Bulk Charging of Microlite Ceramic under Fast Electron Irradiation

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Abstract – Bulk charging of dielectric ceramic microlite by an electron beam has been studied using the split Faraday cup technique. Electron energy (2 MeV) has been such that electrons stopped in the sample. Experimental results are compared with theory taking into account depth dose and charge injection profiles, bremsstrahlung radiation and non-linear field effects in radiation induced conductivity. Unusually fast current decay has been accounted for. It has been shown that the method used allows one to investigate these non-linear effects at extremely high electric fields close to the breakdown strength of a dielectric.

1. Introduction

Ceramics are heat resistant, vacuum-proof materials with high radiation and chemical resistance but under electron irradiation are easily electrified to retain bulk charges for long times after irradiation [1-3]. So, it is imperative to find conditions under which this electrification do not lead to electric discharge. Electron electrification and radiation induced conductivity (RIC) of microlite (MK) have long been studied [4, 5], but theoretical analysis of these events is not available.

MK has crystallinity of 97-99 %, glass fraction 1-3 % and a very low dark conductivity. Simulation of fast electron transfer and RIC analysis in polymers greatly increased our understanding of this complex phenomenon [6-9]. It is interesting to extend these studies for inorganic insulator – MK ceramic. The aim of this paper is to investigate both experimentally and theoretically electron charging of MK ceramic.

2. Experimental technique

To experimentally study the charging of MK, we used the split Faraday cup technique [10]. It consists essentially of irradiation of planar sample supplied with thin metal electrodes on both sides by monoenergetic electrons whose total range L is less than sample thickness h. To probe the space charge field we measure the back electrode current $I_2(t)$ to the ground (both electrodes have nearly zero potential).

Ceramic samples (4.5 mm thick) have been provided with circular Al electrodes 40 mm in diameter. As a radiation source we used electrostatic generator of 2 MeV electrons, at the beam current density I_0=12.2 nA/cм^2. Electron beam passed through a collimator 30 mm in diameter. Electrons impinged the sample at right angle.

Irradiation has been done at room temperature in a vacuum chamber at a pressure of less than 10^{-2} Pa. For details see [6, 7].

Fig. 1 presents a typical back-electrode current transient $I_2(t)$. It could be seen that quite for a long time after starting irradiation current decay may well be approximated by an exponential as already noted in literature [2]. For times of irradiation ≥55 s (electron fluences ≥ 4.2×10^{12} cm^{-2} (6.7×10^{-7} C/cm^2)) the current decay presumably changes to the power law $I_2 \sim t^{-2}$.

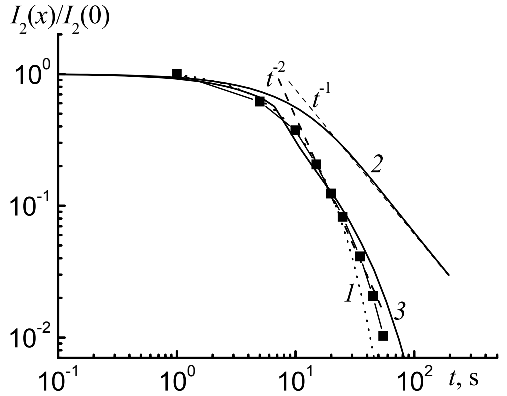

Fig. 1. Experimental (data points) and computed (*1-3*) transient back-electrode currents in microlite sample (h=4.5 mm) irradiated with fast electrons (E_e=2 MeV, I_0=12.2 nA/cm^2). 1 – using range-energy relation as in [7]. *2*, *3* – with due account of the dose rate and the electron introduction rate depth dependence, for linear (*2*) and non-linear (*3*) RIC current-voltage characteristic

3. Numerical simulation

Using "range-energy" relationship, i.e. neglecting electron range straggling and both spatial distributions of the dose $g(x)$ and the electron driven current $f(x)$, $I_2(t)$ becomes exponential [2, 10]

$$I_2(t) \sim exp\left(-\frac{h-L}{h}\frac{\gamma_r}{\varepsilon\varepsilon_0}t\right) \qquad (1)$$

where γ_r is the RIC in the irradiated region (=const) and $\varepsilon\varepsilon_0$ is the absolute dielectric permittivity of the dielectric.

Experimental value of RIC according to Eq. (1) is 3.2×10^{-11} $(\Omega\ m)^{-1}$ while the real value of it in MK for the dose rate 18 Gy/s is only 7.5×10^{-12} $(\Omega\ m)^{-1}$ [4] which is 4 times less. It is clear that discrepancy exists.

