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CONDITIONS FOR SPUTTER EMISSION IN HIGH-PRESSURE SPATIAL GASEOUS DISCHARGES

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The contraction of a high-pressure spatial gaseous discharge is associated with formation of a cathode spot and an outgrowth from the latter of a high-conductance spark channel [1-3]. In an earlier study [4] there was proposed a model of spot initiation under high electric field intensities E(0) at the cathode, when spontaneous emission from individual microasperities becomes significant. Then the cathodic layer is unstable relative to fluctuations of the spontaneous-emission current [5, 6] so that heating of their tips by the electron current and the ion current cause this layer to sputter and a cathode spot is formed. The electric field intensity E(0) is related to the ion current density j according to the law of similitude $E(0)/p = f(j/p^2)$, with p denoting the gas pressure. This relation yields the dependence of the discharge current density on the pressure at a beforehand given electric field intensity $E(0) = E_*$ sufficiently high for initiating a cathodic instability. This study will deal with the determination of the critical electric field intensities E_* and the current densities in spatial discharge at which such intensities are attained.

Calculation of the Electric Field Intensity at the Cathode

In order to find the relation j(p) at a given electric field intensity $E(0) = E_*$, it is necessary to solve the system of nonlinear continuity and Poisson equations

$$-\frac{\partial j_+}{\partial x} = \frac{\partial j_-}{\partial x} = \alpha j_-; \quad (1)$$

$$\frac{dE}{dx} = -\frac{e}{\varepsilon}(n_+ - n_-); \quad (2)$$

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$$j_-(0) = \gamma j_+(0), \quad (3)$$

where $j^{\pm}$ are the ion and the electron current densities, $n^{\pm}$ are the ion and the electron concentrations, α is the impact ionization coefficient, γ is the secondary emission coefficient, e is the charge of an electron, and ε is the dielectric permittivity.

In another study [7] there was proposed a method of solving Eqs. (1)-(3), namely by transformation of this system of equations to a differential equation of second order with respect to the dimensionless electric field intensity y and once integrable with certain boundary conditions for the first derivative. A comparsion of results obtained by that method with results of numerical solutions [8-10] is shown in Fig. 1 (curve 1). For the impact ionization coefficient and the ion drift velocity were used the respective approximations $\alpha/p = A \exp(-Bp/E)$ and $v_+ = \mu_+E/p$ with A = 5.7, B = 260, $\mu_+ = 2\cdot10^3$, $\gamma = 0.1$, and $E(0) = 4\cdot10^5$ (the dimensions of these constants follow from the corresponding approximations). It is evident here that curve 1 closely agrees with numerical calculations and, therefore, the subsequent analysis will be based on the method of integrating the system (1)-(3) [7].

In the range of high E/p values, characteristic of conditions in the given problem, to the ion drift velocity v_+ can be applied the approximation of a weak dependence on E/p. In nitrogen at $E/p \geq 200$ V/cm•mm Hg, for instance, $v_+ = k_+(E/p)^{1/2}$ [11] with $k_+ = 1.1\cdot10^4$ cm$^{3/2}$ (mm Hg)$^{1/2}$/sec•V$^{1/2}$. In this case the function j(p) becomes

$$j = \frac{2AB^{3/2}k_+\varepsilon p^2}{3[2\gamma - \ln\gamma - 1]} f_2, \quad f_2 = \exp(-y^{-2/3})[y - 2y^{1/3}] + 2\sqrt{\pi}\,[1 - \Phi(\sqrt{2}y^{-1/3})], \quad (4)$$

where $y = [E(0)/Bp]^{3/2}$, and Φ is the probability integral.

