Electron yield of glow discharge cathode materials under helium ion bombardment

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The secondary electron emission coefficient of materials for helium ion bombardment in the energy range 0.5–20 keV was measured for the surface conditions of cathodes in high voltage glow discharges. The materials studied are oxidized aluminum, oxidized magnesium, a molybdenum-aluminum oxide sintered composite, molybdenum, stainless steel, copper, gold, and graphite. Each sample was surface conditioned by operating it as cathode of a helium glow discharge shortly before the electron yield measurement. The results are relevant to the modeling of glow discharges and the design of cold cathode electron guns.

In cold cathode glow discharges a large fraction of the electron emission is due to the ion bombardment of the cathode surface.[1] Consequently, the value of the secondary element emission coefficient of the cathode surface plays an important role in determining the discharge characteristics. In the particular case of the generation of high-energy electron beams by high voltage glow discharges, the electron beam current density and generation efficiency depend on the secondary electron emission coefficient.[2] Also knowledge of the secondary emission coefficient is necessary to model many fundamental aspects of glow discharges.[3,4] Careful measurements of the secondary electron emission coefficient for atomically clean surfaces in ultrahigh vacuum conditions have been reported (for reviews see Refs. 5–10). However, since the emission coefficient depends strongly on the surface conditions, most of the measured values do not apply to the conditions present in many gas discharges. For example, these yields fail to correlate with the relative glow discharge current values obtained from different cathode materials. Electron yield measurements for gas-covered surfaces also exist, but they were usually performed under poorly controlled conditions, or for only a few specific surface states.[11–19]

In this letter we report the first measurements of secondary electron emission coefficient under helium ion bombardment of eight cathode materials for surface conditions that closely resemble those present in a high voltage glow discharge. To achieve this surface condition, we designed an experiment in which the material samples are the cathodes of a 5 kV glow discharge and in which secondary electron emission measurements are made *in situ* using an ion beam during an interruption of the discharge. The discharge current intensity, which is very sensitive to the cathode surface conditions, is digitized and recorded before and after the discharge interruption. The verification that the current intensity remains unchanged is taken as indication that the surface emissivity does not significantly change during the electron yield measurements, and corresponds to the values during the discharge interrupted shortly before.

The eight materials studied are oxidized aluminum, oxidized magnesium, a molybdenum-aluminum oxide sintered composite, molybdenum, stainless steel, copper, gold, and graphite. The first four have been reported to be used under helium ion bombardment as cathodes in high current density electron guns.[2,20–22] The other materials have also been used as cathodes in glow discharges.[23,24] Helium is one of the most commonly used gases in glow discharges.[22–24] In order to get electron yield data applicable to typical glow discharge cathode materials we used polycrystalline, commercial purity samples, machined, polished, and cleaned ultrasonically in methanol. The sintered material composition is 40% aluminum oxide and 60% molybdenum by weight, containing particles approximately 10 μm in diameter. The stainless steel is a 304 alloy.

The experimental setup used to perform the measurements is schematically illustrated in Fig. 1. The targets are 1.2 cm in diameter and are mounted in a rotatable vacuum feedthrough which can hold up to three samples and a Faraday cup. Rotating the feedthrough allows us to place the cathodes in front of a water-cooled anode for surface conditioning, or in the axis of a helium ion beam for the electron yield measurements. The helium ion beam is generated in an electron impact ionization ion gun. Helium gas is flowed through the gun, which has a 2 mm ion beam exit orifice. Ion

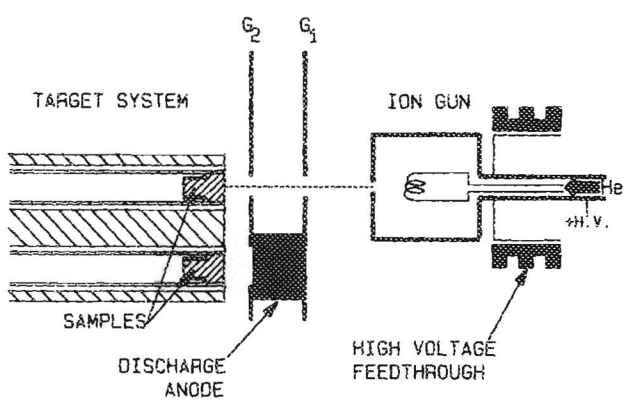

FIG. 1. Experimental setup. The samples and the discharge anode are water cooled. The cathodes are surrounded by ceramic tubes that, when discharged, limit the emission to the front face. The vacuum chamber and electrical circuits are not shown. The plates G_1 and G_2 are grounded.

