Mechanism of field-enhanced self-sustaining secondary electron emission in porous dielectrics

P. M. Shikhaliev

A. F. Ioffe Physicotechnical Institute, St. Petersburg
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A model is proposed for field-enhanced self-sustaining electron emission in secondary-emission porous dielectrics. It is shown that the mechanism for the formation of primary electrons at the metal–porous dielectric interface is field emission from the metal, and the electric field of the required intensity for field emission is formed by redistribution of the field in the layer as a result of the avalanche formation of secondary electrons. © *1998 American Institute of Physics.* [S1063-7850(98)00310-3]

Porous materials made from dielectrics with a high coefficient of secondary electron emission are potentially useful as working media for various types of radiation detector[1–3] which use the phenomenon of field-enhanced secondary electron emission in porous dielectrics.

Unlike secondary electron emission from solid materials, in which slow secondary electrons are emitted only from within a thin surface layer at most hundreds of angstrom thick, in porous dielectrics the thickness of the layer from which slow secondary electrons are emitted reaches tens and hundreds of microns, and an electric field of 10^4–10^5 V/cm, which expels the slow electrons from the material, forms within these layers.[3–5] The role of the electric field is to balance the losses of the slow electrons due to scattering by phonons within the pore walls by accelerating these electrons inside the pore, thereby lowering their recombination probability. This type of emission (like the secondary electron emission from solid materials) has an almost instantaneous response—the emission appears and disappears at the times when the primary electron beam is switched on and off.[5]

When the field in a layer of porous dielectric increases above a certain critical value, the secondary emission current increases sharply and the coefficient of secondary electron emission may reach hundreds or thousands. An explanation of this effect was given in Refs. 5 and 6 as follows. In fairly strong electron fields the slow electron energy collected inside the pore is sufficient for impact ionization of the dielectric material and an avalanche-like increase in the density of the slow electrons in the porous layer parallel to the electric field. A characteristic feature of this type of emission is its slow response: after the primary electron beam has been switched off, the emission decreases very slowly and in some cases does not cease for many hours, i.e., it is self-sustaining.[5,6]

At present, no satisfactory model is available to explain this self-sustaining emission. In particular, the mechanism for transfer of electrons from the metal substrate to the bulk of the dielectric after its irradiation by primary electrons has not been fully clarified (in the presence of irradiation electron–hole transitions occur at the metal–dielectric interface; electron–hole pairs are excited by fast primary electrons.[1,5]) The most probable mechanism for this transfer is field emission from the metal into the dielectric in the absence of a primary electron beam, although the electric field needed to induce field emission should be two orders of magnitude higher than the field produced in the dielectric layer.[5,6]

Here it will be shown that the mechanism for transfer of electrons from the metal to a porous dielectric in the absence of primary electron beam is field emission from the metal. The field required for the field emission is formed by means of nonuniform redistribution of the potential within the porous layer as a result of an avalanche-like increase in the excitation density of the slow electrons. This is accompanied by increased conductivity of the material in the direction away from the metal substrate toward the surface of the porous layer and an increase in the field in the inner part of the layer (near the metal substrate).

Let us assume that a sample of porous material of thickness L on a metal substrate of thickness $\ll L$ is irradiated by a penetrating beam of primary electrons. We shall consider a longitudinal section of this layer of unit cross section (Fig. 1). The current i_0 flowing through this cross section does not depend on the coordinate x (current conservation law). Thus, it satisfies $dU(x)/dR(x)=i_0=\text{const}$, and we have $dR(x)=\rho(x)dx$, where $\rho(x)=1/e\mu n(x)$ is the resistivity of the material caused by the excitation of free secondary electrons in the layer, and μ and $n(x)$ are the mobility and density of the secondary electrons.