Let us examine the effect of changes in the functional relation $\alpha/p(E/p)$ on the trend of function j(p). At large values of E/p the relation for α is usually assumed in the form $\alpha/p = A \exp(-Bp/E)$ or $\alpha/p = \sqrt{A_1E/p} - B_1$, the latter expression yielding a steeper rise of α with increasing E/p in the range $E/p > 10^3$ V/cm•mm Hg [12]. Assuming that this expression describes α from some value of E_1/p and above, we obtain for j(p)

$$j = \frac{2AB^{3/2}k_+\varepsilon p^2}{3[2\gamma - \ln\gamma - 1]}\left\{f_2(y_1) + \frac{3\sqrt{A_1B}}{4A}\left[y^{4/3} - y_1^{4/3}\right] - \frac{B_1}{A}\,[y - y_1]\right\}, \quad (5)$$

where $y_1 = [E_1/Bp]^{3/2}$, $A_1 = 0.24$ (V•cm•mm Hg)$^{-1}$, and $B_1 = 3.65$ (cm•mm Hg)$^{-1}$.

The graph in Fig. 1 depicts functions j(p) at $E(0) = 4\cdot10^5$ V/cm calculated according to (4) (curve 2) and (5) (curve 3). The agreement is close at high pressures $p \geq 500$ mm Hg, but discrepancies due to the different approximations of the impact ionization coefficient appear at low pressures. Since no reliable data on coefficients for large values of E/p are available, the calculation of j(p) at $E/p > 2\cdot10^3$ V/cm•mm Hg is only rough. We note that several new effects such as "escape of electrons" must be taken into account when E/p is so large.

At relatively high pressures, therefore, j(p) can be calculated for the range of electric field intensities of the order of 10^6 V/cm on the basis of the known approximations of α and v_+.

Electric Field Intensity Necessary for Initiating Cathode Instability and Sputter Emission

In order to cause cathode instability and, associated with it, sputter from microasperities, it is necessary that the electric field intensity at the cathode exceed some critical level E_*. This critical electric field intensity E_* depends on several factors: purity and treatment of the cathode material, form of the material, kind of gas, etc. A quantitative determination of E_* can be made and these various factors can be taken into account on the basis of the results in another study [5], where the role of spontaneous emission in causing the breakdown voltages to depart from Paschen's law at high gas pressures has been explained and a breakdown criterion accounting for spontaneous emission has been established. The electron current initiating a discharge has been assumed there to result from emission from individual microasperities on the cathode surface and to satisfy the Fowler—Nordheim equation. At some critical electric field intensity, then, ions coming from a primary avalanche and entering the region of a microasperity cause the electric field intensity at the latter to rise and the electron current to further increase, which will result in buildup of a self-sustained discharge. An analogous reasoning was followed in another study [6] with regard to

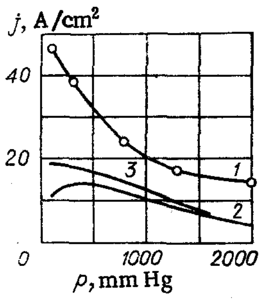

Fig. 1

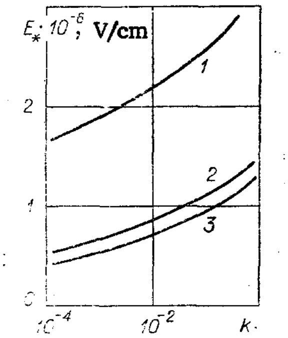

Fig. 2

the cathode layer of a glow discharge, in order to explain the nature of its contraction. The criterion of self-sustenance according to such a model of a discharge will be

$$\exp(-b/E_*) = kE_*^{-1/2}, \quad k = 1.73\cdot 10^{-9}\frac{bw\varepsilon k_+}{p^{1/2}\varphi^2 r^2 N}, \tag{6}$$

where w is the mean electron energy within the region at the cathode, k_+ is the ion mobility, φ is the work function of the cathode material, r is the microasperity radius, N is the number of ions in a single avalanche developing within the field of the cathodic layer, and b is a constant in the exponential factor in the Fowler—Nordheim equation accounting for the work function and for field amplification at the microasperity tip.

