An easy method to determine carrier-capture cross sections: Application to GaAs

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A new technique of measuring capture cross sections is presented, based on a simplified analysis of the kinetics of filling of the traps in the slow regime of filling. The main interest of this technique is that it uses large impulsions, easy to apply on any sample, contrary to previous work which needed very short impulsions. A simplified theory is also developed to extract capture cross sections from the experimental data. The results are compared with those obtained by other techniques on the trap E3, created by irradiation of electrons in n-type GaAs, showing very good agreement.

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I. INTRODUCTION

Carrier cross sections are often very difficult to measure because they vary between 10^{-12} and 10^{-18} cm^2, with an average of 10^{-15} cm^2. In deep level transient spectroscopy (DLTS), this requires refilling pulses short with respect to $(c_n\, n)^{-1}$ in n-type material ($c_n\, n$: capture rate for electrons; n: density of free electrons)[1] or short with respect to e_n^{-1} (Ref. 2) (e_n: thermal emission rate of electrons). To apply such pulses, it is necessary to have samples with a small capacitance such as field-effect transistors (FETS), which is not always possible in practice. Moreover, during the filling pulse, it is difficult to put the semiconductor under flat-band conditions. Then, there is a region in the bulk where $n = N_D$, which gives a fast and constant filling rate and another one, between the edge of the depletion layer and the metal-semiconductor interface $(0 < n < N_D)$ (for a Schottky diode) where the density of carriers decreases like a Gaussian function with depth.[3] This gives a slow filling rate, with the problem of a distribution of capture constants, which is more difficult to analyze. The variation of the fraction of the filled traps versus the filling time (Fig. 1) in n-GaAs has been simulated by D. Pons.[4]

Here, we show that it is possible to determine in a simple way the capture cross sections using the slow region of filling. Thus, from the experimental point of view, we use large impulsions, which are easy to perform on any sample. We also develop a simplified theory that we apply to our measurements on n-GaAs. We consider, particularly, the trap E3,[5] produced by irradiation of electrons at room temperature in n-type GaAs. We give its capture cross section σ versus temperature from which we calculate its activation energy E_B.

Finally, we compare our results with those obtained from techniques based on measurements under fast filling conditions.[4,5] This comparison demonstrates the validity of our procedure which also proves to be simpler and of wider applicability.

II. THEORY

The basis of our theory consists in making an approximation on the fraction of filled traps: it is clear from Fig. 1 that for a long filling pulse, the fraction of filled traps is a quasistep function. Thus, to simplify the calculation of the relative variation of the capacitance which is observed by DLTS, we make this approximation (of a quasistep function) and then, the calculations, as we will see later, become much easier. However, let us first establish the relation between the

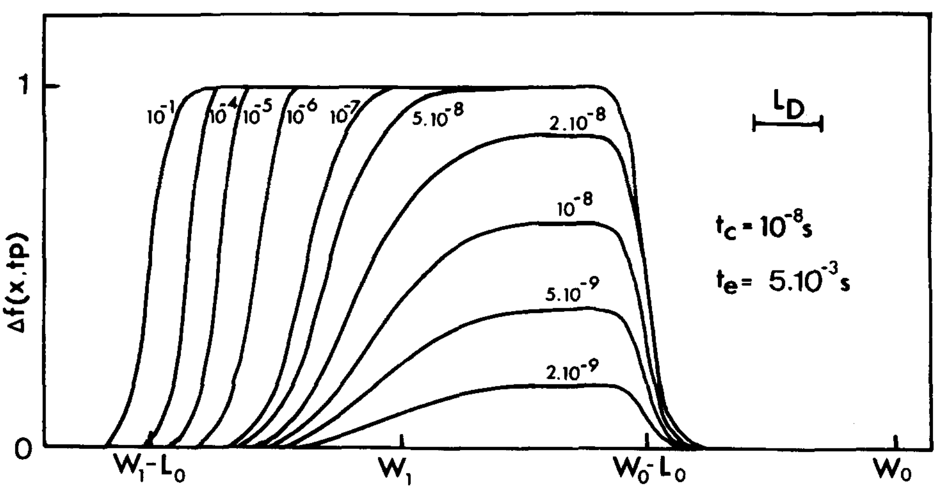

FIG. 1. Fraction of the filled traps vs the filling time.

