Model for Explosive Electron Emission in a Pseudospark "Superdense Glow"

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The pseudospark cathode has the remarkable property of macroscopically homogeneous electron emission at very high current density (>1 kA/cm^2) over a large area (some cm^2). Experimental results and the model presented here provide evidence that the pseudospark microscopically utilizes explosive arc processes, as distinct from the earlier model [Phys. Rev. Lett. **60**, 2371 (1988)].

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The pseudospark is a hollow cathode, hollow anode device that operates with low pressure discharge and has remarkable capabilities for high power switching and electron beam generation [1]. During operation the discharge occurs in several phases including (i) ignition, (ii) a transient high-voltage, relatively low-current phase (hollow cathode discharge), and (iii) a high-current (conducting) phase wherein a "glow-type" (≈ 200 V) or "arc type" (≈ 50 V) voltage drop is observed. In a previous paper [2] it was assumed that a homogeneous electron emission was responsible for the third, very high-current or superemissive phase, because the plasma appears homogeneous (i.e., "superdense" glow [3]) for currents up to several kiloampere or even tens of kiloampere. Recent experiments suggest that there are several regimes of high-current conduction involving arc processes [4]. Here we discuss a new model of cathode electron emission for the high-current phases of pseudospark operation. The physics of this model provides insight into the relationship between glow and arc discharges, and is also applicable to some extent to other physical situations such as high-pressure excimer discharges and plasma immersion ion implantation.

The earlier phenomenological model of anomalous emission during the conducting phase following closure is based on the assumption that field-enhanced thermionic emission from a thin, hot cathode layer is responsible for the high current density [2,5]. In the case of a molybdenum cathode, the temperature of the cathode surface must exceed the melting temperature and, indeed, a molten area was found by inspecting the cathode after switching operation in a scanning electron microscope [6]. It was pointed out that "Up to now no final decision can be made whether the superdense glow is homogeneously distributed over the whole cathode surface from a microscopic point of view" [6].

Field-enhanced thermionic emission is described by the Richardson-Schottky equation. A more general approach is to consider thermofield emission [7], which is a nonlinear combination of thermionic and field emission that is valid for both extremes of very high temperature and very high electric field.

Following Hartmann *et al.* [6] we consider a molybdenum cathode and assume emission from a thin, homogeneously heated surface layer. Then, in agreement with their findings, the surface temperature must exceed the melting temperature (Mo: 2893 K) in order to provide the high current density of 10^8 A/m^2 in the high-current ("superemissive") phase.

To study the question of whether or not the surface has reached a temperature at the end of the hollow cathode phase which is higher than the melting temperature, we have to investigate the energy balance at the cathode in the hollow cathode phase, including ion bombardment heating. Ohmic heating, Nottingham heating and cooling, heat conduction cooling, electron emission cooling, evaporative cooling, sputtering cooling, and radiation heating and cooling. Fortunately, most of these terms are negligible and we need to consider the time-dependent heat conduction equation where the source term involves ion bombardment heating only. All other terms are small in comparison with the energy flux density due to ion bombardment, since the ions gain a high energy when accelerated in the cathode drop without collisions.

The heat conduction equation was solved by applying the Bohm criterion for the maximum ion current density, using the observed [8] maximum plasma density [$(0.5$–$3.5)\times10^{21}$m^{-3}] and the maximum cathode drop voltage of 10^4 V. In this estimate, upper limit values were used for simplicity; maximum voltage and density do not appear simultaneously, of course. The maximum power density available is only 3×10^{10} W/m^2, too low to heat the cathode surface fast enough to the high temperature required for thermofield emission (Fig. 1).

There are two basic directions in which to look for a solution. One is to search for efficient mechanisms which increase the plasma density above the cathode surface, and the other is to assume emission from emission centers (cathode spots).

