The mechanism of controlled secondary electron emission

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We have investigated the controlled secondary electron emission (CSEE) on passage of single fast electrons ($E_p = 0.7$–2 MeV) through porous films of KCl. Emission characteristics $\bar{\sigma}(E)$ and energy spectra of the secondary electrons have been obtained when an electric field $E \sim 10^4$–10^5 V/cm was maintained in the porous dielectric film. It is shown that the internal amplification of CSEE in the film under the action of the field E can be explained by a process similar to a semi-self-maintaining Townsend discharge in a gas. An estimate of the mean free path of the secondary electrons L_e on the assumption of this emission-enhancement mechanism is in good agreement with an independent estimate of L_e on the basis of the energy spectra of the secondary electrons. The effect of the first critical potential U_{i1} and the electron affinity of the dielectric χ on the CSEE formation process in a porous dielectric film is discussed.

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We have previously reported[1-5] the phenomenon of controlled secondary electron emission (CSEE) from porous dielectric films in a strong electric field $E \sim 10^4 - 10^5$ V/cm on passage of fast primary electrons. The average secondary emission coefficient for CSEE $\bar{\sigma}$ reached values $\bar{\sigma} \approx 10$ in bombardment of films by a primary electron beam with $E_p = 50$ MeV and $\bar{\sigma} \approx 230$ on passage through the film of single electrons with energy $E_p \approx 0.7-2$ MeV. The limiting value of $\bar{\sigma}$ was determined by the stability of emission as the result of local electric breakdown of the films at $E > E_{cr}$. In refs. 4 and 5 we showed that the anomalously high values of $\bar{\sigma}$ for CSEE are determined to a substantial degree by the porosity of the dielectric layer and do not depend on the substrate material. Jacobs et al.[6] in a study of anomalous secondary emission made the assumption that in a porous film, as in a gas, a semi-self-maintaining discharge arises under the influence of a strong electric field. Townsend and many later investigators confirmed the correctness of this interpretation for anomalous secondary emission.

In the present work we have attempted to compare the data obtained by us on CSEE on passage of fast single electrons with the enhancement mechanism in a Townsend discharge.

1. Let us formulate the ideas which will enable us to compare the mechanism of a semi-self-maintaining discharge in a gas with field-enhanced CSEE on bombardment. In a superficial analogy with a Townsend discharge, we can write

$$\bar{\sigma} = \exp(\alpha x), \tag{1}$$

where α is the number of internal secondary electrons produced by one electron of an avalanche per unit path-length, and x is the average depth of avalanche creation in the dielectric film. However, in the case of emission due to a transmitted particle the initial electrons in the particle track are distributed uniformly and their paths in the avalanche, which are equal to the distance from the place of appearance of the electron in the track to the positive electrode, are different. The emission observed in this case will be a superposition of avalanches, i.e.,

$$\bar{\sigma} = \int_0^d e^{\alpha x}\, dx = \frac{1}{\alpha}(e^{\alpha d} - 1), \tag{2}$$

where d is the thickness of the dielectric film.

Jacobs et al.[6] showed that for a dielectric in a strong field

$$\alpha = A \exp(-eU_i/kT_e), \tag{3}$$

where $A \approx$ const, e is the electronic charge, U_i is the ionization potential, k is Boltzmann's constant, and T_e is the equivalent temperature of the electron gas. Expressing kT_e in terms of the field strength E and the secondary-electron mean free path L_e, we obtain[6]

$$eU_i/kT_e = 1.64U_i/L_eE, \tag{4}$$

The complicated form of the function $\bar{\sigma}(E)$ does not permit direct graphical analysis of the experimental curve $\bar{\sigma}_{exp}(E)$ or evaluation of L_e as was done in ref. 6. However, the values of L_e and A can be determined indirectly in our case.

For this purpose we shall use expression (2) and construct graphically the function $\bar{\sigma}(\alpha)$ for a known dielectric film thickness d. From the plotted curve we shall find values of α corresponding to the experimentally obtained value $\bar{\sigma}_{exp}$. On the other hand, for these same values of $\bar{\sigma}_{exp}$ the field strength $E = V_c/d$ is known (V_c is the positive electrode potential relative to the substrate), and we can now compare corresponding values of α and e for each value of $\bar{\sigma}_{exp}$.

