EXPLOSIVE PLASMA FORMATION ON ELECTRODES

F. Schwirzke, M. P. Hallal, Jr. and X. K. Maruyama
Naval Postgraduate School, Monterey, California 93943

Abstract:

Breakdown and "explosive" plasma formation on electrodes are basic processes in pulsed power discharges. Despite their fundamental importance, the details of cathode spot formation have not been well understood. Breakdown in a vacuum diode is initiated by field emitted electrons. Besides joule heating of the emitting spot, the electrons also ionize desorbed gas layers. These ions fall back to the cathode, heating the surface of the electron emitting spot. Ion surface heating is initially orders of magnitude larger than joule heating. Surface heating and the build-up of positive space charge rapidly lead to further enhanced field emission and, finally, thermionic electron emission. The localized build-up of plasma above the electron emitting spot naturally leads to pressure and electric field distributions which ignite unipolar arcs. The high current density of the unipolar arc and the associated surface heating by ions provide the "explosive" plasma formation of a cathode spot. Experimental results will be presented concerning the plasma formation on the cathode of a vacuum diode.

Introduction

Onset of breakdown and "explosive" plasma formation on electrodes are basic processes in pulsed power discharges. Vacuum breakdown in a pulsed high voltage diode is initiated by the explosive like phase transition of a field emitting spot into the dense plasma of a cathode spot. High current, high voltage diodes operate during the time interval between plasma formation and diode gap closure. This makes the understanding and prediction of the onset of plasma formation essential. Despite the fundamental importance of cathode spots for the breakdown process, the structure of cathode spots and the origin of the high current density were not yet fully understood. The field emission current provides joule heating. However, current density of about 10^{12} A/m^2 would be needed for transforming a speck of solid material into a dense plasma within nanoseconds. In the literature estimates of the current density j for a cathode spot vary by orders of magnitude between 10^9 A/m^2 [1], and 10^{13} A/m^2 [2]. This value is of critical importance since j and the electric field E determine field emission of electrons, joule heating, and plasma formation. If the physics of the breakdown process can be understood, it may be possible to design diodes which have the precise characteristics required by the application.

The purpose of this paper is to describe the processes involved in the onset of plasma formation in the fast pulsed vacuum diode. The first part describes a theoretical model for plasma formation in a high vacuum diode. This model makes quantitative predictions for the time delay of the onset of plasma formation. The second part describes an experiment performed to time resolve the plasma formation process in an actual fast pulsed vacuum diode. The time delay between the onset of the voltage pulse across the diode and the onset of plasma formation has been measured for different operating voltages of the diode. The measured time delay and voltage at onset can be compared to those predicted by the model.

Onset of Field Emission and Ionization

When an increasing voltage is applied across the gap of a vacuum diode, enhanced field of emission of electrons will begin from a growing number of small spots on the cold cathode surface if the applied electric field becomes sufficiently strong ($E \geq 10^7$ V/m). The field emission current density j_{FE} is described by the Fowler-Nordheim equation.

$$j_{FE} = c_1 \beta^2 E^2 \exp\left(\frac{c_2}{\beta E}\right)$$

β is the field enhancement factor, and c_1, c_2 are constants. Whiskers, dust particles, oxide spots and similar microscopic nonuniformities provide enhanced field emissions of electrons. Once a sufficiently large current begins to flow through the diode, the electric field distribution is altered by the presence of "electron space charge" and the maximum current density j_{CL} is limited by Child-Langmuir's law,

$$j_{CL} = \frac{4}{9}\varepsilon_o\left(2\frac{e}{m}\right)^{\frac{1}{2}}\frac{V_o^{\frac{3}{2}}}{D^2}$$

V_0 is the magnitude of the electric potential across the diode, and D is the width of the gap. In general one would expect that $j_{FE} << j_{CL}$. The Child-Langmuir current to the anode represents an upper limit. A Pulserad Model 112 flash X-ray and electron accelerator system was used in this experiment. The diode has a gap of D = 2.54 cm and a 1.0 MV potential pulse of 30 ns FWHM applied. For these values the space charge limited current density of $j_{CL} = 3.6 \times 10^6$ A/m^2 is much smaller than the $j \approx 10^{12} - 10^{13}$ A/m^2 required to ionize a whisker by joule heating within a few nanoseconds [3]. The field emitted electron current will become space charge limited at a value which is insufficient for the explosive like transition of the whisker into a dense plasma. Furthermore, the externally applied electric field vanishes near the cathode surface when the current becomes space charge limited. This should turn off the field emission current. The question, then, is how can the relatively small field emission current lead to the "explosive" formation of a cathode spot within nanoseconds?