Only the cathode surface itself can be the source of a higher plasma density. Desorption of a gas layer takes place at the very beginning of the discharge and is therefore already included in the measured value of the interelectrode plasma density. Further ablation of the cathode material is caused by sputtering. We have calculated the sputter rate for various gases and cathode ma-

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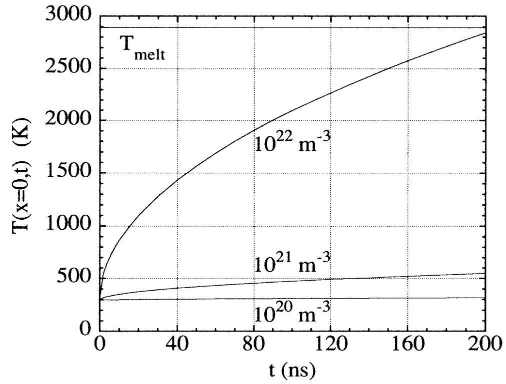

FIG. 1. Surface temperature of a molybdenum cathode as a function of time with the plasma density as a parameter, $U_c = 10^4$ V, hydrogen plasma with $kT_e = 1$ eV.

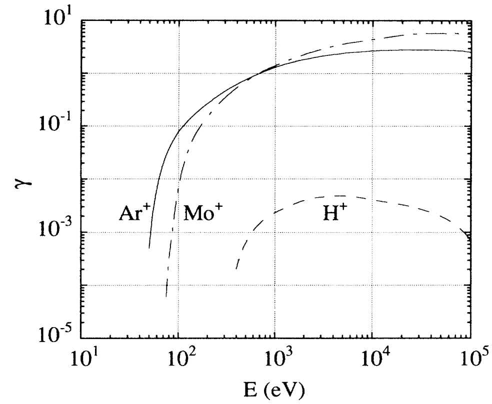

FIG. 2. Sputter rate of molybdenum [γ is the (number of sputtered atoms)/(number of incident ions)] as a function of the primary ion energy, calculated with the T-DYN code.

terials using the T-DYN Monte Carlo computer code. The results for a molybdenum cathode are shown in Fig. 2. The sputter rate for hydrogen is obviously negligible. The sputter effects for the case of argon and cathode self-sputtering have to be considered in more detail.

The density of sputtered cathode atoms can be determined by $n_c = J_c/v_c$, where $J_c = \gamma j_i/Ze$ is the flux of sputtered atoms, γ is the sputter rate, v_c is the velocity of sputtered atoms, j_i is the ion current density determined by the Bohm condition, and Ze is the mean charge of primary ions. Using the T-DYN results we have obtained densities of sputtered cathode material which are always much smaller than the initial plasma density.

Cathode self-sputtering is also negligible. The sputtered atoms have a mean free path with respect to ionizing collisions given by $\lambda = (n_e\sigma)^{-1}$, where σ is the cross section for this process. Considering the limiting case of high electron density (3×10^{21} m^{-3}) and a maximum of σ ($\sigma \leq 2.5\times10^{-20}$ m^{-2} for molybdenum) we obtain $\lambda \geq 1.3$ cm. This is larger than the electrode gap distance, and thus ionization of the sputtered material is unlikely. If the sputtered particle leaves the surface as an ion, it will immediately "see" the surface electric field and return to the cathode. Then it has the same energy as it had when it left the cathode, i.e., according to T-DYN calculations, a maximum of 50 eV. Molybdenum ions hitting a molybdenum cathode with this energy have a sputter rate $\gamma < 10^{-6}$; thus there is no self-sputtering. In conclusion, sputtering cannot enhance the plasma density near the cathode. Although there is an intense ion bombardment, its *power density is not great enough to justify the assumption of a homogeneous thermofield emission.*

In the model presented here, no homogeneous heating at all is necessary. Instead we propose that the appearance of a virtual plasma anode in close proximity to the cathode can explain the observed current density, macroscopically homogeneous current distribution, and time constants.

It has been shown by computer simulation [9] that the anode equipotential line moves toward the cathode during the hollow cathode phase. After some 100 ns the anode-cathode voltage drops almost completely in a thin sheath adjacent to the cathode surface. The situation at the cathode surface becomes similar to that of a vacuum arc cathode, with a key difference being that the anode will be the bulk plasma that is within a few tens or hundreds of microns from the cathode, rather than a microscopic ($\approx$ mm or cm) distance away. The bulk plasma has the feature of adapting to the cathode morphology, hence an anode is formed in close proximity that has the same shape as the cathode, and an extremely high electric field is therefore homogeneously provided over a large area (≈ 1 cm^2). The bulk plasma density (electron density n_e) increases during the hollow cathode phase which causes the cathode sheath to contract because its thickness, d_c, is related to n_e by [10]

$$d_c = (2\varepsilon_0 U_c/en_e)^{1/2},$$

where U_c is the voltage drop across the sheath. The electric field at the cathode surface can be estimated by

$$E_c \approx \beta\frac{U_c}{d_c} = \beta\left(\frac{en_eU_c}{2\varepsilon_0}\right)^{1/2},$$

where β is the field enhancement factor, introduced to describe the properties of the cathode surface [11].

