SAND--77-0809C

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ELECTRON TRAJECTORIES IN THE AVALANCHE PROCESS*

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CONF-771028--1

INTRODUCTION

Surface flashover on solid insulators is an important breakdown mechanism in vacuum. It is believed that an electron avalanche, which occurs prior to flashover, plays a role in the breakdown mechanism. The avalanche involves electron multiplication on the insulator surface via secondary emission. Boersch, et al. have studied insulator surface charging by secondary emission,[1] but a detailed analysis of the avalanche process is lacking.

We have calculated the trajectories of electrons emitted from an insulator under electrical stress in vacuum as a first step toward time-dependent numerical simulation of a secondary electron emission avalanche. Results indicate that most of the electrons strike the insulator at shallow angles of incidence with respect to the plane of the insulator surface, and that the angle of incidence depends on the incident energy when the space charge sheath of electrons above the insulator surface is taken into consideration.

TRAJECTORY CALCULATION

Figure 1 depicts the trajectory of an electron which reencounters the surface of an insulator from which it was emitted. The angles θ_e and θ_i are the angles of emission and incidence, respectively, and are measured with respect to the insulator surface, the x-y plane. The angle α is the angle between the projection of the initial velocity in the x-y plane and the y axis.

*Work supported by U. S. Energy Research & Development Administration

The electric field E lies in the y-z plane, at an angle ϕ with respect to the -y axis. The field E includes all sources of field (polarization charge, real charge, electrode potential), except the z component of the electric field arising from space charge due to the swarm of electrons in flight above the insulator surface (the space charge sheath).

Expressions may be obtained for the incident energy, A_i and the angle of incidence as functions of the emission energy, A_e, and the angular variables defined by Fig. 1. Calculations are simplified if the electric field E of Fig. 1 is assumed to be constant over the length of a trajectory. This is a reasonable assumption in most cases. The space charge sheath, however, contributes a z-component of electric field which is a function of z. This field component affects the time of flight of electrons, as will be explained later.

In order to obtain the incident energy and the angle of incidence, the three components of the incident velocity must be determined. The x and z components are equal to the velocity components at emission, except the z component is reversed in sign. The y component is given by

$$v_{yi} = v_{ye} + eE_y \, t/m' \quad , \qquad (1)$$

where E_y is the y component of the electric field, e and m are the electronic charge and mass, and t is the time of flight. The time of flight is

$$t = -2m \, v_{ze} \, \beta/cE_z \quad , \qquad (2)$$

where E_z is the z component of the electric field excluding the z component due to the space charge sheath, and β is a factor that accounts for the perturbation of the electron trajectory due to the presence of a space charge sheath.

The factor β is a function of the emission velocity component v_{ze} and the relative density of space charge compared to surface charge. Values of β have been determined by a self-consistent calculation of the time of flight of electrons above the insulator surface. A brief description of the numerical simulation employed may be found in Ref. 2. The space charge is considered to be saturated if the z component of the electric field in the vacuum is zero above the swarm of electrons. Under this circumstance, electrons emitted with a large v_{ze} penetrate nearly to the top of the space charge, where they remain for a relatively long time. The factor β is large for these electrons. (Such electrons gain large amounts of energy from the electric field and strike the insulator surface at low angles of incidence.)

The following expressions for incident energy and angle may be obtained with the aid of Eqns. (1) and (2) and the definition of variables in Fig. 1.

$$A_i = A_e (1 + F) \quad , \tag{3}$$

$$\tan\theta_i = \sin\theta_e (\cos^2\theta_e + F)^{-1/2} \quad , \tag{4}$$

where the quantity F is given by

$$F = 4 \beta \cot\phi \sin\theta_e (\cos\alpha \cos\theta_e + \beta \cot\phi \sin\theta_e) \quad . \tag{5}$$

It is interesting to note that the magnitude of the electric field E does not appear in these equations.

RESULTS AND DISCUSSION

The information contained in Eqns. (3) through (5) may be visualized by plotting A_i versus θ_i for a large number of electrons. For this purpose, 1000 "electrons" were selected at random from a cosine angular distribution[3] (flux proportional to $\sin\theta_e$ according to the definition of angles here and independent of α), and a simplified emission energy spectrum (short-tail spectrum in Ref. 2) that approximates typical energy distributions over the energy range from 0 to 16 eV.

