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Short Note

Evaluating Polarization in Dielectrics with Continuously Distributed Dipole Relaxation Time by Discharge Current Transient Spectroscopy

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The application of discharge current transient spectroscopy (DCTS) to the evaluation of the steady-state polarization $P_s(\tau)$ in dielectrics with continuously distributed dipole relaxation time (τ) is discussed. The method proposed in Jpn. J. Appl. Phys. **35** (1996) 2216 can be used to evaluate $P_s(\tau)$ only in dielectrics with discrete τ. Using the method discussed here, $P_s(\tau)$ corresponding to the transient discharge current, which obeys a power law with respect to discharge time, can easily be evaluated.

KEYWORDS: dielectric, ferroelectric, continuously distributed relaxation time, polarization, discharge current transient spectroscopy (DCTS)

Dielectrics and ferroelectrics with high dielectric constants have been investigated in order to make use of these materials instead of SiO_2 in capacitors and metal-insulator-semiconductor field-effect transistors in LSI circuits. In order to realize the application of these materials, an understanding of the mechanism of dipole relaxation in these materials is essential.

In order to evaluate the steady-state polarization $P_s(\tau)$ in a material with dipole relaxation time (τ), discharge current transient spectroscopy (DCTS) has recently been applied.[1] However, this method cannot be used to evaluate $P_s(\tau)$ in materials with continuously distributed τ. Therefore, the author aims to evaluate $P_s(\tau)$ in such materials by modifying the method proposed previously.[1]

A capacitor, consisting of a dielectric (or ferroelectric) between two electrodes of unit area, is considered. In the elementary theory of dielectrics,[2,3] the buildup of polarization $P_p(W,\tau)$ in the capacitor during time W after the application of an electric field F_p at a temperature T is given by an exponential function of W:

$$P_p(W,\tau) = P_s(\tau)\left[1 - \exp\left(-\frac{W}{\tau}\right)\right]. \quad (1)$$

Since the decay of polarization after removal of the electric field is given by

$$P(t) = \int P_p(W,\tau)\exp\left(-\frac{t}{\tau}\right)\mathrm{d}\tau, \quad (2)$$

the depolarization current density (i.e., transient discharge current density) $J_{dis}(t)$ can be written as

$$J_{dis}(t) = -\frac{\mathrm{d}P(t)}{\mathrm{d}t} = \int P_p(W,\tau)\frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)\mathrm{d}\tau. \quad (3)$$

In DCTS,[1] a function $S(t)$ is defined as

$$S(t) \equiv tJ_{dis}(t)\exp(1), \quad (4)$$

which can be theoretically expressed by

$$S(t) = \int P_p(W,\tau)\exp(1)\frac{t}{\tau}\exp\left(-\frac{t}{\tau}\right)\mathrm{d}\tau. \quad (5)$$

A way of evaluating $P_p(W,\tau)$ and $P_s(\tau)$ is discussed, based on the curve-fitting procedure incorporated in the heterojunction-monitored capacitance (HMC) method,[4,5] which is used to evaluate the density-of-state distribution in the band gap of amorphous semiconductors.

The value of $S(t)$ is calculated from $J_{dis}(t)$ using eq. (4). Using the first trial function $P_p^{(0)}(W,\tau)$,[6] the value of $S^{(0)}(t)$ is calculated using eq. (5). Since the function

$$\frac{t}{\tau}\exp\left(-\frac{t}{\tau}\right) \quad (6)$$

in eq. (5) has a maximum at $t = \tau$, $P_p^{(n-1)}(W,\tau)$ has the greatest influence on the value of $S^{(n-1)}(t)$ at $t = \tau$, where n is an integer and $n \geq 1$. Therefore, the next trial function $P_p^{(n)}(W,\tau)$ is given by

$$P_p^{(n)}(W,\tau) = \frac{S(\tau)}{S^{(n-1)}(\tau)}P_p^{(n-1)}(W,\tau). \quad (7)$$

