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ON THE THEORY OF CURRENT DLTS

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An alternative approach to the theory of current DLTS, based on the general expression for the transient current of the form $j(t_0) = U[\mathrm{d}C/\mathrm{d}t]_{t_0}$, where U is the quiescent applied bias and C the capacitance of the device, is presented for both Schottky diodes and MIS structures. The solution obtained for emission of charge carriers from deep traps within a depletion region of a Schottky diode is identical with the formula generally used, while a more general formula is derived for MIS structures in comparison with that suggested previously. The latter finding is relevant to charge DLTS, too.

ТЕОРИЯ СПЕКТРОСКОПИИ ГЛУБОКИХ УРОВНЕЙ, ОСНОВАННОЙ НА ПЕРЕХОДНОМ ТОКЕ

В работе приводится альтернативный подход к теории переходного тока в спектроскопии глубоких уровней, основанной на общем выражении для переходного тока в форме $j(t_0) = U[\mathrm{d}C/\mathrm{d}t]_{t_0}$, где U представляет приложенное статическое смещение и C обозначает емкость образца для случая диодов Шотки и для случая МДП-структур. Решение, полученное для эмиссии носителей заряда из глубоких центров захвата области обеднения диода Шотки, совпадает в общем с обычно используемой формулой, в то время как для МДП-структур получена более общая формула по сравнению с формулой, предложенной раньше. Последний факт относится также к спектроскопии глубоких уровней, основанной на измерении переходного заряда.

I. INTRODUCTION

The deep-level transient spectroscopy DLTS introduced by Lang [1] has proved to be a powerful tool when investigating deep defect states in the semiconductor junctions like Schottky and p-n diodes or MIS structures. The current transient response of an MIS structure to a change in the reverse gate voltage U, with no minority carriers pile-up at the semiconductor-insulator interface, was analysed first by Sah and Fu [2]. They derived an expression for transient current due to emission (p-type substrate)

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$$j(t)^* = C(\mathrm{d}U/\mathrm{d}t) + \left[\frac{C_{0x}}{C_{0x}+C_w}\right] qwN_T \left(\frac{e_n e_p}{e_n+e_p}\right)\left\{1+\frac{1}{2}\left(\frac{e_p}{e_n}-1\right)\exp\left(-t/\tau_t\right)\right\}, \tag{1}$$

where $\tau_t = (e_n + e_p)^{-1}$.

The second term on the right-hand side of (1) is evidently equal to $U(\mathrm{d}C/\mathrm{d}t)$. Recently, it has been suggested to apply (1) to current DLTS [3]. Under the assumption that $e_p \gg e_n$, with sampling instant set at t_0 (1) is reduced to

$$j^*(t_0, T) = \frac{C_{0x}}{C_{0x}+C_w} qwN_T \frac{e_p}{2} \exp(-e_p t_0), \tag{2}$$

where C_{0x} is the oxide capacitance, C_w the differential (geometrical) capacitance of the depletion region, w stands for the excited depletion region width of the semiconductor, N_T for the concentration of deep traps and e_p for the emission rate of holes

$$e_p = \sigma_p v N_v \exp[(E_v - E_t)/kT].$$

When deriving (1), Sah and Fu [2] eliminated the unknown surface potential of the semiconductor from the set of equations to be solved. As will be shown in the next section, on the basis of the general expression for current DLTS [3]

$$j(t_0) = U[\mathrm{d}C/\mathrm{d}t]_{t=t_0} \tag{3}$$

one can arrive at a formula for current DLTS, which represents a more general approach to the problem. The latter approach utilizes the time dependence of the surface potential of the semiconductor $\Psi_s(t)$, which is relevant to the equivalent capacitance C_s of the depletion region. Finally, a comparison will be made between the novel and the previously suggested treatment of the problem.

