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DARK EMISSION OF EXOELECTRONS FROM PLASTICALLY DEFORMED ALUMINIUM COVERED WITH OXIDE AND EXCITED BY ELECTRONS

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Exoelectron emission is observed during the plastic deformation of aluminium on the surface of which there is an oxide layer with thickness $D > 70$ nm previously excited by electron bombardment. The emission intensity increases with strain until sample failure after which it decays slowly. The curve of intensity of dark emission of exoelectrons *vs* strain is to a certain extent similar to that in the case of photostimulated emission of exoelectrons.

The following factors have been found to influence the investigated dark emission: oxide layer thickness — D, time of bombardment with electrons — t_b, bombarding electron current — i_e, energy of bombarding electrons — U_b.

It is assumed that the observed dark emission of electrons during plastic deformation is due to a strong electric field in the oxide layer on the surface of the sample. This field is the resultant of the electric field in micro-fissures produced in the oxide and the internal field ("frozen") in the oxide which is due to previous bombardment with electrons. The observed phenomenon is not a classical Malter effect; it occurs only after exceeding a certain threshold value ε_{od} — which will be called initial strain.

1. *Introduction*

Recent reports on the results of studies on exoelectron emission from plastically deformed aluminium in vacuum carried out in our laboratory, have pointed out the role of the oxide layer on aluminium surface played in the mechanism of exoelectron emission (Sujak *et al.* 1965 a, b.

Although the proposed and many times discussed model of electrified fissures *e.g.* Gieroszyński *et al.* (1964); Sujak *et al.* (1965a) has explained many of observed dependences of photostimulated emission of exoelectrons on parameters of measurement there was a need of checking this model.

In order to do this it was necessary to charge the electric field in the oxide layer in a rather controlled manner, *e.g.* by bombardment with electrons, and to observe the emission kinetics.

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Gieroszyński (1968) has succeded to show that in such a way one can distinguish photostimulated emission of electrons from micro-fissures bottoms from the emission from the oxide layer itself. In this way Gieroszyński has realized the idea initiated by Sujak (1961) to separate the two phenomena in deformaed aluminium.

By bombarding with electrons it is possible to change the electric field in micro-fissures and induce the appearence of "frozen" space charge of electrons in oxide layer.

The present report describes dark emission of electrons observed during the deformation of the sample which shows however a different kinetics from that reported so fas (Gieroszyński *et al.* 1965). This phenomenon occurs only after previous excitation of the sample by bombardment with electrons. It is probably due to the existence of strong electric fields resulting from the superposition of the electric field in micro-fissures and the "frozen in" field produced in the whole volume of aluminium oxide by previous bombardment with electrons.

2. *Apparatus*

The experimental set-up and the manner in which the samples are prepared, have been already described in earlier papers (*cf.* Sujak *et al.* 1965 a; Gieroszyński *et al.* 1964). The deformation rate applied was $\frac{d\varepsilon}{dt} = 0.2\%\ \mathrm{sec}^{-1}$.

The electron source used for bombardment of samples was an incandescent tungsten filament placed 0.5 cm above the sample *cf.* Gieroszyński (1968). This filament was also used as UV-source with wavelengths $\lambda < 300$ nm.

Only samples covered with oxider layer thicker than 70 nm were investigated.

3. *Dark emission*

When samples covered with oxide layer of thickness $D > 70$ nm are subject to deformation after previous bombardment with electrons, one observes at a certain strain value measurable dark emission of exoelectrons. This strain value is called initial strain ε_{od} of

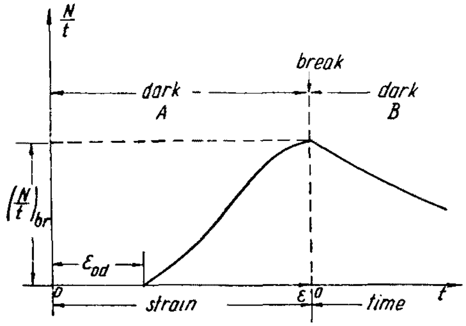

Fig. 1. Kinetics of dark emission increase during the deformation of the sample (region A)and emission decay after stopping the deformation process (region B). ε_{od}— initial strain of sample, $\left(\frac{N}{t}\right)_{br}$ — emission intensity at the instant of sample break-up

the sample. The intensity of emission increases with increasing strain until the sample breaks up. After the break up the intensity of exoemision decays slowly. A schematic illustration of this process is shown in Fig. 1.

