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# Transient States of Electric Conduction in Solid Dielectric Including Carrier Recombination. II. Ideal Dielectric with Deep Traps

by

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**Summary.** Electric conduction in a dielectric with deep traps is analysed. The space charge is made up of free electrons, holes and trapped electrons. The effect of injection mechanisms and carrier mobility on time curves of absorption current density is investigated. The problem is solved numerically.

**1. Introduction.** In part I of the present work we considered a model of solid dielectric in which charge carriers were free electrons and holes. Defects of the crystalline structure and contaminations may lead to localization (trapping) of negative charge carriers [1–3]. In such a case the equation describing the change of free electron concentration takes the form

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}\{\mu_n nE\} - \beta(np - n_0 p_0) - \frac{\partial n_t}{\partial t} \tag{1}$$

where $n_t$ is the concentration of trapped electrons. The change of trapped electron concentration is described by the equation [1, 3]

$$\frac{\partial n_t}{\partial t} = C_n\left[n\left(1 - \frac{n_t}{N_t}\right) - n_1 \frac{n_t}{N_t}\right] \tag{2}$$

where $C_n$ — speed of trapping calculated for one electron when all the traps are empty, $N_t$ — trap concentration, $n_1$ — material constant at the given temperature. The second component on the right hand side of Eq. (2) $C_n n_1 n_t/N_t$ describes the concentration of electrons released from traps in unit time. In a dielectric there may exist trap centers from which the trapped electrons cannot escape. Such centers are called "deep traps". The change of concentration of electrons localized in deep traps is described by the formula

$$\frac{\partial n_t}{\partial t} = \frac{n}{T_t}\left(1 - \frac{n_t}{N_t}\right) \tag{3}$$

where $T_t = C_n^{-1}$ is the time constant of trapping.

The aim of the work is the analysis of transient states of electric conduction in a solid dielectric with deep traps.

**2. Problem solution.** The space charge in a dielectric is made up of free electrons, holes and trapped electrons. The density of the space charge $q_v(x, t)$ is determined by excess concentrations of free electrons, holes and trapped electrons [2]

$$q_v(x, t) = e_0 \left[(p(x, t) - p_0) - (n(x, t) - n_0) - n_t(x, t)\right]. \tag{4}$$

Initial values $p(x, 0)$ and $n(x, 0)$ depend on the relevant values of equilibrium concentrations $p_0$ and $n_0$. In what follows we consider electric conduction in an ideal dielectric ($p_0 = n_0 = 0$). Assuming that transport current density is equal to the sum of densities of free electron and hole currents, the electric conduction in a dielectric with deep traps is described by the equations

$$\varepsilon \frac{\partial E}{\partial x}(x, t) = e_0 \left[p(x, t) - n(x, t) - n_t(x, t)\right] \tag{5}$$

$$\frac{\partial}{\partial x}\{\mu_p p(x, t) E(x, t) + \mu_n n(x, t) E(x, t)\} + \frac{\partial p(x, t)}{\partial t} - \frac{\partial n(x, t)}{\partial t} - \frac{\partial n_t(x, t)}{\partial t} = 0 \tag{6}$$

$$\frac{\partial n(x, t)}{\partial t} = \frac{\partial}{\partial x}\{\mu_n n(x, t) E(x, t)\} - \beta n(x, t) p(x, t) - \frac{\partial n_t(x, t)}{\partial t} \tag{7}$$

$$\frac{\partial n_t(x, t)}{\partial t} = \frac{n(x, t)}{\tau_t}\left(1 - \frac{n_t(x, t)}{N_t}\right) \tag{8}$$

with the voltage condition

$$\int_0^L E(x, t)\, dx = U; \qquad U = \text{const}; \qquad U > 0. \tag{9}$$

The absorption current density $j_a(t)$ is described by the formula

(10) $$j_a(t) = \varepsilon \frac{\partial E(x,t)}{\partial t} + e_0 \mu_p p(x,t) E(x,t) + e_0 \mu_n n(x,t) E(x,t).$$

We intend to determine the time courses of absorption current density $j_a(t)$. The problem is solved numerically.

The considerations are performed in the system of dimensionless variables $E', u', x', p', n', n_t', t', r, \tau_t, \beta_R, N_t'$ and $j_a'$ described by the equations

(11) $$E' = \frac{LE}{U_0}; \quad u' = \frac{U}{U_0}; \quad x' = \frac{x}{L}; \quad p' = \frac{e_0 L^2 p}{\varepsilon U_0}; \quad n' = \frac{e_0 L^2 n}{\varepsilon U_0}$$
$$n_t' = \frac{e_0 L^2 n_t}{\varepsilon U_0}; \quad t' = \frac{\mu_n U_0 t}{L^2}; \quad r = \frac{\mu_p}{\mu_n}; \quad \tau_t = \frac{\mu_n U_0 T_t}{L^2}$$
$$\beta_R = \frac{e_0 \mu_n}{\beta \varepsilon}; \quad N_t' = \frac{e_0 L^2 N_t}{\varepsilon U_0}; \quad j_a' = \frac{L^3 j_a}{\varepsilon U_0^2 \mu_n}$$

where $U_0$ is the reference voltage.