II. THEORY OF CURRENT DLTS

Let us start with the case of the majority carrier emission from a depleted region of a Schottky junction. If one tends to use (3) as the starting point, it is necessary to specify physically the equivalent capacitance of the semiconductor, appearing in (3). We suggest to treat the semiconductor depletion region as a solid with the net charge $q(N_A - p_t)w$ positioned between two conducting plates a distance w apart from each other, N_A being the concentration of ionized acceptors and p_t the concentration of trapped holes. This situation is similar to that of an injected charge between two electrodes [4]. According to Lampert and Mark [4] the equivalent capacitance of such a system is nearly twice the geometrical capacitance of the capacitor without the injected charge $C_w = \varepsilon_s/w$. Indeed, within the depletion approximation [5] the net charge contained in the depletion region is (no traps)

$$Q_s = qN_A w = qN_A \left[\frac{2\varepsilon_s \psi_s}{qN_A}\right]^{1/2} = [2qN_A\varepsilon_s\psi_s]^{1/2}.$$

Modelling the depletion region by a capacitor $C_s = Q_s/\psi_s$, it follows immediately that

$$C_s = 2C_w = 2(\mathrm{d}Q_s/\mathrm{d}\psi_s) = \left[\frac{2qN_A\varepsilon_s}{\psi_s}\right]^{1/2}. \tag{4}$$

If there are also trapped holes in the depletion region after a majority carrier pulse [1] ($U \simeq 0$), the time dependence of the capacitance C_s can be approximated by

$$C_s(t) = \left\{\frac{2q[N_A - p_t(t)]\varepsilon_s}{\psi_s}\right\}^{1/2}. \tag{5}$$

Denoting the concentration of empty traps by $p_e(t)$, evidently $N_T = p_t(t) + p_e(t)$. The hole traps are assumed to empty exponentially with time, i.e. $p_e(t) = N_T[1 - \exp(-e_p t)]$. Now, starting from (3) and neglecting the built-in voltage ($\psi_s \simeq U$)

$$j(t_0, T) = \psi_s \left[\frac{\mathrm{d}C_s}{\mathrm{d}t}\right]_{t_0} = \left[\frac{2q\varepsilon_s\psi_s}{N_A - p_t(t_0)}\right]^{1/2} N_T \frac{e_p}{2} \exp(-e_p t_0). \tag{6}$$

Keeping in mind that

$$w = [2\varepsilon_s\psi_s/q(N_A - p_t)]^{1/2},$$

we arrive at the formula

$$j(t_0, T) = qw(t_0) N_T \frac{e_p}{2} \exp(-e_p t_0). \tag{7}$$

Note that (7) is identical with the well-known formula for current DLTS of a Schottky junction [6].

Before starting the derivation of $j(t_0, T)$ for MIS structures, it should be emphasized that in the previous case the surface potential ψ_s of the semiconductor was kept constant and the variation of C_s with time was due entirely to $p_t(t)$, appearing in (5). By contrast, when dealing with an MIS structure, ψ_s is no more constant in time. It is therefore evident that the response of the depletion region capacitance C_s as well as that of the overall MIS capacitance $C = C_{0x}C_s/(C_{0x} + C_s)$ in the time domain experiment is expected to differ from (7). In other words, the current DLTS signal from an MIS capacitor should in general be of a different shape in comparison with the more simple case of a Schottky diode.

On the basis of the above considerations we suggest to characterize an MIS capacitor by the overall capacitance $C=C[t,\psi_s(t)]$, which should enter the general equation (3). Then (3) takes the general form

$$j(t_0,T)=U\left[\frac{\partial C}{\partial t}+\frac{\partial C}{\partial\psi_s}\frac{d\psi_s}{dt}\right]_{t_0}. \tag{8}$$

It might be obvious that (6) is only a special form of the general equation (8) ($C_{0x}\to\infty$, $d\psi_s/dt\simeq 0$). Evidently, to find the more general $j(t_0,T)$ one has to express $\psi_s(t)$. It is convenient to assume that the applied reverse bias is divided between the two capacitors C_{0x} and C_s (rather than C_w), respectively. For simplicity only the "small-signal" case will be treated further with $N_T/N_A\ll 1$, in which case C_s can be approximated as

$$C_s[t,\psi_s(t)]\simeq f(t)\,\psi_s(t)^{-1/2}, \tag{9}$$

where

$$f(t)=[2q\varepsilon_s N_A]^{1/2}\left[1-\frac{N_T}{2N_A}\exp(-e_p t)\right].$$

In order to find $\psi_s(t)$ we use the relations $U=U_{0x}+\psi_s$, $C_{0x}U_{0x}=C_s\psi_s$, U_{0x} being the potential drop across the oxide. Then using (9)

$$\psi_s(t)=\frac{C_{0x}}{C_s+C_{0x}}\quad U=\frac{\psi_s^{1/2}}{\dfrac{f(t)}{C_{0x}}+\psi_s^{1/2}}\,U. \tag{10}$$