When $S^{(n)}(t)$ approaches $S(t)$, we obtain the solution:

$$P_p(W,\tau) = P_p^{(n)}(W,\tau). \quad (8)$$

In order to simplify the following arguments, W is assumed to be much greater than τ; that is,

$$P_s(\tau) \simeq P_p(W,\tau), \quad (9)$$

as is clear from eq. (1). The two kinds of $J_{dis}(t)$ shown in Fig. 1 are considered. The solid line represents $J_{dis}(t) \propto t^{-m}$, which is frequently observed in dielectrics, and the broken line represents $J_{dis}(t)$ for a dielectric with three kinds of dipoles: ($P_s(\tau)$ [C/cm^2], τ [s]) = (1×10^{-5}, 0.3), (1×10^{-5}, 3.0), and (1×10^{-5}, 30). In Fig. 1, m is 1.12.

Figure 2 shows $S(t)$ curves corresponding to each $J_{dis}(t)$ curve in Fig. 1. In this figure, the broken line has three distinct peaks corresponding to the three kinds of dipoles. However, the solid line has no peaks, suggesting that τ is distributed continuously.

We consider $P_p(W,\tau)$ expressed in units of C/cm^2/log$_{10}$ s; that is, we replace dτ in eq. (2) with d(log$_{10}\tau$). The solid line in Fig. 3 shows the $P_p(W,\tau)$ curve for which $S^{(n)}(t)$ approaches $S(t)$.[7] From Figs. 2 and 3, the value of $P_p(W,\tau)$ is found to be close to that of $S(t)$ at $t = \tau$, except for the difference between the units of $P_p(W,\tau)$ and those of $S(t)$, that is, C/cm^2/log$_{10}$ s and C/cm^2, indicating that $P_p^{(0)}(W,\tau)$ is a good first trial function. Since $W \gg \tau$, $P_s(\tau)$ can be obtained from eq. (9). The integral value of $P_s(\tau)$ from 0.1 s to 100 s is 1.49×10^{-5} C/cm^2.

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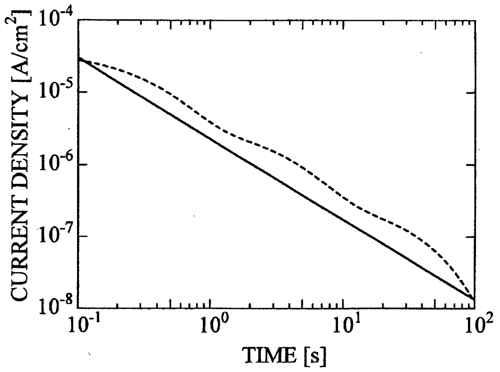

Fig. 1. Transient discharge current density due to dipole relaxation in a dielectric.

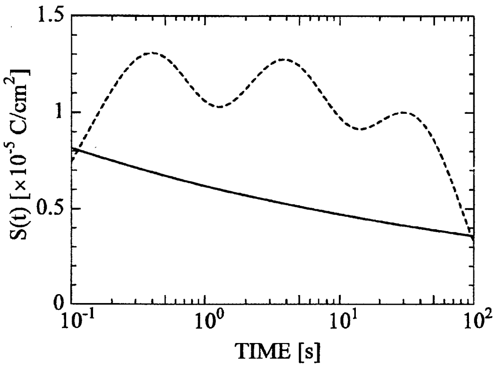

Fig. 2. $S(t)$ curves corresponding to $J_{\rm dis}(t)$ curves in Fig. 1.

By applying the above method to a dielectric with discrete τ (the broken line in Fig. 2), the $P_{\rm p}(W,\tau)$ curve indicated by the broken line in Fig. 3 is obtained. In this figure, it is found that there are three distinct peaks. The values of τ at the maxima and the corresponding integral values of $P_{\rm s}(\tau)$ are (0.324 s, 1.05×10^{-5} C/cm^2), (3.24 s, 1.02×10^{-5} C/cm^2), and (31.6 s, 1.01×10^{-5} C/cm^2).[8] These values are found to be close to the actual values, indicating that this method can be applied to dielectrics with discrete τ. Although the method reported previously can be used to evaluate τ more accurately,[1] it requires experimental results for various W. Therefore, the method discussed here is a simpler method for the evaluation of $P_{\rm s}(\tau)$ with discrete τ than the previous method.