The following factors exert an influence on the exoemission in the case of sample deformed after previous excitation by electron bombardment; oxide layer thickness D, time of excitation by electron bombardment t_b, energy U_b and current i_e of electrons bombarding the sample. The occurrence of the emission of exoelectrons described is conditioned by the selection of suitable values of D, t_b, i_e and U_b.

The influence of these parameters (D, t_b, i_e and U_b) has been investigated in respect to:

a) initial strain value ε_{od},

b) kinetics of emission intensity increase with increasing strain $\frac{N}{t}(\varepsilon)$,

c) exoelectron emission intensity at the time of sample break-up $\left(\frac{N}{t}\right)_{br}$

d) kinetics of emission decay after terminated deformation $\frac{N}{t}(t)$.

4. *Initial strain of the sample ε_{od}*

a) Influence of oxide layer thickness D

The characteristic feature of the dark emission of electrons occurring during the deformation process is that it occurs when the aluminium samples are covered with oxide layers thicker than 70 nm. In contrast with photostimulated exoemission of electrons where ε_0 increases with increasing oxide layer thickness D, the exoelectron dark emission described here appears at smaller initial strain values ε_{0d}, the greater the oxide layer thickness. The dependence of initial strain value ε_{0d} on oxide layer thickness is shown in Fig. 2.

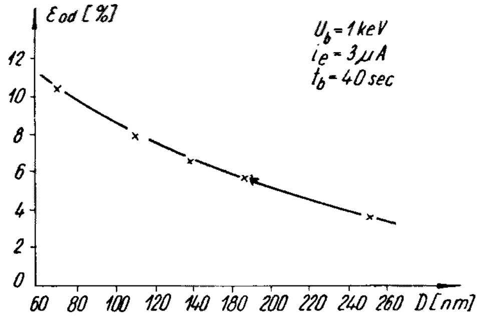

Fig. 2. Dependence of initial strain ε_{od} on oxide layer thickness D. Excitation parameters: bombardment time $t_b = 40$ sec, intensity of bombarding current $i_e = 3$ μA, electron energy $U_b = 1$ keV

b) Influence of time of excitation by electron bombardment t_b

For the parameters of the excitation process $i_e = 3\,\mu A$, $D = 140$ nm, $U_b = 1$ keV the dark emission of exoelectrons during deformation occurs only after the time of bombardment t_b is of about 20 sec.

With increasing time of bombardment t_b the ε_{od}-value decreases (Fig. 3).

c) Influence of the intensity of electron current exciting the sample — i_e

The influence of the intensity of the bombarding electron current i_e on the ε_{od} value is similar to that of the excitation time (of bombardment). The results are shown in Fig. 4.

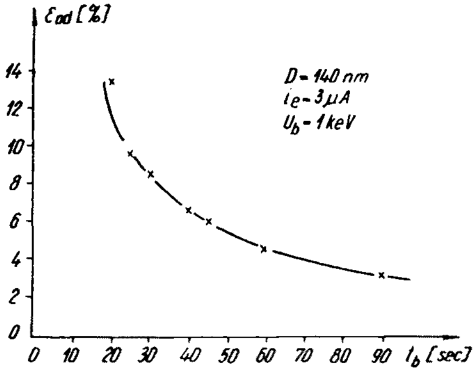

Fig. 3. Dependence of initial strain ε_{od} on bombardment time t_b, $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $U_b = 1$ keV

As it can be seen from this figure the ε_{od} value decreases with the increase in i_e for other excitation parameters constant: $D = 140$ nm, $t_b = 40$ sec, $U_b = 1$ keV.

