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ELECTRICAL SURFACE BREAKDOWN: SECONDARY ELECTRON EMISSION AND ELECTRON SPECTROSCOPY OF INSULATORS

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Abstract

These results question the usual scheme of flashover. They lead to a different interpretation based on classical concepts in solid state physics which can be verified at every step. An ionizing cascade in the bands, rather than a cascade of electron multiplication on the insulating surface, could explain the flashover, the conditioning and the deconditioning of high voltage generators through the building of a surface charge. As in the usual model the positive charge is responsible for the flashover, in this new model the building of this charge is the basis of the conditioning. The ionizing cascade in the bands is initiated by a tunnel injection into the insulator from the soldering metal-insulator junction or by electronic excitation. This interpretation is supported by the analysis of charging phenomena in insulators, the study of localization sites of carriers and by the neutralization mechanisms, charge diffusion or defect annealing. These studies are achieved by scanning electron microscopy and electron spectroscopy.

Key Words: Breakdown phenomena, flashover, surface science, charging mechanism, insulators, electron cascade.

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Introduction

The traditional model of surface breakdown -flashover- of insulators placed in an intense external electrical field relies on the cascade theory proposed by Boersch (Boersch, 1963) (Figure 1). Here, the surface of the insulator is bombarded by electrons field-emitted into the vacuum from whiskers and because its secondary electron yield is greater than one, leads to electron multiplication and creation of a positive surface charge propagating towards the anode. The observed pressure increase is assumed to be produced by the desorption of gas from the inner walls (Anderson, 1980).

This model which is based on earlier ideas by Gleichauf (Gleichauf, 1951) and Kofoid (Kofoid, 1960) requires five hypotheses to support it: H_1: plane condenser geometry; H_2: classical shape of secondary electron yield; H_3: the secondary electrons emitted in the vacuum have all the same mean energy of reemission E_0; H_4: reemission angular distribution is isotropic; H_5: the space charge due to the electronic current is neglected. Bergeron (Bergeron, 1977) has made more precise calculations abandoning the H_3 and H_5 hypotheses and considering an energy distribution of the emitted electrons in agreement with solid state physics and shown that these differences do not drastically change the adopted model. The field-emitted electrons at the triple point hit the inner surface with an energy between the two cross-over values E_1 and E_2, where the yield is greater than 1. They induce therefore a positive charge on the surface responsible for the recall to the surface of the secondary electrons. However, there is no unanimity among the advocates of this model about the value of the equilibrium potential of the inner surface. Some of them consider the first cross-over E_1 value (Avdienko, 1977a,b), others the second cross-over E_2 (Anderson, 1980), with 20 V and 2500 V respectively. Anderson and Brainard emphasize that the

stability of the charge governed by E_1 has not been demonstrated rigorously. The positive charge has been evidenced indirectly in terms of the deviation of an electron beam in the vicinity of the surface after flashover or by electro-optical measurements (de Tourreil, 1972; Thompson, et al., 1976 1980). One can deduce from these experiments the field increase at the cathode and the modifications of the interelectrode field due to a surface charge propagating towards the anode.

Let us consider a plane section of a cathode-insulator-anode junction having a linear surface charge distribution σ, $\sigma > 0$, (Figure 2), for which a rough calculation permits us to determine the shape of the total field induced by σ. The total electric field at the interface in a point M close to the surface is

$$\vec{\mathcal{E}} = \vec{\mathcal{E}}_o + \vec{\mathcal{E}}_\perp \qquad (1)$$

where $\mathcal{E}_o$ is the field created by the potential between the electrodes and $\vec{\mathcal{E}}_\perp$ the orthogonal field induced by the positive charge. The components of $\vec{\mathcal{E}}_\perp$ in M are:

$$\vec{\mathcal{E}}_\perp^x = \sigma \left\{ \frac{1}{\sqrt{a^2+(\ell-x)^2}} - \frac{1}{\sqrt{a^2+x^2}} \right\}$$
$$\vec{\mathcal{E}}_\perp^y = \frac{\sigma}{a} \left\{ \frac{\ell-X}{\sqrt{a^2+(\ell-x)^2}} \quad \frac{X}{\sqrt{a^2+X^2}} \right\} \qquad (2)$$

