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QUASI-EQUILIBRIUM MODEL OF SMALL-SIGNAL DLTS RESPONSE FROM INSULATOR-SEMICONDUCTOR INTERFACIAL TRAPS IN MIS STRUTURES

M. GRENDEL[1], Bratislava

A model of the DLTS response from insulator-semiconductor interfacial traps in metal-insulator-semicounductor (MIS) structures is proposed. The model is based upon the assumption that at sufficiently high temperatures the time constant of the formation of the quasi-equilibrium space-charge layer in the semiconductor is negligible in comparison with the duration of the whole transient process investigated. A method for calculating the current, charge and capacitance curves of the small-signal DLTS is described for the case of n arbitrary discrete interface-trap levels. Simple final formulae and numerical results are presented for $n = 1$ and $n = 2$.

I. INTRODUCTION

The deep-level transient spectroscopy (DLTS) has proved to be a useful tool for investigating various kinds of defects in MIS structures. The DLTS is applicable not only to bulk defects, but it can also give some valuable information about insulator-semiconductor interface states. For that purpose several modifications of the DLTS were developed. The response of an MIS structure to an applied voltage step can be recorded as a capacitance transient (C-DLTS) [1], as a gate-voltage transient (at the constant capacitance — CC-DLTS) [2], as a current transient (DLTCS) [3], or the released charge can be measured (Q-DLTS) [4]. Experimental results of each modification of the DLTS deserve a careful theoretical analysis of the processes which contribute to the measured signal.

Mostly, it is supposed that the measured signal is due to the emission of carriers from interface traps [1—4]. This assumption leads to simple mathematical formulae for processing the data. However, a more complete description of the DLTS response should comprise also the capture of carriers on interface traps. Although there exist a few investigations concerning the capture (see, e. g., [1]), this case seems to be, unlike the emission [5], more complicated from the theoretical point of view.

In many cases the capture of carriers may accompany or even prevail over the emission. For example, if the applied gate voltage is such that the equilibrium occupancy of a trap level varies rapidly between 0 and 1 with the change in the equilibrium surface potential, the capture can play an important role at least in the last phase of the transient process (at the end of which all the system of electrons and holes reaches thermal equilibrium). As it follows from [6], this should be kept in mind when investigating the small-signal response of interface-trap levels located at the midgap of the semiconductor.

In the present paper we investigate the quasi-equilibrium model of the DLTS response which is a generalization of the model suggested in [6]. Similarly as in [6] we suppose that both the emission and capture may take place during the transient process under investigation. In contrast to [6] we consider an arbitrary distribution of interface-trap levels in the semiconductor band gap. The basic equations of the quasi-equilibrium model are linearized in the case of small voltage steps and an integral equation for the change in the surface potencial is derived. This equation is solved by means of the Laplace transform technique, and in the case of n arbitrary discrete interface-trap levels, formulae for the current, charge and capacitance modification of the small-signal DLTS are derived. Finally, simple formulae and numerical results are obtained for $n=1$ and $n=2$.

II. THE QUASI-EQUILIBRIUM MODEL

Similarly as in [6] we shall investigate the response of an ideal MIS structure to an applied voltage step. We shall suppose that the insulator-semiconductor interface contains traps characterized by the density $N(E_j)$, which is defined as follows: $N(E_j)\,\mathrm{d}E_j$ is the number of interfacial traps with energies from the interval $(E_j,\ E_j+\mathrm{d}E_j)$ per unit area. For simplicity, we shall consider only monovalent acceptor-like traps. Immediately after the application of the voltage step to the MIS structure, free electrons and holes in the semicounductor tend to form a quasi-equilibrium distribution. The rate of formation of the quasi-equilibrium distribution depends on the following two basic mechanisms: the conductivity mechanism (i. e., transport of free carriers) and the transition mechanism (i. e., emission, capture, generation and recombination of free carriers). We shall suppose that both mechanisms in the bulk are sufficiently efficient to establish the quasi-equilibrium distribution before the transient process due to transitions through interface-trap levels can take place. Then, according to the Shockley-Read-Hall statistics [7], the rate equation for the occupancy f_j of an interface-trap level at an energy E_j can be written in the form

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[1] Institute of Physics, EPRC, Slov. Acad. Sci., Dúbravská cesta, 842 28 BRATISLAVA, Czechoslovakia.

$$\frac{\partial f_j}{\partial t} = -(c_{nj}n_\infty \mathrm{e}^{-v} + c_{pj}p_\infty \mathrm{e}^{v} + e_{nj} + e_{pj})f_j + c_{nj}n_\infty \mathrm{e}^{-v} + e_{pj}, \tag{1}$$

where t is time; $e_{nj}(e_{pj})$, $c_{nj}(c_{pj})$ and $n_\infty(p_\infty)$ are the emission rate, the capture coefficient and the bulk concentration of electrons (holes), respectively. The dimensionless surface potential v in (1) is defined as

$$v = \frac{e\varphi_s}{kT} \tag{2}$$

where T is the absolute temperature, φ_s is the surface potential, e is the electronic charge, and k is the Boltzmann constant. We shall assume that the emission rates and capture coefficients in (1) satisfy the well-known relations:

$$e_{nj} = c_{nj} \exp\left(\frac{E_j - E_c}{kT}\right), \quad e_{pj} = c_{pj} \exp\left(\frac{E_v - E_j}{kT}\right) \tag{3}$$

where E_c is the energy of the bottom of the conductivity band of the semiconductor, and E_v is the corresponding energy of the top of the valence band. Both the functions f_j and v in (1) are considered to be dependent on time and temperature.

