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Production of foil electrets by ionizing radiation in air

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Isothermal charge deposition on polymers to form stable foil electrets by using apparatuses resembling parallel-plate ionization chambers is reported. Charge carriers produced by irradiation of the sensitive chamber air volume drift in an externally applied electric field and get trapped on the polymer surface to form electrets with maximum charge densities close to 10^{-6} C/cm^2. Charge density as a function of applied voltage follows the form typical of a Schottky or Poole-Frenkel process.

The existence of electrets has been known since the 1920s[1] but it was only in the last decade that they have gained prominence because of numerous practical applications found for them in science and industry. Originally, electrets were produced through thermal[2] (thermoelectrets) or optical[3] (photoelectrets) charge-deposition methods; recently, however, isothermal charge-deposition techniques are favored because of the ease and speed at which they allow polymer films to be charged. The most widely applied isothermal technique is corona charging,[4,5] which depends on the use of an inhomogeneous electric field to produce a discharge in air at atmospheric pressure. Other techniques are based on spark discharge,[6] liquid contact,[7] injection of monoenergetic particle beams[8,9] (electrons or ions) of range smaller than the thickness of the dielectric, or carrier displacement by large doses of x rays or γ rays (radioelectrets).[10]

In this paper we describe a new isothermal technique for production of foil electrets, based on air ionization produced by x rays in a chamber resembling a parallel-plate ionization chamber. The technique is simple, the charge deposition extremely well controllable, and the surface charge density, which easily reaches the theoretical limit, is very uniform.

A schematic diagram for the foil electret charging and discharging process is shown in Fig. 1. The electret is produced on a polymer (Mylar) sheet which is metallized on one side and has a thickness p of a few μm. As shown in Fig. 1(a) the metal on the polymer is used as the measuring electrode in a chamber closely resembling a parallel-plate cylindrical ionization chamber. The polymer is facing the polarizing electrode over an air gap a typically a few cm thick. Any conductor can be used as the polarizing electrode; the initial electret charging current, however, is proportional to the atomic number Z of the polarizing electrode because of the photoemission efficiency dependence on Z. The air in the chamber sensitive volume is ionized by electrons produced by the direct interactions of photons with air molecules, and by electrons produced by photoelectric interactions of x rays in the polarizing electrode.

Before irradiation the electric field inside the chamber air gap is produced by the external power supply V_0. It may be written in terms of V_0, a, and p, and dielectric constants ϵ_p and ϵ_a as follows:

$$E_a(0)=V_0\epsilon_p/(p\epsilon_a+a\epsilon_p) \ . \tag{1}$$

During irradiation ion pairs are produced in the chamber sensitive air volume. In contrast to a normal ionization chamber where the charges impinge directly onto the appropriate metal electrode, in our chamber the charges moving in the direction of the measuring electrode get stopped and trapped on or near the polymer surface as indicated in Fig. 1(b). The current measured in the external circuit is due to compensation charges moving onto the measuring electrode; this current is, in magnitude and direction, initially equal to a normal ionization current obtained in a standard ionization chamber under the same conditions. The polymer with the charges deposited onto its surface as shown in Fig. 1(b) is actually a foil electret and in the following we will discuss some of the properties of this electret state.

Because of the trapped charges on the polymer surface, which produce an electric field $E_\sigma(t)$ in the vicinity of the surface in a direction opposite to $E_a(0)$, the ion pairs produced by radiation see an effective electric field which is decreasing in time. Using Gauss's and Kirchoff's laws the effective field in the air gap at a given time t may be written as

$$E_{\text{eff}}(t)=E_a(0)-E_\sigma(t)=\frac{V_0\epsilon_p-p\sigma(t)/\epsilon_0}{p\epsilon_a+a\epsilon_p} \ . \tag{2}$$

