Effective Secondary Emission Coefficient for "Rough" Cathode Surfaces

We show that even very fine topographic non-uniformities on the cathode surface can have a significant effect on the secondary emission (second Townsend) coefficient in high-pressure discharges. The non-uniformities may lead to a considerable increase of this coefficient near metal surfaces and, under certain conditions, to its considerable decrease near the dielectric surfaces (used in capacitively coupled discharges).

Key words: *gas breakdown, secondary emission, surface phenomena, surface imperfections.*

1. INTRODUCTION

Gas discharge physics is a fascinating area of research and a source of many important applications. In our present note we describe an interesting phenomenon which is related to one of the most fundamental characteristics of the gas breakdown, sometimes called the second Townsend coefficient - the parameter that characterizes the multiplication of the current carriers near the cathode surface.[1] We will show that, in high-pressure discharges, even very fine, sub-micron, non-uniformities of the cathode surface can considerably affect this coefficient and, what is even more surprising, the effect can have either sign (depending on the material of the cathode). Observations made in the present note are of a specific interest to the miniature discharges used in plasma display technology as the source of UV-irradiation of phosphors. A survey of this rapidly growing area of research

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and technology can be found in Ref. 2. It is interesting to note that the dimension of every discharge cell is approximately 0.1mm, and a display of the size of an ordinary TV screen consists of millions of the discharge cells!

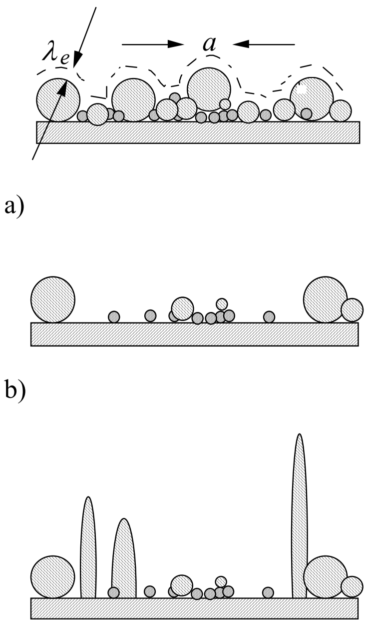
The effective secondary emission coefficient, ESEC (this term is currently used more often than “the second Townsend coefficient” - and we will follow this trend) is defined as the number of electrons leaving the cathode surface per incident ion. We will denote this coefficient as γ. At low E/p values (where E is the electric field and p is the gas pressure) 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 some of the secondary electrons from the gas atoms back to the cathode surface in the vicinity of the cathode [1,3-4]. A kinetic theory of this phenomenon has been developed only recently [5]. All these analyses were carried out for flat surfaces.

In the present communication, we consider the effect of surface “roughness” on γ. As we show below, the effect is significant if the topographic features of the surface have a characteristic scale length exceeding the electron mean free path, λ_e. As a numerical example, one can consider the breakdown of argon at atmospheric pressure (a situation typical for plasma display applications). The mean free path of a $5eV$ electrons is then only $0.2\ \mu m$ so that the new effect becomes important when the size of surface non-uniformities exceeds a mere $0.3-0.4\ \mu m$.

We consider only one source of secondary electrons - their liberation from the cathode by incident ions. Other possible sources of secondary electrons (e.g. photoemission or emission under the action of excited atoms) can be investigated in a similar way.

Throughout this paper we assume that the roughness of the surface can be characterized by a single parameter a, which stands both for the height of the non-uniformities and the distance between them, as shown in Fig. 1a. Although the theory can be extended to the other possible types of surfaces, like the ones shown on Figs. 1b and 1c, they will not be considered in this paper.

Qualitatively, the effect of the surface roughness can be explained as follows: the electric field near a non-uniform surface, be it metal or dielectric, varies in some way over the surface. If $a >> \lambda_e$, it is possible to divide the surface into smaller surface elements which are almost planar and have a size much larger than λ_e, with the electric field varying from one element to another. As stated above, γ is a function of electric field and thus it will also vary from one element to another and, generally speaking, its average value will differ from that of a flat surface.



a)

b)

c)

FIGURE 1. Schematic of the surface relief: a) A single-scale distribution, with a characteristic height of the topographic features comparable with the distance between them; b,c) More complex distributions, which can not be described by a single parameter of the dimension of length.