Using Eqs. (3) and (4) we obtain

$$\ln \alpha = \ln A - 1.64U_i/L_eE. \tag{5}$$

Thus, if we make a plot of $\ln \alpha$ as a function of E^{-1}, then the points for the values of α found as described above should lie on a straight line with a slope $-1.64U_i/L_e$. Measuring the slope of the line and knowing U_i, we can evaluate L_e, and the intersection of the straight line with the $\ln \alpha$ axis gives a value of $\ln A$.

In addition, the value of L_e can be determined in accordance with ref. 6 from the energy distribution of the secondary electrons. Assuming that the energy distribution of the secondary electrons leaving the surface of the dielectric film is similar to the distribution of secondary electrons inside the dielectric layer, we can write

$$\overline{W}_e = {}^3/_2 kT_e = {}^3/_{16}\pi^2 m \overline{V}_e^2. \tag{6}$$

Expressing the average electron velocity in terms of L_e and E:

$$\overline{V}_e = (\pi L_e E e/2m)^{1/2},$$

we obtain

$$\overline{W}_e = {}^3/_{32}\pi^2 L_e e E, \quad (7)$$

where $\overline{W}_e$ is the average energy of the secondary electrons in the experimentally measured energy spectrum. Then, knowing the value of the field E at which the secondary electron spectrum was measured, we find the value of L_e:

$$L_e \approx 10.66 \overline{W}_e / \pi^2 e E. \quad (8)$$

2. The study of CSEE was carried in KCl films with a density ~2% of the normal density for thicknesses of 50, 100, 200, 300, and 400 μ. The films were deposited in an argon atmosphere on a substrate of foil (Al, thickness 7 μ). The deposition technique has been described previously.[7, 8]

The measurements were made with a technique permitting study of CSEE on passage of fast single electrons as described in refs. 3 and 9. The schematic arrangement of the apparatus is shown in Fig. 1.

Primary electrons from a $SR^{90}-Y^{90}$ source, after passing through the KCl film 1 being investigated, were detected by a scintillation counter 2, and from the energy dissipated in this scintillator we selected primary electrons with energy $E_p > 0.7$ MeV, i.e., we detected only events with minimum ionization in the film. The group of secondary electrons emitted from the film was focused and accelerated by an electrostatic focusing system and directed onto a scintillation detector with an anthracene crystal 3, the detection of each emission event being carried out in coincidence with a fast primary electron. The number of emitted secondary electrons was determined from the combined energy dissipation of the entire group of accelerated secondary electrons in the detector 3. For the average secondary emission coefficient $\bar{\sigma}$ we took the ratio of the total number of secondary electrons to the number of primary electrons which passed through the film and had an energy $E_p > 0.7$ MeV.

The film studied was placed in a module consisting of a ring 4 with the substrate fastened to it and two fine high-transparency grids. The controlling grid 5 touched the surface of the film and maintained it at a potential V_c positive with respect to the substrate and which determined the electric field strength E in the film. The grid 6 served only for analysis of the energy spectra of the secondary electrons by the plane retarding-field method, the retarding field being produced by supplying to grid 6 a potential V_r negative with respect to the control grid 5. Retarding-potential curves were taken, i.e., the number of emission events as a function of the potential V_r.

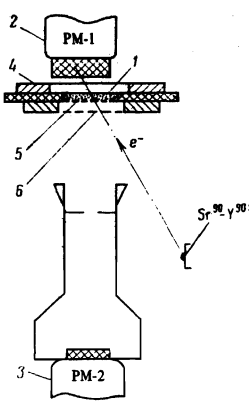

FIG. 1. Schematic arrangement of apparatus for study of secondary electron emission on transmission of single fast electrons.

The method chosen for the measurements permitted obtaining for the same film both the average emission coefficients $\bar{\sigma}_{exp}$ for stepped values of the field E and a family of retarding-potential curves for the same values of the field E. We note that measurements were made in this detail for films of thickness 100 μ, while for films of other thicknesses we studied only the function $\bar{\sigma}_{exp}(E)$; in this case the films were placed in a module with only the control grid.