Numerical simulation of MK electrification has been performed in two steps:

– Monte-Carlo simulation of fast electron transport and determination of the spatial distributions of the dose $g(x)$ and electron driven current $f(x)$ per one incident electron;

– numerical solution of the continuity equation for the electron driven and RIC currents simultaneously with the Poisson equation to obtain electrification parameters sought (bulk charge density and field, back electrode current).

The electron driven current is an algebraic sum of the forward and backward currents of electrons with energy ≥ 1 keV. Normalized by its value at x=0 (irradiated electrode) it produces depth profile $g(x)$. Similar depth dose profile is given by $g(x)=\frac{D(x)}{D_0}$ where D_0 is the stopping power of the dielectric. One more function $\frac{df(x)}{dx}$ reflecting depth profile of bulk charge introduction rate is also useful in these studies.

To calculate $g(x)$ and $f(x)$ we use program complex XRAY and method of "condensed history" [11, 12]. In the energy range E_e=1.0÷2.0 MeV both methods give consistent results. To obtain $g(x)$ and $f(x)$ we traced ~10^6 trajectories in at least 70 layers along electron range. It was found expedient to use the reduced coordinate $\xi=x/L$ with L being the maximum electron range.

Two other integral parameters are also important [13]

$$a=\int_0^1 f(\xi)d\xi \quad \text{и} \quad b=\int_0^1 \frac{f(\xi)}{g(\xi)}d\xi \tag{2}$$

The former quantity defines $I_2(t)$ at the start of irradiation

$$I_2(0)=\frac{I_0}{h}\int_0^L f(x)dx = a\frac{L}{h}I_0 \tag{3}$$

as well as the centroid of the injection rate of the bulk charge (under condition that $f(0)=f(1)=0$, of course)

$$\int_0^1 \xi\frac{df(\xi)}{d\xi}d\xi = \int_0^1 f(\xi)d\xi = a \tag{4}$$

The latter quantity b enters the expression for the steady-state field in the unirradiated region under condition that dark conductivity of the dielectric may be assumed negligible

$$\widetilde{E}(\xi>1)=\frac{I_0}{A_r P}\frac{L}{(h-L)}\int_0^1 \frac{f(\xi)}{g(\xi)}d\xi \tag{5}$$

Calculation results are presented in Table 1 and Fig. 2.

Table 1. Main parameters characterising fast electron transport in MK

E_e, MeV	L, cm	D_0	g_{max}	L_d, cm	L_ρ, cm	a	b	χ
1.0	0.14	1.66	1.98	0.0404	0.078	0.45	0.33	5×10^{-4}
2.0	0.31	1.47	1.94	0.095	0.182	0.49	0.37	1.2×10^{-3}

Footnote. D_0– electron stopping power, (MeV×cm^2)/g; g_{max} – maximum value of function $g(x)$ located at the depth L_d; L_d – the depth at which maximum introduction rate of beam electrons occurs; χ– the ratio of the dose rates at x=1.5L and x=0.

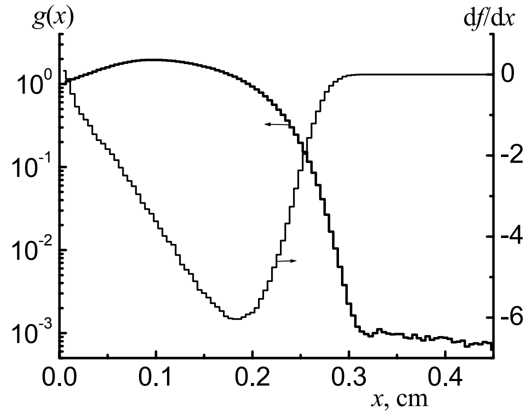

Fig. 2. Depth profiles of dose rate $g(x)$ and electron introduction rate df/dx in microlite ceramic. Electron energy is 2 MeV

Continuity equation coupled with the Poisson relationship form the system of differential equations of the electron electrification of a dielectric:

$$\frac{\partial\rho(x,t)}{\partial t}=-\frac{\partial I(x)}{\partial x}-\frac{\partial}{\partial x}\left[\gamma_r(x)E(x,t)\right], \tag{6}$$

$$\frac{\partial E(x,t)}{\partial x}=\frac{\rho(x,t)}{\varepsilon\varepsilon_0}. \tag{7}$$

Here, ρ is the bulk charge density; E– the electric field; $I(x)=I_0\times f(x)$ – the forward electron-driven current at depth x; $P(x)=P_0 g(x)$ – the dose rate at depth x (P_0 is the dose rate at x=0); γ_r – is the RIC ($\gamma_r=A_r\times P^\Delta$, A_r and Δ are material constants); $\varepsilon\varepsilon_0$ is the absolute dielectric permittivity of the dielectric.