One more phenomenon that is coupled with the aforementioned effect, is a non-uniform distribution of the ion current over the surface. Since the ion mean free path is usually even smaller than the electron mean free path, the ion current in the vicinity of the surface can be described by the usual mobility equation

$$\boldsymbol{j}_i = e n_i \mu_i \boldsymbol{E}. \tag{1}$$

In the above, n_i is the ion density and μ_i is the ion mobility. When one considers the initial stage of the breakdown, the charge density is small, and electric field satisfies the vacuum equation $\nabla \cdot \boldsymbol{E} = 0$. At voltages which do not greatly exceed the breakdown voltage, the time of the development of the avalanche is very long compared to the time for establishing the ion current near the cathode. Therefore, the ion current satisfies the steady-state continuity equation $\nabla \cdot \boldsymbol{j} = 0$ (the contribution of ionization at the distance of a few a 's from the wall is negligible.) Then, Eq. (1) yields:

$$\boldsymbol{E} \cdot \nabla(n_i \mu_i) = 0 , \tag{2}$$

i.e., $n_i \mu_i$ is constant along the electric field lines. At a distance exceeding a few a 's from the cathode electric field and other parameters become independent of the position along the cathode surface. Then, Eq. (1) will show that $n_i \mu_i$ does not vary not only along every field line, but also from one field line to another; in other words, $n_i \mu_i$ is just a constant in the cathode region. Therefore, Eq. (1) shows that the ion current density varies proportionally to $\boldsymbol{E}$. Accordingly, the ion current density is non-uniformly distributed over the rough cathode and this effect interferes with the aforementioned non-uniformity of the secondary emission coefficient, affecting its average value.

The paper is organized as follows: In Sec.2, we consider qualitatively the E/p dependence of γ for a flat surface. Following References [1] and [4], we identify the importance of the energy spectrum of the secondary electrons in establishing the scale for E/p for which saturation of γ occurs. Sections 3 and 4 contain the main results of this work. In Sec. 3 we derive an expression for γ for a rough conducting cathode in the case $a >> \lambda_e$. Here we also discuss the transition to small-scale non-uniformities, $a < \lambda_e$, and show that in this limit the results for a flat surface are recovered. In Sec. 4 we consider the effect of a dielectric coating on the cathode. Sec. 5 contains discussion and summary of our results.

2. *E/P* DEPENDENCE OF THE EFFECTIVE SECONDARY EMISSION COEFFICIENT FOR A FLAT SURFACE

We begin with a more detailed discussion of γ vs. E/p dependence for flat surfaces. Let us consider an electron ejected perpendicularly to the surface with energy W_0. At a distance λ_e (on the average) the electron experiences its first elastic scattering. The distribution of the scattered electrons is more or less isotropic with about half of them moving back toward the cathode. If the electric field is weak enough, so that

$$E << W_0 /(e\lambda_e) , \tag{3}$$

almost all electrons in the backward cone reach the cathode and get absorbed by it (electrons with energy of a few eV don't produce secondary emission). The electrons of the forward "cone" undergo another scattering with a considerable fraction of these electrons returning to the cathode, and so on. This consideration clearly shows that at small E (small in the sense of the inequality (3)), only a small fraction of the initially emitted electrons eventually leave the cathode region. In other words, the backscattering makes γ much smaller than the secondary emission coefficient γ_i (the number of electrons emitted from the surface by one ion into empty space).

Conversely, at large E,

$$E >> W_0 /(e\lambda_e) , \tag{4}$$

the electron acquires energy (from the electric field) much larger than W_0 before its first collision. In this case after the first scattering almost all of the electrons scattered towards the cathode will be deflected by the electric field towards the anode. Accordingly, γ in this case will be very close to the vacuum value γ_i.

