur quickly.

4.6.2 *High Shunt Resistance Cells*:

4.6.2.1 The worst case shadowing conditions occur when a small fraction of the cell is shadowed.

4.6.2.2 High shunt resistance cells limit the reverse current flow of the circuit and therefore heat up. The cell with the highest shunt resistance will have the highest power dissipation.

4.6.2.3 Because the heating is uniform over the whole area of the cell, it can take a long time for the cell to heat to the point of causing damage.

4.6.2.4 High shunt resistance cells define the need for bypass diodes in the module’s circuit, and their performance characteristics determine the number of cells that can be protected by each diode.

4.7 The major technical issue is how to identify the highest and lowest shunt resistance cells and then how to determine the worst case shadowing for those cells. If the bypass diodes are removable, cells with localized shunts can be identified by reverse biasing the cell string and using an IR camera to observe hot spots. If the module circuit is accessible the current flow through the shadowed cell can be monitored directly. However, many PV modules do not have removable diodes or accessible electric circuits. Therefore a non-intrusive method is needed that can be utilized on those modules.

4.8 The selected approach is based on taking a set of I-V curves for a module with each cell shadowed in turn. **Fig. 3** shows the resultant set of I-V curves for a sample module. The curve with the highest leakage current at the point where the diode turns on was taken when the cell with the lowest shunt resistance was shadowed. The curve with the lowest leakage current at the point where the diode turns on was taken when the cell with the highest shunt resistance was shadowed.

**FIG. 3 Module I-V Characteristics with Different Cells Totally Shadowed**
4.9 If the module to be tested has parallel strings, each string must be tested separately.

4.10 This test method may be specified as part of a series of qualification tests including performance measurements and demonstration of functional requirements. It is the responsibility of the user of this test method to specify the minimum acceptance criteria for physical or electrical degradation.

1. Scope

1.1 This test method provides a procedure to determine the ability of a photovoltaic (PV) module to endure the long-term effects of periodic “hot spot” heating associated with common fault conditions such as severely cracked or mismatched cells, single-point open circuit failures (for example, interconnect failures), partial (or non-uniform) shadowing or soiling. Such effects typically include solder melting or deterioration of the encapsulation, but in severe cases could progress to combustion of the PV module and surrounding materials.

1.2 There are two ways that cells can cause a hot spot problem: either by having a high resistance so that there is a large resistance in the circuit, or by having a low resistance area (shunt) such that there is a high-current flow in a localized region. This test method selects cells of both types to be stressed.

1.3 This test method does not establish pass or fail levels. The determination of acceptable or unacceptable results is beyond the scope of this test method.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents (purchase separately)

ASTM Standards

E772 Terminology of Solar Energy Conversion
E927 Specification for Solar Simulation for Photovoltaic Testing
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E1799 Practice for Visual Inspections of Photovoltaic Modules
E1802 Test Methods for Wet Insulation Integrity Testing of Photovoltaic Modules

Keywords
Hot Spot Protection Test - Performance Test - Photovoltaic Modules - Photovoltaic Panels And Modules - Solar Energy

ICS Code

ICS Number Code 27.160 (Solar energy engineering)

UNSPSC Code

UNSPSC Code 32111701(Photovoltaic cells)

DOI: 10.1520/E2481-12

ASTM International is a member of CrossRef.
APPENDIX C: Grape Solar Model GS-STAR-100W Solar PV Module Specs

MODEL: GS-STAR-100W

Overview
- High efficiency solar cells (approx. 17.4%) with quality silicon material for high module conversion efficiency and long term output stability and reliability.
- Rigorous quality control to meet the highest international standards.
- High transmittance, low iron tempered glass with enhanced stiffness and impact resistance.
- Unique frame design with strong mechanical strength for greater than 50 lbs/ft² wind load and snow load withstanding and easy installation.
- Advanced encapsulation material with multi-layer sheet lamination to provide long-life and enhanced cell performance.
- Outstanding electrical performance under high temperature and weak light environments.

Applications
- Any large or small off-grid solar power stations.
- Commercial/industrial buildings rooftop and ground systems for off-grid uses.
- Residential rooftop and ground systems for off-grid uses.

Warranty
- 10 year limited product warranty on materials and workmanship.
- 25 year warranty on >80% power output and 10 year warranty on >90% power output.
- Refer to warranty document for detailed warranty information.