Setting $\psi_s^{1/2}=x$, (10) transforms to

$$x^2+\frac{f(t)}{C_{0x}}x-U=0,$$

which equation has two solutions:

$$x_{1,2}=-\frac{f(t)}{2C_{0x}}\pm\sqrt{\left[\frac{f(t)}{2C_{0x}}\right]^2+U}.$$

Since $f(t)>0$, $\psi_s>0$, $U>0$ and ψ_s cannot exceed U, the real solution is

$$\psi_s(t)^{1/2}=-\frac{f(t)}{2C_{0x}}+\sqrt{\left[\frac{f(t)}{2C_{0x}}\right]^2+U}. \tag{11}$$

It should be pointed out that with an n-type substrate $\psi_s<0$ and one has to solve

for $q\psi_s$ rather than ψ_s, expressing C_s as $f'(t)[q\psi_s(t)]^{-1/2}$. The surface potential being known, one can show that (8) leads to

$$j(t_0,T)=qN_T\frac{e_p}{2}\exp(-e_p t_0)\left[\frac{2\varepsilon_s}{qN_A}\right]^{1/2}\frac{\left[-\dfrac{f(t)}{2C_{0x}}+\sqrt{\left[\dfrac{f(t)}{2C_{0x}}\right]^2+U}\right]^2}{\sqrt{\left[\dfrac{f(t)}{2C_{0x}}\right]^2+U}}. \tag{12}$$

Thus we have obtained the desired formula for current DLTS relevant to MIS capacitors, in which formula an explicit dependence of the signal on U is contained.

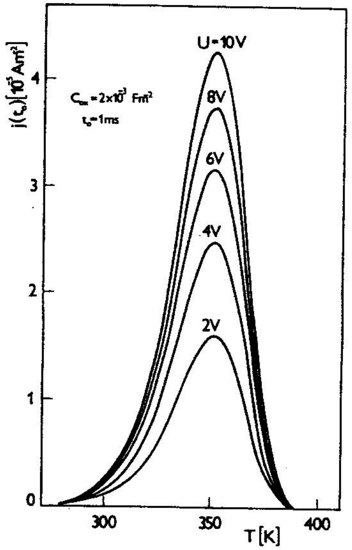

Fig. 1. A set of current DLTS spectra, computed from equation (12) in the text, taking $N_A=2.5\times10^{23}\,\mathrm{m^{-3}}$, $N_T=2.5\times10^{19}\,\mathrm{m^{-3}}$, $\varepsilon_s=8.82\times10^{-11}\,\mathrm{Fm^{-1}}$, $\sigma_p v N_v=3.2\times10^6\,T^2\mathrm{s^{-1}}$, $E_t-E_v=0.6\,\mathrm{eV}$.

In Fig. 1 there is shown the behaviour of the current DLTS with respect to U for a chosen set of parameters. The current DLTS peak height is a sublinear function of U, yet one cannot express it by AU^n, taking a unique n. Let us mention that for a Schottky diode $n=1/2$. For the sake of illustration we have computed the two contributions due to $\partial C/\partial t$ and $\partial C/\partial\psi_s\,d\psi_s/dt$ in (8) separately. As expected, the relative contributions of the two terms are strongly dependent on C_{0x} — see Fig. 2. By contrast, as it is evident from an inspection of Fig. 3, the relative contributions are only slightly affected by N_A, unless N_T becomes comparable to N_A. The latter case is not treated here.