During the measurements a vacuum of 10^{-7} Torr or better was maintained in the apparatus by continuous pumping with a titanium ion pump.

3. In Fig. 2 we have shown experimental curves which illustrate the dependence of the coefficient $\bar{\sigma}_{exp}$ for CSEE on the electric field strength E for various film thicknesses. As can be seen from the curves, the emission begins to increase significantly for $E > 10^4$ V/cm, and for thicker films this rise appears more rapidly and the limiting values of $\bar{\sigma}_{exp}$ above which emission is unstable as the result of local electric breakdown of the film are achieved at lower values of the field strength E.

For a KCl film of thickness 100 μ we obtained experimental retarding-potential curves for secondary electrons for three field strengths E: 2×10^4 V/cm, 3×10^4 V/cm, and 4×10^4 V/cm. It was found that practically complete stopping of the secondary electrons occurs for potentials V_r much less than the corresponding potential of the control grid $V_c = Ed$ for each curve. This fact indicates that the energy of the emitted secondary electrons is limited not by the potential of the control grid but by the mean free path of the secondary electrons between collisions with the walls of the voids when the electrons are moving to the surface of the film under the influence of the field E. Thus, for a given KCl density $\rho \sim 2\%$ the mean free path of the secondary electrons L_e is clearly less than the film thickness $d = 100$ μ.

In Fig. 3 we have shown curves $F(W_e)$ of the distribution of secondary electrons in energy, which corresponds to the electron velocity component normal to the surface of the film. These curves were plotted by graphical differentiation of the experimental retarding-potential curves. The function $F(W_e)$ is similar to a Maxwellian distribution, and with increase of field strength E_e in the film its maximum shifts towards higher values of W_e.

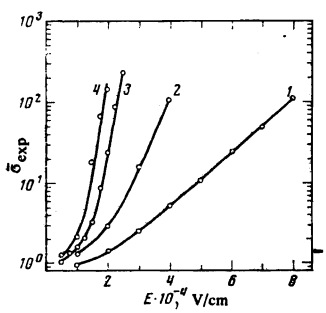

FIG. 2

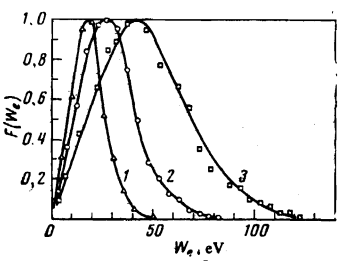

FIG. 3

FIG. 2. Family of curves determining the dependence of the average secondary-electron emission coefficient $\bar{\sigma}_{exp}$ on electric field strength E in CSEE from porous KCl films of various thicknesses: 1–50 μ, 2–100 μ, 3–200 μ; 4–400 μ; E is the electric field strength in the film.

FIG. 3. Energy spectra of secondary electrons for a porous KCl film of thickness 100 μ, obtained by graphical differentiation of retarding-potential curves. 1–E = 2×10^4 V/cm, 2–E = 3×10^4 V/cm, 3–E = 4×10^4 V/cm. The spectra have been normalized at the maximum value.

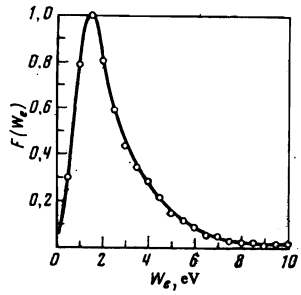

FIG. 4

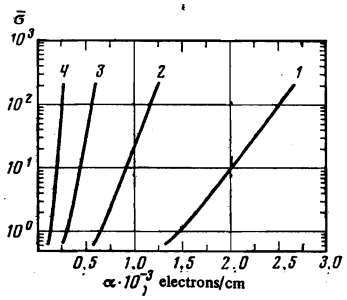

FIG. 5

FIG. 4. Energy spectrum of secondary electrons for porous KCl film of thickness 100 μ when the electric field strength is E = 0. The spectrum has been normalized at the peak value.

FIG. 5. Family of theoretical curves determining the dependence of the average emission coefficient $\bar{\sigma}$ on α–the number of internal secondary electrons produced by one electron of an avalanche per centimeter of path. 1–d = 50 μ, 2–d = 100 μ, 3–d = 200 μ, 4–d = 400 μ.