where a, ℓ, and X are defined on figure 2. Thompson made a measure of the positive charge σ from the displacement time of the field towards the cathode. Let us consider the applied voltage to have the gaussian form:

$$\mathcal{E}_o(t) = \mathcal{E}_o \exp - \frac{(t-t_o)}{b^2} \qquad (3)$$

and the charge distribution to vary linearly with time according to:

$$\sigma(t) = \sigma \cdot t \qquad (4)$$

Close to the cathode, the response of the total field to the $\mathcal{E}_o$ excitation presents a maximum of a time $t > t_o$, corresponding to a field increase, even after the decrease of the impulse. These experiments emphasize the presence of a positive charge at the beginning of the voltage application but do not take into account the character of induced σ by the applied field. The positive charge creates a field $\mathcal{E}_\perp$ perpendicular to the surface, able to recall the emitted electrons. When this flux hits the surface again, new negative and positive charges are created, depending on its E impact energy, where this E energy is given by:

$$E = E_o \left\{ 1 + 2\left(\frac{\mathcal{E}_\perp^x}{\mathcal{E}_\perp^y}\right)^2 \right\} \qquad (5)$$

The stable regime would be reached when $E = E_1$. If $E > E_1$, a positive charge is created, $\mathcal{E}^y$ increases and E decreases to E_1, and vice versa when $E < E_1$. The stable regime would correspond to a angle between $\mathcal{E}$ and the surface where:

$$\operatorname{tg} \Theta = \sqrt{\frac{2E_o}{E_1 - E_o}} \qquad (6)$$

and where the surface charge is given by:

$$\sigma = 2\, \mathcal{E}_o\, \mathcal{E}_\perp^x \operatorname{tg} \Theta \qquad (7)$$

Admitting that the positive charge is created by the first impacts, one cannot understand by which mechanism it propagates. What force recalls the electrons reemitted beyond this initially charged zone? Bergeron proposes that they hit the surface with an energy greater than E_1, creating a positive charge in a previously neutral zone, which is then assumed to propagate towards the anode. This attempted explanation implicitly admits the existence of the stationary regime of cascade, although one considers electrons after only one impact. On the other hand the question of the characteristic life time of a positive carrier is never considered.

All these ambiguities are due to a much too macroscopic approach of charge phenomena in insulators.

The use of the secondary electron emission from insulators imposes a correlation between emission and charge which is not necessary and depends on the structure of the gap. The emission comes essentially from excitation of interband transitions while the charge mechanism implies carrier localization on localized levels in the band gap. A positively charged surface at a V potential cannot emit secondary electrons with kinetic energy inferior to e.V, because these electrons are deviated towards the ionized atoms of the lattice. Because secondary emission is intense only on the first unoccupied levels of the conduction band situated just above the vacuum level, the emission beyond 20 eV is weak. In other words, (a) the yield at energies greater than 20 eV is certainly less than unity and cannot lead to a diverging system, (b) excitation of interband transitions in the vicinity of a positive charge favours neutralization of this charge. Without magnetic field or extracting electric field, the electron bombardment favours formation of negative charges or neutral surfaces, (c) the positive charge is stable only if it is weak (a few fractions of the gap). The secondary electrons with at least the energy of the gap are not submitted to coulombic attraction and cannot escape without neutralizing this charge. More recently, attempted explanations of electrical discharge and avalanche have been

proposed on the basis of classical models from solid state physics (Latham, 1982; Kao 1983). Only Vigouroux et al. (1983), as far as we know, have attempted to isolate experimentally the different phases of flashover including initiation, propagation and their consequences on the state of the surface (conditioning effect).

The study of the "charging up" phenomenon appears (Le Gressus, 1984) essential to the understanding of flashover. Against the classical approach and as shown by the experiments on monocrystalline insulators, there is no direct correlation between charge and conductivity. Our approach is therefore based on: (a) physical description of the mechanisms of secondary electron emission on insulators; (b) study of physico-chemical nature of localized levels in the band gap; and (c) study of charge stability under diverse excitations. We propose a model for the breakdown which takes into account all the macroscopic phenomena and where all the steps can be isolated and simulated separately.