Besides (1), the functions f_j and v must satisfy the condition

$$U = -(Q_s(v) + e \int N(E_j) f_j \, \mathrm{d}E_j)/C_0 + kTv/e + \varphi_{MS} \quad (\text{for } t \geq 0), \tag{4}$$

where U is the gate voltage applied to the MIS structure at the time moment $t=0$ and kept constant during the trasient process investigated, C_0 is the capacitance of the insulator per unit area, φ_{MS} is the contact potential difference between metal and semiconductor, and $Q_s(v)$ is the semiconductor charge per unit area which can be expressed by the well-known formulae from the space charge theory. Equation (4) together with (1) forms a system of equations from which the functions f_j, v may, in principle, be calculated. Since (1) is a first-order differential equation with respect to f_j, its particular solution is determined by the initial condition

$$f_j(t=0) = f_{0j}. \tag{5}$$

Provided that before the time moment $t=0$ all the system of electrons and holes (free or captured) is in thermal equilibrium, the initial value f_{0j} in (5) can be considered as known. For example, f_{0j} can be given by the function of the Fermi-Dirac type

$$f_{0j} = \left\{1 + \exp\left(\frac{E_j - E_F}{kT} + v_0\right)\right\}^{-1}, \tag{6}$$

where E_F is the Fermi energy and v_0 is the equilibrium value of v. The value v_0 is determined by

$$U_0 = -(Q_s(v_0) + e \int N(E_j) f_{0j} \, \mathrm{d}E_j)/C_0 + kTv_0/e + \varphi_{MS}, \tag{7}$$

where U_0 is the gate voltage applied to the MIS structure before the application of the voltage U, and f_{0j} is given by (6).

By eliminating f_j from equations (1), (4) and utilizing the conditions (5)—(7), one could obtain a nonlinear integral equation for v. Generally, this equation could be solved only numerically. It is worthwhile to notice that in the particular case when only a single discrete interface-trap level at energy E_T is present, the problem of finding v can be simplified. In fact, in such a case, $N(E_j) = N_T\delta(E_j - E_T)$, and from equations (1), (4) we obtain the following first-order ordinary differential equation:

$$\left(\frac{\mathrm{d}v}{\mathrm{d}t}\right)_T = \frac{e^2 N_T}{kT} \frac{F(v)}{C_0 + C_s(v)} \tag{8}$$

where

$$F(v) = [U + Q_s(v)/C_0 - kTv/e - \varphi_{MS}]\,(c_n n_\infty \mathrm{e}^{-v} + e_p p_\infty \mathrm{e}^{v} + e_n + e_p)\,\frac{C_0}{eN_T} +$$
$$+ c_n n_\infty \mathrm{e}^{-v} + e_p \tag{9}$$

(here c_n, c_p, e_n, e_p have the meaning of c_{nj}, c_{pj}, e_{nj}, e_{pj} for the trap of energy E_T) and

$$C_s(v) = -(kT/e)\,\partial Q_s(v)/\partial v. \tag{10}$$

Equation (8) can be solved for an arbitrary voltage step $\Delta U = U - U_0$ by means of standard numerical methods.

With the function $v(t, T)$ known, one can easily calculate the DLTS signal. The current density $j(t, T)$ can be calculated according to the formula

$$j(t, T) = -\frac{C_0 kT}{e}\left(\frac{\partial v}{\partial t}\right)_U \tag{11}$$

and the released charge per unit area is

$$Q(t, T) = -\frac{C_0 kT}{e}(v - v(0, T)). \tag{12}$$

The capacitance of the MIS structure per unit area (measured by a small-amplitude probe signal which does not affect the occupancy of the interface trap levels)is

$$C(t, T) = C_0 C_s(v)/(C_0 + C_s(v)) \tag{13}$$

where $C_s(v)$ is given by the formula (10).

III. THE SMALL-SIGNAL DLTS RESPONSE

In order to obtain explicit formulae for the current, charge and capacitance transient, we shall confine ourselves to small applied-voltage steps, i. e., the fulfilment of the condition

$$|v - v_0| \ll 1 \tag{14}$$

will be assumed throughout all this section. For simplicity, we shall suppose that neither emission rates nor capture coefficients depend on v. With these assumptions we can linearize equations (1), (4). In the linear approximation, by utilizing the relations (5), (6), (10), (14), after some arrangements we have

$$\Delta f_j = -\frac{f_{0j}(1-f_{0j})}{\tau_{0j}} \int_0^t \Delta v(t') \exp\left(\frac{t'-t}{\tau_{0j}}\right) \mathrm{d}t' \tag{15}$$

$$\Delta u = \left(1 + \frac{C_{s0}}{C_0}\right) \Delta v(t) - \frac{e^2}{kTC_0} \int N(E_j)\, \Delta f_j\, \mathrm{d}E_j \tag{16}$$

where

$$\Delta f_j = f_j - f_{0j},\quad \Delta v(t) = v - v_0,\quad C_{s0} = C_s(v_0),\quad \Delta u = \frac{e\Delta U}{kT} \tag{17}$$

and

$$\frac{1}{\tau_{0j}} = c_{nj} n_\infty\, \mathrm{e}^{-v_0} + c_{pj} p_\infty\, \mathrm{e}^{v_0} + e_{nj} + e_{pj}. \tag{18}$$