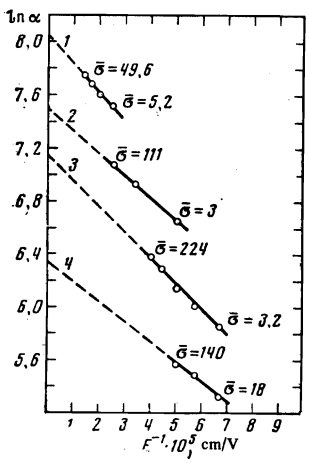

FIG. 6

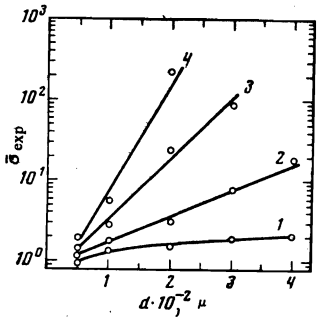

FIG. 7

FIG. 6. Plot of ln α as a function of E^{-1} for porous KCl films ($\rho \approx 2\%$): 1–d = 50 μ, $L_e = 7.4 \pm 0.7$ μ; 2–d = 100 μ, $L_e = 9.9 \pm 0.5$ μ; 3–d = 200 μ, $L_e = 8.4 \pm 0.3$ μ; 4–d = 400 μ, $L_e = 11.0 \pm 1.5$ μ.

FIG. 7. Family of curves determining the dependence of the average secondary-electron emission coefficient $\bar{\sigma}_{exp}$ on the thickness d of a porous KCl film for various electric strengths E: 1–E = 1.0 × 10^4 V/cm; 2–E = 1.5 × 10^4 V/cm; 3–E = 2.0 × 10^4 V/cm; 4–E = 2.5 × 10^4 V/cm.

In Fig. 4 we have shown the secondary electron energy spectrum $F(W_e)$ obtained in the same way by graphical differentiation of the retarding-potential curve for the case of emission from the same KCl film when the control grid was short-circuited to the substrate and the electric field strength in the dielectric was zero. The distortions introduced into the spectrum here as the result of emission from the control grid are insignificant as a result of the high transparency (~88%) and significantly lower emission coefficient[10, 11] for metals in comparison with KCl at $E_p \sim 1$ MeV. The peak of the $F(W_e)$ curve corresponds to an energy $W_{em} \sim 1.5-1.6$ eV, and the main part of the spectrum lies in the energy region $W_e = 0-10$ eV. These results agree with those in the literature[12] for the energy spectrum of true secondary electrons for a single crystal of KCl ($W_{em} \approx 1.5$ eV, $W_e = 0-10$ eV), which were obtained for primary electron energies $E_p \sim 2$ keV. Bronshteyn and Frayman[12] point out that for dielectrics with a high secondary-emission coefficient the shape of the spectrum of true secondary electrons stops changing with increasing primary energy, beginning with $E_p \gtrsim 1.5-2$ keV.

4. We can extract from the experimental results important arguments in favor of the correctness of the assumption of an avalanche mechanism of enhancement of the emission by the field also for the case observed by us of CSEE induced by transmission of an electron in porous KCl films. Let us turn to the family of emission curves, Fig. 2. The rapid rise of emission in the region $E > 10^4$ V/cm can be explained by the fact that as the field strength E increases, avalanche multiplication of secondary electrons accelerated in the voids of the dielectric begins to dominate. This process has a cascade nature, and with increasing thickness of the dielectric layer the number of effective cascades increases. Therefore in thicker films higher values of $\bar{\sigma}_{exp}$ are obtained for the same field strength E.

We shall analyze the emission curves of Fig. 2 on the assumption of an avalanche mechanism of emission enhancement. For this purpose let us construct a family of curves $\bar{\sigma}(\alpha)$ in accordance with Eq. (2) for the film thicknesses studied. These curves are presented on a logarithmic scale in Fig. 5.