From vacuum breakdown studies it is known that microtips of a cathode surface heat up explosively and form a metal plasma if the field strength surpasses a critical value. For example, this was calculated and measured for a tungsten cathode in vacuum [11]. Using these data one can easily see that the electric surface field is a very sensitive function of the bulk plasma electron density (Fig. 3), which is due to the strong nonlinearity in the electron emission and heating processes. Note that an increase in the electric field (or corresponding density of

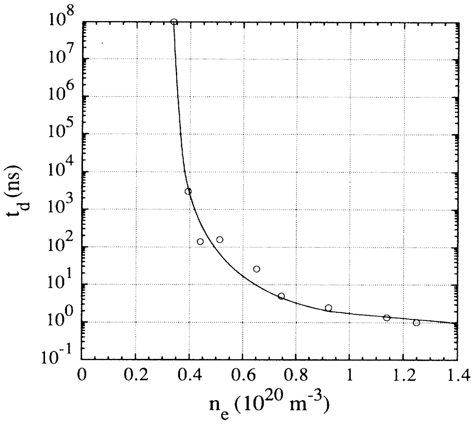

FIG. 3. Delay time of explosion of cathodic microprotrusions as a function of electron bulk density (tungsten cathode, $U_c = 10$ kV, data from [11]). Note the extremely large change in t_d corresponding to small change in n_e.

the bulk plasma) by a small factor reduces the delay time of microtip explosions by *many* orders of magnitude. That means practically that a transition from "nonexplosion" to "explosive processes" occurs nearly instantaneously if a critical field strength (plasma density) is reached.

A criterion can be derived for the transition from the hollow cathode phase to the highly conducting phase taking into account that the unavoidable explosions of many microscopic cathode protrusions, dielectric inclusions, and other irregularities lead to a new type of discharge mechanism. The criterion determines what value the electron density must reach in the hollow cathode phase to switch over to the new, highly conducting phase,

$$n_e \geq n_e^{\mathrm{cr}} \frac{2\varepsilon_0}{eU_c} \left(\frac{E_c}{\beta} \right)^2 ,$$

where E_c^{cr} is the critical field strength at the cathode surface at which explosions occur within nanoseconds. In the case of tungsten [11] it is $E_c^{\mathrm{cr}} \approx 1 \times 10^{10}$ V/m and $n_e^{\mathrm{cr}} \approx 5 \times 10^{19}$ m^{-3} (Fig. 3). The relation between the critical field strength and the critical density is not trivial because E_e^{cr} is a function of the cathode material and structure only but n_e^{cr} depends also on the applied voltage and electron temperature. In contrast to vacuum breakdown, the microprotrusions of the cathode surface are not only heated by Joule heating but also by ion bombardment. However, as shown in Fig. 1, ion bombardment is inefficient at plasma densities as low as 5×10^{19} m^{-3}, hence the above criterion remains valid also when the gas plasma is present.

It was found experimentally that the plasma density increases from 10^{15} m^{-3} at the beginning of the hollow cathode phase up to 10^{21} m^{-3} in the conducting phase. This means that vacuum arc processes must indeed be included in an accurate model, as previously suggested by Ecker [12], Mesyats and Puchkarev [13], Almen, Frank, and others [4,14].