According to (5)—(7) and (10), the initial condition for the function $\Delta v(t)$ can be written in the form

$$\Delta v(0) = \frac{\Delta u}{1 + C_{s0}/C_0}. \tag{19}$$

From the relations (15), (16) and (19) we obtain the equation

$$\Delta v(t) - \Delta v(0) = -\int_0^t \left(\int \beta_j \exp\left(\frac{t'-t}{\tau_{0j}}\right) \mathrm{d}E_j\right) \Delta v(t')\, \mathrm{d}t' \tag{20}$$

where

$$\beta_j = \frac{e^2 N(E_j) f_{0j}(1-f_{0j})}{kT(C_0 + C_{s0})\tau_{0j}}. \tag{21}$$

To find the solution of the integral equation (20), we shall use the Laplace transform technique. It can be shown that for the function $\Delta v(t)$, the Laplace transform $\Delta v(p)$ is given by the relation

$$\Delta v(p) = \frac{\Delta v(0)}{p\left(1 + \displaystyle\int \frac{\beta_j}{p + \frac{1}{\tau_{0j}}} \mathrm{d}E_j\right)} \tag{22}$$

hence

$$\Delta v(t) = \frac{\Delta v(0)}{2\pi \mathrm{i}} \int_{s-\mathrm{i}\infty}^{s+\mathrm{i}\infty} \frac{\mathrm{e}^{pt}\, \mathrm{d}p}{p\left(1 + \displaystyle\int \frac{\beta_j}{p + \frac{1}{\tau_{0j}}} \mathrm{d}E_j\right)}. \tag{23}$$

By substituting $\Delta v(t)$ from relation (23) into (11), (12), and (13), one can obtain formulae for $j(t, T)$, $Q(t, T)$, and $C(t, T)$. The applicability of these formulae depends on the possibility of evaluating the integrals in (23).

Now, let the energy spectrum of the interfacial traps consist of n different energy levels $E_1, E_2, \ldots, E_n$ with the corresponding trap densities $N_1, N_2, \ldots, N_n$ so that $N(E_j) = \sum_k N_k \delta(E_j - E_k)$. In such a case the integral over E_j can be replaced by the sum over j, and the integral over p can be evaluated by utilizing Cauchy's residue theorem. Thus, from formula (23) we have

$$\frac{\partial \Delta v(t)}{\partial t} = \Delta v(0) \sum_{j=1}^{n} \frac{\mathrm{e}^{p_j t}}{P_n'(p_j)} \prod_{k=1}^{n} \left(p + \frac{1}{\tau_{0k}}\right) \tag{24}$$

where p_j ($j = 1, 2, \ldots, n$) are the roots of the polynomial

$$P_n(p) = \left(1 + \sum_{j=1}^{n} \frac{\beta_j}{p + \frac{1}{\tau_{0j}}}\right) \prod_{k=1}^{n} \left(p + \frac{1}{\tau_{0k}}\right) \tag{25}$$

and $P_n'(p)$ means the first derivative of $P_n(p)$. In formula (25), β_j is given by

$$\beta_j = \frac{e^2 N_j f_{0j}(1-f_{0j})}{kT(C_0 + C_{s0})\tau_{0j}}. \tag{26}$$

By utilizing the relation (24), from formulae (11), (12) and (13), we obtain the following result:

$$j(t, T) = -\frac{C_0 kT}{e} \Delta v(0) \sum_{j=1}^{n} \frac{\mathrm{e}^{p_j t}}{P_n'(p_j)} \prod_{k=1}^{n} \left(p_j + \frac{1}{\tau_{0k}}\right) \tag{27}$$

$$Q(t, T) = -\frac{C_0 kT}{e} \Delta v(0) \sum_{j=1}^{n} \frac{\mathrm{e}^{p_j t} - 1}{p_j P_n'(p_j)} \prod_{k=1}^{n} \left(p_j + \frac{1}{\tau_{0k}}\right) \tag{28}$$

$$C(t, T) = C(0, T) + \frac{C_{s0}' \Delta v(0)}{(1 + C_{s0}/C_0)^2} \sum_{j=1}^{n} \frac{\mathrm{e}^{p_j t} - 1}{p_j P_n'(p_j)} \prod_{k=1}^{n} \left(p_j + \frac{1}{\tau_{0k}}\right) \tag{29}$$

where

$$C(0,\ T)=(C_0^{-1}+C_s^{-1}(v(0,\ T)))^{-1},\qquad C'_{s0}=\partial C_s(v_0)/\partial v_0. \tag{30}$$