Comparing these curves with the family of experimental curves $\bar{\sigma}_{exp}(E)$ of Fig. 2, we find values of α for the point $\bar{\sigma} = \bar{\sigma}_{exp}$ in the avalanche development region. The field strength E for these points can be determined from Fig. 2, and we have shown the values of α found in this way on a logarithmic scale as a function of E^{-1} (Fig. 6). The points plotted from the experimental data actually lie on straight lines. The values of α and A at which the straight lines intersect the ln α axis increase somewhat with decreasing film thickness. This is explained by the large uncertainty in calculation of the field strength $E = V_c/d$ and $\bar{\sigma}(\alpha)$ as the result of increase in the relative error in measurement of the thickness of the layer (for d = 50 μ, the uncertainty is $\Delta d/d = \pm 10\%$). In addition, the effective intensity of the electric field in the thinner films is reduced relative to the calculated value $E = V_c/d$ as the result of drooping of the electric field in the cells of the control grid (the size of the grid mesh is 200 × 200 μ).

By determining the slope of the straight line and assuming for KCl $eU_i \approx 10$ eV, we estimate L_e from Eq. (5) for each film thickness; the values of L_e are given in the caption to Fig. 6.

For a KCl film of thickness 100 μ, L_e can be independently evaluated from the energy spectra constructed from the experimental retarding-potential curves. Calculations carried out with Eq. (8) for the $\overline{W}_e$ values found from the family of curves in Fig. 3 gave an average value $L_e = 10 \pm 1.5$ μ which is in good agreement with the estimate of L_e from the emission curve for the same emitter (see Fig. 6).

Thus, the entire set of experimental data presented permits us to state that for the observed CSEE induced by a transmitted electron from a porous dielectric the effect of avalanche multiplication of secondary electrons in the voids of the film plays an important role, and Eqs. (2)–(4) correctly reflect the dependence of the average emission coefficient $\bar{\sigma}$ on the field E.

However, the porosity of the dielectric layer and the strong electric field in it are not sufficient conditions for achievement of high values of $\bar{\sigma}$. For efficient avalanche production it is necessary that in the dielectric there be a sufficiently low first critical potential (for KCl this value is ~10 V), or else the energy of electrons

accelerated by the field in the voids of the dielectric will be insufficient for multiplication of these electrons.[13] This situation is readily illustrated by the dependence of $\bar{\sigma}_{exp}$ on the thickness of the porous film for increasing field strengths E (Fig. 7). As can be seen from the curves, the coefficient $\bar{\sigma}_{exp}$ begins to rise exponentially with d for a field strength $E > 10^4$ V/cm, since for a mean free path $L_e \sim 10\ \mu$ and a first critical potential ~10 V the secondary electrons can accumulate the energy necessary for multiplication in the film only at a field $E > 10^4$ V/cm.

We shall now discuss the features of the yield of secondary electrons from the walls of the voids. For description of this process in the absence of an electric field we can draw on the mechanism of secondary-electron yield from the crystal lattice of alkali halide compounds.[12] As Bronshteyn and Frayman[12] point out, the secondary-electron yield is greatly enhanced in dielectrics with a low electron affinity χ, and in the energy spectrum of true secondary electrons in such dielectrics there is a significant fraction of electrons with energies $\sim\chi$.

The energy spectrum of true secondary electrons obtained by us for KCl in the absence of a field E at an energy $E_p = 0.7-2$ MeV (Fig. 4) indicates a low value of electron affinity. It must be supposed that this makes possible an increase in the secondary emission coefficient for CSEE in a porous film of KCl.

The alkali halide compounds CsI and CsBr in which the electron affinity is $\chi = 0.1-0.2$ eV show higher secondary-emission characteristics[14] than KCl, and for CsI this is confirmed experimentally both for ordinary secondary-electron emission and for field-enhanced emission.[15,16]

In considering the mechanism of CSEE from porous dielectric films it is necessary also to take into account the effect of the strong electric field on the yield of secondary electrons from the walls of the voids. Bakhshyan and Garibyan[17] in considering this process as applied to very thin ($\lesssim 10^{-5}$ cm) dense layers of dielectric (in our case these can be the walls between the voids) showed that a strong electric field will have an effect which increases both the number of internal true secondary electrons produced in the film and the fraction of them which will be emitted from the film. However, a detailed quantitative analysis was carried out only for the case in which the primary particle is extreme relativistic and the field in the film is $E \geq 10^5-10^6$ V/cm.

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68