Electrode surfaces are usually far from ultra high vacuum clean. Adsorbates are weakly bound to the surface by van der Waals interactions. The emission of electrons, and the impact of ions stimulate desorption [4,5] of weakly bound adsorbates from the surface of the whisker. Moving with sound velocity v $\approx$ 330 m/s, a suddenly released monolayer of 2×10^{19} molecules/m^2 forms a dense expanding neutral gas layer. After a time t, the average particle density of the neutrals is $n_0 = (2 \times 10^{19}/m^2)/vt$. The neutrals need 6 ns to expand to a distance z = vt = 2 μm. The average particle density of the neutrals is then quite high, $n_0 = (2 \times 10^{19}/m^2)/vt = 10^{25}/m^3$. If a source of field emitted electrons is present, the electrons will begin to ionize the desorbed neutral gas layer. The electron mean free path length $\lambda = 1/(n_0\sigma_0)$ depends on the ionization cross section σ_0 which in turn is a function of the electron energy. For many gases the ionization cross section has a broad maximum value of about $\sigma_0 \approx 10^{-20}$ m^2 for electrons with an energy between 50 to 150 eV. For the diode with 1 MV applied over a gap of 2.54 cm a field emitted electron has gained 100 eV at the distance of 2.54 μm from the cathode surface. Thus $\lambda \approx 10$ μm and about one out of four of the emitted electrons has a chance for an ionizing collision within 2.5 μm. The probability for ionizing collisions increases with n_0, i.e., if several monolayers have been initially desorbed.

Figure 1 depicts a typical ionization cross section as it changes with the energy gained by the electrons as they accelerate away from the cathode surface. Figure 1 also

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1991	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Explosive Plasma Formation On Electrodes	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School, Monterey, California 93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
Breakdown and "explosive" plasma formation on electrodes are basic processes in pulsed power discharges. Despite their fundamental importance, the details of cathode spot formation have not been well understood. Breakdown in a vacuum diode is initiated by field emitted electrons. Besides joule heating of the emitting spot, the electrons also ionize desorbed gas layers. These ions fall back to the cathode, heating the surface of the electron emitting spot. Ion surface heating is initially orders of magnitude larger than joule heating.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

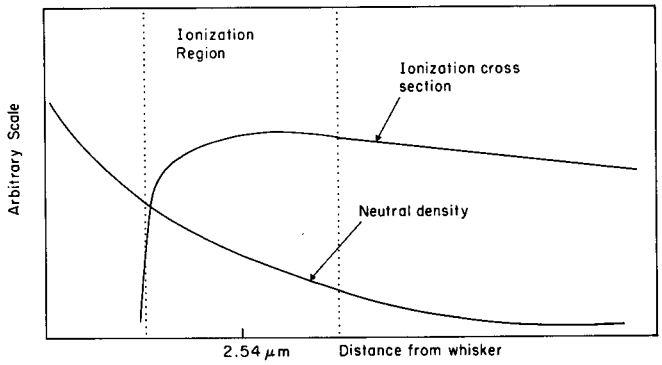

Figure 1. Schematic figure of typical ionization cross section and neutral density distribution at a time shortly after the voltage is applied.

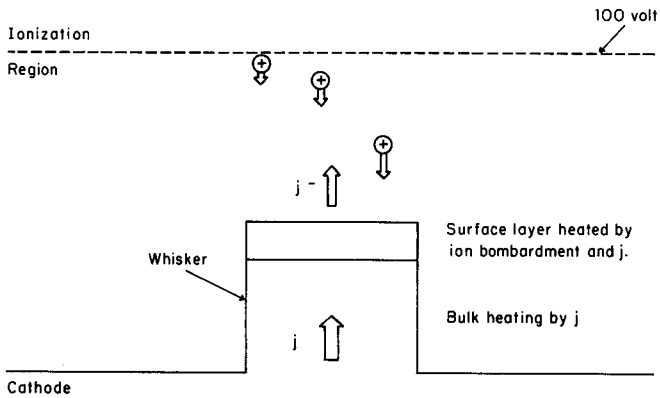

Figure 2. Basic setup of the model.

schematically depicts a neutral density profile for the onset of ionization. The "ionization region" is the region where the ionization cross section and neutral density are sufficient to have a reasonable probability for ionization of neutrals. This region is approximated as having a thickness of d = 1 μm and is centered on the 100 volt potential. On average the ions are produced at z = 2.54 μm. These ions are accelerated toward the whisker and deliver 100 eV of energy each to the surface layer. This surface layer may be many monolayers thick. The surface layer is heated by ion bombardment as well as by ohmic heating, Figure 2.