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beam currents of 1–10 nA can be obtained with chamber helium pressures of 7×10^{-4} Torr. At this background pressure the helium ion mean free path for charge transfer and momentum transfer collisions is more than one order of magnitude larger than the distance between the gun and the samples. The ion gun can be floated to voltages up to 20 kV to permit the acceleration of the ion beam to the desired energy between the ion gun output orifice and the first grounded plate G_1. A second grounded plate G_2 reduces the penetration of the acceleration gap electric field in the vicinity of the sample.

The surface of the samples is conditioned by operating them as cathodes of a -5 kV, 1.5 Torr helium glow discharge. The cathodes and the anode are water cooled to minimize outgassing effects. The temporal evolution of the discharge is monitored until a steady-state value is reached. The discharge is then interrupted, the chamber is pumped down to 10^{-6} Torr, and the discharged sample is placed on the ion gun axis to perform the electron yield measurements. After the measurement is performed, the initial discharge conditions are reproduced, the discharge is re-ignited, and the current is again monitored to check that no significant changes in the surface emissivity occurred during the interruption. The secondary electron emission coefficient $\gamma = I_e/I_i$ is obtained by measuring the total current to the sample $I_T = I_e + I_i$, and the incident ion beam current I_i. The ion beam current is measured either by applying a positive bias to the sample to trap the emitted electrons or by placing the Faraday cup in front of the ion beam.

As expected, the secondary electron yields measured before discharging the samples show no relation to their current emission in a glow discharge. The yields of surfaces not previously discharged are associated with the presence of water vapor and other impurities. They were observed to be relatively independent of the material and to keep no relation with the yields measured after discharge conditioning. When a discharge is first initiated the current changes as the cathode surface is being sputtered, until a new surface condition is established and the current stabilizes, as observed in Fig. 2. After this initial variation, and for all materials listed above, the discharge current was observed to remain constant, even following a discharge interruption lasting several minutes. The illustration in Fig. 2 corresponds to an aluminum cathode discharged in an atmosphere of 1.5 Torr helium with 10 mTorr of oxygen added. For aluminum and magnesium this small amount of oxygen was added to the discharge to establish a stable oxide layer, as is frequently done in high voltage glow discharges to enhance the electron yield and decrease sputtering.[2,20,21] Figure 2 shows that when the oxygen flow is interrupted the electron emissivity decreases significantly. The addition of oxygen was observed to cause only small changes in the electron yield of the other six materials, and in obtaining the results reported herein these materials were discharged in pure helium.

Figure 3 shows the electron yields for helium ion beam energies between 0.5 and 20 keV. Figure 3(a) illustrates the secondary emission coefficient results for high yield materials commonly used as cathodes in cold cathode electron guns.[2,21,22] Oxidized magnesium and aluminum present the higher yields, followed by the sintered composite. This result is in agreement with previous observations of the current intensity emitted by high-power dc cold cathode electron guns that use the same materials.[2] The coefficients for lower yield materials are shown in Fig. 3(b). The yields for molybdenum, copper, and gold are approximately a factor 2–3 higher than those measured under ultraclean conditions.[25,26] Comparison of scanning electron microscope photographs of the gold cathode surface taken before and after discharging shows a significant increase in surface roughness due to

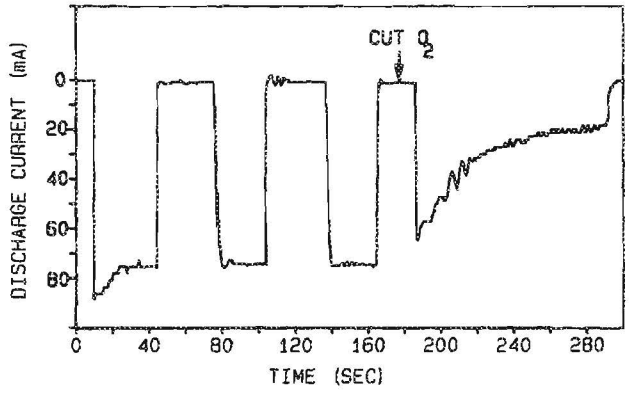

FIG. 2. Temporal evolution of the discharge current for an oxidized aluminum cathode. 5 kV was applied across the discharge and a 20 kΩ ballast resistor; the helium pressure was 1.5 Torr. 10 mTorr of oxygen was added. The first current peak corresponds to the initial discharge of the cathode. A steady-state condition is reached after a few tens of seconds. The oxygen flow is interrupted at the marked time. The following starting current intensity is lower due to the fact that now the discharge occurs at a lower pressure in pure helium. The subsequent current drop is due to the depletion of the cathode surface oxide layer due to sputtering.