Numerical calculations of $j(t,\ T)$, $Q(t,\ T)$, $C(t,\ T)$ given by (27)—(30) require to know the values of the roots p_j $(j=1,\ 2,\ \ldots,\ n)$ of the polynomial (25). For $n>2$, these values could be found approximately by means of the numerical methods of solving algebraic equations. In the case when $n=1$ or $n=2$, the roots p_j $(j=1,\ 2)$

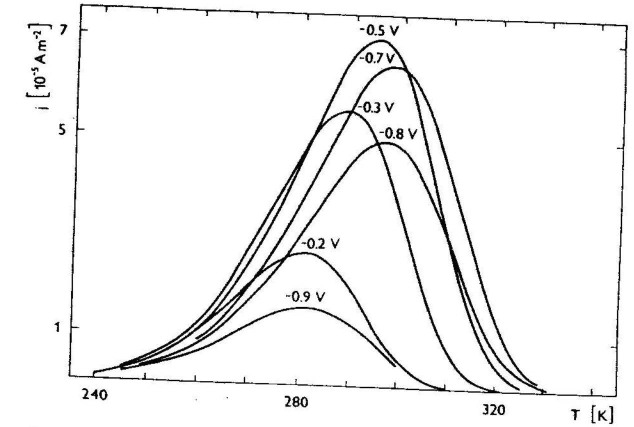

Fig. 1. The set of j—T curves computed for various gate voltages U_0, taking E_T—$E_C=-0.54$ eV, $t=1$ ms, $N_T=10^{15}$ m^{-2}, $\Delta U=1$ mV.

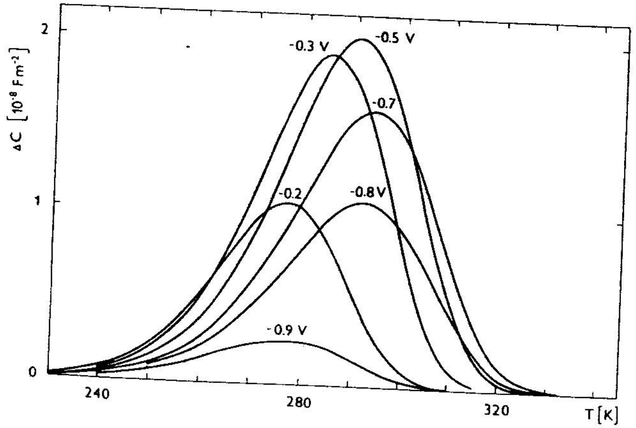

Fig. 2. The set of ΔC—T curves computed for various gate voltages U_0. The values of parameters are the same as in Fig. 1.

can be expressed in an explicit form. Then, utilizing the formula (27), the current density $j(t,\ T)$ can be expressed as follows:
For $n=1$,

$$j\,(t,\ T)=\frac{C_0kT}{e}\,\beta_1\,\Delta v(0)\,\exp\left[-\left(\beta_1+\frac{1}{\tau_{01}}\right)t\right], \tag{31}$$

whilst for $n=2$,

$$j(t,\ T)=\frac{C_0kT\,\Delta v(0)}{e(p_2-p_1)}\left[\left(p_1+\frac{1}{\tau_{01}}\right)\left(p_1+\frac{1}{\tau_{02}}\right)e^{p_1t}-\left(p_2+\frac{1}{\tau_{01}}\right)\left(p_2+\frac{1}{\tau_{02}}\right)e^{p_2t}\right], \tag{32}$$

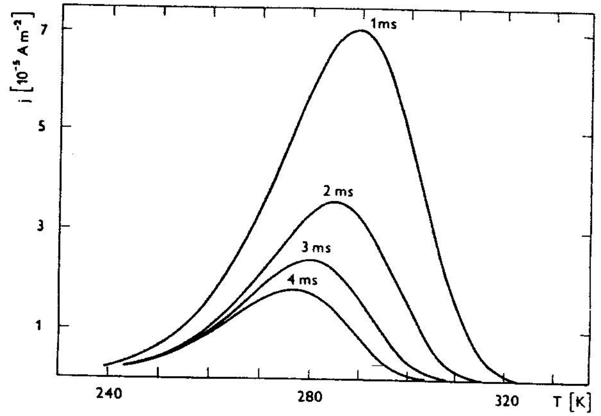

Fig. 3. The set of j—T curves computed for various delay times t. ($U_0=-0.5$ V, the other parameters are the same as in Fig. 1).

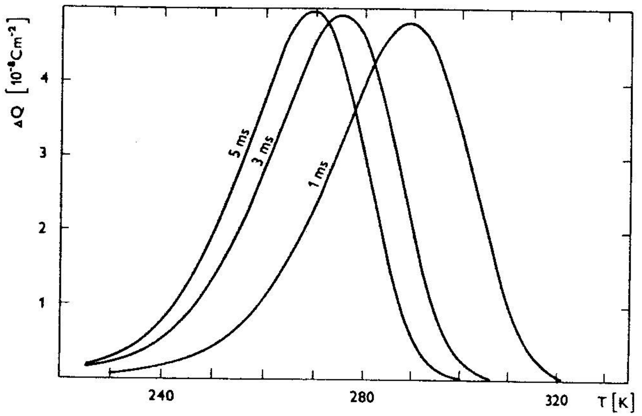

Fig. 4. The set of ΔQ—T curves computed for various delay times t. The values of parameters are the same as in Fig. 3.