The power dissipated per unit volume in the surface layer of the whisker due to ohmic heating is given by

$$\frac{\text{OHMIC POWER}}{\text{VOLUME}} = \frac{j^2 \rho A L}{A L} = j^2 \rho \qquad (1)$$

where A is the surface area of the whisker, ρ is the resistivity of the whisker material, L is the depth of the surface layer, and j is the current density flowing through the whisker. The power dissipated per unit volume in the surface layer due to the ion bombardment is given by

$$\frac{\text{ION POWER}}{\text{VOLUME}} = \frac{(j^+ A)\, 100 \frac{\text{eV}}{\text{ion}} \frac{1.6\times10^{-19}\,\text{J}}{\text{eV}}}{(A L)\, 1.6\times10^{-19} \frac{\text{C}}{\text{ion}}} = \frac{100\, j^+}{L} \qquad (2)$$

where j^+ is the ion return current density, and L is the depth of the surface layer in which the ions deposit all of their energy. This model assumes each ion is singly ionized and falls from the 100 volt equipotential surface thus delivering 100 eV of energy to the whisker surface. Recombination energy is relatively small and thus will be neglected.

j^+ depends on the ionization of neutrals by field emitted electrons with current density j^-. For a neutral cloud of thickness d and λ>d, λ/d electrons will produce one ion. The ratio of current densities is given by

$$\frac{j^+}{j^-} = \frac{e/(\text{area})\,\Delta t^-}{e(\lambda/d)/(\text{area})\,\Delta t^-} = \frac{d}{\lambda} \qquad (3)$$

where Δt^- is the time of flight for an electron at rest on the surface of the whisker to travel to the ionization region. Thus

$$j^+ = \frac{d}{\lambda} j^- = d\, n_o \sigma_o\, j^-. \qquad (4)$$

For every ion that falls back to the surface of the whisker there is an image electron that travels within the whisker to meet and recombine with the ion. Therefore the total current density inside the whisker is $j = j^- + j^+$. In terms of the emitted electron current density

$$j = j^- + \frac{d}{\lambda} j^- = j^- (1 + d n_o \sigma_o). \qquad (5)$$

Let R be the ratio of ohmic + ion heating to ohmic heating in the surface layer. Then from Equations 1 and 2,

$$R = 1 + \frac{100\, j^+ / L}{j^2 \rho} = 1 + \frac{100\, d\, n_o \sigma_o}{j^- L \rho (1 + d n_o \sigma_o)^2}. \qquad (6)$$

Inserting the values d = 1 x 10^{-6} m, σ_o = 1 x 10^{-20} m^2, ρ = 7 x 10^{-8} Ω-m, L = a_ok, where a_o is the lattice parameter for stainless steel (2.9 x 10^{-10} m), ρ is the resistivity for stainless steel, and k is the number of monolayers in the surface layer of the whisker through which the ions penetrate, the ratio becomes

$$R = 1 + \frac{5\times10^{-8} n_o}{(1 + 10^{-26} n_o)^2 j^- k}. \qquad (7)$$

This ratio, R, is plotted in Figure 3 as a function of j^-, n_o, and k. These figures demonstrate that the heating of the surface of the whisker due to return ion current is far more efficient than the heating of the whisker bulk due to ohmic heating. It is important to note that the return ions deposit their energy into a highly localized, thin surface layer.