Secondary electron emission of insulators

The electronic structure of an insulator consists of three zones of binding energies for the weakly bound electrons: (a) the valence band composed of filled states, (b) the band gap in which the defects introduce allowed localized levels, (c) the conduction band composed of allowed empty states, the band bottom is at 1.5 eV below the vacuum level.

Electron-electron interactions or plasmon relaxations induce transitions between filled states below the top of the valence band (-10 eV) and empty states above the bottom of the conduction band. The shape of the distribution (Figure 3) represents the density of states in the valence band if one assumes the interaction probability with these electrons to be uniform. During its transfer to the surface, the electron is submitted to interactions with atoms and electrons in the solid and the energy distribution is reinforced at a mean energy of around $\phi/3$, where ϕ is the potential barrier (Figures 3b and 3c). The secondary emission therefore comes from interband transitions - if their energy is greater than the gap width - but does not involve directly the localized levels in the band gap.

On the other hand the spatial distribution of the electrons emitted into the vacuum is anisotropic and follows a $1/\cos\theta$ law imposed by refraction due to the change of dielectric constant between insulator and vacuum.

Experimental

The experimental methods, electron spectroscopy and scanning electron microscopy, used in this study have already been described in other paper (Le Gressus et al., 1984).

The charge mechanism is linked with the interaction of carriers and localized levels, which are characteristic of point defects as oxygen vacancies or interstitials and which introduce a density of allowed empty states in the gap. Recombination of carriers of opposite signs head to electron emission following an Auger-type mechanism (exoemission) or to a photon emission (luminescence) (Figure 4). Electron loss spectroscopy optical absorption give access to the energetic position of these levels (Underhill, 1981; Gallon, private communication; Griscom, 1978).

There exists in every insulator native intrinsic defects (around 10^{16} cm^{-3}) but electron bombardment induced charge is mainly due to the new defects created by this irradiation. We did observe that an amorphous silica (numerous native intrinsic defects) and a monocrystalline SiO_2 (no defects) charge up in a similar way, evidencing the role of the irradiation doses on the native charge and on the exoemission (Glaefeke, 1981).

Comparing charging up in SiO_2 and Al_2O_3, having quite different dielectric behaviors. Because SiO_2 is much more sensitive to give further information ionizing radiations than Al_2O_3, surface potential observed under electron bombardment in both materials is always negative whatever the primary energy is and higher for SiO_2 than for Al_2O_3. The propensity to charging up follows therefore the same variation as the propensity to radiation damage (Figure 5). This charge property permits us (a) to produce intense local fields (10^5V/cm) of the same order as those responsible for breakdown, (b) to study their stability and reproducibility, (c) to know more about the physico-chemical nature of localization sites and (d) to observe the response of the dielectric to any external excitation (thermal, radiative...).

The new elements of this work are: better understanding of the nature of electron traps, study of their annealling and characterization of the ionization cascade in relation with charge diffusion (Vigouroux, 1984a).

The defects able to trap a charge carrier in SiO_2, determined by electron spin resonance (Griscom, 1978), are the following: (a) a non-bridging oxygen (NBO), (b) the E'-center, created by an oxygen vacancy and the ejection of one of the electrons which participated pre-

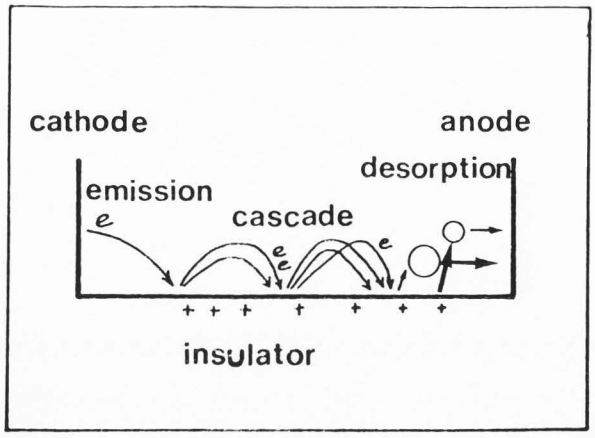

Fig.1. Traditional model of surface flashover.