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relative variation of capacitance $\Delta c/c$ and the duration of the filling pulse t_p.[6]

Consider the polarization applied to a diode with a filling pulse of width t_p and an amplitude ΔV represented on Fig. 2. The polarization V_0 corresponds to a reverse bias while $V_1 = V_0 - \Delta V$ corresponds to a reduced reverse bias. The Fermi–Dirac functions $f_0(x)$ and $f_1(x)$ which give the probability of occupation of the traps in the two steady states corresponding, respectively, to V_0 and V_1 are pictured on Fig. 3. The kinetics of filling, for $t < t_p$ are given by Ref. 6 and Appendix A:

$$f(x, t_p) - f_1(x) = [f(x,0) - f_1(x)] \exp - \frac{e_n t_p}{1 - f_1(x)}, \quad (1)$$

where $f(x, t)$ is the probability of occupation of the traps at depth x and time t.

In the same way, for $t > t_p$,

$$f(x, t) - f_0(x) = [f(x, t_p) - f_0(x)] \exp - \frac{e_n (t - t_p)}{1 - f_0(x)}. \quad (2)$$

We can replace e_n by $[c_n\, n(1-f)/f]$, which means that, in the permanent regime, there is an equality between emission and capture of the carriers.

Then, we can rewrite Eqs. (1) and (2):

$$f(x, t_p) - f_1(x) = [f(x,0) - f_1(x)] A_1(t_p), \quad (3)$$

and

$$f(x, t) - f_0(x) = [f(x, t_p) - f_0(x)] A_0(t), \quad (4)$$

with

$$A_1(t_p) = \exp - \frac{c_n\, n_1\, t_p}{f_1(x)}, \quad (5)$$

where n_1 is the electron concentration for V_1 reverse bias and

$$A_0(t) = \exp - \frac{e_n (t - t_p)}{1 - f_0(x)}. \quad (6)$$

Now, consider the relative variation of capacitance $\Delta c/c$. If we consider that $N_T(x)$ remains constant for x between $W_0 - \lambda_0$ and $W_1 - \lambda_1$, this quantity is given by[6]

$$\frac{\Delta c}{c} = \frac{N_T}{N_D \cdot W_0^2} \int_0^\infty \Delta f(x, t_p) x\, dx, \quad (7)$$

where N_T is the density of traps, N_D the density of shallow donors (supposed to be constant with x), W_0 the depletion layer width for reverse bias V_0, and

$$\Delta f(x, t_p) = f(x, t_p) - f_0(x) \quad (8)$$

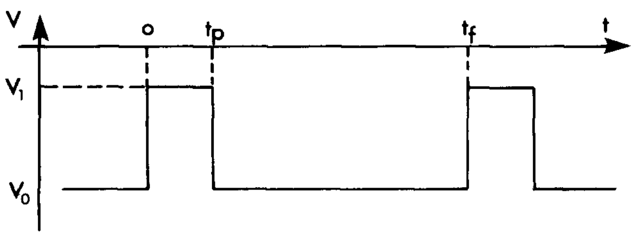

FIG. 2. Polarization of the diode.

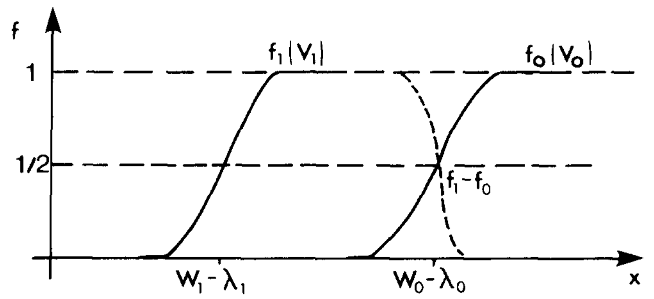

FIG. 3. Probability of the occupation of the traps in the two steady states corresponding, respectively, to V_0 and V_1.

is the fraction of filled traps at $t = t_p$. (The analysis can be extended to other cases where N_T is dependent of x. The shape of $N_T(x)$ is simply required.)

Let us calculate $\Delta f(x, t_p)$. This quantity can be expressed, using Eq. (3) as

$$\Delta f(x, t_p) = [f_1(x) - f_0(x)] + [f(x,0) - f_1(x)] A_1(t_p). \quad (9)$$

If energy losses can be neglected, we can use the relation

$$f(x,0) = f(x, t_f), \quad (10)$$

where t_f is the repetition time of the polarization.

