$ReSi_2$ thin-film infrared detectors

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Two types of thin-film infrared-sensing devices have been investigated using the narrow band-gap semiconductor, rhenium disilicide ($E_g \sim 0.1$ eV). These are the $ReSi_2/n$-Si heterojunction internal photoemission (HIP) detector and the $ReSi_2$ thin-film photoconductor. The HIP device was found to be rectifying and to obey a Fowler-type law with a long-wavelength cutoff of ~2.1 μm (0.59 eV) at room temperature. In hopes of approaching the fundamental limit for a $ReSi_2$-based photonic detector, ~12 μm (0.1 eV), the $ReSi_2$ photoconductor was explored. Indeed, the spectral response (measured at 10 K) of the ohmic photoconductor was found to extend to 6 μm (the present limit of our measurement equipment), with no indication of a detection cutoff. © *1995 American Vacuum Society.*

I. INTRODUCTION

Platinum silicide and mercury cadmium telluride (MCT) are perhaps the two foremost materials systems upon which significant infrared (IR) technologies are based. While PtSi is readily integrated into silicon, the Schottky barrier detectors thus formed are characterized with lower quantum efficiencies than most practitioners desire. MCT photoconductive devices, on the other hand, exhibit larger quantum efficiencies[1] than PtSi detectors but are hindered by lack of silicon integration.[2,3]

The use of a narrow-gap semiconductor, such as $ReSi_2$, in place of a metal silicide (e.g., PtSi), to form a heterojunction with silicon offers the potential for producing internal photoemission detectors of larger quantum efficiencies than those of conventional metal silicide–silicon Schottky barrier diodes.[4] The narrow band gap of $ReSi_2$ (~0.1 eV)[5] makes it a contender for intrinsic detection in the 8–14 μm atmospheric window, with the possibility of band-gap engineering through the use of the pseudobinary alloy $Re_xMo_{1-x}Si_2$.[6] Our best estimates of the values of the intrinsic absorption coefficient of $ReSi_2$ near its band edge[7] are comparable to values for MCT.[18] Finally, strong crystallographic alignment has been observed between $ReSi_2$ and Si(001) oriented wafers (minimum MeV He^+ channeling yield as low as 2%).[9] In summary, these characteristics of $ReSi_2$ suggest its potential for an improved, silicon-compatible IR detector technology.

II. SAMPLE PREPARATION AND EXPERIMENTAL PROCEDURES

Films prepared for heterojunction internal photoemission (HIP) device studies were grown via reactive deposition epitaxy under ultrahigh vacuum conditions (deposition pressure $\sim 10^{-8}$ Torr) in a Perkin–Elmer molecular beam epitaxy system. The growth procedure consisted of the electron-gun evaporation of pure rhenium metal onto Si(001) wafers held at 650 °C. The ensuing reaction between the Re metal and the silicon wafer produced epitaxial orthorhombic $ReSi_2$ (Ref. 10) as confirmed with reflection high-energy electron diffraction and conventional θ–2θ x-ray diffraction. The results presented here are for a representative HIP device with a $ReSi_2$ thickness of approximately 1300 Å. Mesa diode structures were fabricated through a combination of standard photolithography and ion beam milling. Titanium was used as an ohmic contact to $ReSi_2$ (contact resistance ~350 Ω) and aluminum, to the silicon wafer (contact resistance ~10 Ω); the zero-bias incremental device resistance ($dv/di|_{v=0}$) was on the order of 50 kΩ. A gold contact overlayer was used as an aid in wire bonding. (See Fig. 1 for HIP device schematic diagram.)