Mechanical Specifications

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<th>Characteristic</th>
<th>Details</th>
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<tbody>
<tr>
<td>Cell Size</td>
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<tr>
<td>Module Dimension (L x W x T)</td>
<td>1020mm x 670mm x 35mm (40.16” x 26.37” x 1.38”)</td>
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<tr>
<td>No. of Cells</td>
<td>36</td>
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<tr>
<td>Weight</td>
<td>8.9 kg (19.66 lbs)</td>
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<tr>
<td>Cable Length</td>
<td>900mm for positive (+) and negative (-)</td>
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<tr>
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<td>MC-IV Compatible</td>
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<tr>
<td>Junction Box</td>
<td>IP65 Rated</td>
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<tr>
<td>No. of Holes in Frame</td>
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</table>
## MODEL: GS-STAR-100W

### Electrical Specifications
(STC = 25 °C, 1000W/m² Irradiance and AM=1.5)

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<thead>
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<tr>
<td>Maximum Power P&lt;sub&gt;max&lt;/sub&gt;</td>
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<tr>
<td>Listed PTC Power</td>
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<tr>
<td>Current at Maximum Power Point I&lt;sub&gt;max&lt;/sub&gt;</td>
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<tr>
<td>Open Circuit Voltage V&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>21.9 V</td>
</tr>
<tr>
<td>Short Circuit Current I&lt;sub&gt;sc&lt;/sub&gt;</td>
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</tr>
<tr>
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<tr>
<td>Temperature Coefficient of V&lt;sub&gt;oc&lt;/sub&gt;</td>
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<tr>
<td>Temperature Coefficient of I&lt;sub&gt;sc&lt;/sub&gt;</td>
<td>+0.04%/°C</td>
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<tr>
<td>Temperature Coefficient of P&lt;sub&gt;max&lt;/sub&gt;</td>
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*Standard Test Conditions

### Physical Specifications mm

#### Other Performance Data

<table>
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<th>Power Tolerance</th>
<th>Operating Temperature</th>
<th>Max Series Fuse Rating</th>
<th>NOCT°</th>
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<tbody>
<tr>
<td>0%, +6%</td>
<td>-40°C to +65°C</td>
<td>10A</td>
<td>45 +/−2°C</td>
</tr>
</tbody>
</table>

*Nominal Operating Cell Temperature


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Grape Solar reserves the rights to modify these specifications without notice.
Field Wiring and Noise Considerations for Analog Signals

Overview

Unfortunately, measuring analog signals with a data acquisition device is not always as simple as wiring the signal source leads to the data acquisition device. Knowledge of the nature of the signal source, a suitable configuration of the data acquisition device, and an appropriate cabling scheme may be required to produce accurate and noise-free measurements. The integrity of the acquired data depends upon the entire analog signal path. In order to cover a wide variety of applications, most data acquisition devices provide some flexibility in their analog input stage configuration. The price of this flexibility is, however, some confusion as to the proper applications of the various input configurations and their relative merits. This note helps clarify the types of input configurations available on data acquisition devices, explains how the user should choose and use the configuration best for the application, and discusses interference noise pick up mechanisms and how to minimize interference noise by proper cabling and shielding. An understanding of the types of signal sources and measurement systems is a prerequisite to application of good measurement techniques, so we will begin by discussing the same.

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3. Measuring Floating (Nonreferenced) Sources
4. Minimizing Noise Coupling in the Interconnects
5. Balanced Systems
6. Solving Noise Problems in Measurement Setups
7. Signal Processing Techniques for Noise Reduction
8. References
9. Learn More
1. Types of Signal Sources and Measurement Systems

By far the most common electrical equivalent produced by signal conditioning circuitry associated with sensors is in the form of voltage. Transformation to other electrical phenomena such as current and frequency may be encountered in cases where the signal is to be carried over long cabling in harsh environments. Since in virtually all cases the transformed signal is ultimately converted back into a voltage signal before measurement, it is important to understand the voltage signal source.

Remember that a voltage signal is measured as the potential difference across two points. This is depicted in Figure 1.

![Figure 1. Voltage Signal Source and Measurement System Model](image1)

A voltage source can be grouped into one of two categories—grounded or ungrounded (floating). Similarly, a measurement system can be grouped into one of two categories—grounded or ground-referenced, and ungrounded (floating).

**Grounded or Ground-Referenced Signal Source**

A grounded source is one in which the voltage signal is referenced to the building system ground. The most common example of a grounded source is any common plug-in instrument that does not explicitly float its output signal. Figure 2 shows a grounded signal source.

![Figure 2. Grounded Signal Source](image2)

The grounds of two grounded signal sources will generally not be at the same potential. The difference in ground potential between two instruments connected to the same building power system is typically on the order of 10 mV to 200 mV; however, the difference can be higher if power distribution circuits are not properly connected.

**Ungrounded or Nonreferenced (Floating) Signal Source**

A floating source is a source in which the voltage signal is not referred to an absolute reference, such as earth or building ground. Some common examples of floating signal sources are batteries, battery powered signal sources, thermocouples, transformers, isolation amplifiers, and any instrument that explicitly floats its output signal. A nonreferenced or floating signal source is depicted in Figure 3.

