

Dynamics of radiation-induced charging and discharging of foil electrets

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The time dependence of the polarization and depolarization current densities, the effective electric field in the electret chamber, and the electret surface charge densities are presented for the radiation-induced foil electret. With the use of the hyperbolic dependence of the ionization-chamber current density on the effective electric field, one obtains excellent agreement between calculated and measured electret polarization and depolarization current densities.

Recently, an isothermal charge deposition method, which uses ionizing radiation in air to produce stable foil electrets, was reported.¹ In a chamber which resembles a parallel-plate ionization chamber, the charge carriers produced by irradiation of the sensitive chamber air volume drift in an externally applied electric field and get trapped on a polymer surface to form electrets with maximum charge densities close to 10^{-6} C/cm².

In this paper we discuss the dynamics of the polarization (charging) and depolarization (discharg-

ing) process for this radiation-induced foil electret. A schematic diagram for the electret charging and discharging process is shown in Fig. 1(a). The electret is produced on a polymer (Mylar) sheet which is metallized on one side and has a thickness p of the order of 100 μ m. The metal on the polymer is used as the measuring electrode. The polymer is facing the polarizing electrode across an air gap a which is typically a few millimeters thick.

During the polarization process the charge carriers produced by ionizing radiation in the chamber

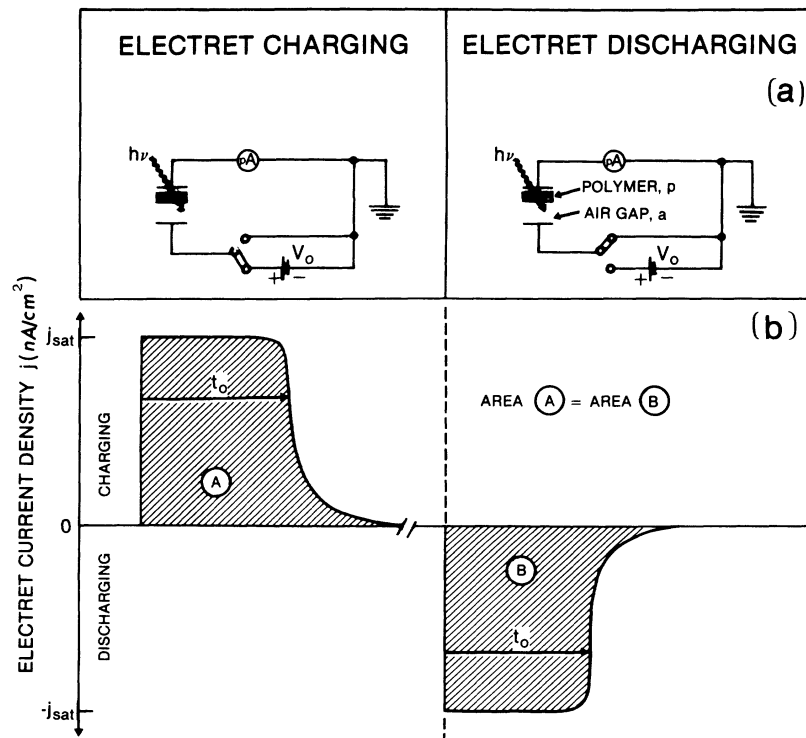


FIG. 1. Time dependence for a typical electret polarization (charging) and/or depolarization (discharging) process: (a) schematics and (b) electret polarization and depolarization current density.

sensitive volume experience an effective electric field $E_{\text{eff}}(t)$ which is equal to the difference between the field $E_a(0)$, produced in the chamber by the external power supply \mathcal{V}_0 and the field $E_\sigma(t)$, produced by the charge density $\sigma(t)$ on the polymer surface. With the use of the laws of Gauss and Kirchoff, $E_{\text{eff}}(t)$ may be written as

$$E_{\text{eff}}(t) = E_a(0) - E_\sigma(t) \\ = \frac{\epsilon_p \mathcal{V}_0 - p\sigma(t)/\epsilon_0}{p\epsilon_a + a\epsilon_p} \quad (1)$$