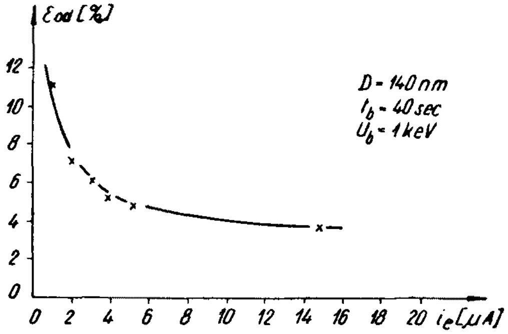

Fig. 4. Dependence of initial strain ε_{od} on bombardment current i_e, $D = 140$ nm, excitation parameters: $t_b = 40$ sec, $U_b = 1$ keV

d) Influence of energy of electrons exciting the sample — U_b

No dark emission of exoelectrons has been observed during the deformation of the sample if the latter was bombarded with electrons of energies $U_b > 1.8$ keV, the remaining parameters amounting to $D = 140$ nm, $t_b = 40$ sec, $i_e = 3$ μA. These parameters were chosen such that exoemission should occur.

In the energy interval of electrons between 260 eV and 1.7 keV the value of ε_{od} increases with increasing U_b (Fig. 5).

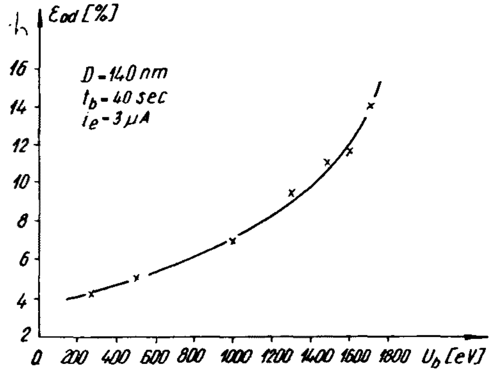

Fig. 5. Dependence of initial strain ε_{od} on the energy of bombarding electrons U_b, $D = 140$ nm excitation parameters: $t_b = 40$ sec, $i_e = 3\mu$A

5. *Kinetics of increase in intensity of dark emission during the deformation* — $\frac{N}{t}(\varepsilon)$

The kinetics of emission intensity increase (region A in Fig. 1) with increasing strain is also dependent on the values of D, t_b, i_e and U_b.

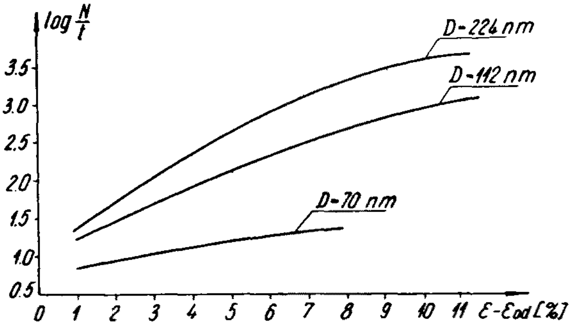

Fig. 6. Dark emission intensity increase with increasing strain for different oxide layer thicknesses D. Excitation parameters: $t_b = 40$ sec, $i_e = 3\mu$A, $U_b = 1$ keV

Fig. 6 shows the emission growth curves $\left(\text{in } \log\frac{N}{t} \text{ coordinate}\right)$ *vs*, deformation $\varepsilon - \varepsilon o_d$ for oxide layer thicknesses of 224 nm, 112 nm and 70 nm, respectively. The kinetics of emission intensity increase is influenced, similarly as by the D-value, by the bombardment time (excitation time) t_b (Fig. 7) and the intensity of electron current exciting the sample (Fig. 8).

Fig. 9 shows the influence of electron energy U_b on the kinetics of emission intensity increase with increasing strain. These results have been given in $\log\frac{N}{t}$ *vs* $\varepsilon - \varepsilon_{od}$ coordinates for three values of $U_b = 1.7$ keV, 1.2 keV and 1 keV.