After omitting the prim symbol in the magnitudes, Eqs (5)–(9) take the following form in the system of dimensionless variables

(12) $$\frac{\partial E(x,t)}{\partial x} = p(x,t) - n(x,t) - n_t(x,t)$$

(13) $$\frac{\partial}{\partial x}\{rp(x,t)E(x,t) + n(x,t)E(x,t)\} + \frac{\partial p(x,t)}{\partial t} - \frac{\partial n(x,t)}{\partial t} - \frac{\partial n_t(x,t)}{\partial t} = 0$$

(14) $$\frac{\partial n(x,t)}{\partial t} = \frac{\partial}{\partial x}\{n(x,t)E(x,t)\} - \frac{1}{\beta_R} n(x,t)p(x,t) - \frac{\partial n_t(x,t)}{\partial t}$$

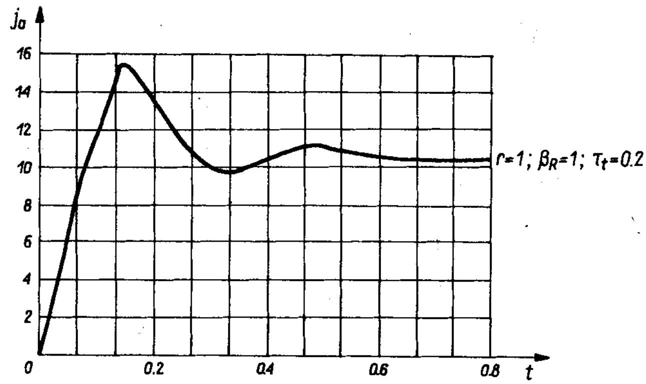
(15) $$\frac{\partial n_t(x,t)}{\partial t} = \frac{n(x,t)}{T_t}\left(1 - \frac{n_t(x,t)}{N_t}\right)$$

(16) $$\int_0^1 E(x,t)\,dx = U.$$

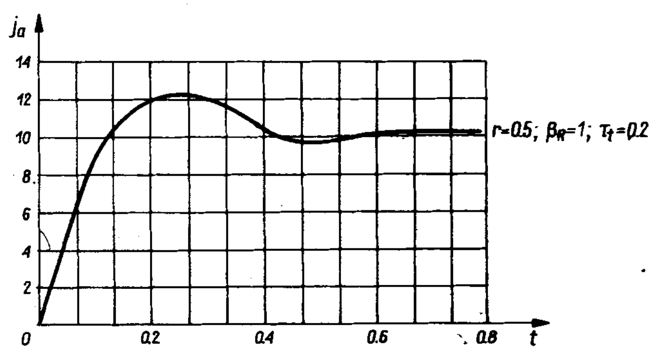
After transformations we get the equations of characteristics

(17) $$\frac{dx_n}{dt} = -E \quad \text{and} \quad \frac{dn}{dt} = n(p-n-n_t) - \frac{1}{\beta_R} np - \frac{n}{\tau_t}\left(1 - \frac{n_t}{N_t}\right)$$

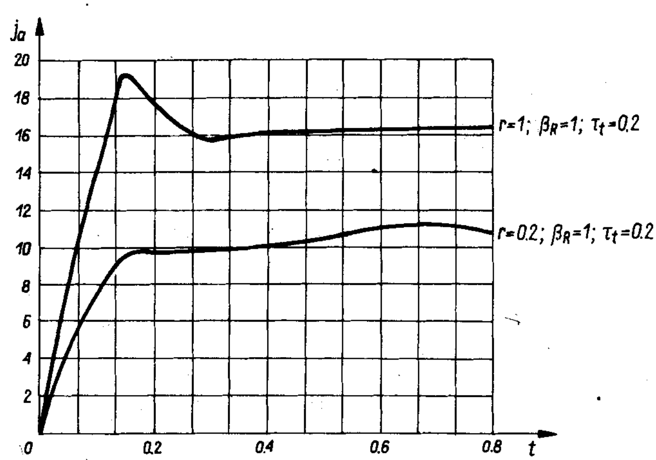
(18) $$\frac{dx_p}{dt} = rE \quad \text{and} \quad \frac{dp}{dt} = -rp(p-n-n_t) - \frac{1}{\beta_R} np.$$




$j_{(0,t)} = a \exp(b\sqrt{E_{(0,t)}});\quad j_{(1,t)} = a_1 E^2_{(1,t)} \exp(-b_1/E_{(1,t)})$

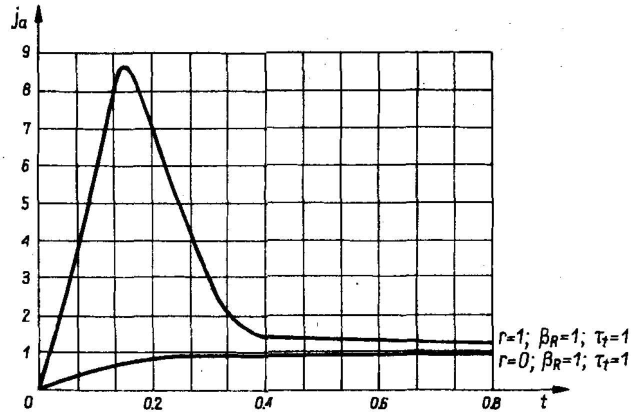



$j_{(0,t)} = a \exp(b\sqrt{E_{(0,t)}});\quad j_{(1,t)} = a_1 E^2_{(1,t)} \exp(-b_1/E_{(1,t)})$