For short-circuited sample we have

$$\int_0^h E(x,t)dx = 0 \tag{8}$$

while as initial conditions we use

$$E(x,0)=0\,,\ \rho(x,0)=0\,. \tag{9}$$

$I_2(t)$ coincides with the total dielectric current and as such in may be represented in the following form

$$I_2(t) = \varepsilon\varepsilon_0 \frac{\partial E(h,t)}{\partial t} + A_r (\chi P_0)^{\Delta} E(h,t). \qquad (10)$$

It is the sum of the displacement current and the conduction current due to the bremsstrahlung radiation taken at $x=L$ but still inside the dielectric.

Table 1 shows that the dose rate arising from this radiation for $x \geq L$ is not negligible (~ 10^{-3} P_0) and changes only slightly for x up to $8L$. Thus, the unirradiated part of the dielectric ($L \leq x \leq h$) is no more a blocking layer it would have been in the absence of the bremsstrahlung radiation. As a result $I_2(t) \rightarrow \tilde{I}_2$ for $t \rightarrow \infty$ where $\tilde{I}_2$ is the stationary value of the back-electrode current.

Numerical analysis [6, 7] shows that that the asymptotic decay of $I_2(t)$ follows an algebraic law

$$I_2 \sim t^{-1/\Delta}. \qquad (11)$$

According to [4] $\gamma_r = (4.2 \pm 0.4) \times 10^{-13} \times P$ in MK (i.e. $\Delta=1.0$). It follows then that $I_2(t) \sim t^{-1}$ as $t \rightarrow \infty$. Numerical calculations confirm this conclusion.

Generally, one should take into account the possible field and temperature dependence of the ceramic RIC. In our experiments the dose was rather small (~ 1 kGy) and radiation heating did not exceed 1 K. Earlier it has been shown that field dependence of RIC enhances the current decay as for example in rubber blends electrified at low temperatures [14]. Field effects has not been found though in MK for $E \leq 3 \times 10^6$ V/m [4]. At still higher fields RIC studies suffer from possible breakdown events. MK electric strength reaches 4×10^7 V/m. So, there is no information about RIC behavior of this ceramic at prebreakdown fields. But it seems quite plausible that its RIC is field dependent at high fields similar to polymers [15].

To fit experimental data in Fig. 1 parameters E_{cr} and δ entering the relationship $\gamma_r \sim E^{\delta}$ describing field effects have been sought. Here E_{cr} is the threshold field above which these effects are believed to occur.

A good agreement is achieved for $E_{cr} = 3.5 \times 10^6$ V/m and $\delta = 4.0$. The specific form of field effects does not matter, for example, it may be accounted for by the formula $\gamma_r \sim E[1 + \sinh(K_E \times E)]$ involving hyperbolic sinus (here K_E is a material constant) [16]. It is important that the idea of field dependent RIC allows one to describe the experimentally observed $I_2(t)$ curve.

A typical $I_2(t)$ curve is presented in Fig. 1. It is seen that spatial field and change profiles appreciably charge as E exceeds E_{cr} (Fig. 3, 4). Due to RIC field dependence the bulk charge removal from high-field near-electrode regions causes charge concentration around zero-field plane. Integrating $\rho(x)$ over x for various times defines the surface density of the accumulated charge. Fig. 5*a* shows that after 10 s of irradiation it begins to lag the electron fluence equal to $I_0 \times t$.