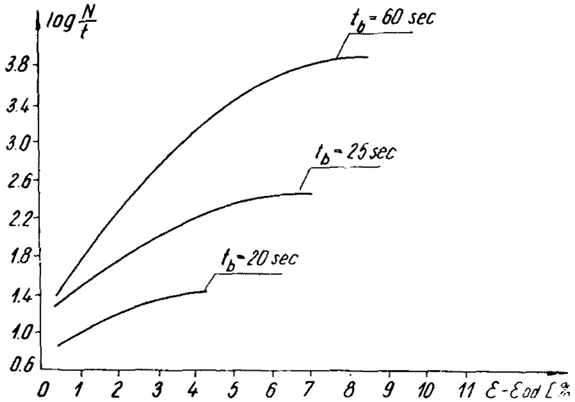

Fig. 7. Dark emission intensity increase with increasing strain for different times of bombardment with electrons t_b, $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $U_b = 1$ keV

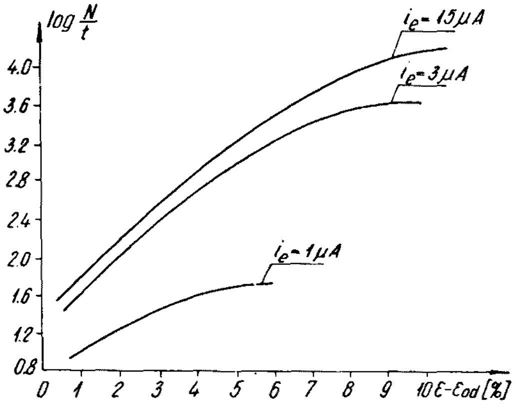

Fig. 8. Dark emission intensity increase with increasing strain for different bombardment currents i_e, $D = 140$ nm, excitation parameters: $t_b = 40$ sec, $U_b = 1$ keV

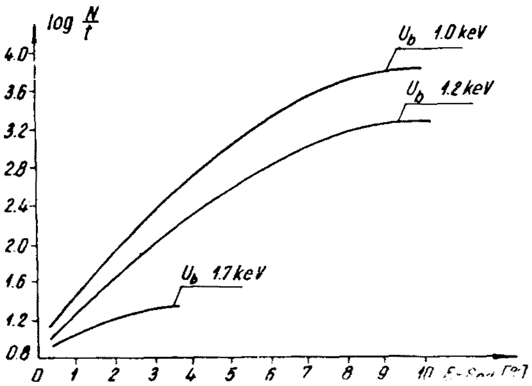

Fig. 9. Dark emission intensity increase with increasing strain for different energies U_b of bombarding electrons. $D = 140$ nm, excitation parameters: $t_b = 40$ sec, $i_e = 3$ μA

6. *Emission intensity at the instant of break up of the sample*

It has been also found that the value of the dark emission intensity at the instant of break-up is strongly influenced by the value of thickness D of the oxide layer covering the deformed sample. The value of $\left(\frac{N}{t}\right)_{br}$ increases with increasing thickness D, which follows from the results of measurements shown in Fig. 10. A similar influence on the value of

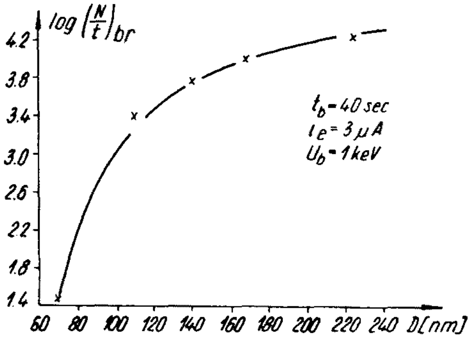

Fig. 10. Dependence of emission intensity at the instant of break-up $\left(\frac{N}{t}\right)_{br}$ on oxide layer thickness. Excitation parameters: $t_b = 40$ sec, $i_e = 3$ μA, $U_b = 1$ keV