When the two opposing fields, $E_a(0)$ and $E_\sigma(t)$, become equal in magnitude at some large time t , $E_{\text{eff}}(t)$ close to the polymer surface becomes zero, the ion pairs produced by radiation no longer drift in an electric field, and no additional charge deposition onto the polymer surface is possible. The surface charge density $\sigma(t)$ thus reached its maximum possible value σ_{max} which may be expressed using $E_{\text{eff}}(t)=0$ in Eq. (1) as follows:

$$\sigma_{\text{max}} = \epsilon_0 \epsilon_p \mathcal{V}_0 F / p \quad (2)$$

In general, $\sigma(t)$ may from Eq. (1) be written as

$$\sigma(t) = \sigma_{\text{max}} - \beta E_{\text{eff}}(t) \quad (3)$$

with

$$\beta = \epsilon_0(a\epsilon_p + p\epsilon_a) / p \quad (4)$$

The electret polarization current density j may be expressed by differentiating Eq. (3) to obtain

$$j = d\sigma/dt = -\beta dE_{\text{eff}}(t)/dt \quad (5)$$

We have shown recently² that the saturation curve of a parallel-plate ionization chamber can be described accurately with the relationship

$$f = j/j_{\text{sat}} = \tanh(E/E^*) \quad (6)$$

where f is the chamber ion collection efficiency defined as the ratio of ion pairs collected to ion pairs produced, j is the measured current density as a function of the applied electric field E in the chamber sensitive volume, and j_{sat} is the saturation current density. The extrapolated electric field E^* is the field at which the collection efficiency would equal unity, if the initial linear relationship between f and E , exhibited at small fields, held for all electric fields E . E^* is a function of the air gap a and the exposure rate.

Figure 2(a) shows a typical saturation curve calculated from Eq. (6) and a curve measured for our electret chamber converted into a regular ionization chamber by removing the thin polymer cover from the measuring electrode. The agreement between measured and calculated data is excellent. With an

air gap a of 0.18 cm and an exposure rate of ~ 9 R/min, E^* is 4 V/cm.

Since the electret chamber closely resembles a standard ionization chamber, Eq. (6) may be used to describe the electret polarization current density j , noting, of course, that the applied field E is now the effective field $E_{\text{eff}}(t)$ given in Eq. (1). The radiation-induced currents in the polymer are negligible compared to the electret charging and discharging currents. With a carrier production rate³ of $10^{11} \text{ cm}^{-3} \text{ s}^{-1}$ per cGy/s and an assumption that all charge carriers produced in the polymer contribute to the current, we estimate the maximum radiation-induced current density as less than 10^{-2} nA/cm^2 . The radiation-induced current is actually much lower than this calculated value since the measured current density with a fully charged electret (i.e., with maximum potential difference across the polymer) was negligibly small compared to the original electret charging current, as shown in Fig. 2(b).

Combining Eq. (5) with Eq. (6) we get the following expression relating $E_{\text{eff}}(t)$ with t :

$$\int_{E_a(0)}^{E_{\text{eff}}(t)} \coth[E_{\text{eff}}(t)/E^*] dE_{\text{eff}} = -(j_{\text{sat}}/\beta) \int_0^t dt, \quad (7)$$

and after solving for t :

$$t = t_0 - \tau \ln \sinh[E_{\text{eff}}(t)/E^*] \quad (8)$$

where τ , the electret relaxation time, and t_0 , the electret characteristic polarization time, are equal to $\beta E^*/j_{\text{sat}}$ and $\tau \ln \sinh[E_a(0)/E^*]$, respectively, with β and $E_a(0)$ defined above. $t=0$ is the time at which the electret polarization process begins. In practice this is achieved either by switching the x rays on at $t < 0$ and the external field at $t=0$, or by switching the external field on at $t < 0$ and the x rays at $t=0$.

