Journal of Applied Mechanics an Technical Physics Vol. 35, No. 2, 1994

STUDY OF THE RADIATION CHARGING OF DIELECTRICS BY IONS

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UDC 539.2;539.12.04

The radiation charging of dielectrics exposed to a flow of charged particles (electrons or ions) has been a subject of intensive investigation over the last two decades. Most of the studies have focused on electron irradiation, which has partly to do with the greater difficulty of generating ion beams and the consequent greater expense of studying dielectric charging by ions.

This obviously makes numerical studies more important, since numerical methods make it possible to account for the various factors which influence the dynamics of the charging process.

Along with experimental results, the authors of [1] presented a phenomenological analysis of the charging of a dielectric irradiated by protons with an energy of ~ 10 MeV. Theoretical results were obtained only for a shorted dielectric ($\int_0^a E(z)dz = 0$, E, where E is the strength of the field and a is the thickness of the dielectric), and the quasi-neutrality approximation that was used basically precludes proper description of carrier drift in the non-irradiated part.

Here, we use the mathematical model in [2] to perform numerical studies of the charging of a dielectric irradiated by ions and neutral atoms. The model considers the dynamics of quasi-free charge carriers of each sign with allowance for ionization of the dielectric by the beam and charge recombination, as well as charge drift in an electric field. The effective mobility of the charge carriers is determined with allowance for its dependence on the dose rate.

The dose rate, the distribution of thermalized particles, and the current of fast particles are found by solving the kinetic equation. The integral kinetic equation in the "continuous trajectories" model [3] was solved for the ions, this equation ignoring elastic scattering but allowing for fluctuations in the energy losses. The specific energy losses of the ions were calculated from the data in [4]. The effect of the electric field on ion transfer was ignored, since the Coulomb force acting on the ions is much weaker than the frictional force – which is equal to the specific energy losses.

The kinetic equation in [3] for ions and electrons was solved by expanding the differential flux into a Fourier series in the space coordinate. The distributions thus obtained for the absorbed energy of the thermalized particles agree well with the results in [5, 6].

In this article, we present results of numerical investigations of the charging of different dielectrics irradiated by protons and atoms of hydrogen with initial energies up to 100 MeV within the range of proton current densities $j^{(b)} = 10^{-9}$-10^{-7} A/cm^2.

Figure 1a shows the scheme of specimen irradiation. A flow of particles moving in a drift region of width l strikes the dielectric. The depth of penetration of the particles is determined by their path length inside the dielectric R_0. The irradiated part (IP) of the dielectric is the region $z \leq R_0$, while the non-irradiated part (NIP) is the region $z > R_0$. The electrode that was placed on the non-irradiated surface functioned as a blocking electrode [7]. The case of a shorted dielectric is regarded as corresponding to transition to the regime to irradiation with a drift region $l = 0$. Here, the electrode on the irradiated surface will be ohmic [7].

Qualitative Description of Charging. Ionization density in the track of a proton slowed inside a dielectric material is much greater than for an electron of comparable energy. Thus, induced conductivity is high in the case of irradiation by protons, and it is reasonable to assume that charging effects are negligible – especially for a shorted dielectric.

Let us evaluate the resistance r of the irradiated part of a dielectric for the case when proton energy amounts to tens of mega-electron-volts:

Chelyabinsk. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 2, pp. 11-17, March-April, 1994. Original article submitted November 6, 1992; revision submitted April 2, 1993.

0023-8944/94/3502-0169$12.50

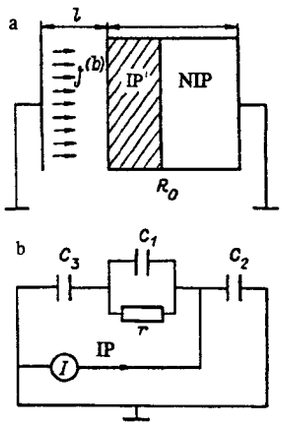

Fig. 1

$$r = S^{-1}\int_0^{R_0} dz/\sigma(z). \tag{1}$$

Here $\sigma(z) = \sigma_0(D)z)/D_0)^{\Delta}$ is the radiative (induced) conductivity of the IP [8]; S is the irradiated area of the target: σ_0 is conductivity with the standard dose rate D_0; Δ is a constant; D(z) is the dose rate at the depth z.