These considerations can be substantiated by a simple analysis of the energy and momentum conservation laws for the scattered electron. Let us denote the angle between the normal to the cathode surface and the velocity vector of scattered electron as θ (Fig. 2), so that $\theta = \pi$ corresponds to backward scattering. The condition that the scattered electron reaches the cathode becomes

$$\sin^2 \theta_c < \frac{W_0}{W_0 + eE\lambda_e} \tag{5}$$

When condition (4) holds, θ_c defined by the inequality (5) is very close to π, and only a small fraction of scattered electrons reach the cathode. Conversely, under condition (3), almost all the backscattered electrons reach the cathode (see Fig. 2).

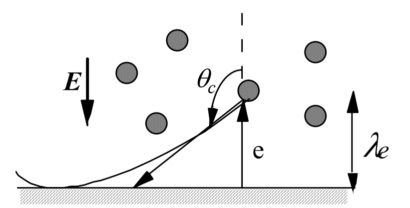


FIGURE 2. Scattering of the electron on a heavy atom. The electron trajectory shown in the picture corresponds to a marginal case when the scattered electron barely reaches the cathode surface.

To find a scaling of $\gamma(E/p)$ for small E/p, one can use the following balance considerations. Let j_i be the ion current at the cathode. Then the electron current at the cathode, for small E, can be represented as

$$j_e = \gamma_i j_i - \frac{e n_e v_0}{4} \tag{6}$$

where n_e is the electron density and $v_0^2 = 2W_0 / m_e$. The last term in (6) describes the flux to the cathode of the electrons which become isotropic under the action of the elastic collisions. Because of the current continuity, j_e doesn't vary with the distance from the cathode, and at a distance from the cathode exceeding λ_e, the same electron current can be written as

$$j_e = e n_e \mu_e E , \tag{7}$$

where μ_e is the electron mobility. Solving for n_e and substituting it into Eq. (6), we obtain

$$j_e = j_i \frac{\gamma_i}{1 + E_0 / E} , \tag{8}$$

or

$$\gamma = \gamma_i \frac{E}{E + E_0} ,\cdot \tag{9}$$

where

$$E_0 \equiv \frac{v_0}{4\mu_e E} = \frac{W_0}{2e\lambda_e} \; . \tag{10}$$

Here we have used that $\mu_e = e/(m\nu_e) = (e\lambda_e / m v_0)$, where $\nu_e \equiv N\sigma_e(v_0)v_0$ is the electron-atom elastic collision frequency in a gas and N is the gas density. In deriving these results we implicitly assumed that the electron density near the cathode [which enters Eq. (6)] and the density a few mean free paths from the cathode [that enters Eq. (7)] are identical. This is valid for small electric fields [small in the sense of the inequality (3)], but becomes wrong for strong electric fields.

In its region of applicability ($E << E_0$) Eq. (9) gives a linear dependence of γ vs. E. Somewhat surprisingly, at $E >> E_0$ it also gives a correct result, i.e. $\gamma = \gamma_i$. Therefore, Eq.(9) can be considered as a convenient expression suitable for quick estimates. We see that both the cathode material and the gas parameters affect E_0 (through the energy spectrum of the emitted electrons and their mean free path in the gas).

For the set of parameters typical for plasma display panels, the electric field is usually weak in the sense of inequality (3). Indeed, taking $W_0 \sim 5eV$, $\lambda_e \sim 0.2\mu m$, one finds that the r.h.s. of this inequality is $25 MV/m$, while the l.h.s. usualy does not exceed $2 MV/m$. In other words, plasma display panels operate under conditions where the effect of the surface roughness plays a most significant role.

A rigorous account for the electron scattering effects near the cathode surface requires a numerical solution of the electron Boltzmann equation. The difficulty in finding an analytical solution arises because the angular distribution of the backscattered electrons approaching the cathode can't be exactly identified as a "half" of the distribution of the electrons at a distance of a few λ_e from the wall. However, at small E, there exists a special case when γ can be found analytically. This is the case of an isotropic angular distribution of the emitted secondary electrons. The corresponding analysis for this case has been carried out in Ref. 5. The expression for γ is:

$$\gamma = \gamma_i \left(1 + \frac{3W_0^{3/2}}{4 v_0 e E} \int_{W_0}^{W_0 + eU} \frac{\nu_e(W) dW}{W^{3/2}} \right)^{-1} , \tag{11}$$

where U is the voltage across the gap.