where

$$p_{1,2} = -\frac{1}{2}\left(\beta_1+\beta_2+\frac{1}{\tau_{01}}+\frac{1}{\tau_{02}}\right) \pm \sqrt{\frac{1}{4}\left(\beta_1+\beta_2+\frac{1}{\tau_{01}}+\frac{1}{\tau_{02}}\right)^2 - \frac{1}{\tau_{01}\tau_{02}} - \frac{\beta_1}{\tau_{02}} - \frac{\beta_2}{\tau_{01}}}\,. \tag{33}$$

In formulae (31) – (33), τ_{0j} and β_j ($j=1, 2$) are given by the relations (18) and

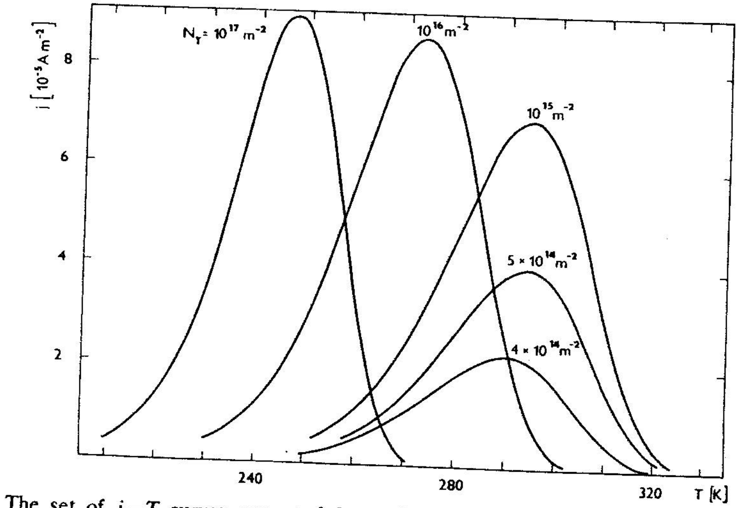

Fig. 5. The set of j—T curves computed for various trap densities N_T ($U_0 = -0.5$ V, the other parameters are the same as in Fig. 1).

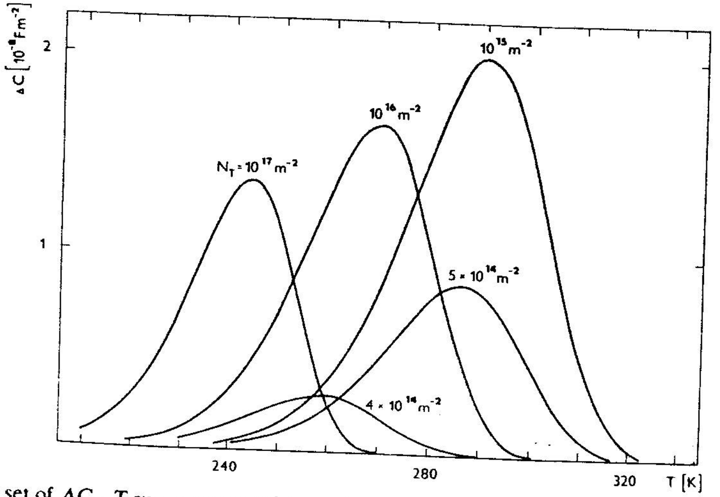

Fig. 6. The set of ΔC—T curves computed for various trap densities N_T. The values of parameters are the same as in Fig. 5.

(26), respectively. Similarly as it was for $j(t, T)$, according to (29) and (30) one could easily write formulae for $Q(t, T)$ and $C(t, T)$, analogous to (31) and (32).

IV. NUMERICAL RESULTS AND DISCUSSION

To compute the small-signal DLTS curves, we set up a program which utilizes the formula (32), formulae for the differencies $\Delta Q = Q(t, T) - Q(2t, T)$ and $\Delta C = C(t, T) - C(2t, T)$, analogous to (32), and also the relations (3)—(7), (10),

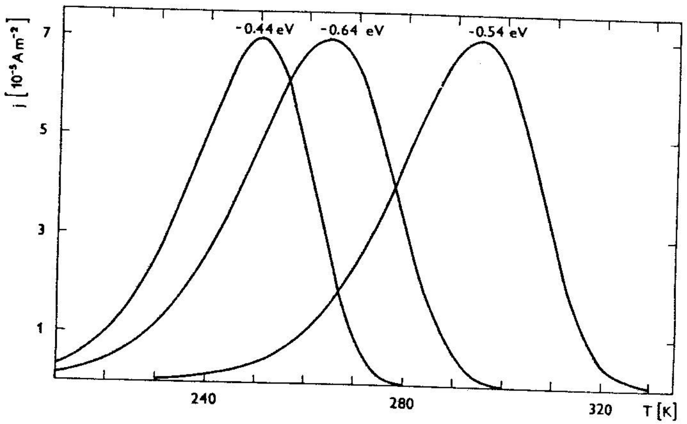

Fig. 7. The set of j—T curves computed for various interface-trap energy levels ($U_0 = -0.5$ V, the other parameters are the same as in Fig. 1).