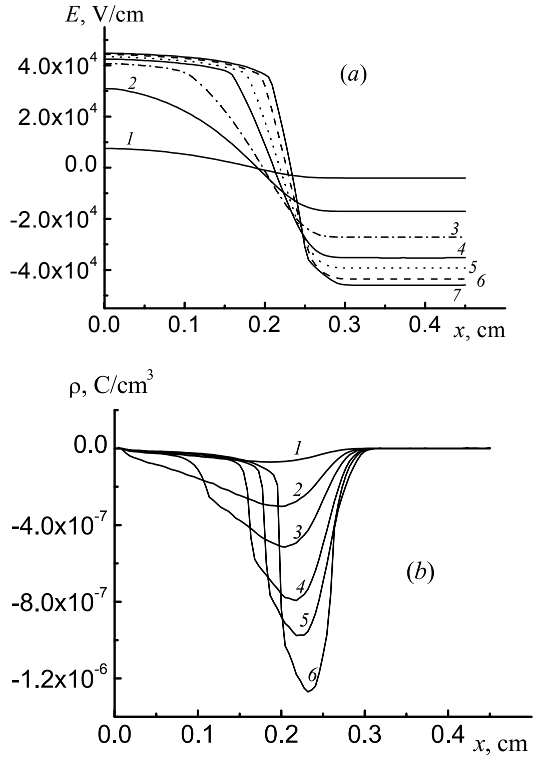

Fig. 3. Field (*a*) and space charge density (*b*) profiles in electron irradiated microlite at t equal to 1 (*1*), 5 (*2*), 10 (*3*), 20 (*4*), 30 (*5*), 55 (*6*) and 200 s (*7*) (E_e =2 MeV and I_0=12.2 nA/cm^2)

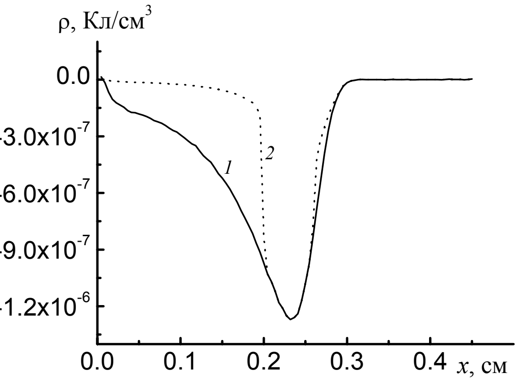

Fig. 4. The same as in Fig. 3(*b*) for t=55 s but for linear (*1*) and non-linear (*2*) RIC current-voltage characteristic

The integral $\int_0^{t_k} I_2(t)dt$ (t_k is the irradiation time) allows one to estimate the lower bound of the accumulated charge ~3×10^{-8} C/cm^2 in agreement with the numerical calculations. Note that accounting for RIC field effects reduces the dielectric's ability to accumulate charges during irradiation.

It is of interest to investigate the way in which RIC non-linearity affects the position of the charge centroid $\langle x \rangle = \int_0^L x\rho dx \Big/ \int_0^L \rho dx$ (Fig. 5*b*). It follows that field effects drive $\langle x \rangle$ away from the irradiated electrode.

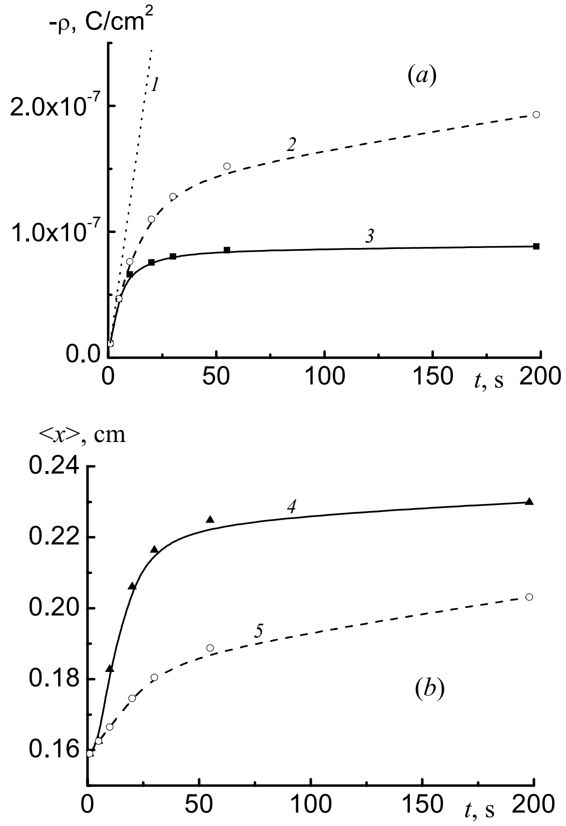

Fig. 5. Time dependence of the surface charge density of the injection electrons (*1*), the calculated surface charge density (*2*, *3*) and the charge centroid position (*4*, *5*) in the microlite for linear (*2*, *4*) and non-linear (*3*, *5*) RIC current-voltage characteristic (E_e =2 MeV and I_0=12.2 nA/cm^2)

4. Conclusions

Experimental investigation of electron electrification of micrilite ceramic has shown considerable discrepancy with theory if RIC is ohmic. To resolve it one should take into account RIC increase at fields exceeding 3.5×10^6 V/m.

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