3. THE EFFECT OF SURFACE ROUGHNESS

In the case of "rough" cathodes the value of the ESEC should be obtained by an appropriate averaging procedure.
Assuming that a is much smaller than the inter-electrode distance, we first consider conducting electrodes with non-uniformities of large scales, $a >> \lambda_e$. We consider a planar gap and introduce a coordinate frame with the axis z directed from the cathode toward the anode (Fig.3). We address ourselves to the early stages of the discharges, when the charge density is small so that the electric field in the gap is not distorted by the space charge. In this case the electric field in the planar gap is uniform where $z >> a$. We denote its value by E_∞. At the cathode the electric field is non-uniform, causing corresponding nonuniformities in the ion current. When $a >> \lambda_e$, one can divide the cathode surface into the small almost planar elements with sizes much larger than λ_e, but still much smaller than a. Each of these elements can be characterized by its own ESEC which, according to Sec.2, depends on the electric field near the surface:

$$\gamma = \gamma(E_n) \tag{12}$$

$$
\int E_n dS = E_\infty S_\infty = \Phi_E \tag{15}
$$

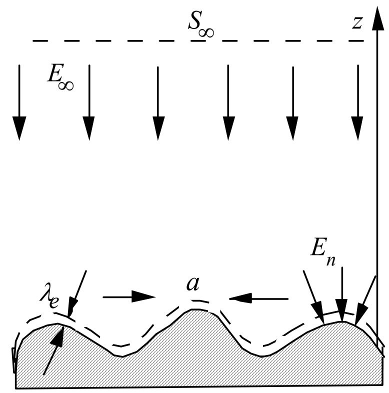


FIGURE 3 Cathode surface (below) and the imaginary "control" surface (dashed line). "Control" surface is situated at a distance of many a 's from the cathode surface; electric field on the "control" surface is uniform and equal to E_∞.

Here E_n is the normal component of the electric field on the surface. Although on a conducting surface this is the only component of the electric field and one could, in principle, delete the subscript "n", we still retain it, because the formula (12) in this form can be used also for dielectric surfaces (see below).

The ion current density also is proportional to E_n (See (1)). The ESEC, averaged over a surface area much larger than a^2, can be defined as $\bar{\gamma} = \bar{j}_e / \bar{j}_i$, where $\bar{j}_e$ and $\bar{j}_i$ are the average electron and ion current densities. Thus,

$$
\bar{\gamma} = \frac{\int \gamma(E_n) j_{in} dS}{\int j_{in} dS}, \tag{13}
$$

where the integrations are carried out over the cathode surface. Using expression (1), we can also write γ in the following form

$$
\bar{\gamma} = \frac{\int \gamma(E_n) E_n dS}{\int E_n dS} \tag{14}
$$

Applying Gauss's theorem to the volume shown in Fig.4 with $S_\infty >> a^2$, we see that

$$
\int E_n dS = E_\infty S_\infty = \Phi_E \tag{15}
$$

For a linear dependence of γ vs. E_n, one can easily show that $\bar{\gamma}$, as defined by Eq. (14), is greater than $\gamma(E_\infty)$. This inequality is equivalent to the following one:

$$
\int E_n^2 dS > E_\infty^2 S_\infty \tag{16}
$$

To prove this inequality, one can consider the cathode surface as one plate of a capacitor, while the "control" surface (which we denote as S_∞) as the other plate. These plates attract each other and the attracting forces are equal (by virtue of the 3rd Newton law). The force acting on the "control" plate is equal to

$$
\frac{E_\infty^2}{8\pi} S_\infty \quad ,
$$

while the force acting on the cathode surface is

$$
\int \frac{E_n^2}{8\pi} \sin\psi \, dS \ ,
$$

where ψ is the angle between the axis z and the surface. Using the fact that these two forces are equal and noting that

$$
\int \frac{E_n^2}{8\pi} \sin\psi \, dS < \int \frac{E_n^2}{8\pi} dS \ ,
$$

one immediately obtains the required inequality (16).