To provide further support of the general formula (8), one can check it in an independent way. The gate current $j(t,T)$ is expressed alternatively in the form [2]

$$j(t,T)=\frac{dq_M}{dt}=\frac{d}{dt}\{C_{0x}[U-\psi_s(t)]\}=C_{0x}\left[-\frac{d\psi_s}{dt}\right],$$

where q_M stands for the charge on the gate. Writing $\psi_s(t)$ through (11), one can readily show that

$$j(t_0, T) = qN_T \frac{e_p}{2} \exp(-e_p t_0) \left[\frac{2\varepsilon_s}{qN_A}\right]^{1/2} \frac{\left[\frac{f(t)}{2C_{0x}} - \sqrt{\left[\frac{f(t)}{2C_{0x}}\right]^2 + U}\right]^2}{\sqrt{\left[\frac{f(t)}{2C_{0x}}\right]^2 + U}},$$

which equation is identical with (12).

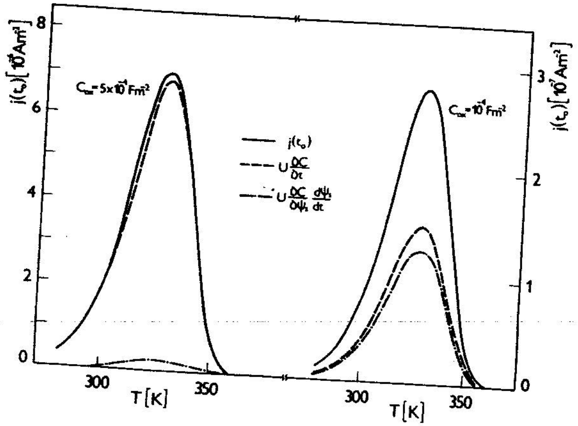

Fig. 2. The relative contributions of the two terms in (8) to the total signal $j(t_0, T)$ are shown to be strongly dependent on C_{0x}; $U = 6$ V, $t_0 = 5$ ms, the remaining parameters being the same as in Fig. 1.

Finally, we will return once more to the previously used formula [3] (equation (2) of the present work) and compare it with the more general result, represented by (12). Since $w = 2\varepsilon_s/C_s$, where C_s is given by (9), one can exclude w from (2) and form a ratio of the two expressions

$$R = \frac{j(t_0, T)}{j^*(t_0, T)} = \left[1 - \frac{N_T}{2N_A} \exp(-e_p t_0)\right].$$

This is an interesting result in that one can use (2) without introducing a substantial error as long as the small-signal condition $N_T/N_A \ll 1$ is fulfilled. In such situation where the concentration of deep traps is comparable to that of shallow impurities, one should use the general formula (8), since then (2) would lead to an overestimate of the concentration of the traps. The question of transient distortion in the "large-signal" case will be discussed elsewhere. As a final note it should be

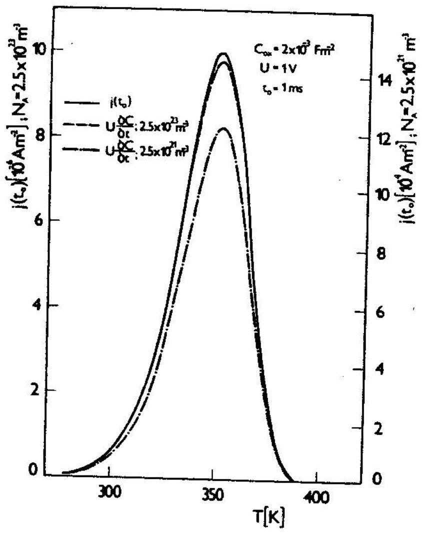

Fig. 3. The relative contribution of the term $U(\partial C/\partial t)$ to the total current DLTS is almost independent of N_A ($N_T \ll N_A$), for other parameters see the caption of Fig. 1.

stated that the above conclusions apply to charge DLTS as well. Now, the basic equation for the charge DLTS signal should read

$$\Delta Q = -[Q_s(t_1) - Q_s(t_2)] = -[C_s(t_1)\psi_s(t_1) - C_s(t_2)\psi_s(t_2)],$$

leading to a modification of the formula introduced by Kirov and Radev [7].

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