When the two opposing fields become equal in magnitude at a time t_1, the effective field close to the polymer surface becomes zero, the ion pairs produced by radiation no longer drift in an electric field, and therefore eventually recombine, so that no additional charge deposition onto the polymer surface is possible. Substituting $E_{\text{eff}}=0$ into Eq. (2) we get the

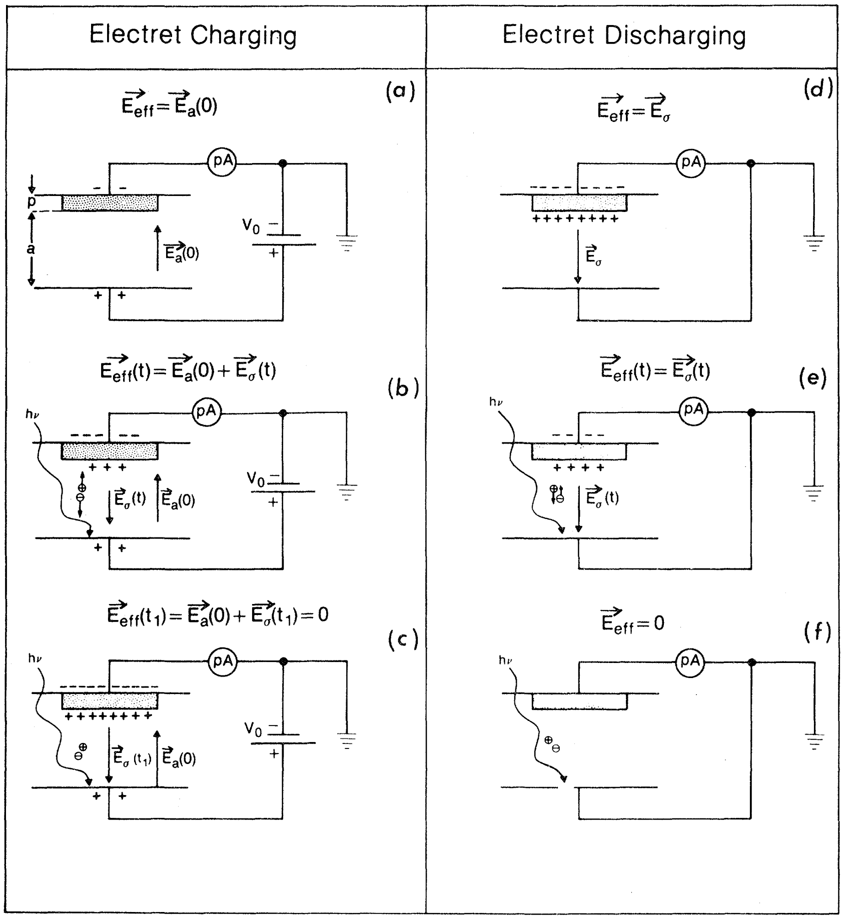

FIG. 1. Schematic representation of the electret charging (a)–(c), and electret discharging (d)–(f) process. $\vec{E}_a(0)$ is the applied electric field in the air gap a, $\vec{E}_\sigma$ the electret electric field, and $\vec{E}_{eff}$ the effective electric field in the air gap.

following relationship for the final surface charge density σ_{max}:

$$\sigma_{max} = \epsilon_p \epsilon_0 V_0 / p = C_e V_0 \ , \tag{3}$$

which is exactly equal to the basic relationship giving the maximum charge density for a parallel-plate dielectric capacitor of a specific capacitance C_e with V_0 across the dielectric of thickness p. The final result of the electret charging process is shown schematically in Fig. 1(c). At its maximum the electret charge density σ_{max} is larger than the original charge densities on the plates of the capacitor defined by the measuring and polarizing electrodes by a factor approximately equal to $(a \epsilon_p / p)$ which is typically equal to 10^3.