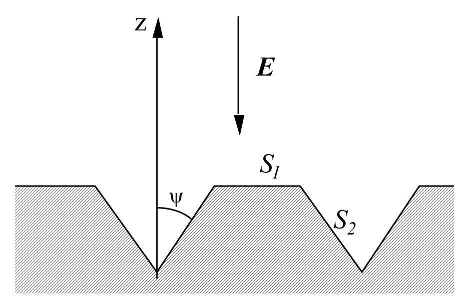


FIGURE 4 A model of a dielectric "cathode"

For random surface non-uniformities, one can introduce a probability distribution of the electric field strength on the surface. We characterize this distribution by a function $P(E_n)$, defined as a fraction of the total flux of the electric field at the cathode area where the electric field strength lies in the range $(E_n, E_n + dE_n)$:

$$P(E_n)dE_n = \frac{E_n dS}{E_\infty S_\infty} \tag{17}$$

Obviously for this definition,

$$\int P(E_n)dE_n = 1 \tag{18}$$

and we can write Eq. (14) in the form

$$\bar{\gamma} = \int \gamma(E_n)P(E_n)dE_n \,. \tag{19}$$

If the probability distribution is known, then using either the experimental dependence of $\gamma(E_n)$ for a perfectly flat surface or expression of the type given by Eq. (9), we can find $\bar{\gamma}$ from Eq. (19). In order to find the probability distribution, one should solve Laplace's equation for a given rough surface.

As an illustration of the use of Eq. (19) we consider the model situation in which the electric field on the cathode can acquire only two values: $E_{n1} > E_\infty$ (hills) and $E_{n2} < E_\infty$ (craters), with probabilities $P_1\delta(E - E_{n1})$ and $P_2\,\delta(E - E_{n2})$. The normalization conditions (18) is then reduced to

$$P_1 + P_2 = 1 \tag{20}$$

If we specify the value P_1, then from (19) and (20) we find:

$$\bar{\gamma} = \gamma(E_{n1})P_1 + \gamma(E_{n2})(1 - P_1). \tag{21}$$

It is useful to introduce an enhancement factor $\alpha = E_{n1}/E_\infty$. For a surface, covered by well separated hemispheres, the enhancement reaches a factor of 3 at the tips of the hemispheres. For more prolate elevations, α can be larger than 3. For a quantitative example, we assume that *all* the electric field lines are terminated on the elevations, which represent the regions of the enhanced electric field, so that $E_{n2} = 0$. In this case

$$\bar{\gamma} = \gamma(E_{n1}) = \frac{\alpha E_\infty}{\alpha E_\infty + E_0}\gamma_i \,. \tag{22}$$

We see that the ESEC on the linear part $(E_\infty << E_0)$ is larger than ESEC for a flat surface by a factor of α, at the same time being small compared to γ_i. If $\alpha E_\infty >> E_0$, then $\bar{\gamma} = \gamma_i$.

Let us now discuss the case of small-scale non-uniformities: $a << \lambda_e$. According to Laplace's equation, the non-uniformities of the electric field vanish at distances of the order of a from the surface, and the motion of the secondary electrons is virtually the same as for a perfectly flat surface. In this case, there is no considerable effect of the surface non-uniformities on ESEC. Thus, $\bar{\gamma}$ remains the same as for a perfectly flat surface [$\bar{\gamma} = \gamma(E_\infty)$, see Sec.2].

Note that if the ions are moving in their own gas, their mean free path is determined by a charge exchange. The cross-section for charge-exchange is usually much larger than the electron elastic cross-section. Accordingly, one can have the situation when $\lambda_i << a << \lambda_e$. In this case the distribution of the ion current over the cathode surface can be still determined by the macroscopic mobility equation (1) and remains strongly non-uniform (as in the case $a > \lambda_e$). However, if γ is independent of E_n, then $\bar{\gamma} = \gamma(E_\infty)$.