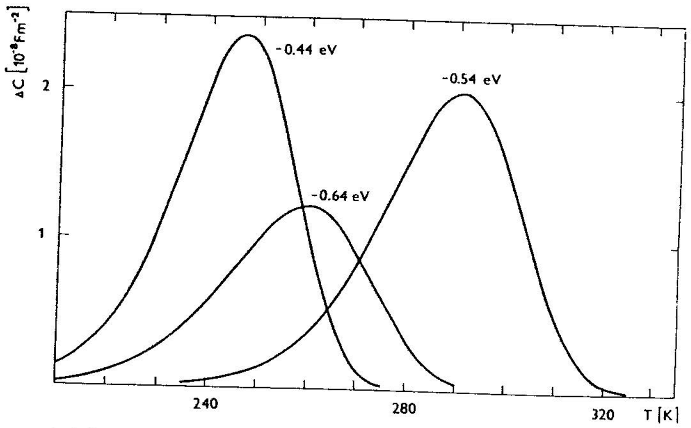

Fig. 8. The set of ΔC—T curves computed for various interface-trap energy levels. The values of parameters are the same as in Fig. 7.

(17)—(19), (26), (33). For a nondegenerate homogeneous semiconductor, the charge $Q_s(v)$ in all the formulae is given by

$$Q_s(v) = \operatorname{sign}(v)\,(2kT\epsilon_s)^{1/2}\left[n_\infty(e^{-v}-1)+p_\infty(e^{v}-1)+N_D\ln\left(\frac{e^{v}+\gamma_D}{1+\gamma_D}\right)\right]^{1/2}, \tag{34}$$

where $\gamma_D = N_D/(n_\infty - p_\infty) - 1$, N_D is the concentration of donors and ϵ_s is the dielectric permittivity of the semiconductor. (In (34) it is assumed that the donors may be partially ionized.) The capture coefficients c_{nj}, c_{pj} in (3) are related to the corresponding capture cross sections by

$$c_{nj} = \sigma_{nj} v_n, \quad c_{pj} = \sigma_{pj} v_p \tag{35}$$

where σ_{nj} (σ_{pj}) and $v_n(v_p)$ are the capture cross section and the mean thermal velocity of electrons (holes), respectively. The contact potential difference φ_{MS} in (4) and (7) is given by the well-known formula

$$\varphi_{MS} = -\frac{1}{e}(\Phi_B - E_C + E_F), \tag{36}$$

where Φ_B is the "height" of the barrier. The location of the Fermi level in the semiconductor band gap is calculated, as usual, from the neutrality condition which is assumed to be fulfilled in the bulk of the semiconductor.

As illustration, the DLTS curves were computed for the system Al/SiO$_2$/n-Si with $\Phi_B = -0.05$ eV, $N_D = 4.3 \times 10^{20}$ m^{-3}. The thickness of the oxide was taken to be 100 nm. For all the energies of interface-trap levels given below, the capture cross sections of electrons and holes were given by $\sigma_n = 2.5 \times 10^{-20}$ m^2 and $\sigma_p = 5 \times 10^{-20} \times (300/T)^4$ m^2, respectively.

IV. 1. SINGLE DISCRETE INTERFACE-TRAP LEVEL

The small-signal DLTS curves ($j-T$, $\Delta C-T$ and $\Delta Q-T$ curves) were computed for a discrete interface-trap level positioned at the energy $E_T = E_C$ — 0.54 eV, which is near the midgap. One can notice that the energy $E_T - E_C = -0.54$ eV and the values $2\sigma_n$, $2\sigma_p$, where σ_n, σ_p are given above, were chosen to agree with the values found from experiments for the bulk impurity of Au in Si [8], [9]. Although this choice may not correspond to any real interfacial trap, the numerical results presented below make it possible to draw general conclusions on the behaviour of the DLTS signal. Each set of the DLTS curves computed for various values of some parameter shows a peak corresponding to the interface-trap level.

The dependence of the j-T curves on the gate voltage U_0 is shown in Fig. 1. One can see that the height and position of the peak change nonlinearly with the increase in the gate voltage U_0. The position at which the peak is the highest does not coincide with the position at which the temperature of the peak maximum is the highest. The peak is the highest when the Fermi level is near the interface-trap level and the trap is about half occupied. In the opposite case (when the occupancy of the interface trap is close to 1 or 0) the height of the peak is negligible. The same qualitative features as those of the j—T curves can be seen in the corresponding ΔC—T and ΔQ—T curves (see Fig. 2; the ΔQ—T curves are similar to the ΔC—T curves and therefore omitted).

The dependence of the j—T curves on the delay time t (Fig. 3) is similar to that for a simple emission since the response from the interface-trap level is an exponential function of the delay time t (see formula (31)). However, the value of energy obtained from the j—T curves in a standard way (as for an emission from a discrete-trap level) may considerably differ from the value of E_T originally used in the computation of these curves. In contrast to the j—T curves, in the case of the ΔQ—T curves (Fig. 4) the height of the peak changes only slightly with the delay time (and the same is true for the ΔC—T curves not shown in this paper).