DCTS is applied to evaluate $P_{\rm s}(\tau)$ with continuously distributed τ in a dielectric (or ferroelectric). Since the value of $P_{\rm p}(W,\tau)$ in units of C/cm^2/$\log_{10}$ s is roughly equal to the value of $S(t)$ in units of C/cm^2 at $t=\tau$, it is easy to judge whether τ is discrete or continuously

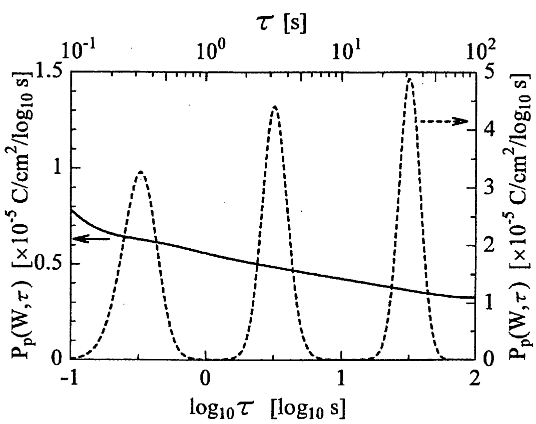

Fig. 3. $P_{\rm p}(W,\tau)$ for which $S^{(n)}(t)$ approaches $S(t)$ shown in Fig. 2. Since $W\gg\tau$, $P_{\rm s}(\tau)\simeq P_{\rm p}(W,\tau)$.

distributed. Then, $P_{\rm p}(W,\tau)$ for the dielectric can be accurately evaluated by a simple fitting procedure using eq. (7). $P_{\rm s}(\tau)$ can be estimated using eq. (1). Since the value of $P_{\rm s}(\tau)$ for a particular T and $F_{\rm p}$ can be evaluated by DCTS, the dependence of $P_{\rm s}(\tau)$ on T or $F_{\rm p}$ can be investigated in detail. Therefore, DCTS is suitable for the evaluation of $P_{\rm s}(\tau)$ of dielectrics (or ferroelectrics) with both discrete and continuously distributed τ.

1) H. Matsuura: Jpn. J. Appl. Phys. **35** (1996) 2216.
2) J. Vanderschueren and J. Gasiot: *Topics in Applied Physics: Thermally Stimulated Relaxation in Solids*, ed. P. Bräunlich (Springer-Verlag, Berlin, 1979) Vol. 37, Chap. 4.
3) C. Bucci and R. Fieschi: Phys. Rev. Lett. **12** (1964) 16.
4) H. Matsuura: J. Appl. Phys. **64** (1988) 1964.
5) H. Matsuura and H. Okushi: *Electrical Properties of Amorphous/Crystalline-Semiconductor Heterojunctions*, ed. J. Kanicki (Artech House, Boston, 1992) *Amorphous and Microcrystalline Semiconductor Devices*, Vol. II: Materials and Device Physics, Chap. 11.
6) The value of $P_{\rm p}^{(0)}(W,\tau)$ is equal to the value of $S(t)$ at $t=\tau$. As is clear from the following discussion, $P_{\rm p}^{(0)}(W,\tau)$ is a good first trail function.
7) In order to obtain a value of $P_{\rm p}^{(n)}(W,\tau)$ as close to the actual value of $P_{\rm p}(W,\tau)$ as possible, the definite integral with respect to $\log_{10}\tau$ of eq. (5) is calculated from $\log_{10}0.1-1$ to $\log_{10}100+1$ on the assumptions that $P_{\rm p}^{(n)}(W,\tau)=P_{\rm p}^{(n)}(W,0.1)$ in the range $0.01\,{\rm s}\le\tau\le0.1\,{\rm s}$ and $P_{\rm p}^{(n)}(W,\tau)=P_{\rm p}^{(n)}(W,100)$ in the range $100\,{\rm s}\le\tau\le1000\,{\rm s}$.
8) The value of τ at each peak of $S^{(n)}(t)$ is slightly greater than that at the corresponding peak of $S(t)$, although the author tried to obtain a value of $S^{(n)}(t)$ as close as possible to that of $S(t)$ using eq. (7). Therefore, the calculated τ is slightly greater than the actual τ.