Cathode spots of vacuum arcs can appear in different modes or types [15]. Cathodes with oxide films, a gas load or other kinds of dielectric layers and inclusions show "type 1" cathode spots if the current is not too high (some 100 A or less). They are characterized by a small current per spot (0.1–1 A per spot or even less), an erosion rate of typically 1–10 μg/A s, and a short lifetime of a few nanoseconds. Type 1 spots cause very small craters on the cathode surface (typically 0.5 μm or less in diameter). Because of their small size and dynamics, these spots show a diffuse brightness. The action of cathode spots and plasma on the cathode causes a cleaning of its surface, and a transition of type 2 cathode spots can be observed. These are characterized by a significantly higher erosion rate (10–100 μg/A s), larger crater diameter (1–5 μm), slower motion, higher brightness, and a higher current per spot (10 A/spot). At higher discharge currents (some kA), cathode spot interactions become important and the spots often form groups or patterns type *A* spots. At even higher currents the anode becomes active too. Then the cathode spots tend to merge into one large spot type *B* or "intense arc"). This results in a dramatic increase in the erosion rate and the crater diameter (some 100 μm up to mm).

The necessary electron emission in the high-current phase of pseudosparks can be easily obtained from a large number of tiny, dense plasmas since the *current density* of the individual spots [16] reaches values of order 10^{12} A/m^2.

The measured *erosion rate* of about 10 μg/A s for a molybdenum pseudospark cathode is smaller than but close to the vacuum arc type 2 erosion rate. The background gas pressure in a pseudospark will lead to an enhanced redepositon by collisions of the expanding cathode plasma with the gas. Therefore we have to distinguish between gross and net erosion rates. The measured net erosion rate depends on both the cathode material and the gas [17], and its reduction becomes important for a gas pressure higher than 1 Pa, i.e., the pressure range of pseudosparks. Therefore, the gross erosion rate of pseudosparks becomes similar to type 2 cathode spots. Another effect of the gas filling is its influence on the surface conditions. In the presence of high temperature close to cathode spots, chemical reactions of the gas and its contaminants with the cathode material will occur. Both the redeposition and the spot type due to surface gas load and contamination can explain why the erosion rate is relatively low.

If the erosion is interpreted as a simple evaporation loss, the surface temperature must be as high as 4050 K, which cannot be explained by the power available. Furthermore, the pseudospark would operate at a much higher pressure since the vapor pressure of molybdenum at 4050 K is 2700 Pa.

Also, the appearance of the *erosion structure* of pseudospark cathodes is similar to that of vacuum arcs. Depending on current, geometry and gas, craters and molten structures of all sizes (0.1 μm up to some 100 μm) have been found [4,6]. This suggests the existence of all kinds of spots—hence several different regimes of operating conditions.

Recent experiments [4] indicate the arc nature of the high-current phase: A voltage drop was found as low as 50 V, and metal plasma was observed by emission spectroscopy and laser-induced fluorescence.

For very high currents, $I > 45$ kA, localized areas with electron densities as high as 5×10^{23} m^{-3} have been detected in the bulk plasma by spectroscopy and interferometry [4]. From the point of view of cathode spots, this could be interpreted as a transition to a high-current mode similar to type B or intense arc. The locations of high plasma density indicate the existence of a small number of large spots which carry much more current than the spots in the previous spot mode. This arcing regime might be avoided by using multiple apertures in an appropriate geometrical configuration because the necessary large number of low-current cathode spots can be distributed over a larger area, and the need for a transition into a high current spot mode is suppressed.

Several conclusions may be drawn. The pseudospark is observed under certain conditions to produce low erosion relative to spark gaps. This occurs because the geometry allows the formation of a uniform glow-type plasma prior to high-current conduction, and thus allows the effective anode to be positioned advantageously, creating an extremely high, homogeneous electric field over a large area of the cathode surface. When the electron density of the glow-type plasma increases beyond a critical density, the surface field becomes high enough to initiate many spots which are similar to low-current vacuum arc cathode spots. The homogeneous distribution of a large number of small spots and an enhanced redeposition of cathode material due to plasma-gas interaction leads to a macroscopically homogeneous discharge with low erosion. For switching applications, this suggests that the pseudospark can be used in place of spark gaps, where its operation can be maintained within a regime of low erosion (for a single gap, single aperture pseudospark, this would be $\approx$2–20 kA peak current). There are likely additional applications, such as intense electron beam production, that are made possible by this new class of emissive devices, wherein the current is several orders of magnitude greater than from externally heated cathodes.

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