Then, Eq. (4), at $t = t_f$, can be written

$$f(x,0) - f_0(x) = [f(x, t_p) - f_0(x)] A_0(t_f). \quad (11)$$

Finally, we obtain from Eqs. (9) and (11)

$$\Delta f(x, t_p) = (f_1(x) - f_0(x)) \left[\frac{1 - A_1(t_p)}{1 - A_0(t_f) A_1(t_p)} \right]. \quad (12)$$

To simplify this expression, we make the following approximations: (i) we neglect t_p in front of t_f; (ii) between W_0–λ_0 and $W_1 - \lambda_1$ (Fig. 3) $f_1(x) \sim 1$ and $f_0(x) \sim 0$ ($W_0 - \lambda_0$ and $W_1 - \lambda_1$ are the x value for which E_T crosses E_{F_e} for V_0 and V_1 bias, respectively, E_T being the energy level of the defect and E_{F_e} the Fermi-level of electrons).

If we define

$$X = \exp - c_n\, n_1\, t_p,$$
$$Y = \exp - c_n\, N_D\, t_p, \quad (13)$$
$$K = \exp - e_n\, t_f,$$

then we can write

$$\Delta f(x, t_p) = \frac{1 - X}{1 - KX}. \quad (14)$$

At this stage, we make our principal approximation: we replace $\Delta f(x, t_p)$ of Fig. 1 by a rectangle of height $\Delta f(x, t_p)_{\rm MAX}$ between $x = W_0 - \lambda_0$, its upper limit and $W_1 - L_1(t_p)$, its lower limit.

At $x = W_0 - \lambda_0, f_0(x) = 1/2$ and $x = W_1 - L_1(t_p)$,

$$\Delta f(x, t_p) = \frac{1}{2} \Delta f(x, t_p)_{\rm MAX}. \quad (15)$$

We can make this approximation because $\Delta f(x, t_p)$ decreases exponentially with

$$n_1(x) = N_D \exp - \frac{(x - W_1)^2}{2L_D^2} \text{ (Ref. 3)}, \quad (16)$$

where L_D is the Debye length.

Thus, in the depletion layer, for $x < W_1$, $n_1(x)$, and $\Delta f(x, t_p)$ vary quite rapidly and a rectangular approximation is good (Fig. 4). According to Eq. (15), $L_1(t_p)$ must satisfy the relation

$$\frac{1-X}{1-KX} = \frac{1}{2} \cdot \frac{1-Y}{1-KY},$$

and, with Eq. (16), we obtain finally

$$n_1[W_1 - L_1(t_p)] = \frac{1}{c_n\, t_p} \log \frac{2-K-KY}{1+Y-2KY},$$

$$= N_D \exp - \frac{L_1^2(t_p)}{2L_D^2}. \tag{17}$$

Then, we have

$$L_1^2(t_p) = 2L_D^2 \log\left[\frac{c_n\, N_D\, t_p}{\log \dfrac{2-K-KY}{1+Y-2KY}}\right]. \tag{18}$$

To simplify further it is interesting to see the magnitude of K and Y. First, K [given by Eq. (13)] is equal to 0.18 since e_n is given by 1.72 $(t_f)^{-1}$ (case of the lock-in detection).

Second, Y defined in Eq. (13) is equal to

$$Y = \exp - \frac{t_p}{t_c}, \tag{19}$$

with

$$t_c = (c_n\, N_D)^{-1}. \tag{20}$$

Typically, t_p varies between 20 μs and 2 ms, and t_c varies from a few microseconds (in the slow region) to 10^{-11} s (in the fast region). In all cases, Y is of order of 6×10^{-3} thus much smaller than unity. Under these conditions the expression of $L_1^2(t_p)$ may be reduced to

$$L_1^2(t_p) = 2L_D^2 \log\left[\frac{t_p}{t_c \log(2-K)}\right]. \tag{21}$$

Now, the calculation of $\Delta c/c$ is easy and gives

$$\frac{\Delta c}{c} = \frac{N_T}{N_D\, W_0^2}(f_0 - f_1)\int_{W_1 - L_1}^{W_0 - \lambda_0} x\, dx\ .$$

$$= B\{(W_0 - \lambda_0)^2 - [W_1 - L_1(t_p)]^2\}, \tag{22}$$

with

$$B = \frac{1}{2}\frac{N_T}{N_D \cdot W_0^2}(f_0 - f_1). \tag{23}$$

If $|V_0 - V_1|$ is weak, $f_0 - f_1$ may be less than 1. Then, the program adjusts its value.