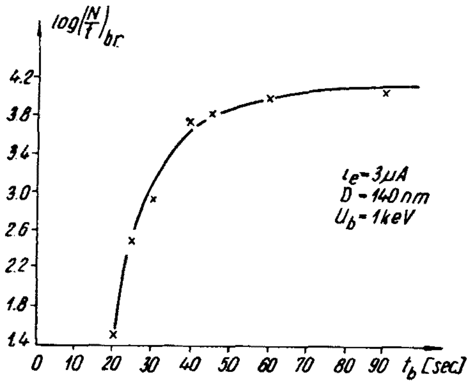

Fig. 11. Dependence of emission intensity at the instant of break-up $\left(\frac{N}{t}\right)_{br}$ on bombardment time t_b, $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $U_b = 1$ keV

$\left(\frac{N}{t}\right)_{br}$ is exerted by: bombardment (excitation) time t_b and the intensity of bombarding electron current i_e. Fig. 11 shows the dependende of log $\left(\frac{N}{t}\right)_{br}$ on t_b while the log $\left(\frac{N}{t}\right)_{br}$ *vs* i_e dependence is shown in Fig. 12.

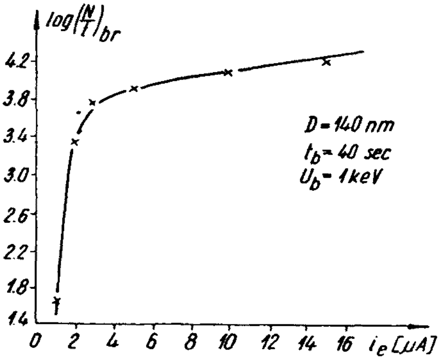

Fig. 12. Dependence of emission intensity at the instant of break-up on bombardment current i_e. $D = 140$ nm, excitation parameters: $t_b = 40$ sec, $U_b = 1$ keV

With increasing energy of bombarding electrons U_b (in the range from 260 eV to 1.7 keV) the value of log $\left(\frac{N}{t}\right)_{br}$ decreases as it is shown in Fig. 13. For $U_b > 1.8$ keV there is no emission of exoelectrons for $D = 140$ nm, $i_e = 3$ μA, and $t_b = 40$ sec, even when the sample breaks up.

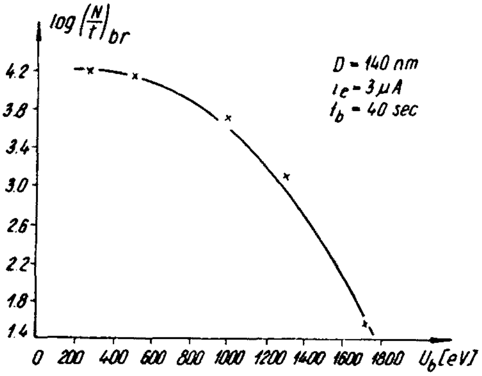

Fig. 13. Dependence of emission intensity at the instant of break-up $\left(\frac{N}{t}\right)_{br}$ on the energy bombarding electrons U_b. $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $t_b = 40$ sec

7. *Dark emission decay*

We have accepted the value of the slope tg α of the decay curve log $\frac{N}{t}$ *vs* t at a point in the vicinity of $t = 0$ as the measure of the decay rate of dark emission of exoelectrons after sample failure.

In contrast to photostimulated exoelectron emission the parameters D, t_b, i_e and U_b do not influence the value of $tg\,\alpha$.

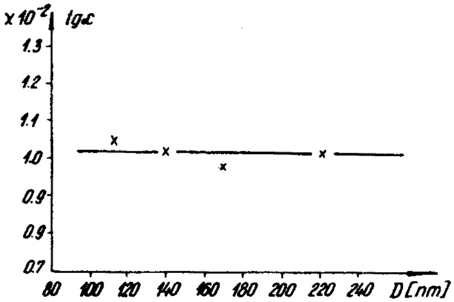

Fig. 14. Influence of oxide layer thickness D on tg α. Excitation parameters: $i_e = 3$ μA, $t_b = 40$ sec, $U_b = 1$ keV