The dependence of the j—T curves on the trap density N_T (Fig. 5) is a nonlinear one. Although the height of the peak increases with increasing N_T as it is natural to expect, its position does not remain constant and the peak shifts non-linearly with the change in N_T. The last property is characteristic also for the ΔC—T curves (Fig. 6), but the dependence of the height of the peak on N_T is not monotonous in

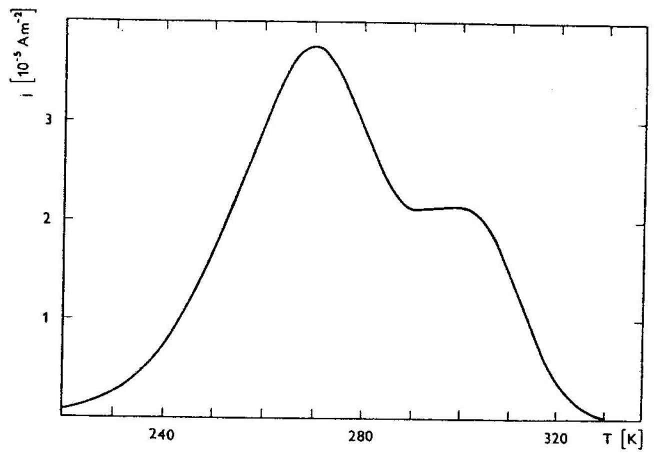

Fig. 9. The j—T curve computed for a system of two interface-trap levels, taking $E_1 = E_c - 0.54$ eV, $E_2 = E_c - 0.44$ eV, $N_1 = N_2 = 5 \times 10^{14}$ m^{-2}, $t = 1$ ms, $U_0 = -0.5$ V, $\Delta U = 1$ mV.

this case, which is due to the coefficient C'_{s0} in (29). The corresponding ΔQ—T curves (not shown in this paper) behave similarly as the j—T curves.

In order to obtain an idea about the behaviour of the peak with the change in energy E_T, the small-signal DLTS curves were computed also for various values of $E_T - E_C$. The peak shifts nonlinearly with energy E_T for both the j—T curves (Fig. 7) and the ΔC—T curves (Fig. 8). As to its height, it changes slightly for the j—T curves but remarkably for the ΔC—T curves. For the ΔQ—T curves (not shown in this paper) the behaviour of the peak is similar to that for the j—T curves.

IV. 2. Two discrete interface-trap levels

The small-signal DLTS curves were computed for the system of two interface-trap levels at energies $E_1 = E_C - 0.54$ eV, $E_2 = E_C - 0.44$ eV with trap densities $N_1 = N_2 = 5 \times 10^{14}$ m^{-2}. The greatest change in shape, in comparison with the one-level j—T curves, , was found to be for the j—T curves (a two level j—T curve is shown in Fig. 9). The two peaks corresponding to the energy levels E_1 and E_2 can be better resolved when the difference $\Delta j = j(t, T) - j(2t, T)$ is computed, and their heights and positions depend on the gate voltage U_0 (Fig. 10).

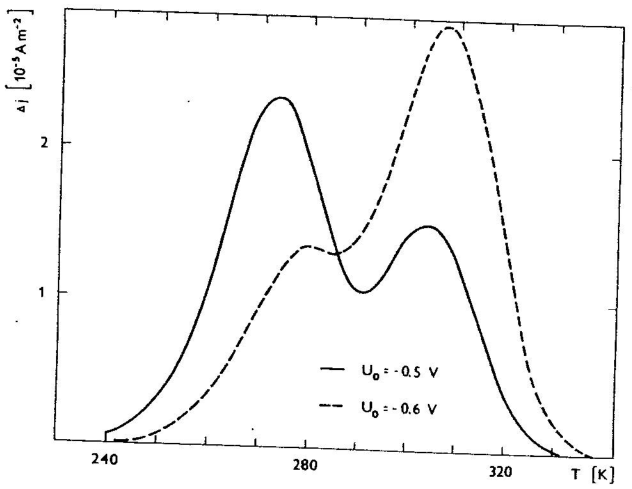

Fig. 10. Two Δj—T curves for a system of two interface-trap levels, computed for the gate voltages $U_0 = -0.5$ V and $U_0 = -0.6$ V. The other parameters are the same as in Fig. 9.

V. CONCLUSIONS

The quasi-equilibrium model presented in this paper is applicable to the small-signal DLTS response from insulator-semiconductor interfacial-traps under the condition that the transport and transition mechanisms in the semiconductor are sufficiently efficient to establish the quasi-equilibrium distribution of free carriers at the interface instantaneously as compared to the time scale of the observed interacial transient process. This condition may be fulfilled at higher temperatures when the concentration of minority carriers is such that the corresponding Maxwell relaxation time is much smaller than the characteristic relaxation time of the transient process. In the opposite case (at low temperatures) it is necessary to consider non-equilibrium distributions of electrons and holes which may be characterized by two diffferent quasi-Fermi levels, and at certain voltages the emission of carriers from interface traps and the generation of minority carriers through the interface traps can be distinguished as two separate processes. As to the transition mechanism in the bulk of the semiconductor, the condition of validity of our model may be fulfilled when the relaxation times corresponding to transitions through bulk levels (which can be estimated similarly as for the interface traps, by means of formula (18)) are much smaller than the characteristic relaxation time of the observed interfacial transient process. This may be the case of shallow impurities (donors or acceptors) if one investigates interface trap levels sufficiently deep in the semiconductor energy gap (for which the absolute values of the differences between the shallow levels and the level under investigation are much greater than kT).