For the thin-film photoconductor studies, pure Re metal was electron-gun evaporated onto thermally oxidized silicon wafers (SiO_2 thickness of 95 nm) which had been coated with ~500 nm of undoped ($\rho \sim 10^6$ Ω cm) polycrystalline silicon after oxidation. The SiO_2 layer was used to electrically isolate the disilicide thin film from the silicon substrate and the polycrystalline silicon provided the silicon necessary for silicide formation. The formation of polycrystalline $ReSi_2$ (thickness ~2200 Å) was confirmed by observation of its 001, 110, 103, and 200 peaks in the films's θ–2θ x-ray diffraction pattern. The contacts to the photoconductor consisted of evaporated layers of nickel and gold (5000 Å each), with patterning accomplished through a standard ‘‘lift-off’’ process (see device schematic diagram in Fig. 2). The sample was mounted into a plug-in package, wirebonded, and placed in a closed-cycle helium cryostat whose temperature is controllable from ~10 to 300 K. (The temperature was monitored by a silicon diode sensor positioned near the sample.)

Current–voltage characteristics of the devices were measured with a Hewlett–Packard 4145B semiconductor parameter analyzer while standard lock-in techniques (chopping frequency ~42 Hz) were used in photoresponse measurements. Light from either a 100 W quartz–tungsten halogen bulb (HIP device studies) or a silicon carbide glowbar (photoconductor studies) was passed through a grating monochrometer and order-sorting filters to provide the monochromatized (bandwidth ~75 nm for HIP device studies and ~150 nm for photoconductor studies) IR radiation. The open-circuit voltage of the HIP devices was measured. The

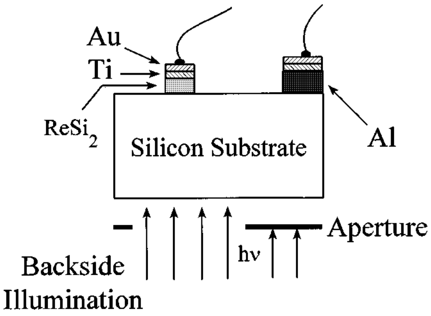

FIG. 1. Schematic representation of a ReSi$_2$/n-Si heterojunction internal photoemission (HIP) detector. Photoresponse studies were carried out using backside IR illumination.

short-circuit current was obtained using the value of the device's zero-bias incremental resistance in Ohm's law. (The signal voltages that were measured were extremely small, falling in the region in which the ideal diode equation, applicable for the rectifying HIP device, is approximately linear; that is, where e^x may be approximated by the truncated Taylor series polynomial $1+x$.)

The photoresponse of the photoconductor devices was determined as the change in voltage due to monochromatized IR illumination with a constant current ($I=1.65$ mA) flowing through the device. Measurement of the light intensity was accomplished with either a Newport power meter or a thermopile detector.

III. RESULTS

A. The ReSi$_2$/n-Si HIP detector

The ReSi$_2$/n-Si heterojunction was found to be rectifying with a reverse saturation current density on the order of 10 μA/cm^2. The proposed conduction mechanism under forward bias (silicide biased positively with respect to the n-type silicon) is injection of electrons from the n-type silicon substrate into the silicide. Assuming ReSi$_2$ to be p type as found in previous studies,[11,12] an energy-band diagram for the heterojunction was constructed and is shown in Fig. 3. The barrier height was obtained from the photoresponse of the junction and will be discussed.

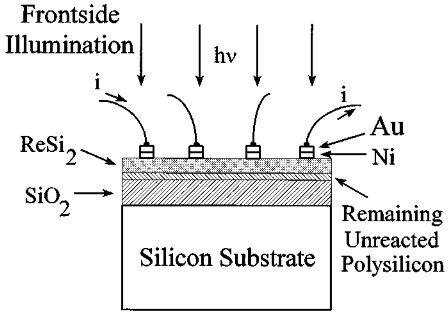

FIG. 2. Schematic representation of a ReSi$_2$ thin-film photoconductor structure. A constant current was passed through the device as shown, and the photoresponse observed by measuring the potential difference between these or other pairs of contacts.