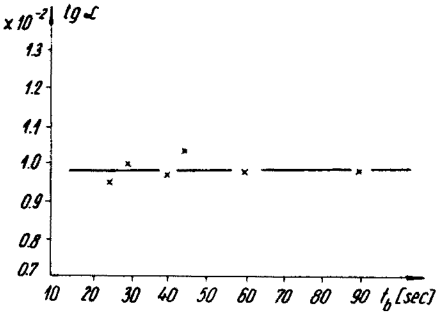

Fig. 15. Influence of bombardment time t_b on tg α. $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $U_b = 1$ keV

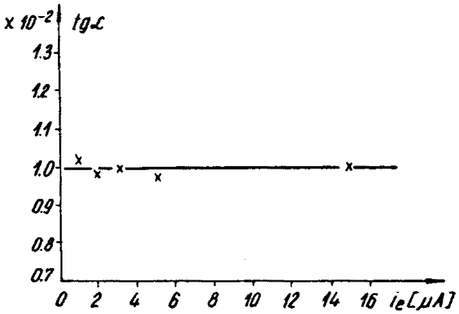

Fig. 16. Influence of bombarding current i_e on tg α. $D = 140$ nm, excitation parameters: $t_b = 40$ sec, $U_b = 1$ keV

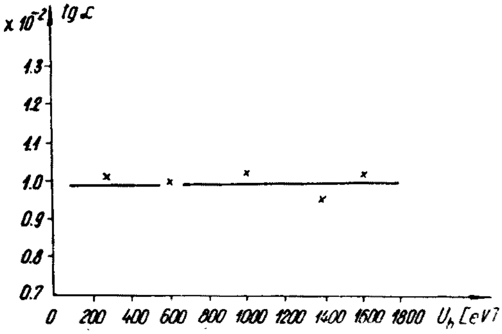

Fig. 17. Influence of electron energy U_b on tg α. $D = 140$ nm, excitation parameters: $i_e = 3$ μA, $t_b = 40$ sec

The subsequent Figures 14, 15, 16 and 17 show the experimental results of the dependences of tg α on D, t_b, i_e, and U_b, respectively. As it can be seen they are always straight lines parallel to the abscissae axes. The mean value of tg α is about 10^{-2} sec^{-1}.

8. *Discussion*

In a previous work (Gieroszyński 1968) concerning the influence of bombardment with electrons and UV irradiation on exoelectron emission, the latter has been found to occur without illumination with light and to increase with increasing deformation. It was assumed in this paper that this emission is due to the presence of strong electric fields produced in the oxide after bombardment with electrons. The present experimental results confirm this emission mechanism in the case of dark emission during the deformation of aluminium covered with oxide layer.

It may be argued from the fact that dark emission of exoelectrons occurs only during the deformation of the sample that it is associated with micro-fissures produced in the oxide layer. These fissures are assumed to be electrified, and the electric field strengths in them are estimated to be about 10^9 V m^{-1} (Sujak *et al.* 1966). The strengths of the electric field procuced in the oxide layer after bombardment with electrons are the same order of magnitude. If one accepts that dark emission of exoelectrons is due to the presence of a strong electric field, this field will be the resultant field from the superposition of the electric field in the oxide E_t and the effective field in micro-fissures E_0. Fig. 18 once more shows a micro-fissure and the resultant field strength E_w which is the vector sum of E_t and E_0.

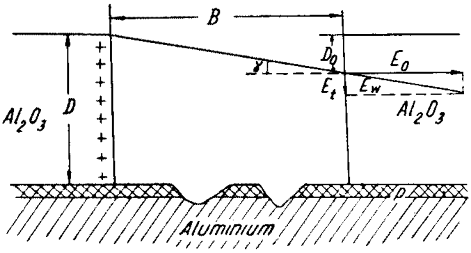

Fig. 18. Schematic drawing of a micro-fissure. D — oxide layer thickness, B — fissure width, E_0 — effective electric field strenght in the fissure, E_t — internal electric field strenght in the oxide layer, E_w — resultant field strenght

Let us accept that an electron emitted from a side wall of a micro-fissure may emerge outside if it does not encounter the opposite wall.