The quantities D can be expressed through the ionization losses B(T) in the form

$$D = j^{(b)}B(T)/e. \tag{2}$$

Considering that B(T) ~ b/T within the proton energy range 1-100 MeV [9], we find from Eqs. (1) and (2) that

$$r = (eD_0/j^{(b)}b)^{\Delta}T^{\Delta+2}/((\Delta + 2)\sigma_0 S b \rho_m), \tag{3}$$

where ρ_m is the mass density of the dielectric.

For a short-circuited dielectric, we can use (3) to find the steady-state value on the IP:

$$U(\infty) = j^{(b)}Sr = (eD_0/b)^{\Delta}T^{\Delta+2}(j^{(b)})^{1-\Delta} / ((\Delta + 2)\sigma_0 b \rho_m). \tag{4}$$

The value of Δ is close to unity for a number of materials [8], and it follows from Eq. (4) that the voltage applied to the IP is independent of beam current density, since an increase in the induced charge is compensated for by an increase in conductivity. The quantity $U(\infty) \sim T^3$, i.e., is determined only by the energy of the beam.

Field strength in the IP can be evaluated as

$$E \sim U(\infty)/R_0. \tag{5}$$

Since $R_0 = \int_0^T dT'/B(T')$, it follows from Eqs. (4) and (5) that E ~ T. Thus, the higher the energy of the primary particles, the more rapidly the space charge increases. Since the value of $U(\infty)$ given by Eq. (4) applies to the non-irradiated part of the dielectric, then $E \sim U(\infty)/(a - R_0)$ in this part. If the thickness of the specimen is such that $(a - R_0) << R_0$, then field strength in the non-irradiated part may be extremely high.

The time characteristics of the charging process can be evaluated within the framework of the capacitor model in [7]. The scheme employed to irradiate the dielectric is illustrated by the electric circuit in Fig. 1b (C_1 and C_2 are the capacitances of the irradiated and non-irradiated parts, respectively; C_3 is capacitance in the drift region; r is the resistance of the irradiated part (Eq. (3)), and I represents the beam-current generator. Here, $I_0 = j^{(b)}S$).

Having written Kirchhoff's laws for the given circuit, we obtain

$$\begin{aligned} U_1(t) &= I_0 r(C_3/(C_2 + C_3))(1 - \exp(-t/rC)), \\ U_2(t) &= I_0(t + rC_3(C_3/(C_2 + C_3)))(1 - \exp(-t/rC))/(C_2 + C_3), \\ U_3(t) &= I_0(t - rC_2(C_3/(C_2 + C_3)))(1 - \exp(-t/rC))/(C_2 + C_3), \end{aligned} \tag{6}$$

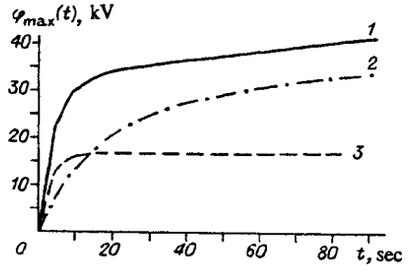

Fig. 2

where $C = (C_1C_2 + C_1C_3 + C_2C_3)/(C_2 + C_3)$; U_1, U_2, U_3 are the voltages applied to the irradiated and non-irradiated parts and the drift region.

It is evident from Eqs. (6) that no steady state exists in the case of irradiation of a dielectric with an open surface. This can be attributed to the absence of ion emission from the irradiated surface and the very low conductivity of the nonirradiated part (equal to zero in the model we are examining). The characteristics time of the process rC is determined by geometry of the radiation and the parameters of the beam.

For a shorted specimen we have $C_3 \to \infty$. It then follows from Eqs. (6) that

$$U_1(t) = U_2(t) = I_0 r(1 - \exp(-t/r(C_1 + C_2))). \tag{7}$$

At $t \to \infty$, we find steady state (4) from Eqs. (7). This qualitative description of the charging process makes it possible to obtain several useful relations linking the voltages and fields with the parameters of the beam and the dielectric. It also follows simple interpretation of experimental and numerical results.

Numerical Study of Sharging. Numerical studies were conducted for teflon ($\rho_m = 2.2$ g/cm^3, $\varepsilon = 2.0$) and polymethylmethacrylate (PMMA) ($\rho_m = 1.19$ g/cm^3, $\varepsilon = 2.5$).