Equation (6) indicates a strong dependence of the electric field intensity E_* on the constant b, i.e., on the condition of the cathode surface treatment. Usually the value of constant b is determined through experiments and found to be approximately 10^7 V/cm, which corresponds to a field amplification factor of approximately 50. According to the measurements in [5, 6], for instance, $b = 2.6\cdot 10^7$ V/cm for stainless steel, $b = 1.1\cdot 10^7$ V/cm for palladium, and $b = 9.3\cdot 10^6$ V/cm for aluminum. The coefficient k includes the ion mobility, the gas pressure, the number of ions in an avalanche, and thus is a universal parameter characterizing the dependence of the critical electric field intensity E_* on the kind of gas.

The solution to Eq. (6) is shown in Fig. 2 for various values of b, namely for stainless steel (curve 1), palladium (curve 2), and aluminum (curve 3), covering the likely range of E_*. An estimate of the factor k for nitrogen, argon, and krypton indicates that the critical electric field intensity in these gases is $E_* = (0.8\text{–}2)\cdot 10^6$ V/cm. It is somewhat higher in hydrogen, which can be explained by the high mobility of hydrogen ions $k_+ = 9\cdot 10^4$ cm$^{3/2}$ (mm Hg)$^{1/2}$/sec$\cdot$V$^{1/2}$. The data in Fig. 2 suggest that the critical electric field intensity for calculation of function j(p) be taken within the $(0.5\text{–}1)\cdot 10^6$ V/cm range.

Discussion of the Results

Curves of j(p) for nitrogen and hydrogen have been plotted in Fig. 3a, b. Curves for argon and krypton are shown together on the same diagram (Fig. 3c), because the current densities calculated for these two gases are identical for both within a few percent accuracy. Curves 1 correspond to $E(0) = 5\cdot 10^5$ V/cm and curves 2 correspond to $E(0) = 10^6$ V/cm. The graphs in Fig. 3 depict the relations j_n/p^2 = const, i.e., the change in the density of the normal flow-discharge current with pressure. The shaded area represents the region of glow discharge, according to the constants j_n/p^2 measured in various experimental studies. A juxtaposition of j(p) and $j_n(p)$ curves indicates within which range of glow discharge (normal, subnormal, or anomalous) formation of a cathode spot the said mechanism of sputter from microasperities is possible under a given pressure.

In order to compare the results of calculations with experimental data, let us review studies made regarding a nanosecond discharge and the microsputter and formation of cathode spots which have been observed. We will compare an experimentally determined current density prior to initiation of a cathode spot with that current density calculated and shown in Fig. 3. It is evident that the proposed mechanism of spot initiation can work, if the measured current density is higher than or equal to the calculated one. A study was made [1] of discharge in hydrogen at $j \approx 800$ A/cm^2 and $p = 500\text{–}2500$ mm Hg. A study was also made [2] of discharge in hydrogen and in krypton at $j \approx 100$ A/cm^2. In both cases microsputter at the

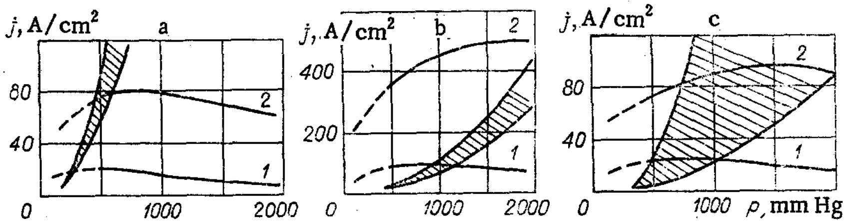

Fig. 3

cathode was found to be initiated within a few tens of nanoseconds. These results can be regarded as confirming the model of cathode spot formation.

An increase in the discharge current density accelerates the initiation of sputter. In one study [3], e.g., no sputter from microasperities at the cathode occurred with a current pulse of 30-nsec duration and 10^2 A/cm² density, but a current density of 10^3 A/cm² produced such sputter. With the current density increasing above 10^3 A/cm², the flow period of spatial discharge was found to become shortened to approximately a few nanoseconds or less [13-15].