Employing Eq. (6) in conjunction with Eq. (8) we can now express the electret polarization current density j as follows:

$$j = j_{\text{sat}} \exp[(t_0 - t)/\tau] \{1 + \exp[2(t_0 - t)/\tau]\}^{-1/2} \quad (9)$$

The polarization current density is equal to j_{sat} at $t=0$ and for small t , begins to decrease as t approaches t_0 , is equal to $(1/\sqrt{2})j_{\text{sat}}$ for $t=t_0$, and then rapidly falls to zero as t increases further. The agreement between the current density calculated from Eq. (9) and the experimental data is excellent as shown in Fig. 2(b).

The effective electric field $E_{\text{eff}}(t)$, which was defined in Eq. (1), may now be rewritten from Eq. (8) as

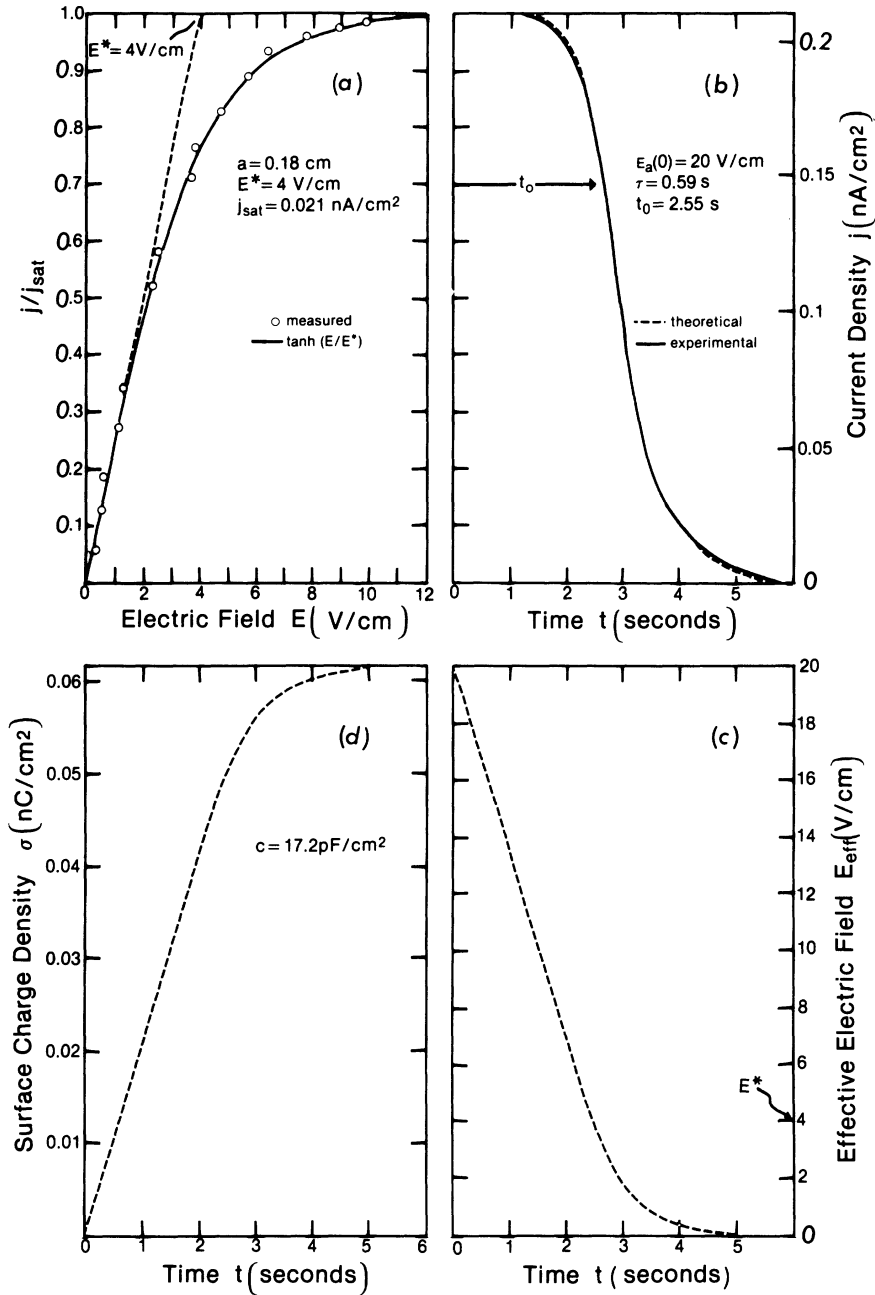


FIG. 2. (a) Measured and calculated ion collection efficiency for a parallel-plate ionization chamber with an air gap a of 0.18 cm; (b) measured and calculated electret polarization current density j as a function of time for an air gap a of 0.18 cm, polymer thickness p of 0.018 cm, polymer dielectric constant ϵ_p of 3.5, and an applied voltage \mathcal{V}_0 of 3.7 V; (c) calculated effective electric field E_{eff} as a function of time for same parameters as in (b); (d) calculated electret surface charge density σ as a function of time for same parameters as in (b).

$$E_{\text{eff}}(t) = E^* \operatorname{arcsinh}\{\exp[(t_0 - t)/\tau]\}, \quad (10)$$

and is plotted in Fig. 2(c) for our particular example ($t_0 = 2.55 \text{ s}$ and $\tau = 0.59 \text{ s}$). As expected, E_{eff} initially decreases linearly with time to compensate for the linear increase in $E_\sigma(t)$ resulting from a constant in-

itial polarization current density j equal to j_{sat} . As t gets larger, however, the decrease in E_{eff} becomes progressively slower to reflect the hyperbolic behavior of j [Eq. (6)] for effective fields smaller than $3E^*$ [note that $\tanh(E/E^*) = 1$ for $(E/E^*) \geq 3$].

The electret surface charge density $\sigma(t)$, which can be written combining Eqs. (3) and (10) as

$$\sigma(t) = \sigma_{\max} - \beta E^* \operatorname{arcsinh}\{\exp[(t_0 - t)/\tau]\}, \quad (11)$$