The dependence of the effective mobility of the charge carriers on dose rate has the form [7]

$$\mu_{n,p} = \mu_{n,p}^{(0)}(D(z)/D_0)^{2\Delta-1},$$

where $\mu_{n,p}^{(0)}$ is the mobility of the carriers for a certain standard does rate D_0.

The parameters of teflon are well-known [7]: $\mu_p^{(0)} = 4 \cdot 10^{-14}$ m^2/(V·sec) at $D_0 = 100$ rad/sec, $\Delta = 1$. Since teflon is a dielectric with hole conductivity, the mobility of the negative carriers $\mu_n^{(0)} = 0.01\mu_p^{(0)}$.

Only data on radiation conductivity is available for PMMA [8], and no information was given here on the type conductivity or carrier mobility. We assume that unipolar electron conduction is realized in PMMA. The same assumption was made in [2] in a calculation of the charge of a dielectric irradiated by an electron beam in order to compare numerical and experimental results. The effective mobility of electrons in PMMA can be evaluated from the values on radiation conductivity in [8] and Fowler's recombination law [7]: $\mu_n^{(0)} = 4 \cdot 10^{-14}$ m^2/(V·sec) at $D_0 = 100$ rad/sec, $\Delta \approx 1$. Hole mobility in PMMA $\mu_p^{(0)} = 0.01\mu_n^{(0)}$. Dark values of effective carrier mobility were measured in [10] for polytetrafluorethylene (PTFE) and polyvinylidene fluoride (PVDF). Dark mobility is $2 \cdot 10^{-16}$ m^2/(V·sec) in PTFE (which is close to an ideal dielectric) and $\sim 10^{-14}$ m^2/(V·sec) in PVDF (a true dielectric).

In our calculations, we assume that the effective dark mobility of the carriers is much less than radiation mobility and has the value $1 \cdot 10^{-16}$ m^2/(V·sec). The value of the recombination coefficient is 10^{-15} m^3/sec, while mean ionization energy is 100 eV [2, 7].

When field strength in the dielectric exceeds the critical value $E_c \sim 10^5$ V/cm, Ohm's law may be violated and the field dependence of current may become superlinear [8, 11]. This development is related to the fact that the probability of recombination of ionized molecules of the dielectric depends on the field. In the case of unipolar conduction, the following expression for effective mobility can be obtained from the Fowler recombination law and the field dependence of conductivity [8]

$$\mu_{n,p} = \mu_{n,p}^{(0)}(D(z)/D_0)^{2\Delta-1}|E|^{\beta}, \tag{8}$$

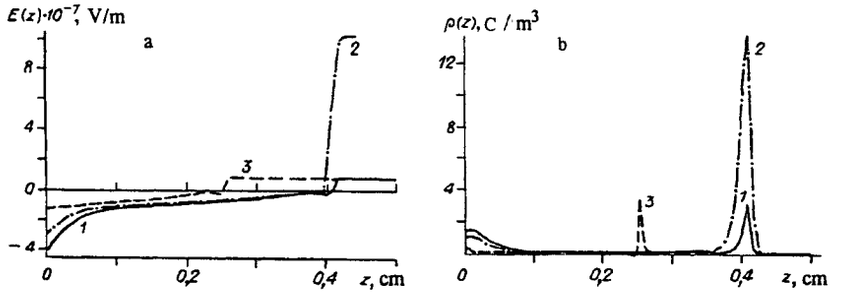

Fig. 3

where $\beta = 0$ at $|E| < E_c$; $\beta > 0$ at $|E| \geq E_c$.

Let us examine the pattern of charge accumulation in a shorted dielectric. Figure 2 shows the time dependence of the maximum of potential in the dielectric when irradiated by protons with an energy of 20 MeV and a current density $j^{(b)} = 10^{-8}$ A/cm^2 (curve 1 – PMMA, $a = 1$ g/cm^2; 2 – PMMA, $a = 0.5$ g/cm^2; 3 – fluoroplastic, $a = 1$ g/cm^2). A feature common to all of the cases being considered is the establishment of a steady state. Comparison of curves 1 and 2 shows that charging proceeds more rapidly in a thick specimen than in a thin specimen. This result is in complete agreement with Eq. (7). In fact, capacitance of the non-irradiated part C_2 decreases with an increase in specimen thickness, while the capacitance C_1 and resistance r of the irradiated part remain unchanged. The charge constant $r(C_1 + C_2)$ will decrease with an increase in the thickness of the dielectric. A decrease in capacitance C_2 with an increase in thickness leads to a more rapid increase in the potential applied to the irradiated part, which increases the field and, thus, the relaxation current.

