Origin of Anomalous Emission in Superdense Glow Discharge

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(Received 26 February 1988)

A theory, supported by new experimental data, for recently observed anomalous large pseudospark and back-lighted thyratron cathode emission into a superdense glow discharge is reported. The current density at the cathode surface, ≈ 10 kA/cm^2, is produced by an ion "beam," extends over a surface area of ≈ 1 cm^2, and is orders of magnitude larger than that of heated thermionic cathodes.

PACS numbers: 52.40.Hf, 52.75.Kq, 52.75.Pv

High-power devices such as power modulators have historically been limited by switch technology, and power switch technology, in turn, has been limited by peak current, pulse energy, voltage fall time, and repetition rate. A new class of high-power, low-pressure gas, glow-discharge switches, including the pseudospark[1-3] and the related optically gated back-lighted thyratron,[4] operate with a superdense[5,6] glow discharge—without arcing—yet produce extremely high current density at an initially cold cathode surface. This current density is of the order of or greater than 10^4 kA/cm^2.[1-4] This is especially remarkable when compared with the emission achieved in a high-power glow-discharge switch with a heated thermionic cathode, which under high-current conditions is typically of the order of 50-200 A/cm^2. To our knowledge, this anomalous large emission has not been explained or understood. In this Letter, a study of several possible mechanisms is briefly reviewed. Results of scanning electron microscope investigations of the surfaces of Mo and nickel cathodes, and a streak-camera study of the plasma, are presented. We conclude from this study that a modified thermionic emission process resulting from a high-current-density ion "beam" produced in the cathode fall is responsible for the anomalous high emission.

The experimental apparatus is described in Ref. 4. For this work, electrically and optically triggered switches of the pseudospark type were investigated. In this apparatus high standoff voltage (≈ 5-35 kV) is achieved by positioning of the anode and cathode within a few millimeters of each other, so that premature breakdown is prevented by operation on the left-hand part of the Paschen curve.[1-5] The electrodes are hollow, with an annular hole. The emission process was investigated with both Ni and Mo electrodes. The anode-cathode distance for both Mo and Ni electrodes was 3.5 mm, and the cathode-hole diameter was 5 mm. The triggering method (flashlamp or pulsed glow-discharge triggering) had no observable influence on the spatial and temporal behavior of the discharge plasma. The Mo and Ni cathodes were exposed to $\simeq 10^5$ discharges each at peak currents of 8 kA (Mo) and 6 kA (Ni), respectively, and pulse durations (FWHM) of 0.5 and 1 μsec, respectively. After about 10^5 discharges in hydrogen at a pressure of 27 Pa, the switch was disassembled and the cathode surface facing the anode was investigated by means of a scanning electron microscope.

Streak-camera recordings with ≈ 1-mm spatial resolution in the radial direction demonstrate that a homogeneous discharge plasma exists without arcing. In occasional situations, arcing is observed to start on arbitrary locations in the vicinity of the cathode hole, however, after the build up of the homogeneous superdense glow discharge. The spatially resolved electron density was also determined from measurements of the Stark broadening of the hydrogen Balmer-β transition. Doppler broadening, with the assumption of a neutral hydrogen temperature of less than 1 eV, could be neglected at densities $> 1\times 10^{15}$ cm^{-3} with an error of less than 15%. The electron density is clearly centered around the cathode hole, with a diameter comparable to or slightly larger than that of the hole, during the rising part of the pulse. Shortly after the maximum of the current pulse, the electron density reaches its maximum of $\simeq 3\times 10^{15}$ cm^{-3}, the diameter (at FWHM) of $\simeq 17.4$ mm being close to the outer diameter of the intensely sputtered zone on the cathode surface. In addition, the electron temperature was calculated from the intensity ratios of the hydrogen Balmer-α/Balmer-β transitions for different times and radii after Abel inversion of the raw data, with two different models for the plasma. In this apparatus, the percentage of arcing events was observed to increase with increasing total discharge current. Therefore, the peak current was limited to $\simeq 8$ kA in order to prevent arcing in the switches used for this study.

Several processes have to be considered for an explanation of the high current density observed in the experiments described above. A more detailed analysis of these processes is to be published. First, the requirement of current balance at the surface of the cathode means that the sum of electron current from the cathode plus ion current onto the cathode surface must be equal to the total discharge current at any time. (A simple estimation shows that the displacement current is at least 2 orders of magnitude lower than the total discharge current and can therefore be neglected.) Second, the emissivity of the cathode must be high enough to act as an electron source able to support the discharge current, if most of the current in the cathode fall is due to electrons. Different electron-emission processes can contribute to the total cathode emission: photoeffect due to incident uv photons, release of electrons due to impact of atoms (neutrals and metastables) and ions, thermionic emission (eventually field enhanced) from a heated surface layer, and field emission in the presence of a high electric field at the cathode surface. Third, the limitation in current density for the electron and ion flow in the cathode-fall region due to their own space charge sets an upper limit, making it possible to estimate the voltage drop and the width of the cathode fall.