![Figure 3. Ungrounded Signal Source](image3)
Notice that neither terminal of the source is referred to the electrical outlet ground. Thus, each terminal is independent of earth.

**Differential or Nonreferenced Measurement System**

A differential, or nonreferenced, measurement system has neither of its inputs tied to a fixed reference such as earth or building ground. Hand-held, battery-powered instruments and data acquisition devices with instrumentation amplifiers are examples of differential or nonreferenced measurement systems. Figure 4 depicts an implementation of an 8-channel differential measurement system used in a typical device from National Instruments. Analog multiplexers are used in the signal path to increase the number of measurement channels while still using a single instrumentation amplifier. For this device, the pin labeled AI GND, the analog input ground, is the measurement system ground.

![Figure 4. An 8-Channel Differential Measurement System](image)
An ideal differential measurement system responds only to the potential difference between its two terminals—the (+) and (–) inputs. Any voltage measured with respect to the instrumentation amplifier ground that is present at both amplifier inputs is referred to as a common-mode voltage. Common-mode voltage is completely rejected (not measured) by an ideal differential measurement system. This capability is useful in rejection of noise, as unwanted noise is often introduced in the circuit making up the cabling system as common-mode voltage. Practical devices, however, have several limitations, described by parameters such as common-mode voltage range and common-mode rejection ratio (CMRR), which limit this ability to reject the common-mode voltage.

Common-mode voltage \( V_{cm} \) is defined as follows:

\[
V_{cm} = \frac{(V^+ + V^-)}{2}
\]

where \( V^+ = \) Voltage at the noninverting terminal of the measurement system with respect to the measurement system ground, \( V^- = \) Voltage at the inverting terminal of the measurement system with respect to the measurement system ground and CMRR in dB is defined as follows:

\[
\text{CMRR (dB)} = 20 \log \left( \frac{\text{Differential Gain}}{\text{Common-Mode Gain}} \right).
\]

A simple circuit that illustrates the CMRR is shown in Figure 5. In this circuit, CMRR in dB is measured as \( 20 \log \frac{V_{cm}}{V_{out}} \) where \( V^+ = V^- = V_{cm} \).

The common-mode voltage range limits the allowable voltage swing on each input with respect to the measurement system ground. Violating this constraint results not only in measurement error but also in possible damage to components on the device. As the term implies, the CMRR measures the ability of a differential measurement system to reject the common-mode voltage signal. The CMRR is a function of frequency and typically reduces with frequency. The CMRR can be optimized by using a balanced circuit. This issue is discussed in more detail later in this application note. Most data acquisition devices will specify the CMRR up to 60 Hz, the power line frequency.

Grounded or Ground-Referenced Measurement System

A grounded or ground-referenced measurement system is similar to a grounded source in that the measurement is made with respect to ground. Figure 6 depicts an 8-channel grounded measurement system. This is also referred to as a single-ended measurement system.
Figure 6. An 8-Channel Ground-Referenced Single-Ended (RSE) Measurement System

A variant of the single-ended measurement technique, known as nonreferenced single-ended (NRSE), is often found in data acquisition devices. A NRSE measurement system is depicted in Figure 7.

Figure 7. An 8-Channel NRSE Measurement System

In an NRSE measurement system, all measurements are still made with respect to a single-node Analog Input Sense (AI SENSE), but the potential at this node can vary with respect to the measurement system ground (AI GND). Figure 7 illustrates that a single-channel NRSE measurement system is the same as a single-channel differential measurement system.

Now that we have identified the different signal source type and measurement systems, we can discuss the proper measurement system for each type of signal source.

2. Measuring Grounded Signal Sources

A grounded signal source is best measured with a differential or nonreferenced measurement system. Figure 8 shows the pitfall of using a ground-referenced measurement system to measure a grounded signal source. In this case, the measured voltage, $V_m$, is the sum of the signal voltage, $V_s$, and the potential difference, $DV_g$, that exists between the signal source ground and the measurement system ground. This
potential difference is generally not a DC level; thus, the result is a noisy measurement system often showing power-line frequency (60 Hz) components in the readings. Ground-loop introduced noise may have both AC and DC components, thus introducing offset errors as well as noise in the measurements. The potential difference between the two grounds causes a current to flow in the interconnection. This current is called ground-loop current.

Figure 8. A Grounded Signal Source Measured with a Ground-Referenced System Introduces Ground Loop

A ground-referenced system can still be used if the signal voltage levels are high and the interconnection wiring between the source and the measurement device has a low impedance. In this case, the signal voltage measurement is degraded by ground loop, but the degradation may be tolerable. The polarity of a grounded signal source must be carefully observed before connecting it to a ground-referenced measurement system because the signal source can be shorted to ground, thus possibly damaging the signal source. Wiring considerations are discussed in more detail later in this application note.