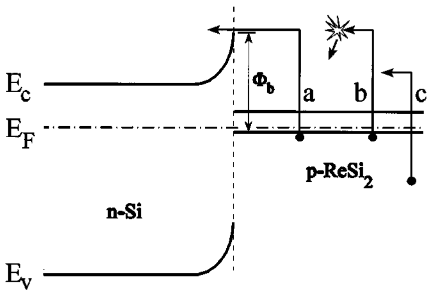

FIG. 3. A proposed energy-band diagram for the HIP device based on an interpretation of current–voltage and photoresponse measurements. Three IR excitation processes are shown (excitations are of equal energy): (a) internal photoemission of an electron, (b) excitation followed by inelastic scattering, (c) excitation in which an electron is promoted to a state of insufficient energy to the surmount barrier. Processes (b) and (c) are potential loss mechanisms in the device.

Under IR illumination using wavelengths beyond the absorption edge of silicon, any resulting photocurrent must be due to internal photoemission of either electrons or holes originating in the silicide. Due to the nature of the band bending on the silicon side of the junction (as depicted in Fig. 3), it is clear that the collection of electrons would be much more efficient than the collection of holes. Therefore, we expect this photocurrent to be due to excited electrons within the silicide which successfully migrate to the junction, surmount the junction barrier, and are collected in the n-type silicon [process (a), Fig. 3].

A typical photoresponse plot for an HIP detector is displayed in Fig. 4. According to theory, the linear extrapolation of the data to the energy axis should yield the barrier height that the electrons must surmount to generate a photocurrent.[13] Figure 4 gives an approximate barrier height of 0.59 eV (±0.03 eV as determined by linear regression analysis). The scatter in the data, and our inability to obtain

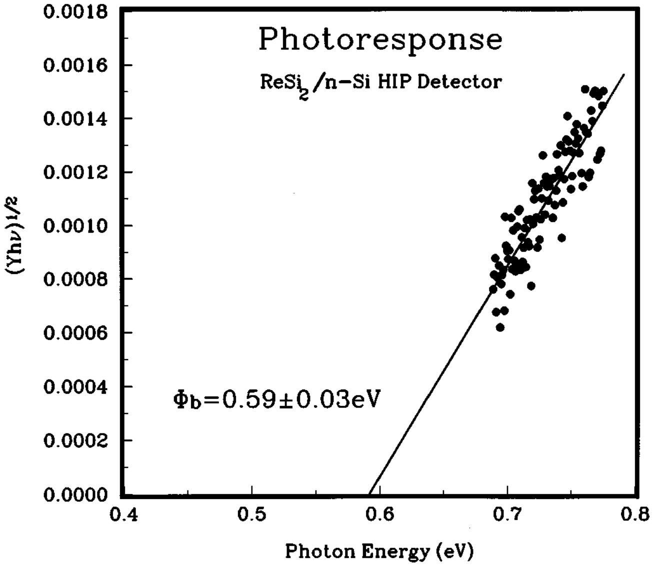

FIG. 4. A representative room-temperature photoresponse (quantum efficiency Y multiplied by photon energy $h\nu$) plot for a ReSi$_2$/n-Si HIP device.

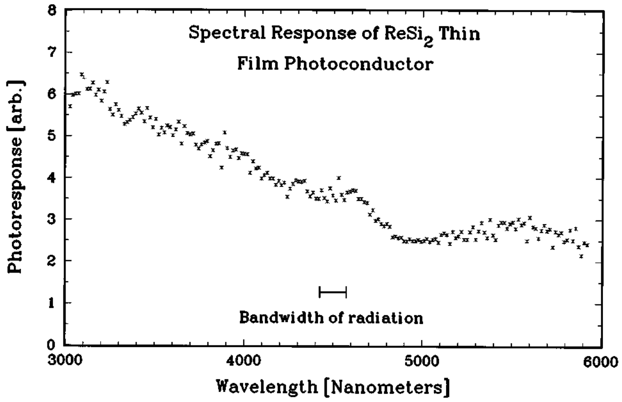

FIG. 5. Spectral response of a polycrystalline ReSi$_2$ thin-film photoconductor normalized to photon flux. The light intensity was determined with a thermopile detector.

data for lower energies than shown, reflect the low quantum efficiency, on the order of 10^{-6}, that this device exhibits.