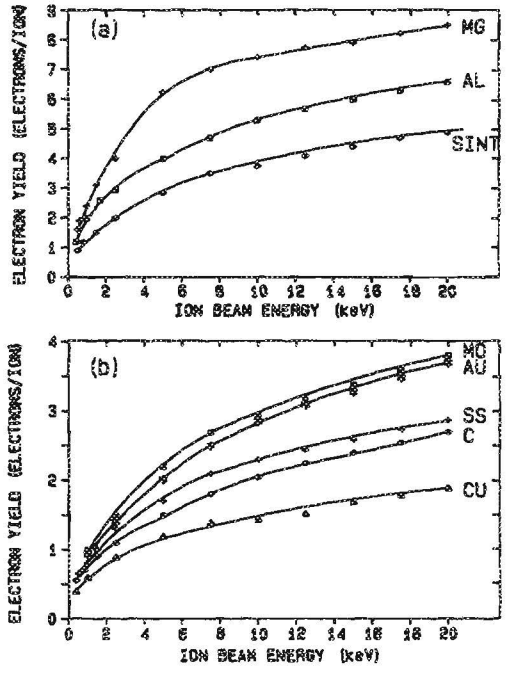

FIG. 3. Variation of the electron yield with helium ion beam energy. (a) Data for oxidized magnesium, oxidized aluminum, and sintered Mo-Al_2O_3 (60%–40%). (b) data for molybdenum, gold, 304 stainless steel, graphite, and copper.

sputtering. After the discharge the surface presents a wavy structure with irregularities of approximately 1 μm in size, that might contribute to increase the yield. Gas loading over the surface probably also makes significant contribution. It becomes obvious that the results of Fig. 3 might be dependent on the discharge conditions. Nevertheless, measurements obtained after discharging the cathodes under significantly different discharge currents gave yield values differing by less than 10%. Consequently, the results of Fig. 3 can be considered useful to describe conditions prevalent in many glow discharges, where the use of yields measured under ultraclean conditions of flat, elemental surfaces would in general be inappropriate.

The significance of the measured yields in relation to the characteristics of glow discharges is illustrated in Fig. 4. This figure shows the relation between electron yield and the discharge current delivered by the different materials when operated at 1.2 cm in diameter cathodes in 1.5 Torr of helium by applying 5 kV across the discharge and a 20 kΩ ballast resistor. The values of the electron yields used in Fig. 4 for the different materials are those measured for 5 keV helium ion beam energy. Notice, however, that this ion energy is to a certain extent arbitrary since the actual voltage drop across the discharges is not 5 kV in all cases, being lower for high yield cathodes due to the larger voltage drop in the ballast resistor. The graph consequently should be considered only as indicative of the strong dependence of the discharge current on the electron yield. The supralinear current increase of Fig. 4 would be even more pronounced if the voltage drop across the discharge would have been identical.[27] The nonlinear increase is due to the fact that a larger emission produces a higher electron current that in turn produces increased ionization and a larger ion flux directed towards the cathode. As a consequence, the plasma density and the charged particle fluxes self-consistently adjust to values that reflect an amplification with respect to the increase in the electron yield, thereby showing the importance of the selection of high electron yield cathode materials for the generation of high current density glow discharges.

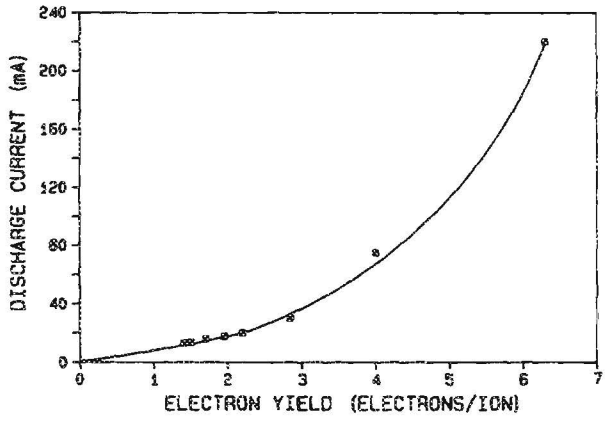

FIG. 4. Discharge current as a function of the electron yield for 5 keV helium ion bombardment. The data points correspond to copper, graphite, stainless steel, gold, molybdenum, sintered Mo-Al_2O_3 (60%–40%), oxidized aluminum, and oxidized magnesium, in order of increasing discharge currents. The cathodes are 1.2 cm in diameter. Discharge conditions are 5 kV, 1.5 Torr helium pressure (10 mTorr of oxygen added in the aluminum and magnesium discharges), 20 kΩ ballast resistor.

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[27]Maintaining the same voltage drop across the discharge for all cathode materials was not practically feasible. This would have required to overheat the setup with the several hundred watt electron beams produced by high yield materials, or alternatively to run the lower yield materials in a normal or near normal glow regime.