The space-charge limitation to the electron current is primarily due to the size of the cathode fall. In this plasma the electron density is $\approx 10^{15}$ cm^{-1}, and the electron temperature is $1 \text{ eV} \leq T_e \leq 3$ eV; hence the sheath size will be of the order of a Debye length, or of the order of 1 μm. With this assumption the space-charge limitation for electron current is

$$j_e \approx 2\times 10^5 \text{ A/cm}^2,$$

which is much larger than the current density observed in the experiment, and therefore does not limit the current density. The maximal ion (proton) current from the plasma to the cathode under the same assumptions is

$$j_i = 4.6\times 10^3 \text{ A/cm}^2,$$

which is comparable to the current density observed in the experiment. The ion current j_{ia} entering the cathode sheath from the anode side can be written as

$$j_{ia} = 0.4 e n_i (2kT_i/m_i)^{1/2},$$

and is the maximum (saturation) ion current that can be drawn from the plasma with a stationary plasma boundary. n_i, T_i, and m_i are the ion density, temperature, and mass, respectively, at the plasma boundary. This yields an upper limit for the ion current of $\simeq 200$ A/cm^2 which is much less ($\simeq 1$ order of magnitude) than the total discharge current. Therefore, it is necessary to investigate other processes leading to electron release at the cathode surface, including photoeffect, field-enhanced thermionic emission, field emission, and release of electrons due to impact of atoms (neutrals and excited atoms) and ions.

On the basis of an analysis of photoemission produced by molecular and atomic hydrogen, a power flux of the order of 5×10^6 W/cm^2 is necessary to support an electron current density of 5×10^3 A/cm^2. This extremely high uv-light power flux cannot be emitted from a plasma of electron density $(1\text{-}3)\times 10^{15}$ cm^{-3} and temperature $\simeq 1\text{-}3$ eV. Similar considerations are valid for uv radiation from molecular hydrogen transitions, and we conclude that photoemission does not contribute significantly to the high current density observed in the experiment.

A further source of cathode electron production is the impact of ions, neutrals, and metastables, in this specific case protons, neutral and excited hydrogen atoms and molecules, and atoms, metastables and ions from sputtered Mo. The total amount of electron current due to ion impact can be estimated to be <10% of the ion current. The secondary-electron emission coefficient in the case of metastable or neutral impact can be significantly higher, up to the order of unity. However, on the basis of an estimate of metastable production processes, the probability for these processes to occur in the cathode fall is very low, and, correspondingly, the contribution of neutrals and metastables to the production of electrons at the cathode surface is expected to be small.

Although the cathode is a "cold" cathode, during the transition phase (rise of the current, buildup of the plasma) and the conduction phase, some of the loss processes involved (particle impact on the walls, radiation, etc.) can lead to a noticeable energy deposition on the walls, which in turn can be the reason for appreciable heating of a thin surface layer during the current pulse. This hot layer only exists for short times, but can act as a thermionic cathode when heated at a sufficiently fast rate. There are two emission processes for a hot surface in the presence of large electric fields, field-enhanced thermionic emission (Schottky emission) and field emission (Fowler and Nordheim).

The field-enhanced thermionic emission can produce current densities of the order observed for electric fields appropriate to these conditions when the surface temperature is between about 2500 and 2900 K. The order of magnitude of the electric field is estimated from the assumed cathode-fall voltage drop of $\simeq (1\text{-}2)\times 10^2$ V and the estimated cathode-fall thickness of $\simeq 1$ μm. Thus a temperature close to the melting temperature of Mo (≈ 2900 K) is required to explain electron current densities of the order of the total current densities observed in the experiment. Such a high temperature can be achieved only in a thin surface layer for a short time. (There is no evidence for excessive overall cathode heating in the experiments.) The surface temperature, determined by the surface power load (watts per square centimeter) and the thermal properties of the cathode material from the heat diffusion equation, can be shown for a constant (rectangular) power flux F_0 during the time interval t_0 to be

$$T(t) = (1.128 F_0\sqrt{\kappa})/K[t^{1/2} - (t-t_0)^{1/2}],$$

where K is the thermal conductivity, κ is defined as $\kappa = K/\rho c_s$, ρ is the mass density, and c_s is the specific heat. These calculations show that a power density of the order of 10-20 MW/cm^2 is necessary, on a time scale $\leq 10^{-7}$ sec, to heat a thin surface layer (several micrometers) to the temperature required by the process of field-enhanced thermionic emission in order to achieve cathode emissivities of several times 10^3 A/cm^2. Such a high rate of energy deposition cannot be achieved by radiation heating (as pointed out before) from the plasma.

If we assume that the discharge current at the cathode surface is determined mainly by ions (protons), then the power density related to this ion flux is ≈ 25 MW/cm^2, and the time required to heat the surface to $T_s = 3000$ K is $\simeq 30$ nsec. The maximal power available during the initial phase is limited by the discharge circuit to ≤ 25 MW, which means that up to 1 cm^2 can be heated to such a high temperature. Field-enhanced thermionic emission, therefore, is a possible mechanism of electron release from the cathode surface during the conduction phase after initial heating by ion impact.