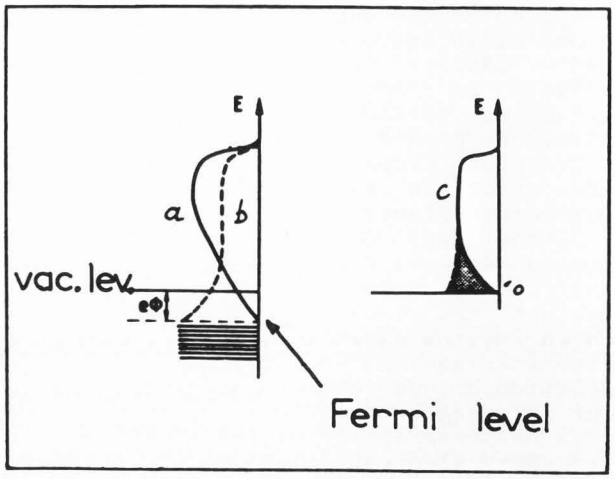

Fig.3. Steps of the secondary electron emission: (a) excitation, (b) transfer towards the surface, (c) emission into the vacuum.

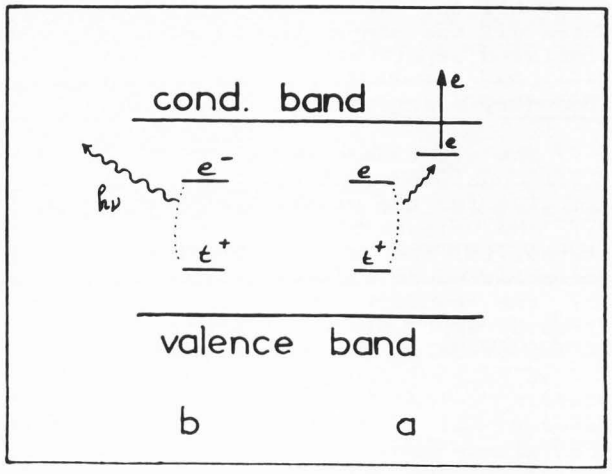

Fig.4. Electron-hole recombination: (a) exoemission, (b) luminescence.

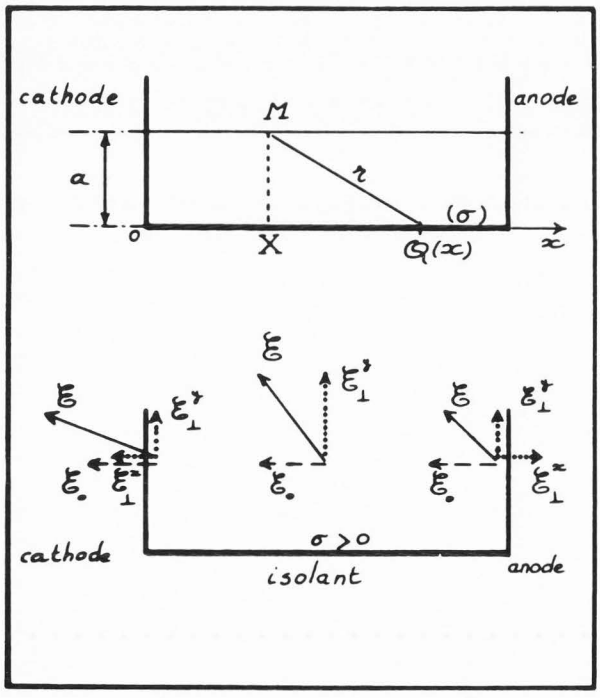

Fig.2: Model for calculation of the diverse electric field due to a surface charge. l is the inter-electrode length.