It thus appears that the mechanism of cathode spot initiation based on the model of sputter emission is directly realizable in nanosecond high-current discharges. There is, however, also some experimental evidence [16-19] of cathode spots recorded in discharges with a low current density during the spatial stage. In this case the delay in appearance of a cathode spot should be much longer and consist of two periods: time for the electric field intensity at the cathode to reach the critical level, and sputter time. Let us, therefore, examine some factors which cause the electric field intensity at the cathode in low-current discharges to rise to the level E_*. The mechanism of thermal instability in the cathode layer has already been analyzed [18]. According to that model, the electrode surface has some inhomogeneity and near the latter more energy is released so that instability develops resulting in the buildup of a local region of high plasma concentration. This, in turn, causes a rise in the electric field intensity and development of cathodic instability.

Another cause of rising electric field intensity E(0) could be buildup of charge on dielectric inclusions and contaminants at the cathode surface by the ion current. In the presence of such inclusions with a high electrical resistivity the electric field intensity E(0) can rise to 10^6 V/cm or higher, i.e., to levels of spontaneous emission, dielectric breakdown, and cathode spot formation. This conceptualization, together with confirming experimental evidence, has been developed in another study [19] for the purpose of explaining the transition from a low-pressure glow discharge to an arc.

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ELECTROMAGNETIC FIELDS EXCITED BY NEUTRONS IN AIR

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It is well known [1] that γ radiation emanating into air excites in the space around its source electromagnetic fields. Other authors [1, 2] have calculated fields in the current zone and in the wave zone for the case of a γ radiation pulse decaying exponentially with time while the distribution of emitting currents has a weak spatial asymmetry. Neither the character nor the origin of this asymmetry have not been dealt with specifically in [1, 2]. In another study [3] there has been solved the model problem of fields excited by a transient source of γ radiation on the plane boundary between an ideal conductor and homogeneous air. In still another study [4] the field problem was considered for the case of an isotropic source in nonhomogeneous air, without taking into account the effect of a ground surface. In all these studies [1-4] the air was assumed to be of standard or nearly standard density. An electromagnetic pulse, as theoretically calculated in [1-4], is characterized by half-periods several microseconds long and by a total duration of the order of ten microseconds. The ratio of amplitudes of the field intensity in different half-periods is of the order of 10. In a further study [5] the vertical component of the electric field intensity was recorded as a function of time at a distance of 44.6 km from the source. A comparison of theoretical data [1-4] and experimental data [5] indicates appreciable quantitative discrepancies between them [6], and experimental pulse of electric field intensity having a characteristic time of the order of ten microseconds and a ratio of amplitudes in the first few half-periods of the order of 1:1, with a total duration of the order of a hundred microseconds. Since none of the possible physical modifications of the emission mechanism considered in studies [2-4] seems to bring theory and experiment closer together, it has been proposed in study [6] that emission of an electromagnetic pulse such as in [5] is due not only to Compton electron currents but also to an effect of another nature, associated with evolution of a heat wave and its transformation to a shock wave. The total signal is regarded there as a result of addition of two signals, one of them (the shorter) emitted by Compton electron currents flowing from the pulse of γ radiation [2, 3] and one (the longer) emitted by currents flowing along the front of the heat wave. The orders of magnitude of the amplitude and of the characteristic duration of the emitted signal according to the estimates in [6] agree with experimentally measured values. The nature of a signal extracted in [6] from a recording of a signal in [5], with a characteristic duration of the order of tens of microseconds, will in this study be attributed to γ radiation initiated in air by neutrons of less than 14 MeV energy [7]. The corresponding processes here will be seen as process with a threshold, then threshold energy being 3 MeV [8]. The time of neutron retardation from 14 to 3 MeV is approximately 50 μsec so that a pulse of initiated γ radiation as well as Compton

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