The electric field in the cathode fall is $\approx 10^6$ V/cm, and field emission is a candidate mechanism, especially under the influence of an elevated surface temperature. The field-emission current density at low (room) temperature is

$$j_0 = [e^3 E^2 / 8\pi^2 h \Phi t^2(y)] \exp[-8\pi(2m_e)^{1/2} \Phi v/(y) 3hE], \quad y = (e^3 E)^{1/2}/\Phi,$$

where v and t are functions containing elliptical integrals and are functions of the work function Φ, the electron potential energy W in the metal, and the electric field E. With use of this equation, for an electric field of over 10^7 V/cm (which is 1 order of magnitude larger than that of the cathode fall), this produces an insignificant enhancement of j_0. Treatments including both field emission and thermionic emission do not significantly modify the above results.

An upper limit for the power density P_i/A of ion current from the plasma boundary, with the cathode-fall voltage drop estimated by the lower energy limit of the sputtering efficiency (200–500 V, see above), gives 1 MW/cm$^2 \leq P_i/A \leq 2.5$ MW/cm^2. During the initial (transient) phase of the discharge, e.g., the first 100 nsec, however, the voltage drop can be substantially higher, with an upper limit for the surface power given by the properties of the discharge circuit as $\simeq 25$ MW/A in the present case. This would be enough for an initial heating of the cathode surface to a temperature where field-enhanced thermionic emission begins to play a role in the current balance equation. If the total discharge current, however, were then determined mainly by thermionic electrons from the cathode, then the cathode surface would rapidly cool and thermionic emission would cease. We therefore conclude that the contribution of the ion current remains at a level of the order of $\simeq 50\%$, in order to assure a cathode heating high enough to sustain the cathode surface temperature at a level where thermionic emission becomes appreciable. In the absence of thermionic emission, the ratio of plasma boundary ion current to total current can reach 80%–90%, which means that most of the discharge current at the cathode surface is carried by ions from the plasma boundary. In any of the cases, the high ion-current density cannot be supplied by the plasma on a long time scale: During the quasisteady state of the discharge the space-charge-limited ion flow in the cathode fall is in addition hindered by the limited drift velocity of ions into the plasma boundary. For a hydrogen plasma the ion density would have to be ≈ 1 order of magnitude larger than the electron density observed, and of the order of the neutral gas density (on the assumption of a dissociation degree of $\simeq 1$). Additionally, the total charge transferred by the ions in a single pulse is of the order of $\simeq 3 \times 10^{-3}$ C, which requires a total number of ions per pulse of $\simeq 1.9 \times 10^{16}$/cm^2 or approximately the whole gas inventory available in the discharge region. The only additional source of protons which can deliver enough ions on the time scale employed (of order nanoseconds) is the release of hydrogen from the cathode surface due to ion impact or due to thermal desorption; a monolayer of atomic hydrogen on Mo represents a surface density of $\simeq (1\text{–}1.5) \times 10^{15}$/cm^2, which is sufficient to support the assumed ion current density.

A scanning-electron-microscope study of the cathode surfaces shows that the surface in the immediate vicinity of the cathode hole has been melted uniformly over an area of ≈ 1 cm^2. We estimate the melt depth to be several micrometers, occurring within a short time interval, subsequently undergoing a very rapid quenching due to heat conduction into the cold bulk material of the cathode. From the melting point of Mo (2893 K) we conclude that the surface temperature, up to a radius of $\simeq 8$–9 mm, must have been ≈ 3000 K. The outer limit of the melting zone coincides very well with the radius (HWHM) of the plasma column as derived from the streak-camera measurements. There is no evidence for melting of the cathode surface at radii $r = 11$ mm or larger. Similar results are observed with Ni cathodes. We conclude that the most intense interaction between the gas discharge plasma and the cathode surface is restricted to a relatively small area, approximately $\simeq 40$ cm^2 around the "edge" of the cathode hole.

The surface power density necessary to heat a Mo (or nickel) surface to a temperature of nearly 3000 K is between 10 and 25 MW/cm^2, under the assumption of a constant power flux in a time interval between 100 and $\simeq 30$ nsec. On the basis of the above discussion, the only possible source of energy for the process is an intense ion current, produced in the cathode fall during the initial part of the discharge.

In conclusion, it has been shown that the extraordinary emission produced under these conditions is the result of thermionic emission that is caused by ion "beam" heating of the cathode surface. A detailed examination of all the physical processes involved, including surface-related phenomena, and presentation of additional experimental results to support the above theory will be presented in a forthcoming paper.[5] Experimental data further demonstrate earlier conclusions that this emission leads to a superdense glow discharge, and is not produced by arcing. Because the current density is extremely high, this emission mechanism is of importance for a variety of applications.

This work was supported by the U.S. Air Force Office of Scientific Research, the U.S. Army Research Office, and the Deutsche Forschungsgemeinschaft.

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