The lower steady-state potential in fluoroplastic compared to PMMA can be attributed to the resistance of the IP. Since the linear energy losses by protons in the fluoroplastic are almost twice as great as the energy losses in PMMA, a smaller (in volume) irradiated part with a higher concentration of charge carriers is seen in the former.

Figure 3 shows the distribution of the field (a) and charge density (b) for the above-examined case (the numbers next to the curves correspond to Fig. 2). The distribution is given for the moments of time $t = 92$ sec and $t = 81$ sec for PMMA and fluoroplastic, respectively. It is evident from the figure that the cumulative charge in the thinner dielectric (curve 2) is considerably greater than the charge in the thick target (curve 1), despite the small difference in the values of maximum potential (Fig. 2). The difference in cumulative charge is due to the change in the capacitance of the non-irradiated part that accompanies a change in the thickness of the dielectric. An important feature of the charge distribution is its concentration at the end of the path of the particles. This is the same distribution seen as when dielectrics are irradiated with electrons.

With an increase in proton energy to 70 MeV, the maximum potential in PMMA ($a = 8$ g/cm^2) at $t = 55$ sec was 3.67 MV. This result agrees qualitatively with the result obtained from Eq. (4). In fact, the increase in maximum potential with an increase in energy is greater than the increase associated with the relation $T^{\Delta+2}$, since the expression for ionization losses used in the derivation of Eq. (4) overstates the induced conduction near the path.

Let us now examine the dynamics of the radiation charging of a dielectric with an open surface. We ignore particle emission from the irradiated surface, since the space charge prevents electron leakage and since the ion emission coefficient for protons with an energy of tens of mega-electron-volts is extremely small [11] except in special cases (such as when the particles are incident at angles close to 90°). The absence of ion emission from the open surface of the dielectric and electron flow through it leaves a single path for the relaxation of a charge injected into the volume – drift through the non-irradiated region. Since the dark values of effective mobility are several orders lower than mobility in the IP, we can expect a nearly linear (over time) increase in the cumulative charge and the potential of the surface. Due to the high conductivity of the irradiated region, the potential of the open surface of the dielectric is applied to the non-irradiated region, and a rapid increase in field strength in this region can lead to a superlinear dependence of relaxation current on the field. Thus, in our calculations of the charging of dielectrics with an open surface, we also considered the effect of a electric field on effective mobility in accordance with law (8).

To find the coefficient β in Eq. (8), we used the results of an experiment involving the charging of a dielectric (fluoroplastic) with an open surface by an electron beam [12]. With $\beta = 0.2$, the solution of this problem that is obtained using the above model agrees well with [12] in regard to the time dependence of the potential of the open surface. We used the value of β that was obtained in calculations of the dynamics of charge accumulation in PMMA and fluoroplastic during proton irradiation.

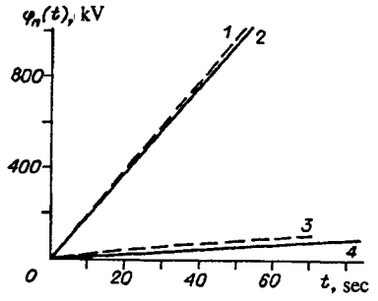

Fig. 4

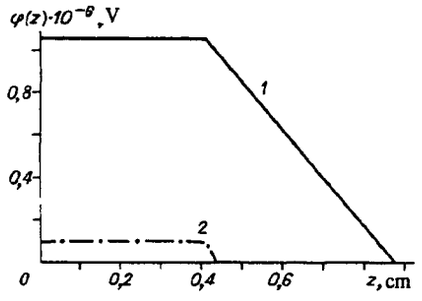

Fig. 5

Figure 4 shows the time dependence of the potential of the open surface of a dielectric (PMMA) irradiated by protons with an energy of 20 MeV at a current density of 10^{-8} A/cm^2 (curves 1 and 3 are calculated with the use of Eq. (7) for effective mobility, while 2 and 4 were calculated with Eq. (8)). Lines 1 and 2 correspond to a thickness a = 1 g/cm^2, while lines 3 and 4 correspond to a = 0.5 g/cm^2. It can be seen from the figure that increased field mobility does not lead to substantial changes in the pattern of charging. The field has a somewhat greater effect on mobility in the thin dielectric, where the field is stronger.