Then, the determination of $\sigma(T)$ is made as follows: (a) at a temperature T, corresponding to the maximum of the DLTS peak we measure $\Delta c/c$ vs t_p; (b) we determine t_c with a program (developed on an HP85) which fits the theory Eq. (22) to the experimental points; (c) with $t_c = (1/\sigma v_n\, N_D)$, where v_n is the thermal velocity of electrons, we calculate

$$\sigma(T) = \frac{1}{t_c \cdot v_n \cdot N_D}; \tag{24}$$

(d) by changing the temperature, we draw $l_n[\sigma_n(T)]$ vs $1/T$ and writing

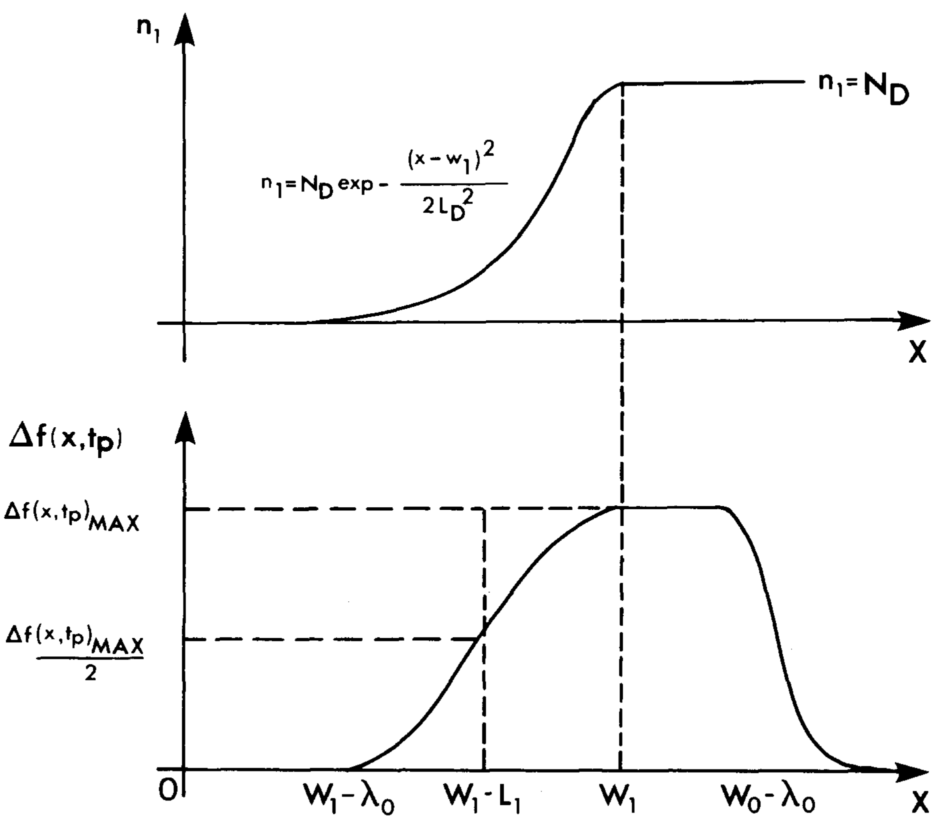

FIG. 4. Variations of $n_1(x)$ and of $\Delta f(x,t_p)$ vs x.