The electret discharging process, which is used in studies of the electret-state dynamics, is shown schematically in Figs. 1(d)–1(f). The chamber polarizing and measuring electrodes are shorted through an electrometer as shown in Fig. 1(d). Since the externally applied field is now equal to zero, the effective field in the sensitive chamber volume is equal to the field produced by the electret charge layer. The ion pairs produced by radiation are thus moving in directions opposite to directions in the charging process, causing the depletion of the electret charge layer through annihilation of opposite charge carriers on the polymer surface [Fig. 1(e)]. Consequently, the effective electric field in the air gap is steadily decreasing and it reaches zero when the electret is completely discharged as shown in Fig. 1(f). A similar electret depolarization process has been proposed as a radiation monitoring technique.[11]

In Fig. 2 we show schematically for a typical electret charging-discharging cycle the time dependence of (a) experiment configuration, (b) electret charging and discharging current, (c) applied voltage V_0, and (d) x-ray exposure. Initially, the charging current is constant and equal to a standard ionization chamber current under same conditions. After a characteristic time t_0, however, when the polymer is almost fully charged, the current drops to zero, and the result is a foil electret charged to its theoretical limit as given by Eq. (3) and shown in Fig. 1(c). For a typical expo-

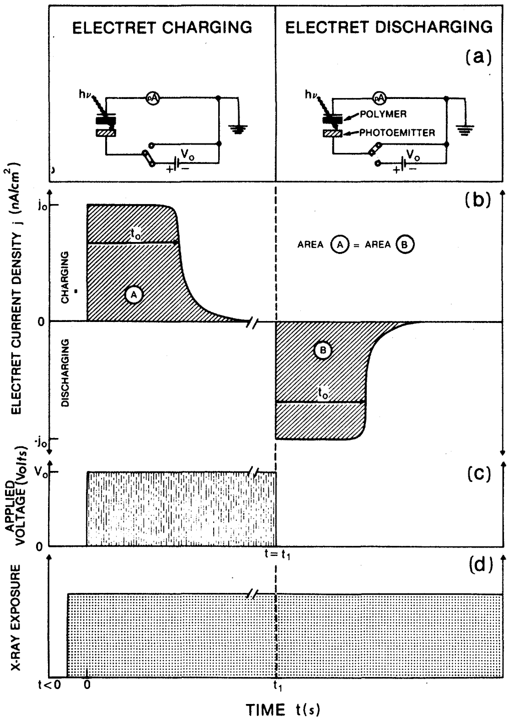

FIG. 2. Time dependence for a typical electret charging-discharging cycle; (a) schematics, (b) electret current density, (c) applied voltage, and (d) x-ray exposure.

sure rate of 10 R/min the time t_0 varies from a few seconds to few minutes depending on the chamber parameters. The profile of the discharging current, which is obtained when the chamber electrodes are shorted, is identical in magnitude but opposite in sign to the charging current profile. The charge conservation is thus preserved, since the areas under the current charging and discharging profiles are identical.

The maximum surface charge density $\sigma_{\max}$ is given by Eq. (3) but is, at high applied voltages, limited by the dielectric strength of the electret material. For Mylar the dielectric strength is equal to 2.8 MV/cm.[6] In Fig. 3 we show the measured $\sigma_{\max}$ as a function of potential difference V_0 for two thicknesses of Mylar (0.05 and 0.175 mm). For applied voltages below 1000 V there is a perfect agreement between Eq. (3) and experiment. For voltages above 1000 V but below the dielectric strength limit, however, the measured charge densities become progressively lower than values calculated from Eq. (3). Empirically, we find that $\sigma_{\max}$ depends upon the polarizing voltage V_0 according to an expression resembling a Schottky[12,13] or Poole-Frenkel[13] process,

$$\sigma_{\max} = 2C_e v_B^{1/2}[(V_0+v_B)^{1/2} - v_B^{1/2}] \ , \qquad (4)$$

where C_e is the electret specific capacitance obtained from Eq. (3), and v_B the breakpoint voltage between