The low value of quantum efficiency for the narrow-gap semiconductor/silicon (NGS/Si) heterostructure is a result quite in contrast with the ideal NGS/Si device proposed by Scott.[4] The cause of this discrepancy most likely rests in the band offset of the two semiconductors. The "ideal" NGS/Si device as proposed by Scott, Mercer and Helms calls for the NGS to have a band gap "from near threshold to 1/2 that value to minimize inelastic processes." The observed barrier height for photodetection in the ReSi$_2$/n-Si HIP device is several times that of the band gap of the NGS, ReSi$_2$. Therefore, after excitation, hot electrons have many empty conduction band states to scatter into, thus reducing their chances of reaching the junction with sufficient energy to surmount the barrier [process (b), Fig. 3]. In addition, we can expect many of the excited carriers to be promoted to final states of insufficient energy [process (c), Fig. 3]. These two effects would produce an inherently inefficient device. We believe that the unfavorable band offset in this system is dictated by Fermi-level pinning as a result of the existence of interface states. The observed value of the cutoff wavelength, ~2.1 μm, shows that the device cannot be applied to detection in the 8–14 μm atmospheric window. To better exploit the narrow band gap of ReSi$_2$, a thin-film photoconductor structure was explored.

B. The ReSi$_2$ thin-film photoconductor

The photoconductor structure, as portrayed in Fig. 2, was found to be ohmic as expected, with a typical device resistance of ~1.7 kΩ (6 mil×6 mil contacts, ~0.5 cm apart) and a contact resistance of ~750 Ω at room temperature (~16 and ~7 kΩ at 10 K, respectively). Figure 5 displays the spectral response of a device between 3000 and 6000 nm at 10 K. (A broadband IR response for the continuous spectrum from ~2.5 to 7.5 μm range was observable up to 100 K; for monochromatized radiation, however, further sample cooling was necessary.)

The decreasing spectral response with increasing wavelength, as shown in Fig. 5, roughly follows the number of photons absorbed as estimated from the optical absorption coefficient[7] of the disilicide. This behavior strongly suggests that the device is a *quantum* detector as opposed to a *thermal* detector. The mechanism of detection is believed to be photoconductivity as a result of excess carrier generation. In contrast to the HIP device, the intrinsic absorption mechanism will allow the material to be utilized for IR detection out to wavelengths approaching its absorption edge. It is worth emphasizing that the results presented here for the ReSi$_2$ thin-film photoconductor are for a *polycrystalline* thin film. One might hope for an improved photoelectronic response from an *epitaxial* ReSi$_2$ thin film if adequate electrical isolation from the silicon substrate can be achieved.

IV. SUMMARY AND CONCLUSIONS

Two types of silicon-compatible IR sensing devices have been demonstrated with the narrow band-gap semiconductor, ReSi$_2$. Internal photoemission of electrons from the silicide film into the silicon substrate is believed to be the detection mechanism for the ReSi$_2$/n-Si HIP device. The HIP device is characterized by extremely small quantum efficiencies (on the order of 10^{-6}) and a long-wavelength cutoff of ~2.1 μm. IR detection by a ReSi$_2$ thin-film photoconductor, on the other hand, is believed to be accomplished via intrinsic band-to-band absorption. Measurements in the 3–6 μm range, when compared with absorption coefficient data for ReSi$_2$, suggest that the polycrystalline photoconductor is indeed a *quantum* detector. With its fundamental absorption edge believed to be near 0.1 eV (~12 μm), a ReSi$_2$ photoconductive IR detector should reach well into the 8–14 μm window of atmospheric transparency. Further investigation of this novel material is necessary to determine whether other practical constraints will be satisfied.

ACKNOWLEDGMENT

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