A nonreferenced measurement is provided by both the differential (DIFF) and the NRSE input configurations on a typical data acquisition device. With either of these configurations, any potential difference between references of the source and the measuring device appears as common-mode voltage to the measurement system and is subtracted from the measured signal. This is illustrated in Figure 9.

Figure 9. A Differential Measurement System Used to Measure a Grounded Signal Source
3. Measuring Floating (Nonreferenced) Sources

Floating signal sources can be measured with both differential and single-ended measurement systems. In the case of the differential measurement system, however, care should be taken to ensure that the common-mode voltage level of the signal with respect to the measurement system ground remains in the common-mode input range of the measurement device.

A variety of phenomena—for example, the instrumentation amplifier input bias currents—can move the voltage level of the floating source out of the valid range of the input stage of a data acquisition device. To anchor this voltage level to some reference, resistors are used as illustrated in Figure 10. These resistors, called bias resistors, provide a DC path from the instrumentation amplifier inputs to the instrumentation amplifier ground. These resistors should be of a large enough value to allow the source to float with respect to the measurement reference (AI GND in the previously described measurement system) and not load the signal source, but small enough to keep the voltage in the range of the input stage of the device. Typically, values between 10 kΩ and 100 kΩ work well with low-impedance sources such as thermocouples and signal conditioning module outputs. These bias resistors are connected between each lead and the measurement system ground.

Warning: Failure to use these resistors will result in erratic or saturated (positive full-scale or negative full-scale) readings.

If the input signal is DC-coupled, only one resistor connected from the (−) input to the measurement system ground is required to satisfy the bias current path requirement, but this leads to an unbalanced system if the source impedance of the signal source is relatively high. Balanced systems are desirable from a noise immunity point of view. Consequently, two resistors of equal value—one for signal high (+) input and the other for signal low (−) input to ground—should be used if the source impedance of the signal source is high. A single bias resistor is sufficient for low-impedance DC-coupled sources such as thermocouples. Balanced circuits are discussed further later in this application note.

If the input signal is AC-coupled, two bias resistors are required to satisfy the bias current path requirement of the instrumentation amplifier.

Resistors (10 kΩ < R < 100 kΩ) provide a return path to ground for instrumentation amplifier input bias currents, as shown in Figure 10. Only R2 is required for DC-coupled signal sources. For AC-coupled sources, R1 = R2.

![Figure 10. Floating Source and Differential Input Configuration](image)

If the single-ended input mode is to be used, a RSE input system (Figure 11a) can be used for a floating signal source. No ground loop is created in this case. The NRSE input system (Figure 11b) can also be used and is preferable from a noise pickup point of view. Floating sources do require bias resistor(s) between the AI SENSE input and the measurement system ground (AI GND) in the NRSE input configuration.
Figure 11. Floating Signal Source and Single-Ended Configurations

A graphic summary of the previous discussion is presented in Table 1.
### Table 1. Analog Input Connections

**Warning:** Bias resistors must be provided when measuring floating signal sources in DIFF and NRSE configurations. Failure to do so will result in erratic or saturated (positive full-scale or negative full-scale) readings.

In general, a differential measurement system is preferable because it rejects not only ground loop-induced errors, but also the noise picked up in the environment to a certain degree. The single-ended configurations, on the other hand, provide twice as many measurement channels but are justified only if the magnitude of the induced errors is smaller than the required accuracy of the data. Single-ended input connections can be used when all input signals meet the following criteria.

- Input signals are high level (greater than 1 V)
- Signal cabling is short and travels through a noise-free environment or is properly shielded
- All input signals can share a common reference signal at the source

Differential connections should be used when any of the above criteria are violated.

<table>
<thead>
<tr>
<th>Input Configuration</th>
<th>Signal Source Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Floating Signal Source</strong> (Not Connected to Building Ground)</td>
<td>Grounded Signal Source</td>
</tr>
<tr>
<td>Examples</td>
<td>Examples</td>
</tr>
<tr>
<td>• Thermocouples</td>
<td>• Plug-in Instruments with Nonisolated Inputs</td>
</tr>
<tr>
<td>• Signal Conditioning with Isolated Outputs</td>
<td></td>
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<tr>
<td>• Battery Devices</td>
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<tr>
<td><strong>Differential (DIFF)</strong></td>
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<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Two resistors (10 kΩ &lt; R &lt; 100 kΩ)</td>
<td>Two resistors (10 kΩ &lt; R &lt; 100 kΩ) provide return paths to ground for bias currents</td>
</tr>
<tr>
<td><strong>Single-Ended - Ground Referenced (RSE)</strong></td>
<td></td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Ground-loop losses, ( V_{g} ) are added to measured signal.</td>
<td></td>
</tr>
<tr>
<td><strong>Single-Ended - Nonreferenced (NRSE)</strong></td>
<td></td>
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<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
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</tbody>
</table>

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![Diagram](image7.png)