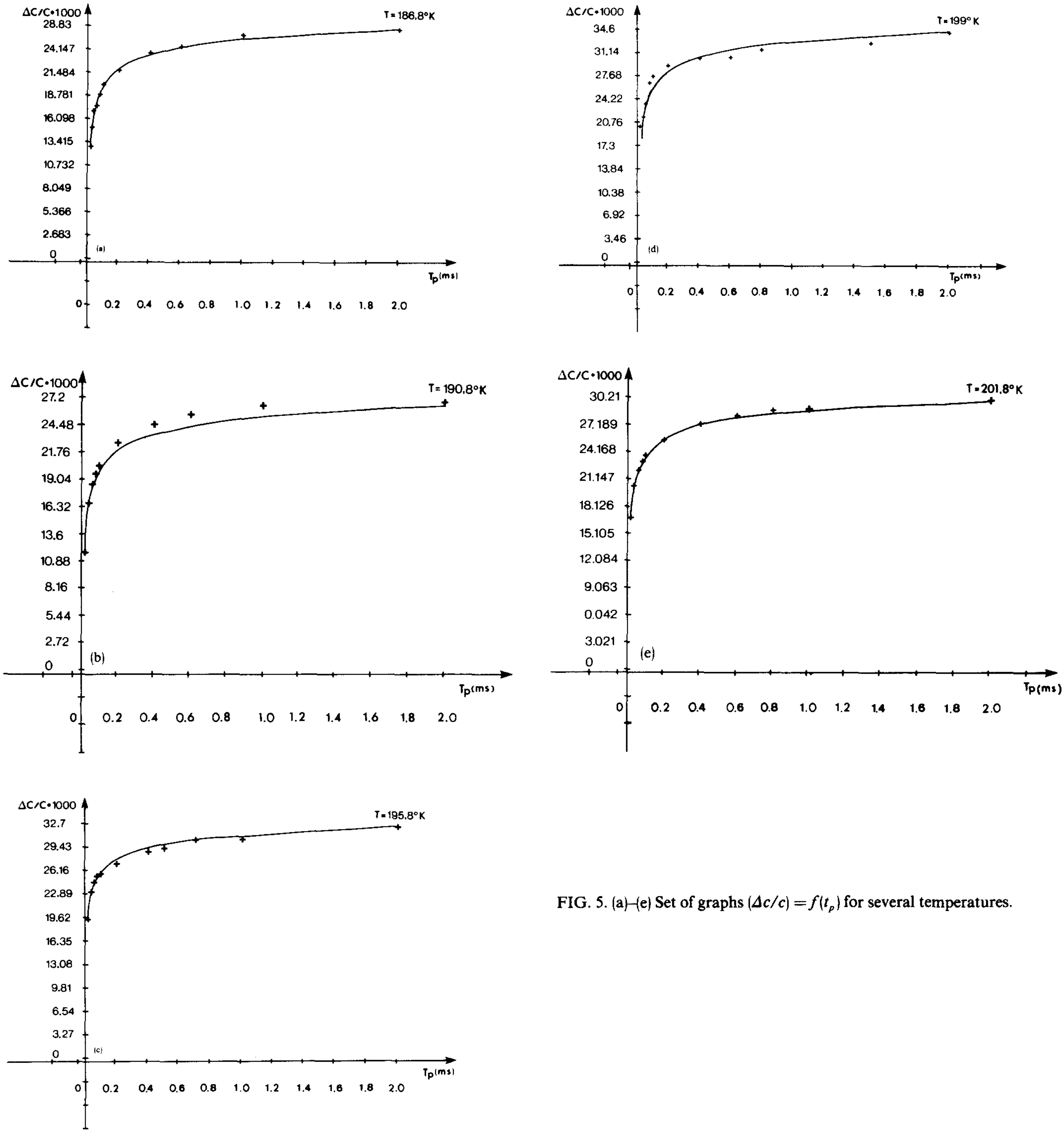

FIG. 5. (a)–(e) Set of graphs $(\Delta c/c) = f(t_p)$ for several temperatures.

$$\sigma_n(T) = \sigma_\infty \exp - \frac{E_B}{kT}, \tag{25}$$

we determine E_B.

III. EXPERIMENT

We have worked with GaAs Schottky diodes, developed on a vapor phase epitaxy (VPE) layer, doped at 5×10^{15} cm^{-3} with silicon, and irradiated with electrons (energy 1 MeV, dose 10^{15} cm^{-2}) on the Van Der Graaf Accelerator of the Groupe de Physique du Solide de l'Ecole Normale Supérieure (Jussieu-Paris VII). We have particularly studied the trap E3 to compare our measurements with those of D. V. Lang[5] and D. Pons.[4] We have explored a range of temperatures from 185 to 205 K. The excursion of temperature (20 K) is fixed by the technique of measurements (A-B technique[5]). Typically, with a lock-in amplifier, the range of frequency measurements is going from a few Hertz to one hundred (if we keep $t_p/t_f \ll 1$), which gives a shift in the DLTS peak of about 20 K. Figure 5 represents the set of graphs $\Delta c/c = f(t_p)$. Our program, at each temperature, allows us to calculate $\sigma_n(T)$. The graph log $\sigma_n(T)$ vs $1/T$ (see