Ion bombardment is especially important at low initial current

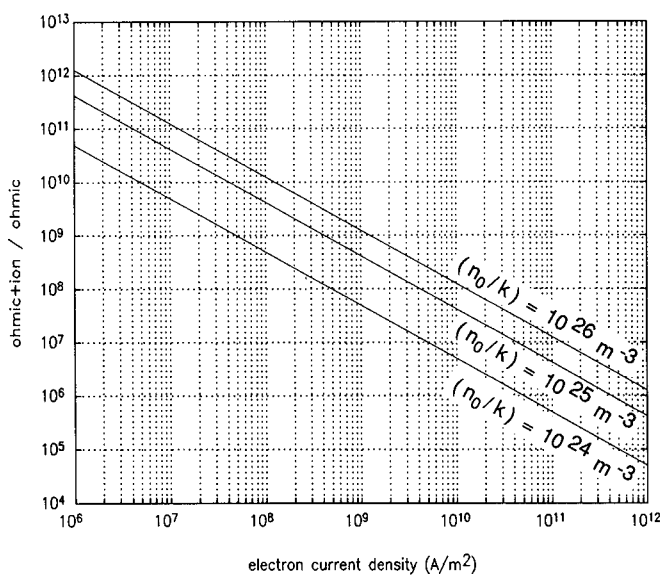

Figure 3. Ratio of ohmic + ion heating to ohmic heating vs. electron current density. The solid lines are plots of Equation 7 for k=1 and various neutral densities (n_o).

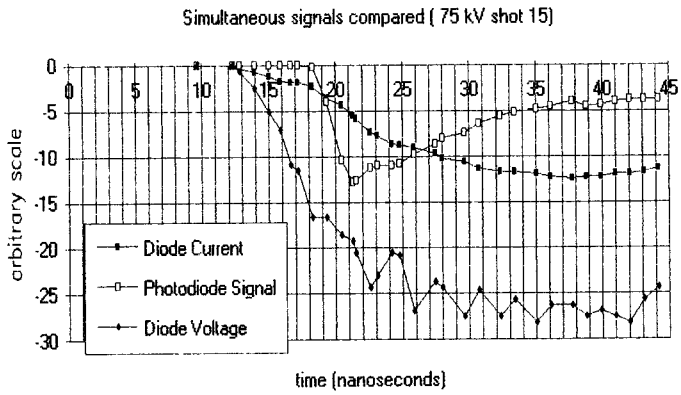

Figure 4. Diode Voltage, Diode Current, and Photodiode waveforms for a 75 kV shot plotted on an arbitrary vertical scale.

densities since it leads efficiently to further desorption of neutrals from the surface and hence increases the neutral density which in turn increases the ionization rate.

Experiment

The purpose of this experiment is to determine the voltage across the diode at which plasma formation begins so that a comparison can be made to the breakdown model discussed above. The plasma formation on the cathode surface, indicated by the onset of the light pulse, is observed through a viewing window using a lens system, fiber optic bundle and an avalanche photodiode. To reach the goal of the experiment, it was necessary to resolve the diode voltage, diode current, and photodiode signals as precisely as possible in time. The diode voltage and diode current pulses have rise times of approximately 10 nanoseconds. After some delay, the photodiode signal begins with a very short risetime of 1 to 2 nanoseconds. Three data runs were performed at different Marx Bank voltages 55 kV, 75 kV and 100 kV, which give typical peak diode voltages of 0.6 MV, 1.2 MV and 1.8 MV, and typical diode currents of 4.1 kA, 12.2 kA and 18 kA respectively. For ease of notation, all future reference to shots of the Flash X-ray machine will be classified by their Marx Bank charge. Approximately 10 shots were fired in each data run. The average delay time from the onset of the diode voltage waveform and the onset of the light signal for the 9 shots in the 55 kV run was 6.1 nanoseconds with a standard deviation of 0.7 nanoseconds. The average diode voltage at which the onset of the plasma occurred, i.e., onset of the light pulse, was 390 kV with a standard deviation of 30 kV. The average delay time for the 10 shots in the 75 kV run was 5.6 nanoseconds with a standard deviation of 0.8 nanoseconds. The average diode voltage at the onset of the plasma formation for the 75 kV shots is 630 kV with a standard deviation of 40 kV. The average delay time for the 11 shots of the 100 kV run was 3.7 nanoseconds with a standard deviation of 0.7 nanoseconds. The average diode voltage at the onset of plasma formation for the 100 kV shots is 590 kV with a standard deviation of 90 kV.

Figure 4 presents the digitized waveforms of the diode voltage, diode current, and photodiode signal for one 75 kV shot. The three waveforms are plotted on an arbitrary vertical scale. The time axis on all three plots are synchronized. The zero time is chosen arbitrarily at a time prior to the onset of the voltage pulse. The delay time from the onset of the diode voltage waveform and the sharp onset of the light signal is 6 ns for this shot. Figure 5 shows the rise of the uniform electric field as function of time for this 75 kV shot. At the onset of the light signal at 18 ns, E has a value of 3.3×10^7 V/m, which is sufficient for enhanced field emission of electrons.