4. EFFECT OF A DIELECTRIC COATING OF THE CATHODE

One can observe another interesting effect in a capacitive discharge, when a gas doesn't interface directly to the conducting electrodes, but rather to an insulating coating covering the electrodes. Of course, in such a discharge the electric field is not stationary, so we must require that the electric field changes slower than processes which determine the value of the ESEC. As a characteristic time for these processes we can choose the time at which an electron drifting in the electric field gains energy enough to produce an inelastic collision (or reaches another electrode). After any such collision the electron will not be able to return back to the cathode surface and will not affect the ESEC.

Electric fields near the surface may depend not only on the topography of the conductor but also on many other factors like the dielectric constant of the coating, thickness and topography of the insulator, etc. For simplicity let us assume that we have a thick "rough" insulator coating with dielectric constant ε on a perfectly flat conducting cathode. As in the previous section, we consider large scale imperfections $a >> \lambda_e$, and divide each of them into smaller quasi-planar elements, still much larger than λ_e, so that each of those elements is characterized by its own electric field. The only difference between this case and the case of conducting electrodes is that now the electric field may have both normal and tangential components to the surface.

To evaluate the average γ in this case let us first consider the effect on γ of the tangential electric field near the surface for a specific small element. We start with a small electric field $E << E_0$. The same balance equation (8), written now for the normal component of the electron current gives (10) with E_n -the normal component of the electric field instead of E.

We can now substitute this expression into the general formula (19) for the average over the surface γ . The result is

$$\bar{\gamma} = \gamma_i \int \frac{E_n}{E_0} P(E_n) dE_n \, . \tag{23}$$

To obtain some more quantitative results let us again consider the discrete two-value model. As before P_1 is the part of the total flux, crossing the cathode surface with the stronger normal component of the electric field E_{n1} and $P_2 = 1 - P_1$ is respectively the part of the total flux related to a field with the strength E_{n2} at the surface. If we again denote the enhancement factor $\alpha = E_{n1} / E_\infty$, then $E_{n2} = E_\infty S_\infty (1 - P_1) / S_2$ and Eqs. (21) and (23) give

$$\bar{\gamma} = \gamma_i \frac{E_\infty}{E_0} \left(\alpha P_1 + (1 - P_1)^2 \frac{S_\infty}{S_2} \right) \tag{24}$$

To determine S_2 let us assume that part of the surface (S_1) is flat and directed normally to the z coordinate, while the rest of the surface (S_2) oriented as shown in Fig. 4. We have

$$S_1 = P_1 S_\infty / \alpha \quad , \qquad S_2 = \frac{S_\infty (1 - P_1 / \alpha)}{\sin \psi} \tag{25}$$

and

$$\bar{\gamma} = \gamma_i \frac{E_\infty \alpha}{E_0} \left(P_1 + \frac{(1 - P_1)^2}{\alpha - P_1} \sin \psi \right) . \tag{26}$$

To compare this result with the one for conducting electrodes we must consider exactly the same topography of the surface in both cases. Although the geometries of the surfaces are the same the values of the electric field along the surfaces are different. This results in different values of $\bar{\gamma}$. In order to demonstrate this point, let us choose the value E_{n1} equal to that near the tip of the hemisphere in a uniform electric field and $\psi = \pi / 4$. Then

$$\alpha = \frac{3\varepsilon}{\varepsilon + 2} . \tag{27}$$

As in the previous section, we let $P_1 = 1$. This will give us $S_1 = S_\infty / 3$ and for the dielectric

$$P_{1\,diel} = \alpha \frac{S_1}{S_\infty} = \frac{\varepsilon}{\varepsilon + 2} . \tag{28}$$