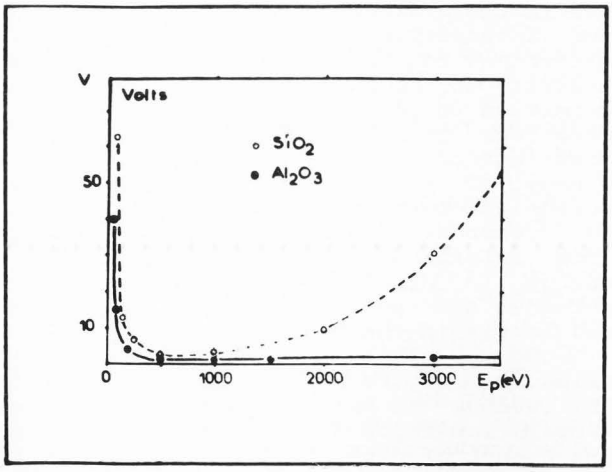

Fig.5. Equilibrium potential under electron bombardment at primary energy E_p, of SiO_2 (a) and Al_2O_3 (b).

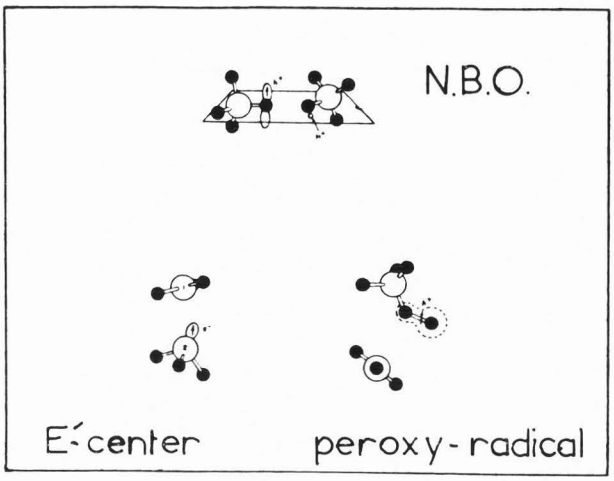

Fig.6. Different types of point defects in SiO_2.

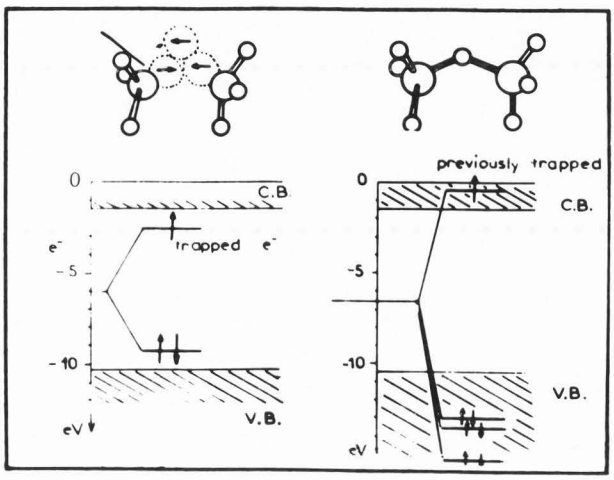

Fig.7. Energetical point of view corresponding to the existence or the lack of point defects.

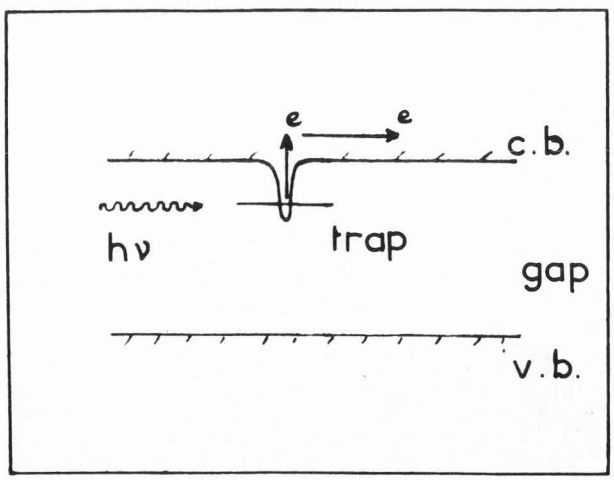

Fig.8. Detrapping mechanism.