The effects of the electric field angle ϕ and various degrees of saturation of the space charge sheath may be seen in Figs. 2 and 3. It is immediately apparent that θ_i is equal, on the average, to $\phi/2$ for the case of no space charge. As the amount of space charge is increased, some of the electrons are accelerated to increasingly high energies and an inverse relationship between A_i and θ_i develops. The highest energy electrons strike the insulator surface with even smaller angles of incidence than for the case of no space charge. The dependence of incident energy A_i on field angle ϕ is also apparent. The average incident energy decreases with increasing electric field angle, regardless of the degree of space charge saturation.

The secondary electron emission yield of many materials is known to depend strongly on the angle of incidence of the primary electrons, and can be much larger at shallow angles of incidence than at normal incidence.[3] During a secondary emission avalanche, the electric field angle reaches a maximum when the insulator surface becomes sufficiently charged to prevent further electron multiplication.[1] Observed values of this maximum field angle include 16° for alumina ceramic[4] and 35° to 40° for Plexiglas.[5] If the maximum angle for most materials falls within this range, the average angle of incidence during the avalanche process, which is approximately one half the field angle, is 20° or less. Yield curves for normally incident primaries may therefore seriously underestimate the actual yields during an electron avalanche.

CONCLUSIONS

Three significant conclusions may be drawn from this work: (1) During the avalanche process secondary electrons are returned to the insulator surface with angles of incidence equal, on the average, to approximately one half the electric field angle, where both angles are measured with respect to the plane of the insulator surface. (2) The appropriate secondary emission yields are those which apply to primary electrons at shallow angles of incidence. Such yields can be significantly higher than the normal-incidence yields. (3) When perturbations of the electron trajectories due to the space charge sheath of electrons above the insulator surface are accounted for, a relationship between incident energy and incident angle is found. The angle of incidence decreases with increasing incident energy.

REFERENCES

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4. J. P. Brainard and D. Jensen, J. Appl. Phys. 45, 3260 (1974).
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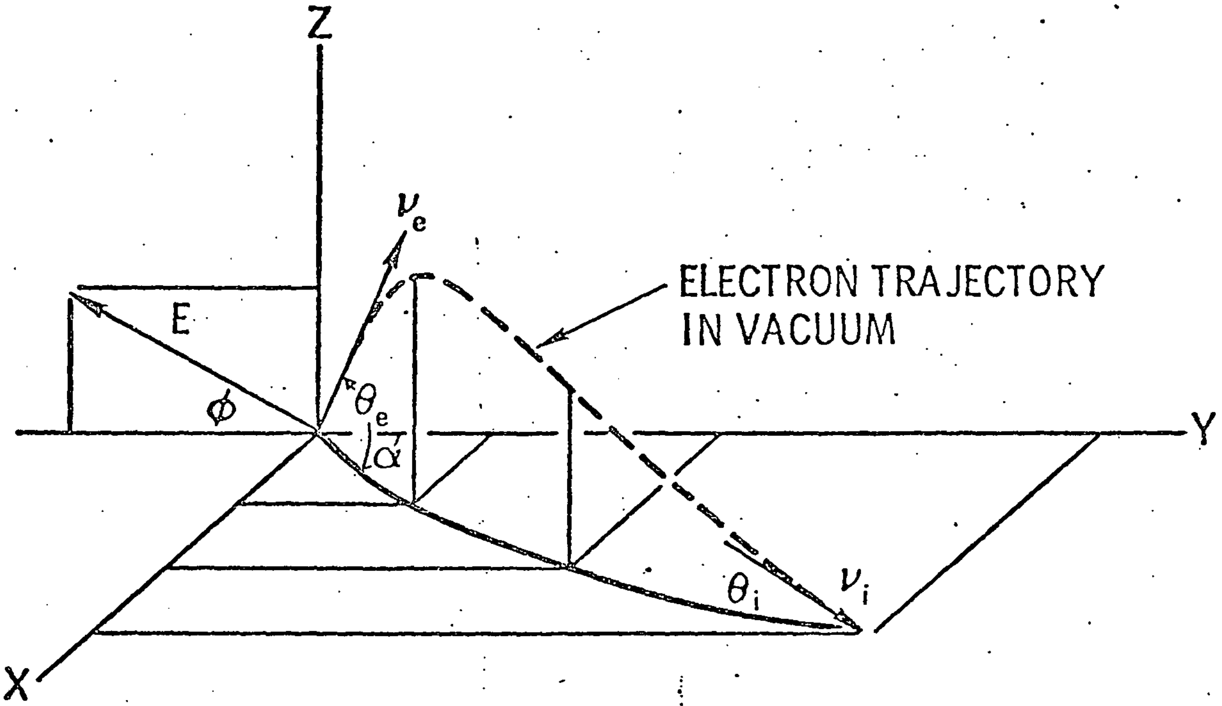
Figure Captions