is plotted in Fig. 2(d) for our particular example. The time dependence is identical to the previous example [Fig. 2(c)] except that here it is subtracted from σ_{\max} , giving a zero value for $\sigma(t)$ at $t=0$, a linear rise for small t , and an asymptotic approach to σ_{\max} for large t .

The examples presented so far were dealing with the electret polarization process, which is terminated when the electret charge density $\sigma(t)$, reaches its maximum value of σ_{\max} , which was determined by Eq. (2). The electret depolarization behavior is investigated by shorting the two chamber electrodes through an electrometer and irradiating the chamber sensitive volume as shown in Fig. 1(a). The effective electric field $E_{\text{eff}}(t)$ is now equal to $E_{\sigma}(t)$, the field produced by the previously formed electret state. This field is opposite in sign but initially equal in magnitude to the original field $E_a(0)$ applied during the electret production process. Thus during the depolarization procedure the charge carriers drifting in the electric field towards the polymer surface are

of opposite polarity to the charges forming the electret. The electret is thus slowly depolarized through the charge cancellation on the polymer surface. As indicated in Fig. 1(b) the measured depolarization current density j is identical in magnitude but opposite in sign to the polarization current density. Since the areas under the two current curves in Fig. 1(b) are identical, it is obvious that the charge conservation is upheld.

In summary, the hyperbolic dependence of the chamber air ionization current density on the effective electric field in the chamber sensitive volume is used in conjunction with the laws of Gauss and Kirchoff in the derivation of the equations governing the polarization and depolarization dynamics of the radiation-induced foil electret. Both polarization and depolarization of the foil electret can be described by identical relationships, the only difference being the polarity of the measured current density.

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¹B. G. Fallone and E. B. Podgorsak, *Phys. Rev. B* **27**, 2615 (1983).

²B. G. Fallone and E. B. Podgorsak, *Med. Phys.* (in press).

³B. Gross, in *Electrets*, Vol. 33 of *Topics in Applied Physics*, edited by G. M. Sessler (Springer, Berlin, 1980), p. 221.