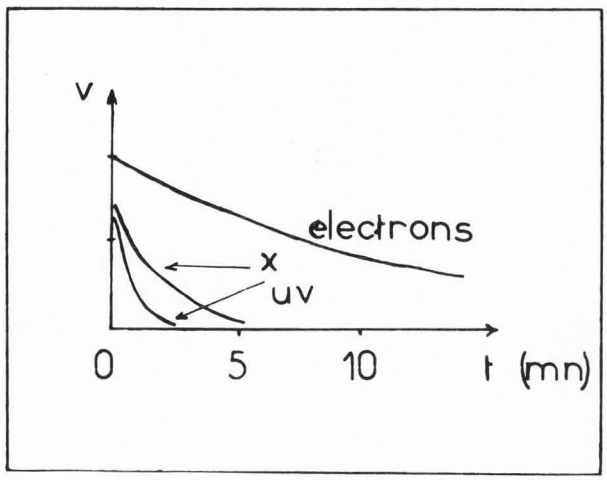

Fig.9. Surface charge behavior of charged insulators under different external excitations.

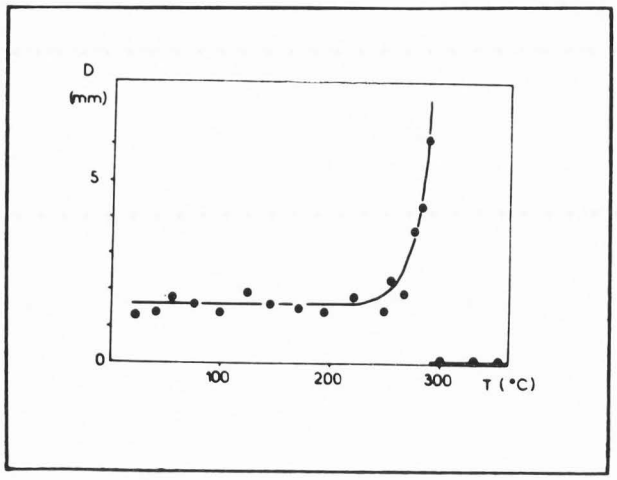

Fig.10. Equilibrium potential behavior with temperature of amorphous SiO_2 submitted to electron bombardment.

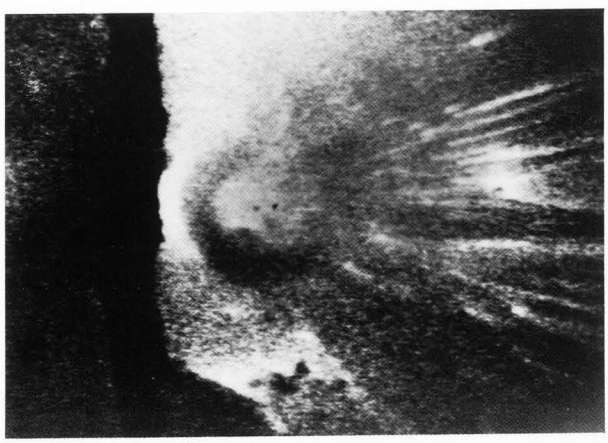

Fig.11. Internal discharge -similar to electrical treeing- observed by scanning electron microscopy. Contrasts are due to local differences of potential.

viously to the bond, (c) the peroxy-radical, molecular oxygen bound to silicon (complementary effect to E'-center) (Figure 6). The charge of the insulator is then assumed to result from the trapping of an electron on a pseudo-bond Si-Si (Figure 7) (precursor state to E'-center). On the energetic point of view, the state of this electron corresponds to a filled localized level in the gap (Vigouroux, 1984b,c).

Under electron, UV photon, X-ray irradiation the charge disappears through carrier detrapping (Figures 8 and 9) mechanism described classically in semiconductor physics (Figure 7) (Pantelides, 1978).

A temperature increase of the charged sample induces annealling of the defects and disappearance of the charge (Figure 10). There are for SiO_2 three zones of equilibrium potential versus temperature (Figure 10): (a) at $T < 250°C$ no influence of temperature, (b) at $250 < T < 280°C$ interstitial oxygen ions diffuse out of the irradiated zone. This simulated diffusion displaces the equilibrium E'-center-peroxy radical towards a greater concentration in E'-centers hence more charges, (c) $T > 280°C$ the anneal is assumed to be described in terms of H_2O diffusion (Vigouroux, 1984c).