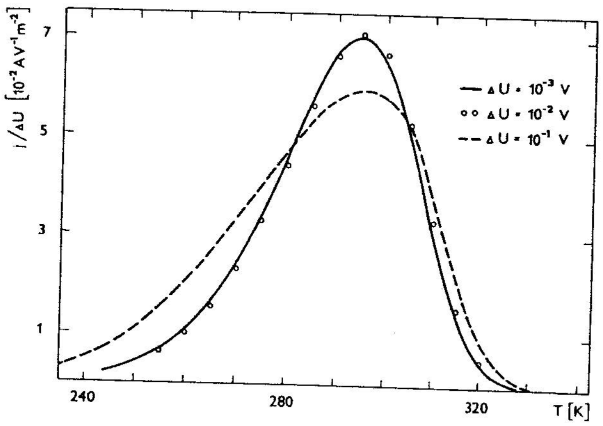

Fig. 11. The shape of current DLTS curves calculated for various applied voltage steps ΔU. All the $j/\Delta U$ — vs T curves were obtained by solving the equation (8) numerically ($U_0 = -0.5$ V, the other parameters are the same as in Fig. 1).

The formulae derived in this paper for the small-signal DLTS response are valid for sufficiently small applied-voltage steps. The change in shape of the j—T curves with the applied-voltage step ΔU is shown in Fig. 11. All the $j/\Delta U$ vs T dependences in Fig. 11 were computed by solving the differential equation (8) numerically. One can see that for $\Delta U \lesssim 10^{-2}$ V the change in the shape of the j—T curves is small (for $\Delta U = 10^{-3}$ V, the one-level DLTS curves presented in Section IV are practically identical to those computed by solving equation (8)). At higher ΔU, the slope of the low-temperature side of the j—T curves decreases, which was observed in DLTS experiments, too. In view of our quasi-equilibrium model it is a consequence of the non-exponentiality of the whole transient process at higher applied-voltage steps.

From Section III it follows that the nonlinear dependences of the small-signal DLTS curves on some parameters depend on the choice of the values of the other parameters. If the choice is different from that given in Section IV, the change in the dependences may, in some cases, be great. For example, it can be shown that when the trap density N_T is sufficiently high ($N_T \gtrsim 10^{18}\,\mathrm{m}^{-2}$), the position of the peak corresponding to the interface-trap level with the other parameters taken from Fig. 1 is practically independent of the gate voltage (which takes the values from Fig. 1).

From the relations (25)—(30) one can see that for the case of n interface-trap levels ($n \geqslant 2$), the net DLTS signal is generally not a sum of one-level contributions although it can be considered as a superposition of n exponential transient processes. An analogous conclusion can be drawn from the relations (11)—(13) and (23) for continuous distribution of interface-trap levels. In principle, the trap levels in our model may be arbitrary, with the only proviso that their position in the band gap does not depend on the surface potential and no transitions of electrons take place between them directly. In more general situations, it would be necessary to introduce a potential dependence of trap parameters and/or consider transition probabilities of direct transitions between trap levels.

Finally, it should be pointed out that our results are applicable, strictly speaking, only to such DLTS measurements at which the initial conditions (5)—(7) are fulfilled. Usually, in DLTS measurements a periodical application of bias pulses of a rectangular shape is used, the time interval between two successive pulses being equal to the pulse duration. The repetition frequency of the bias pulses has to be sufficiently low so that the system of electrons and holes can periodically reach thermal equilibrium, as demanded by (5)—(7).

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КВАЗИРАВНОВЕСНАЯ МОДЕЛЬ ОТКЛИКА, ВЫЗЫВАЕМОГО ПРОЛОЖЕНИЕМ СЛАБОГО СИГНАЛА К МДП-СТРУКТУРЕ И ПОЛУЧАЕМОГО ИЗ ПОВЕРХНОСТНЫХ ЛОВУШЕК НА ГРАНИЦЕ ДИЭЛЕКТРИК-ПОЛУПРОВОДНИК, В МЕТОДЕ СПЕКТРОСКОПИИ ГЛУБОКИХ УРОВНЕЙ

В работе предложена модель для отклика из поверхностных лобушек на границе диэлектрик-полупроводник в МДП-структурах, исследуемых методом спектроскопии глубоких уровней, Модель основана на предположении, что постоянная времени, характеризующая процесс образования слоя пространственного заряда в полупроводнике, при достатчно высоких температурах ничтожно мала по сравнению с длительностью всего рассматриваемого процесса. Описах также метод для вычисления кривых, выражающих зависимость токового, зарядного и емкостного сигнала в спектроскопии глубоких уровней от температуры в случае n произвольных дискретных уровней поверхностных лобушек. Простые конечные формулы и численные результаты приведены для значений $n = 1$ и $n = 2$.