Let us assume that the circuit will register pulses when the electrons are emitted from a wall zone of a micro-fissure from the width (depth) greater or equal to D_0. In order that the electron emitted from the micro-fissure from the depth D_0 would be able to get outside, the width of this fissure has to be

$$B > \frac{D_0}{\tan\gamma} \tag{1}$$

where γ is the angle of inclination of the electron trajectory with respect to the surface of the sample.

The γ-angle is defined by the direction of the resultant field W_w, as

$$\tan\gamma = \frac{E_t}{E_0}. \tag{2}$$

After substituting (2) into (1) one obtains

$$B > D_0 \frac{E_0}{E_t}. \tag{3}$$

Since B was defined earlier as the width of the microfissure at which the first pulses appear and it is known from the previous paper (Gieroszyński *et al.* 1964) that $\varepsilon \sim B$, then the value of ε will have the sense of initial strain εo_d. Thus εo_d will be given by the following dependence:

$$\varepsilon_{od} \sim D_0 \frac{E_0}{E_t}. \tag{4}$$

The influence of such paramenters as D, t_b, i_e and U_b on ε_{od} which has been found experimentally can be qualitatively explained by the relation (4). Making use of the results of Loeb (1958) concencerning the electrification of dielectrics by disrupting the solids we obtain that the value of the charge q accumulated on separated surfaces is proportional to the square root of the area of these surfaces.

Assuming the validity of this dependence for the case of break up of the oxide layer covering the aluminium sample we obtain the electric field strength in the fissure $E_0 \sim \frac{q}{S} \sim \frac{\sqrt{S}}{S} = \frac{1}{\sqrt{S}}$, where S is the area of the side walls of the fissure. Since $S \sim D$ then $E_0 \sim \frac{1}{\sqrt{D}}$.

Assuming that D_0 and E_t are constant we have according to (4) that ε_{od} decreases with increasing oxide layer thickness D which is in agreement with experiment (Fig. 2).

The value of E_0 as well as E_t will change with the change of the parameters t_b, i_e and U_b (Gieroszyński 1968). If one accepts that E_t increases proportionally to the charge Q introduced to the oxide and since $E_0 \sim \sqrt[3]{Q}$ (Gieroszyński 1968) then the $\frac{E_0}{E_t}$ — ratio will decrease with increasing Q and so will εo_d, a fact which is confirmed by the experimental results given in Figs 3 and 4.

The influence of U_b on ε_{od} is associated with the change of the secondary emission coefficient with the energy of exciting electrons U_b. In the interval of bombarding electron energy applied (260—1800 eV) the secondary emission coefficient descreases with increasing U_b and thus the charge Q decreases. The $\frac{E_0}{E_t}$ — ratio will also increase with increasing U_b and according to (4) there will be an increase in ε_{od}. This is confirmed by the experimental dependence of ε_{od} on U_b shown in Fig. 5.

According to the model presented here the kinetics of dark emission during deformation $\frac{N}{t}(\varepsilon)$ may be associated with the increase of the emitter area. It can be seen from Fig. 18 that for increasing fissure width B ($B \sim \varepsilon$) electron may escape from larger surface of fissure wall, *i. e.*, from larger emitter area. The intensity of emission at the instant of break-up for a fixed oxide layer will be dependent on the $\frac{E_t}{E_0}$ — ratio. The greater the value of this ratio the larger the emitter area from which the electrons may emerge outside. For a given value of strain the circuit will then regiser more pulses.

The decay of dark emission after stopping the deformation process can be explained by a parallel decrease in $\frac{E_t}{E_0}$ in time.

The present model of dark emission of exoelectrons during the deformation of aluminium covered with oxide layer explains qualitatively the experimental results obtained. It should be however born in mind that this model concerns only the mechanism of emergence of electrons from the microfissure.

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