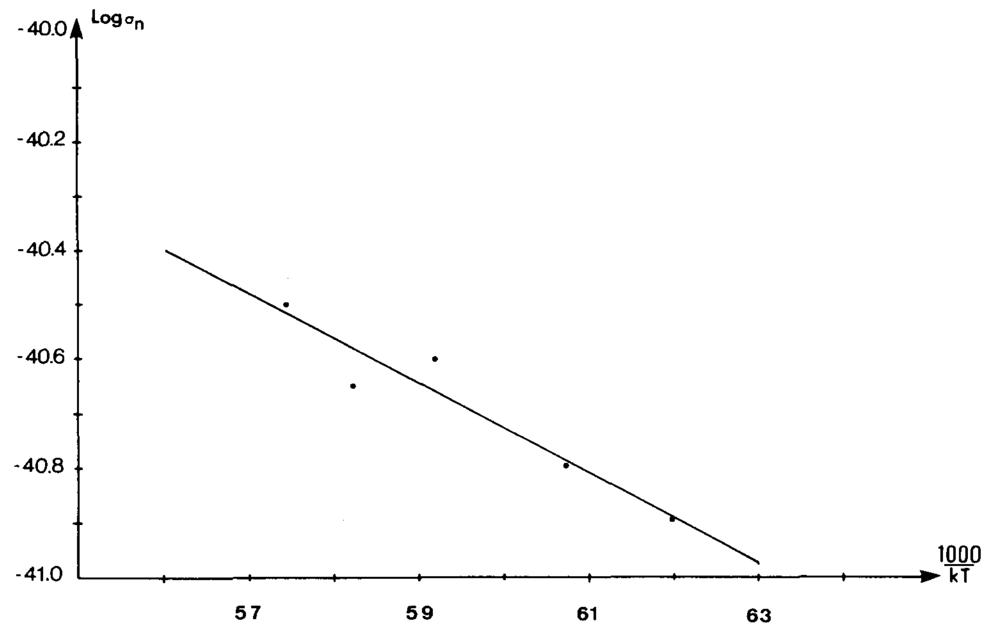

FIG. 6. log σ_n vs $1/kT$.

Fig. 6) gives us E_B. For the trap E3, we have found $E_B = 82 \pm 10$ meV. This value agrees with the measurements of D. Pons ($E_B = 80$ meV); the measurements of D. V. Lang ($E_B = 100$ meV) seems to be too large.

IV. CONCLUSION

We have developed a method of determination of capture cross sections by working in the slow region of filling.

We have elaborated a simplified theory of the filling of the traps which allowed us to use measurements with large pulses, very easy to perform on any sample. This technique has been applied to E3, the trap created by irradiation of electrons in n-GaAs and studied by D. Pons or D. V. Lang. Our theory gives results which agree with those of D. Pons made on the fast region of filling which strongly suggests the validity and the usefullness of our technique.

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APPENDIX A: KINETICS OF FILLING TRAPS

Let us consider the periodic filling pulse of Fig. 2. During the pulse, the traps are filled and at the time $t = t_p$, the electrons are reemitted with a thermal emission rate e_n (we consider an electron trap). The rate of change in defect population is given by

$$\frac{d\Delta b(t)}{dt} = -(e_n + c_n\, n)\Delta b(t), \tag{A1}$$

where Δb is the change in concentration of the occupied states. In most cases, the solution of Eq. (1) is[6]

$$\Delta b(t) = \Delta b(o)\exp - (e_n + c_n\, n)t. \tag{A2}$$

At equilibrium we have[6]

$$\frac{s}{b} = \gamma \exp - \frac{(E_F - E_T)}{kT}, \tag{A3}$$

and

$$c_n\, ns = e_n\, b, \tag{A4}$$

with γ the factor of degeneracy, s the concentration of empty states, and b the concentration of occupied states. $\Delta b(t)$ is then written

$$\Delta b(t) = \Delta b(o)\exp - e_n\left[1 + \frac{1}{\gamma}\exp - \frac{(E_F - E_T)}{kT}\right], \tag{A5}$$

where $(E_F - E_T)$ is corresponding to the steady state induced by V_0 or V_1. If we define the occupancy factor as

$$f = \frac{b}{b+s}, \tag{A6}$$

we have finally Eq. (A5) in function of f:

$$f(t) - f(\infty) = [f(0) - f(\infty)]\exp - \frac{e_n\, t}{1 - f(\infty)}. \tag{A7}$$

This relation leads to the Eqs. (1) and (2) of Sec. II.

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