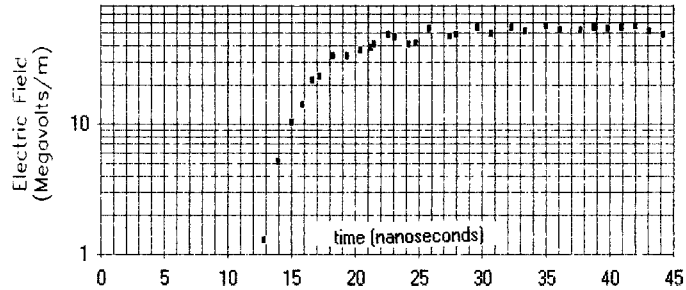

Figure 5. Electric Field vs. time for a 75 kV shot.

Prediction of Onset of Plasma Formation

The ionization of the desorbed neutrals does not become significant until the neutrals reach the 100 volt equipotential surface. Therefore, the onset of plasma formation should be delayed from the onset of desorption by the time of flight of the neutrals to the 100 volt equipotential surface. As the voltage is applied across the diode, the 100 volt equipotential surface moves from the anode side of the diode toward the cathode. The desorbed neutrals expand from the cathode surface toward the anode. The onset of plasma formation will not occur until the 100 volt equipotential surface and the desorbed neutral density reach the same position. For a given time varying voltage waveform and diode gap, the time delay of the onset of plasma formation can be predicted using the following procedure:

1. For the voltage waveform compute the position of the 100 volt equipotential surface away from the cathode as a function of time. 2. Compute the positions of desorbed neutrals which were released at the onset of the voltage pulse as a function of time. 3. Plot both of these functions on the same time axis. The intersection of the two functions occurs at the predicted onset time.

Figure 6 indicates the prediction for the 75 kV shot. The predicted delay time of plasma onset is 8 ns.

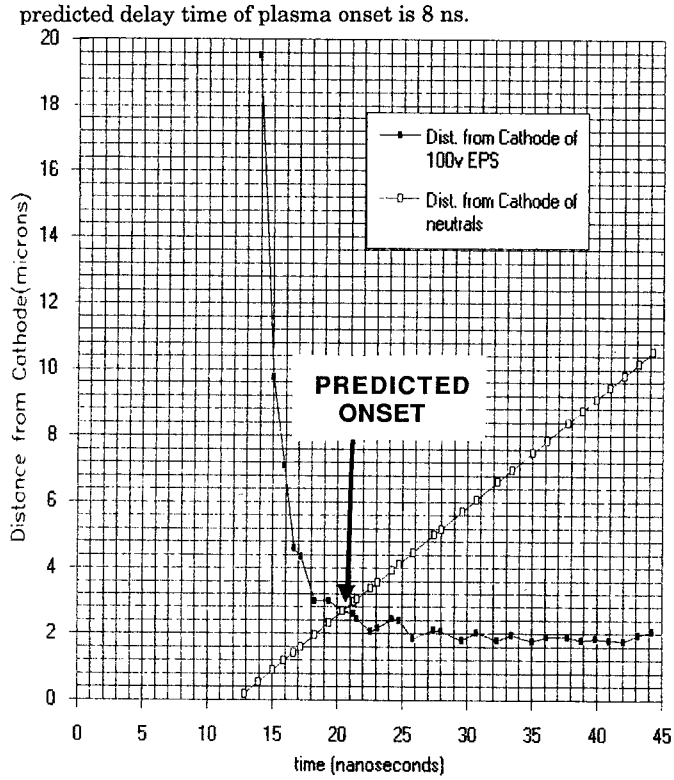

Figure 6. Distance from the cathode of the 100 V equipotential surface (EPS) and distance from cathode of expanding neutrals vs. time for a 75 kV shot. Predicted delay from voltage onset for onset of plasma formation = 8 ns.

The experimentally measured delay time is 6 ns, see Figure 4. The predicted time falls on the sharp rise of the photodiode waveform. The prediction is expected to lag the actual onset of plasma formation because the ionization cross section for the desorbed neutrals is not a step function which turns on suddenly at 100 eV. The cross section for ionization may be nearly as significant at 75 V potential as it is at 100 V thus the ionization will begin before the prediction (approximately 1 ns before on the 75 kV shot). It should also be noted that the model assumes that the neutrals travel away from the cathode with the sound velocity in air. Lighter molecules, such as H_2, H_2O and CH_4, would travel faster than predicted thus reaching the 100 V equipotential surface quicker than predicted.

