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EFFECTIVE SECONDARY EMISSION COEFFICIENT FOR FLAT CATHODES IN A HIGH PRESSURE GAS

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In the theory of gas breakdown, an important role is played by the effective secondary emission coefficient (ESEC) γ : the number of electrons leaving the cathode surface per one impinging ion [1]. Since long ago, it has been known that at low E/p values (where E is the electric field and p is a gas pressure) the so defined γ depends linearly on E/p , reaching a constant value only at high E/p . The mechanism responsible for this dependence was identified as a reflection of a part of the secondary electrons from the gas atoms back to the cathode surface [1-3] and based on J.J. Thomson's simple consideration L.B. Loeb proposed a qualitative expression describing such a behavior [1,2]: $\gamma = \gamma_i[4v_d/(\bar{v}_0 + 4v_d)]$, where γ_i is the vacuum value of the secondary emission coefficient, $\bar{v}_0$ is the average speed of electrons just emitted from the cathode and v_d is the electron drift velocity. In this report we find an expression for ESEC based on a kinetic approach. We limit our consideration to the case of a high density gas or weak electric field. This condition will be explained later. We also assume that the electron mean free path λ_e is small compare to the scale-length L of the problem, and electric field E is weak, so that $eE\lambda_e << W$, where W is the electron kinetic energy. In this case the electron distribution function (EDF) at the distances from the electrodes exceeding a few λ_e is almost isotropic and one can use for it a representation $f(\vec{r},\vec{v},t) = f_0(\vec{r},v,t) + \delta f$, where $f_0(\vec{r},v,t)$ and δf are defined by the following equations [4]:

$$\frac{\partial f_0}{\partial t} = \frac{1}{v^2}\left(v\nabla_r - \frac{e\vec{E}}{m}\frac{\partial}{\partial v}\right)\frac{v^2}{3\nu}\left(v\nabla_r - \frac{e\vec{E}}{m}\frac{\partial}{\partial v}\right)f_0 \quad (1)$$

$$\delta f = -\frac{1}{\nu}(\vec{v}\cdot\nabla_r - \frac{e}{m}\vec{E}\cdot\nabla_v)f_0 \quad (2)$$

where $\nu = N\sigma_{tr}v$ is the electron collision frequency, σ_{tr} is the electron-atom momentum transfer cross-section. The electron density n_e and electron current j_e are related to f_0 and δf , respectively:

$$n_e = 4\pi\int_0^\infty v^2 f_0 dv, \quad \vec{j}_e = -e\int \vec{v}\delta f\, d^3v. \quad (3)$$

Let us consider a planar anode-cathode gap of a width L and direct the z -axis along the normal to the cathode. We treat the gas atoms just as resting scattering centers, assuming that the inelastic processes turn on at larger distances from the cathode. In this sense, our L represents only a fraction of a real discharge gap. We consider only one source of electrons - secondary electron emission from the cathode due to ions striking a cathode, and identify the ESEC γ with the number of electrons reaching the anode of the just defined system per ion hitting the cathode.

Conductive cathode. An electric field may have only component normal to the surface. In this case in the stationary state EDF differs from zero only on the sphere in the velocity space determined by the energy conservation law, $v^2 = v_0^2 + 2eEz/m$. Accordingly,

$$f_0 = F(z)\delta(mv^2 - mv_0^2 - 2eEz). \quad (4)$$

In case of a weak electric field the function $F(z)$ and thus γ can be found analytically and in the case $eU \gg W_0$, where $U = EL$ it is

$$\gamma = \gamma_i\left(1 + \frac{3W_0^{3/2}}{4v_0 eE}\int\limits_{W_0}^{W_0+eU}\frac{\nu(W)dW}{W^{3/2}}\right)^{-1}. \quad (5)$$

We see that, for a given electric field, γ decreases with the increase of the inter-electrode distance (eU). This shows that electron scattering at large distances from the cathode ($L \gg \lambda_e$) contributes to returning electrons to the cathode and hence, to the inhibition of the ESEC γ. In principle, the γ value for the discharge is determined by the electron transport in the whole gap, not only near the cathode.

If the energy dependence of ν is such that the integral in (5) converges, then, in large enough gaps, γ reaches a constant level, independent on L .

If the saturation is reached before the electrons acquire the energy W_{ex} sufficient for the excitation, then this γ_∞ has a "standard" meaning of the number of electrons supplied by the cathode per impinging ion.

If, however, the saturation is reached at energies higher than W_{ex} , then γ itself becomes dependent on the excitation processes and ceases to be a quantity pertaining to the near-cathode region.

For a weak electric field, the second term in the denominator of (5) is dominant, and we find

$$\gamma = \gamma_i\frac{E}{E_0}, \qquad E_0 = \frac{3W_0}{4e\lambda_e}I(eU) \quad (6)$$

where $\lambda_e = 1/N\sigma_{tr}(W_0)$, and $I(eU)$ is a dimensionless factor defined by

$$I(eU) = \frac{1}{\sigma_{tr}(W_0)}\int\limits_{W_0}^{W_0+eU}\frac{\sigma_{tr}(W)\,dW}{W}; \quad (7)$$

In a general case, the number of electrons entering the zone of inelastic collisions depends also on U_{ex} . Generally speaking, that by itself shows that processes in the cathode zone are so tightly interwoven with the ones occurring in the bulk of the discharge that one can't use a standard concept of the second Townsend coefficient. Only a kinetic description of the discharge as a whole allows one to find the electron current from the cathode.

Insulated cathode. In some cases, the surfaces terminating the discharge gap, are covered with dielectric materials. Near such surfaces the electric field may have a tangential component as well as a normal one. What is qualitatively new in this system, is that the electron energy at a certain distance z from the cathode is not uniquely defined by the initial electron energy at the cathode. One can show that the velocity spread in some point situated near the center of the gap is comparable with the average electron energy. This circumstance makes the problem much more difficult than the one with conductive cathode. There are however some special cases when the ESEC can be found analytically.

One of them is the case when the electric field is parallel to the wall of a planar gap. In this case equation (1) allows an exact analytical solution. This situation is possible when the walls are made of dielectric. The solution is of some interest by itself (as it can describe the situation with electron diffusion to the side walls of the gas discharge) and as a benchmark solution for testing the numerical codes.

The solution of Eq. (1) is particularly simple when the electron mean-free path does not depend on its energy:

$$\lambda_e = v/\nu = const. \tag{8}$$

We place the source at the surface $z = 0$ and the sink at the surface $z = L$. This simulates electron emission from the side wall as a result of a photoeffect or a secondary emission under the action of ions and excited particles. Considering only a stationary solution we find,

$$\gamma = \gamma_i \left[\frac{4\lambda_e}{3L} \Big/ \left(1 + \frac{4\lambda_e}{3L} \right) \right] \approx \frac{4\lambda_e}{3L} \gamma_i. \tag{9}$$

For typical conditions: $\gamma_i \sim 1$ and $\lambda_e/L \sim 10^{-2} - 10^{-3}$ the γ in the considered case is very small and does not depend on the magnitude of the electric field. This last and unexpected result is a direct consequence of the assumption that the electron mean free path λ_e does not depend on the electron energy. Simple asymptotic expressions for the high energy tail of the distribution function have also been found.

References

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