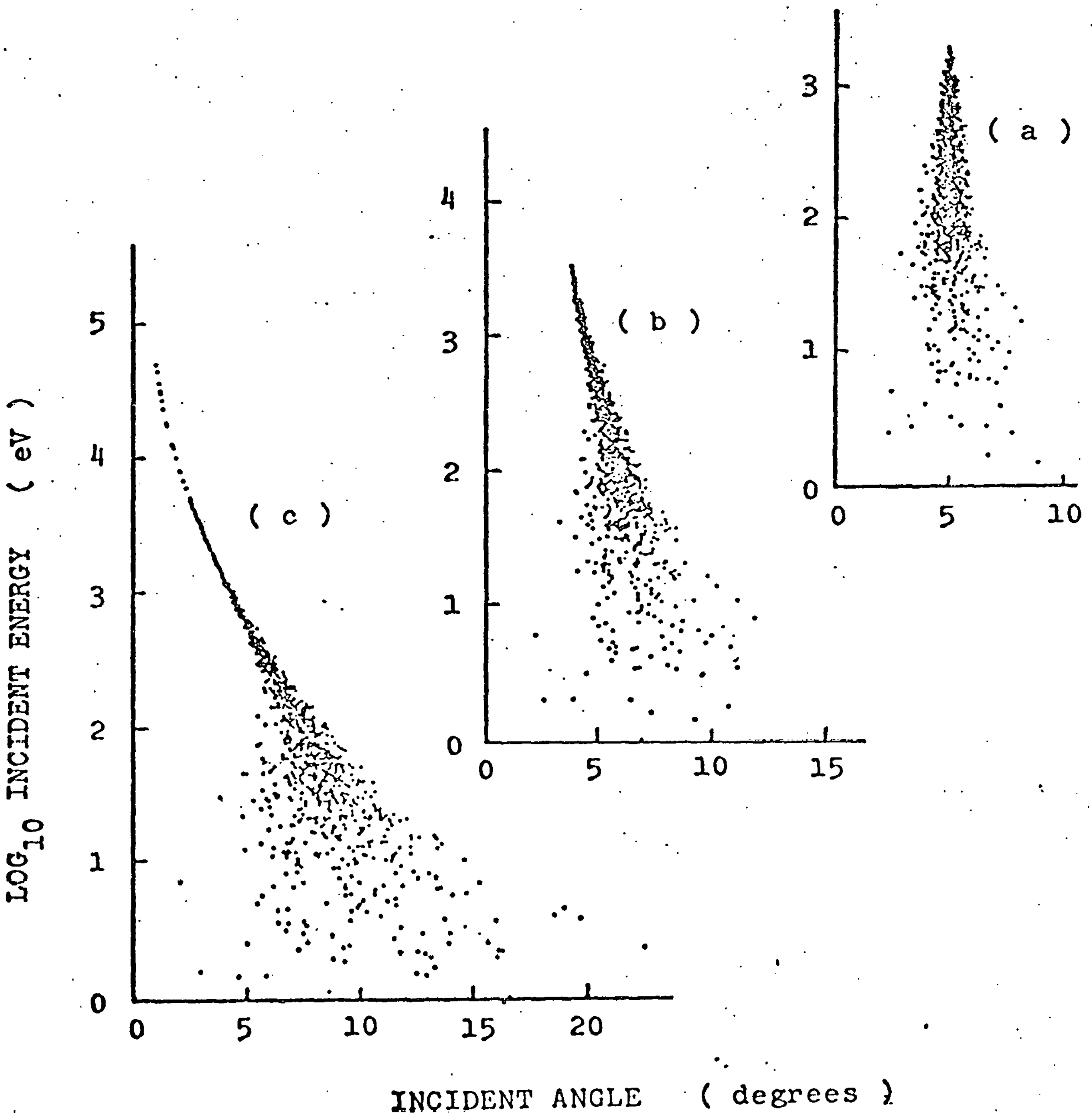
Fig. 1. An electron trajectory above an insulator surface (the x-y plane) illustrating the emission and incident velocity and the electric stress E.

Fig. 2. Plots of incident energy versus incident angle from 1000 randomly selected electrons when the field angle ϕ = 10° for a) no space charge, b) 30% saturated space charge, and c) 90% saturated space charge.