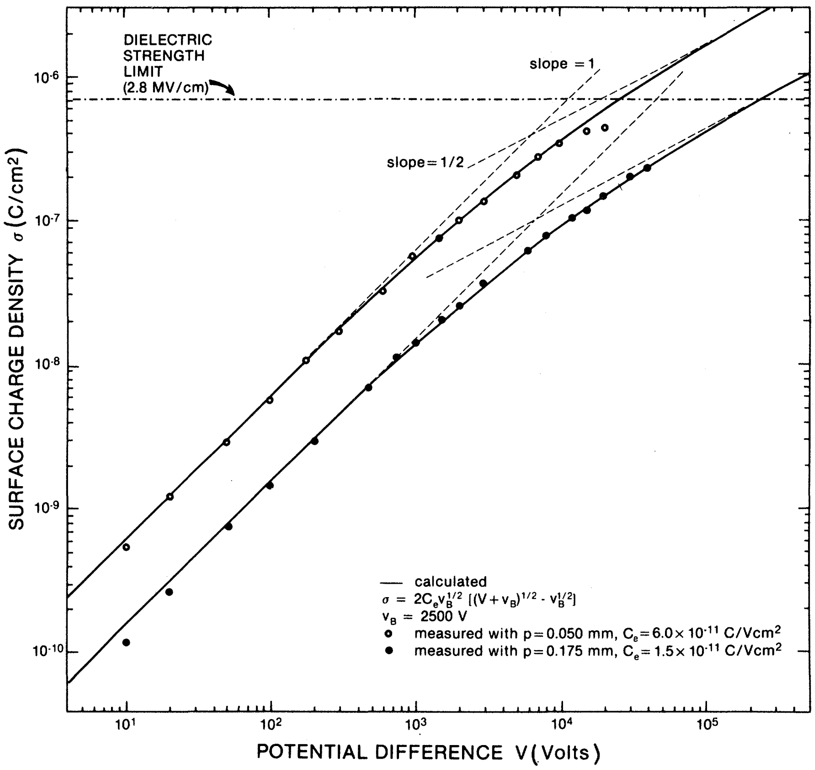

FIG. 3. Dependence of the maximum electret charge density upon the applied electric field for two thicknesses of Mylar.

the low voltage linear ($\sigma_{\max} \propto V_0$) region described by Eq. (3) and high-voltage quadratic ($\sigma^2_{\max} \propto V_0$) region. The solid lines in Fig. 3 are plotted for two polymer thicknesses using Eq. (4) with appropriate values for C_e and a value of 2500 V for v_B. The agreement between Eq. (4) and experimental values is excellent in the whole practical range of voltages. It can be shown that Eq. (4) transforms into Eq. (3) for $V_0 << v_B$. Similar $V_0^{1/2}$ dependence was observed at high voltages for ionic space charge thermoelectrets[14] and electret states in naphtalene crystals.[15]

As shown in Fig. 3 electrets with surface charge densities close to 10^{-6} C/cm^2 can be produced by our new isothermal charging technique. Either positive or negative charge carriers can be trapped on the polymer surface depending on the polarity of the external power supply. Any desired surface charge density can be achieved, since the charging process follows Eq. (4) perfectly. The limitation, of course, is the dielectric strength of the electret material. The electret state is attributed to positive or negative charge carriers which are produced by radiation in the sensitive air volume and later trapped on the polymer surface. The electret thus produced is extremely stable and no charge loss was observed when a sample charge was read out four months after the electret state was produced in the sample.

In summary, a new isothermal charge-deposition technique for production of extremely stable foil electrets is presented. The electrets are produced in a chamber resembling a standard parallel-plate ionization chamber. The charge carriers produced by x rays in the sensitive chamber air volume drift in the externally applied electric field and get trapped on the polymer surface to form the electret. Charge densities close to 10^{-6} C/cm^2 can be achieved. The maximum surface charge density as a function of applied voltage is linear for voltages below 1000 V and quadratic for voltages between a few thousand volts and the dielectric strength limit.

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