Figure 5 shows the distribution of potential in a dielectric with an open surface. The parameters of the beam and the dielectric are the same as in Fig. 4. Lines 1 and 2 show the distribution of potential for a = 1 g/cm^2, t = 55 sec and a = 0.5 g/cm^2, t = 84 sec, respectively.

Technical advances made in the generation of ion beams now make it possible to obtain flows of neutral particles by passing accelerated ions through target-neutralizers [13]. The greatest successes have been achieved in obtaining flows of hydrogen atoms. The percentage of neutral atoms in the beam can be as high as 80% [13].

We will examine the limiting case when the dielectric is irradiated only by hydrogen atoms. The ions of the beam almost instantaneously (relative to the time of deceleration) lose all of their electrons when the beam reaches the medium, the bond energy of these electrons being much lower than the kinetic energy of the ions. This means that a fast hydrogen atom striking a dielectric loses its electron near the irradiated surface. A similar situation prevails if the dielectric is irradiated by a neutralized flow of ions. Since the kinetic energy of the electrons accompanying the ions is lower than the kinetic energy of the ions by the factor m_e/m_i (where m_e and m_i are the masses of an electron and an ion), the electronic background is also lost near the irradiated surface.

It follows from the above that when shorted dielectrics are irradiated by a flow of atoms or neutralized ions, the pattern of charging is similar to that which is seen in the case of irradiation by a flow of ions. The pattern is similar because the electrons are lost in the high-conductivity near-electrode region or on the electrode itself.

A steady state with a small excess of positive charge is established in the case of irradiation of dielectrics with an open surface by a flow of atoms or a neutralized flow of ions. The irradiated surface initially acquires a negative potential due to deposition of electrons near the surface, and the field created in the drift space facilitates the emission of electrons from the surface [2]. This emission in turn creates excess positive charge, so that the potential of the surface becomes positive, emission ceases, and a steady state is established. Charge relaxation in the steady state occurs due to drift of carriers into the irradiated part of the dielectric.

Figure 6 a and b shows stationary distributions of the field and charge in PMMA (curve 1) and fluoroplastic (curve 2) irradiated by a flow of hydrogen atoms with an energy of 20 MeV. Particle current density was equivalent to proton current density $j^{(b)} = 10^{-8}$ A/cm^2. The steady state for these beam parameters was established after ~70 sec. The potential of the open surface was ~50 V.

We performed calculations to characterize the charging of the dielectric specimens up to electric field strengths of approximately 10^7 V/m. This is consistent with tabulated values of the dielectric strength of polymers. However, the following fact must also be kept in mind: The literature data on dielectric strength has generally been obtained with the application of a voltage to electrodes holding a specimen placed between them. When the specimens are irradiated, one of the electrodes is a virtual electrode and is formed by the space charge at the depth corresponding to the path length of the heavy charged particles. In this case, microroughnesses on the non-irradiated surface of the electrode no longer produce local fields strong

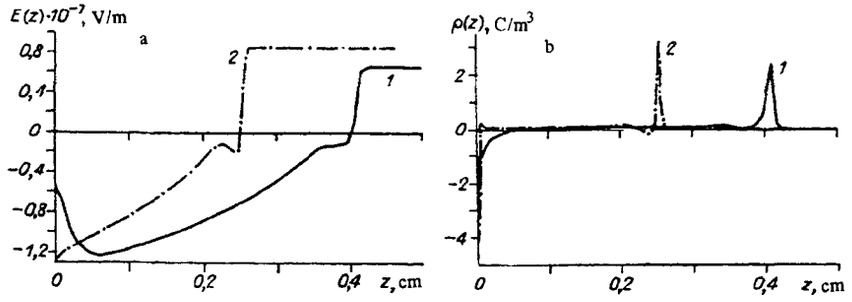

Fig. 6

enough to result in breakdown, since the charge distribution in the virtual electrode tends to "smooth out" irregularities in the field. This probably explains the increased strength of irradiated polymers (~3.5 MeV/cm) noted in [15] and other publications.

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