Accordingly, (see (19), (28)) $\bar{\gamma}$'s in these cases are

$$\bar{\gamma}_{cond} = 3\gamma_i \frac{E_\infty}{E_0} , \tag{29}$$

and,

$$\bar{\gamma}_{diel} = 3\gamma_i \frac{E_\infty}{E_0} \frac{(\varepsilon^2 + \sqrt{2})}{(\varepsilon + 2)^2} . \tag{30}$$

Another effect specific only to a dielectric arises in a high electric field $(eE\lambda_e >> W_0)$. It is caused by the tangential component (E_τ) of the electric field near the dielectric surface. Since $eE\lambda_e >> W_0$, an emitted electron moves prior to its first collision in the direction of electric field. If after a collision its velocity vector is directed inside the cone $\pi - \theta < E_\tau / E$ (see Fig.3), then this electron will return to the surface. This shows that even at high electric fields, reflection of the electrons by the gas atoms may strongly affect the second Townsend coefficient by lowering it. In this example γ_{diel} will depend on the ratio E_τ / E rather than on E / E_0. The last consideration shows that in the case of a dielectric surface the surface roughness can sometimes decrease ESEC (while it always increases ESEC for a conductive surface). Indeed, one can imagine an irregular dielectric surface with a dielectric constant $\varepsilon \approx 1$, which does not influence the electric field, but does affect the ESEC. Those pieces of the surface which are directed normally to the electric field will have γ the same as a flat surface, but those inclined to the electric field will have a smaller γ . Thus, the total $\bar{\gamma}$ will be less than that of a flat surface.

5. SUMMARY

We considered the effect of surface roughness on the effective secondary emission coefficient γ (ESEC). The effect is based on the fact that at high gas pressures a significant part of electrons ejected from the cathode return back to the cathode surface after elastic scattering on the gas atoms. In this situation the efficiency with which they are deflected away from the surface is controlled by an electric field. For small electric fields most of electrons return to the cathode. For high fields they effectively leave this region, and in very high fields one can expect to have ESEC the same as in vacuum. The roughness of the surface creates non-uniformities of the electric field near the surface, which in turn make γ vary from one place on the surface to another and, generally speaking, its average over the surface value will differ from that of a flat surface. Another important phenomenon which strongly enhances this effect is the non-uniform distribution of the ion current over the surface. The ion current density and respectively the emission of electrons is higher in the same regions where the electric field better pulls electrons away from the surface vicinity.

We have shown that the roughness of the surface always increases the value of ESEC (making it closer to its vacuum value) if the surface is made of conductive material, but can both increase and decrease ESEC if the surface is made of a dielectric.

The described effect can be observed only if the scale size of non-uniformities of the surface and electric field are not very small. The one requirement which we already discussed is that this scale size a is large compared to the electron mean free path in the gas. If it is not, then electron motion is essentially the same as in the uniform electric field, and ESEC is the same as for a perfectly flat surface. Another requirement is that a must be larger than the ratio W_0 / eE:

$$a >> W_0 / eE . \qquad (31)$$

To understand this requirement we should return to the basics of the "local $\gamma(E)$" approximation [Eq. (13)] we have used. One can see from Eq. (11) for $\gamma(E)$ that its value is not determined by the electric field in the vicinity of the cathode, but also by its dependence over a wide area [integral in the denominator of Eq. (11)]. For reasonable dependencies of the momentum transfer cross-section on energy, this integral reaches about 70% of its asymptotic value at the "distance" (on energy scale) about $eU \sim W_0$. Thus, we can use the "local γ" approximation if the electron gains this amount of energy (W_0) at a distance smaller than a (where one can still consider electric field as uniform), which results in condition (31). If this condition is not satisfied, then the effect will be weaker, although one can still observe some reflection of it.

P.J. DRALLOS[+], V.P. NAGORNY[+],
D.D.RYUTOV[++] and W. WILLIAMSON, JR.
Department of Physics and Astronomy,
The University of Toledo,
Toledo, Ohio 43606

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[+] Present address: Plasma Dynamics Corporation, 417 E. 8 Mile Road, Hazel Park, MI 48030
[++] Present address: Lawrence Livermore National Laboratory, Livermore, CA, 94550