When the insulator is placed in an electric field, one can observe the result of a cascade of multiplication produced by diffusion of electrons injected in the conduction band. The observation of the surface by scanning microscopy, after propagation of the cascade (Vigouroux, 1984a) shows dielectric heterogeneities (Figure 11). The image contrast is due to a potential contrast. The injected electrons are submitted to the electric field on distances of around a few tens of microns. They acquire kinetic energy (10 meV/Å) and induce electron-electron interactions, as soon as their energy is greater than the gap width. The secondary electrons can either be emitted into the vacuum or enter the cascade processes in the solid. This is the type-mechanism of secondary electron emission. During the propagation of the cascade, the heterogeneities are pinned because their vicinity is a zone of more intense radiation damage and therefore a zone of preferential trapping and ionization.

Discussion

We think that the elementary experiments described above explain the surface breakdown of dielectric materials submitted to intense electric fields. Following a simple scenario, the breakdown is initiated by electron excitation at any point on the surface. This excitation can proceed from emission of electrons or photons following the nature of the generator or can be associated with a tunnel injection at the cathode and at the soldering.

Assuming a p proportion of electrons to be emitted into the vacuum, focused afterwards by the field between cathode and anode, then a 1-p proportion is injected into the insulator and is submitted to the applied field which penetrates the insulator. These electrons would arrive on the anode with a kinetic energy of ed $\mathcal{E}_o$ (where $\mathcal{E}_o$ is the applied field) if they were not subjected to any hit in the insulator. But they are diffused by inelastic interactions, creating a cascade of multiplication along the surface inside the insulator as soon as their energy exceeds the gap width. A proportion of these cascade electrons is emitted into the vacuum where the external field focuses them towards the anode. One would observe therefore the propagation of the cascade in the insulator from the cathode to the anode, increasing the total flow. This ionization cascade is accompanied by stimulated desorption of adsorbed species or components of the insulator. The extracted electrons create a number of positive carriers (holes) in the valence band a part of which is trapped, building a positive charge propagating to the anode following the cascade. This charge modifies the field map in the vicinity of the triple point and would counteract another cascade produced by a new electric prompting. This interpretation is supported by a study of the role of the field distribution at the triple point (Furno, 1982).

Contrary to the former interpretation of flashover, ours gives an account of the origin of conditioning and of the time constants of deconditioning. The surface charge is no longer the cause of the flashover but the consequence. The soldering technique at the triple junction is the technological key point. This conclusion is also in agreement with other previous experimental studies (Sudarshan, 1976).

Conclusion

The former theories of flashover are not based on hypotheses in agreement with the solid state physics point of view about the secondary electron emission. The charging up problems on insulators generally lead experimenters to neutralize these charges, thus losing sight of the dielectric properties of the materials. The study of charge phenomena combined to the application of usual principles in solid state physics and electron-solid interactions permits one a new model for the breakdown where all the steps are separated and verified. We will

show in future works that it is possible to explain the origin of the deconditioning of high voltage generators. These results are more generally applicable to other problems involving the dielectric state of solids.

References

R.A. Anderson, J.P. Brainard, "Mechanism of pulsed surface flashover involving electron-stimulated desorption", J. Appl. Phys., 51, 3 (1980) 1414-1421

A.A. Avdienko, M.D. Malev, "Flashover in vacuum", Vacuum, 27, 12 (1977a) 643-651

A.A. Avdienko, M.D. Malev, "Surface breakdown of solid dielectrics in vacuum. II mechanism for surface breakdown", Sov. Phys. Tech. Phys., 22, 8 (1977b) 986-991

K.D. Bergeron, "Theory of the secondary electron avalanche at electrically stressed insulator-vacuum interfaces", J. Appl. Phys. 48, 7 (1977) 3073-3080

H. Boersch, H. Hamisch, W. Ehrlich, "Oberflächenentladungen über Isolatoren im Vacuum, Z.für angew. Phys. 15, 6 (1963) 518

E.J. Furno, R.E. Shafer, "Field shaping to improve vacuum diode voltage holdoff", Proceedings of the tenth Int. Symp. on Discharges and Electrical Insulation in vacuum, IEEE, NY, (1982) 339

H. Glaefeke, "Thermally stimulated relaxation in solids", Exoemission, Springer Verlag, (1981), 225-273

Gleichauf, "The electrical breakdown over insulators and high vacuum", J. Appl. Phys. 22(5) (1951) 535-541