Thus, we find

$$\frac{dU}{dx}=\frac{i_0}{e\mu}\frac{1}{n(x)}. \tag{1}$$

It is known from the theory of secondary emission detectors that in an avalanche formation process, the electron density in the avalanche increases exponentially:[7,8]

$$n(x)=n_0\exp\left(\frac{x}{L}\ln K_0\right), \tag{2}$$

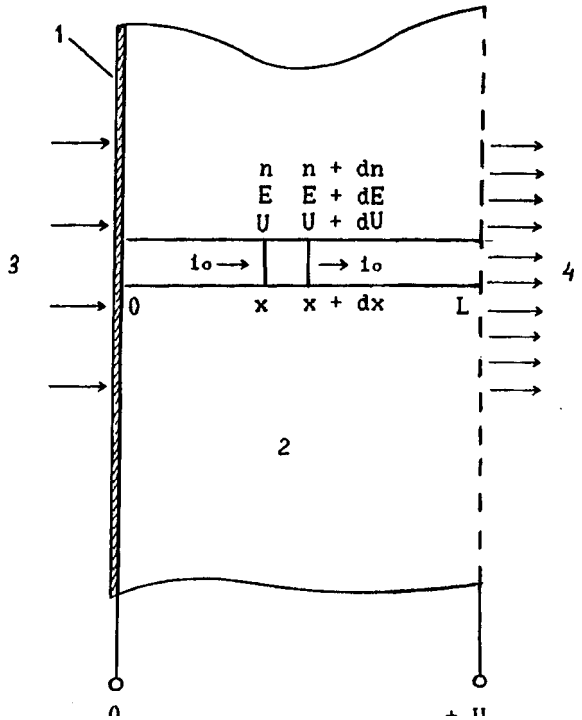

FIG. 1. Cross section of porous dielectric on metal substrate: *1*—metal, *2*—porous layer, *3*—primary electrons, and *4*—secondary electrons.

where we have written $n_0=n(0)$, K_0 is the coefficient of electron multiplication in the avalanche formation process when a potential difference $U_0>U_k$ is applied to the porous layer, and U_k is the critical potential difference at which the avalanche formation process begins. From Eq. (2) we obtain

$$\frac{dn}{dx}=\frac{\ln K_0}{L}n(x), \tag{3}$$

and K_0 can be approximated as

$$\ln K_0=A(U_0-U_k), \tag{4}$$

where A is a known constant. However, expressions (2) and (3) are valid for a linear potential distribution in the layer when the potential is $U(x)=U_0x/L$. Since the conductivity varies along the layer in the avalanche formation process, $U(x)$ is redistributed nonlinearly. In this case, for Eq. (3) to be valid $\ln K_0$ should be replaced by $\ln K_0'=A(U_0'-U_k)$, where $U_0'=(dU/dx)L$ (Ref. 9). Taking this into account, Eq. (3) now has the form

$$\frac{dn}{dx}=\frac{A}{L}\left(\frac{dU}{dx}L-U_k\right)n. \tag{5}$$

Equations (1) and (5) yield the system

$$\begin{cases}\dfrac{dU}{dx}=\dfrac{i_0}{e\mu}\dfrac{1}{n}\\[2ex] \dfrac{dn}{dx}=\dfrac{A}{L}\left(\dfrac{dU}{dx}L-U_k\right)n\end{cases} \tag{6}$$

with the boundary conditions $U(0)=0$, $U(L)=U_0$, and $n(0)=n_0$. The solutions of Eq. (6) with allowance for these boundary conditions are as follows:

$$\begin{aligned}U(x)&=\frac{1}{A}\ln\frac{\exp(AU_kx/L)-a}{1-a},\\ n(x)&=\frac{Li_0}{e\mu U_k}\frac{1-a\exp(-AU_kx/L)}{1-a},\\ E(x)&=\frac{dU}{dx}=\frac{U_k}{L}\frac{1}{1-a\exp(-AU_kx/L)},\end{aligned} \tag{7}$$

where $a=(\exp(AU_0)-\exp(AU_k))/(\exp(AU_0)-1)$.