Fig. 3. Plots of incident energy versus incident angle from 1000 randomly selected electrons when the field angle ϕ = 30° for a) no space charge, b) 30% saturated space charge, and c) 90% saturated space charge.



INSULATOR SURFACE IS IN THE X-Y PLANE


(a)
(b)
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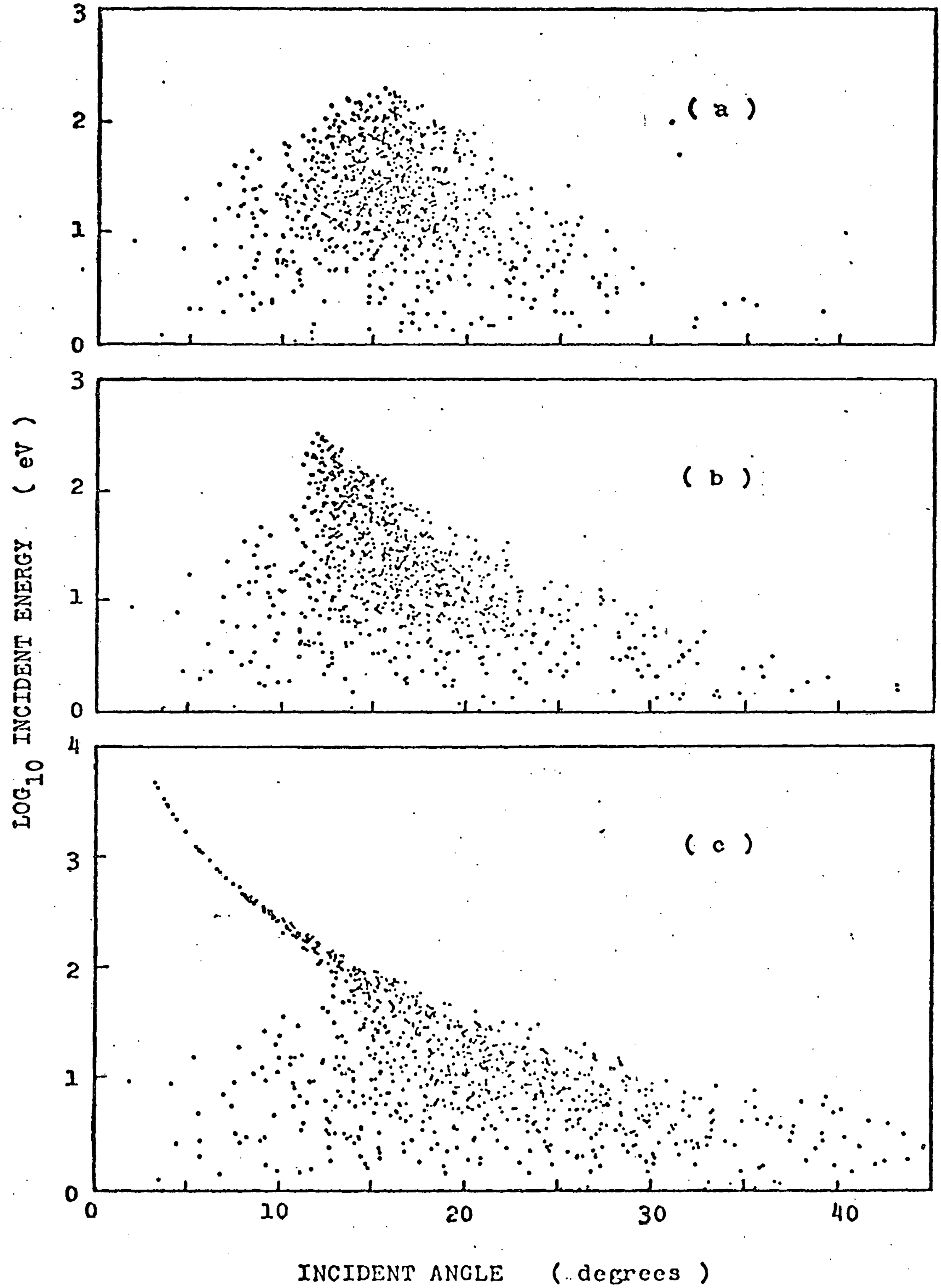
LOG10 INCIDENT ENERGY (eV)
INCIDENT ANGLE (degrees)
0
1
2
3
4
5
10
15
20


(a)
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LOG_{10} INCIDENT ENERGY (eV)
INCIDENT ANGLE (degrees)
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1
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10
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30
40