D.L. Griscom, "Defects in amorphous insulators", J. of non-cryst. Sol., 31 (1978) 241-266

K.C. Kao, "New theory of electrical discharge and breakdown in low-mobility condensed insulators", J. Appl. Phys., 55, 3 (1983) 752

M.J. Kofoid, "Effect of metal dielectric junction phenomena in high voltage breakdown over insulators vacuum transaction power apparatus systems", 79(3), (1960) 999-1004

R.V. Latham, "The origin of prebreak down electron emission from vacuum-isolated high-voltage electrodes", Vacuum, 32, 3 (1982) 137-140

C. Le Gressus, J.P. Vigouroux, J.P. Duraud, C. Boiziau, J. Geller, "Charge neutralization on insulators by electron bombardment", Scanning Electron Microscopy, 1984;I:41-48

S.T. Pantelides, (ed.), The Physics of SiO_2 and its interfaces, Pergamon, New York (1978)

T.S. Sudarshan, J.D. Cross, "The effect of chromium oxide coatings on surface flashover of alumina spacers in 'vacuum'. IEEE Tr. on Elec. Insul. EI-11, 1 (1976) p 32-35

J.E. Thompson, M. Kristiansen, M.O. Hagler, "Optical measurements of high electric and magnetic fields", IEEE Tr. on Instrum. & Meas. 25, 1 (1976) 1-7

J.E. Thompson, J. Lin, K. Mikkelson, M. Kristiansen, "Electro-optical surface flashover measurements", Appl. Phys. Lett., 37, 6 (1980) 574-576

C. H. de Tourreil, K.D. Srivastava, U.J. Woelke, "Experimental observation" of surface charging of high-voltage insulators for vacuum apparatus", IEEE Tr. on Elec. Insul EI-7, 4 (1972) 176-179

P.R. Underhill, T.E. Gallon, "Electron loss studies of the silica surface" Vacuum, 31, 10-12 (1981) 477-481

J.P. Vigouroux, O. Lee-Deacon, C. Le Gressus, C. Juret, C. Boiziau, "Surface processes occurring during break down of high-voltage devices", IEEE Tr. on Elec. Insul., EI-18, 3 (1983) 287-291

J.P. Vigouroux, J.P. Duraud, C. Le Gressus, G. Petite, P. Agostini, C. Boiziau, "Study by SEM and electron spectroscopy of the cascade of electron multiplication in an insulator submitted to an electric field", Scanning Electron Microsc. 1985;I:179-182

J.P. Vigouroux, J.P. Duraud, A. Le Moël, C. Le Gressus, C. Boiziau, "Radiation induced charges in SiO_2", Nucl. Instr. Meth. B1 (1984) 521-525

J.P. Vigouroux, J.P. Duraud, A. Le Moël, C. Le Gressus, D.L. Griscom, "Electron trapping in amorphous SiO_2 studied by charge build-up", (1985) J. Appl. Phys., in press

Discussion with Reviewers

T.J. Shaffner : Macroscopic models of a variety of charging phenomena have been described by Shaffner and Hearle (SEM, 1976) which depend on the fields internal and external to the specimen. Which of these effects can be described by your models ?

Authors: Our models can describe all these effects as they are supported only by creation of high internal field (charges implanted on defects) inducing the external field (mirror effect) and by enhanced propagation of charges.

T.J. Shaffner : How were the potentials in Figure 3 measured ?

Authors: By the energy shift of secondary electron emission onset, corresponding to a surface potential.

T.J. Shaffner : How close to the surface do you propose the point defects shown in Figures 4 and 5 are ? Do these occur within the outermost one or two monolayers ?

Authors: We think they are created at the surface and in the bulk. The preexisting ones must be nevertheless greater at the surface.

T.J. Shaffner : Are elastically scattered primary electrons important to your mechanisms ?
Authors: Yes, they can contribute to brightness increase (Figure 11).

Additional Reference

T.J. Shaffner, J.W.S. Hearle, "Recent advances in understanding specimen charging", Scanning Electron Microsc. 1976; I: 61-70, 82