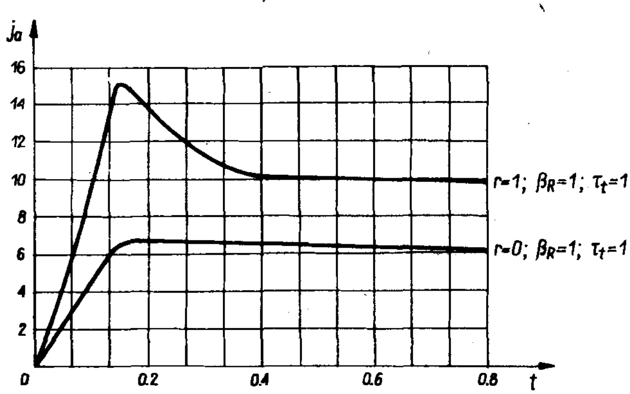



$j_{(0,t)} = a_1 E^2_{(0,t)} \exp(-b_1/E_{(0,t)});\quad j_{(1,t)} = a_1 E^2_{(1,t)} \exp(-b_1/E_{(1,t)})$

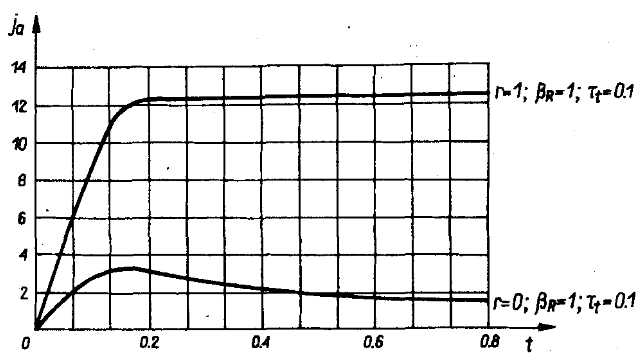
Figs. 1–3. Time course of absorption current density




$p_{(0,t)} = const\,;\quad j_{(1,t)} = const$




$p_{(0,t)} = const\,;\quad j_{(1,t)} = a\exp(b\sqrt{E_{(1,t)}})$




$p_{(0,t)} = const\,;\quad n_{(1,t)} = const$

Figs. 4–6. Time course of absorption current density

We considered a charge flow in which the distribution of electric field intensity is always positive, $E(x, t) > 0$. In such a case, in order to determine the distributions of $p(x, t)$, $n(x, t)$ and $n_t(x, t)$ we need information about the initial values $p(x, 0)$, $n(x, 0)$ and $n_t(x, 0)$ and about boundary values $p(0, t)$ and $n(1, t)$.

According to the adopted assumption, we consider an ideal dielectric, and so $p(x, 0) = n(x, 0) = n_t(x, 0) = 0$. The boundary values $p(0, t)$ and $n(1, t)$ are described by the equations

$$j(0, t) = f_0 [E(0, t)] \tag{19}$$

$$j(1, t) = f_1 [E(1, t)] \tag{20}$$

where functions $f_0$ and $f_1$ describe the mechanism of carrier injection from the electrode into the dielectric.

Moreover, we considered the electrode-dielectric contact in which the boundary values $p(0, t)$ and $n(1, t)$ are constant. In this part of research we examined the effect of the electrode-dielectric contact on the time courses of absorption current density $j_a(t)$ in a dielectric with deep traps. The $j_a(t)$ curves were determined numerically, and examples of the numerical calculations are given in the Figures 1–6.

**3. Conclusions.** Looking back on the results of the first part of this work, we can see that the time course of absorption current density does not change significantly when deep traps in the dielectric are taken into account. This is especially manifested when the mechanism of injection at both the electrodes is described by the function of current density $j_0$ of injected carriers and by electric field intensity $E_0$. When one of the electrodes supplies a constant amount of positive charge carriers and the other electrode supplies negative charge carriers according to the function $j_0 = f(E_0)$ or when both electrodes inject a constant amount of charge carriers, then the curve of $j_a(t)$ is growing or is a curve of variable monotonicity; at the same time the curve has only one extremum, at the highest value at that. In all cases we observe an initial rapid variability of values of the $j_a(t)$ function, followed by a slow tendency to assume a fixed value.

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Б. Свистач, **Нестационарные инжекционные токи в твердом диэлектрике с рекомбинацией носителей зарядов. Часть II. Идеальный диэлектрик с глубокими ловушками**

В настоящей статье рассматривается проводимость тока в диэлектрике с глубокими ловушками. Объемный заряд образуют свободные электроны и дырки, а также захваченные электроны. Исследуется влияние механизмов инжекции и подвижности носителей на переходные характеристики плотности тока абсорбции. Задача решена на вычислительной машине.