The experiment shows a very rapid risetime for the onset of plasma formation. This is a reasonable consequence of the model. The dense region of desorbed neutrals expanding on the nanosecond time scale (≈ 0.3 μm/ns) is met by the 100 V equipotential surface which is also traveling on the nanosecond time scale (≈ 1.5 μm/ns for the 75 kV shot). These two regions proceed from a no overlap condition to a significant amount of overlap on the nanosecond time scale. This results in the sharp risetime for the onset of plasma.

Formation of Cathode Spots by Unipolar Arcing

The return ion bombardment leads to further desorption of neutrals thus increasing the neutral density. The increased neutral density will reduce the mean free path for ionization of neutrals by electrons thus increasing the ionization rate. As more ions are produced, the positive space charge presence enhances the electric field and through the Fowler-Nordheim relation strongly enhances the field emitted electron current. Also due to the enhanced electric field, the 100 volt equipotential surface moves closer to the cathode surface into a region of higher neutral density. This effect also increases the ionization rate. The whole process rapidly becomes unstable and leads to dense plasma formation. The localized build-up of plasma above the electron emitting spot naturally leads to pressure and electric field distributions which ignite unipolar arcs [6]. Figure 7 shows craters produced by cathode spots, i.e. by unipolar arcs, on the cathode of a vacuum diode. Thermal electron emission is from the hole at the center of the crater, the "cathode" of the arc, Figure 8. The outer crater rim defines the electron return current area, the "anode" of the arc. Since both arc "electrodes" are located on the same metal surface the arc is called "unipolar".

The surface of the cathode spot plasma facing the anode of the diode acts now as an electron emitting virtual cathode.

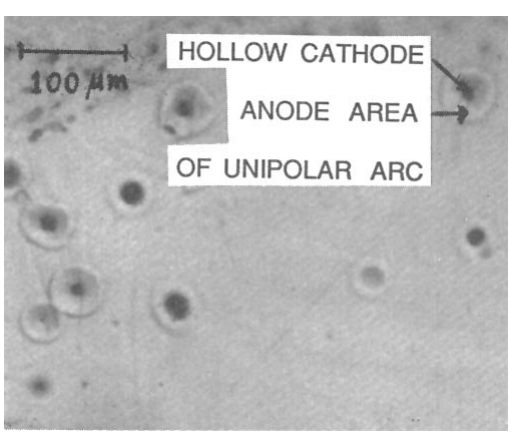

Figure 7. Cathode spot craters

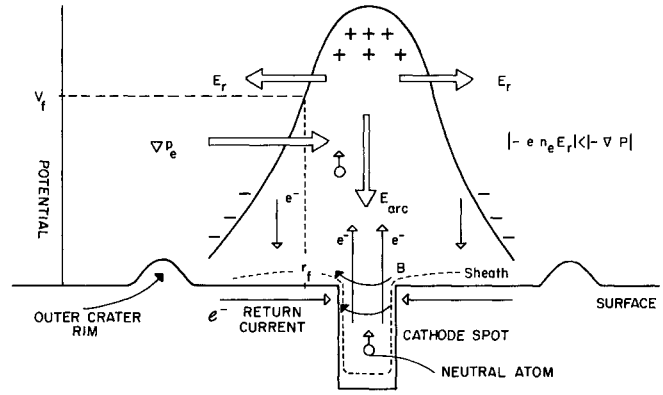

Figure 8. Unipolar arc model

The current density from this surface is space charge limited which implies that the diode electric field is screened by the plasma from reaching the cathode surface. The side of the plasma facing the cathode of the diode forms a positive space charge layer, a sheath, which assures the quasi-neutrality of the cathode spot plasma. The sheath electric field is proportional to the plasma potential. At the bottom of the hole where thermal emission occurs, the sheath potential will be of the order of the cathode fall potential of an arc. The increasing plasma pressure above the electron emitting spot leads within the plasma cloud to a pressure gradient and an electric field in radial direction, tangential to the cathode surface. Associated with this field the plasma potential and thus the sheath potential decrease in radial direction. In the outer region of the expanding plasma $r > r_f$ the sheath potential will be less than the floating potential V_f and more electrons than ions will flow back to the cathode surface. This closes the electron current loop of the unipolar arc. Since the external field is screened from the cathode surface the unipolar arc current density can be many orders of magnitude larger than the Child-Langmuir space charge limited diode current density. The high current density of the unipolar arc in combination with the ion bombardment provides the "explosive" plasma formation of a cathode spot.

This work was sponsored by the Naval Research Laboratory, NSWC and the Naval Postgraduate School.

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