It is easy to see from Eq. (7) that for $U_0=U_k$, $a=0$, and $U(x)=U_0x/L$, we obtain $E(x)=U_0/L=E_0$, $n(x)=i_0/e\mu E_0$, which corresponds to the condition for cessation of avalanche formation. For $U_0>U_k$ at the metal–porous layer interface ($x=0$) we have

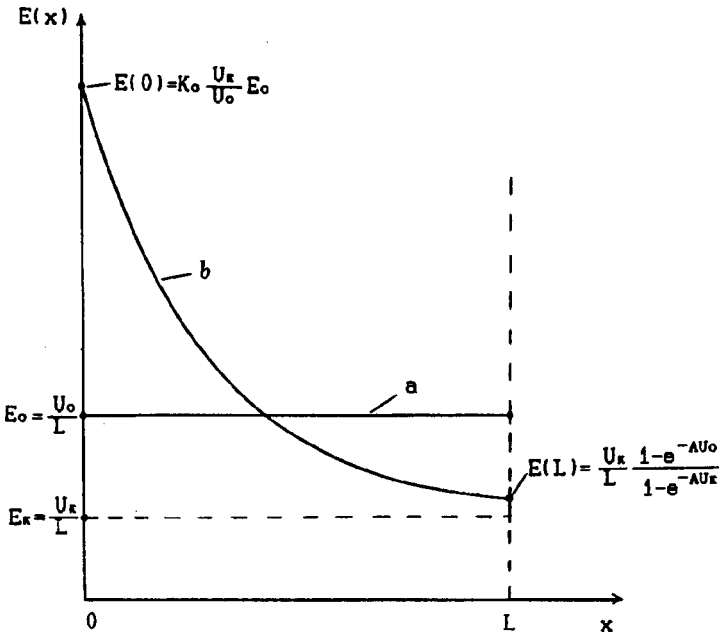

FIG. 2. Electric field distribution in porous layer before (a) and after initiation of primary electron beam (b).

$$E(0)=\frac{U_k}{L}\frac{1}{1-a}. \quad (8)$$

At the exit surface of the porous layer ($x=L$) we find:

$$E(L)=\frac{U_k}{L}\frac{1-\exp(-AU_0)}{1-\exp(-AU_k)},$$

$$n(L)=n_0\frac{1-a\exp(-AU_k)}{1-a}.$$

Allowing for Eq. (4) in Eq. (8), we find $E(0)=(U_k/U_0)K_0E_0$. For the typical values $K_0\approx 200$, $U_k/U_0\approx 0.5$ observed experimentally we obtain $E(0)=100(U_0/L)=100E_0$. Thus, if the potential difference at the porous layer exceeds the critical value, the electric field at the metal–porous layer interface may increase by two orders of magnitude after switching on the primary electron beam (Fig. 2). This field is quite sufficient to initiate field emission from the substrate. After the primary electron beam has been switched off, avalanche formation is initiated by the field electrons and becomes self-sustaining. The duration of this self-sustaining electron emission may be influenced by many factors. One possible reason for the gradual decrease in intensity and cessation of self-sustaining emission is the dissociation of dielectric molecules caused by electron impact which leads to degradation of the emission characteristics of the material.

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[1] J. Edgecumbe and E. L. Garvin, J. Appl. Phys. **37**, 3321 (1966).
[2] C. Chianelli, P. Ageron, J. P. Bouvet *et al.*, Nucl. Instrum. Methods Phys. Res. A **273**, 245 (1988).
[3] M. P. Lorikyan, Usp. Fiz. Nauk **165**, 1323 (1995).
[4] N. L. Yasnopol'skiĭ and A. É. Shabel'nikova, Fiz. Tverd. Tela. (Leningrad) **10**, 103 (1968). [Sov. Phys. Solid State **10**, 75 (1968)].
[5] N. L. Yasnopol'skiĭ, A. É. Shabel'nikova, A. P. Balashov, and N. S. Lozhkina, in *Research in Radio Engineering and Electronics*, Part 2 [in Russian], Moscow (1975), p. 67.
[6] I. M. Bronshteĭn and B. S. Fraĭman, *Secondary Electron Emission* [in Russian], Nauka, Moscow (1969), 408 pp.
[7] C. Loty, Acta Electron. **14**(1), 107 (1971).
[8] M. R. Aĭnbund and B. V. Polenov, *Secondary Electron Emission Multipliers and Their Applications* [in Russian], Énergoatomizdat, Moscow (1981).
[9] P. M. Shikhaliev, Nucl. Instrum. Methods Phys. Res. (1998) (in press).

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