THE EFFECT OF ELECTRON CAPTURE BY NEGATIVELY CHARGED TRAPS ON THE ENERGY DISTRIBUTION OF HOT ELECTRONS IN SEMICONDUCTORS

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The variational method is used to find the solution of the kinetic equation for hot electrons in *n*-type germanium containing gold impurities. The effect of electron capture, by negatively charged gold traps at low temperatures, on the energy distribution of hot electrons is studied. It is shown that the influence of electron capture on the distribution becomes more effective as the lattice temperature is lowered and the trap concentration is increased.

1. Introduction

The energy distribution of hot electron systems in semiconductors has been studied by many investigators [1–4]. Until now not much attention has been paid to the influence of electron capture on the energy distribution of electrons. It is often thought that this effect will be negligibly small. However, the appearance of impurity centres with large capture cross sections [5–7] should increase the role of electron capture in affecting the distribution. In the present work we consider the influence of electron capture, by negatively charged gold traps, on the energy distribution of hot electrons in *n*-type germanium at low temperatures $T = 77$ K and $T = 20$ K. Doubly and triply charged Au centres are created in *n*-Ge by charge compensation of shallow Sb donors. The concentrations of Au and Sb atoms must be such that $2N_{Au} < N_{Sb} < 3N_{Au}$ [8]. By means of a monochromatic source of light, electrons are generated from the triply changed gold centres with energy $E > K_0T$. It is assumed that the relaxation of electron energy is due to acoustic phonon scattering and the capture of electrons takes place by the doubly charged traps.

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2. The kinetic equation

In the absence of external fields and in the presence of generation and recombination processes, the spherically symmetric part of the distribution of electrons $f_0(E)$ is determined from the equation:

$$\left(\frac{\partial f_0(E)}{\partial t}\right)_{ac} - \frac{f_0(E)}{\tau_r(E)} + g(E) = 0. \qquad (i)$$

The first term in (*i*) describes the elastic scattering of electrons by long wave length acoustic phonons. For spherical constant energy surface, $E = \frac{P^2}{2m}$, this term can be written in the form [9]:

$$\left(\frac{\partial f_0(E)}{\partial t}\right)_{ac} = \frac{2(2m)^{1/2}}{1_{ac}} V_s^2 E^{1/2}\left[\frac{E\partial^2 f_0(E)}{\partial E^2} + \left(\frac{E}{K_0 T} + 2\right)\frac{\partial f_0(E)}{\partial E} + \frac{2}{K_0 T} f_0(E)\right], \qquad (ii)$$

where m is the effective mass of the electron, V_s is the velocity of sound, 1_{ac} is the mean free path of the electron when scattered by an acoustic phonon and T is the lattice temperature. The second term in (*i*) describes the rate of change of $f_0(E)$ due to the recombination of electrons with

$$1/\tau_r(E) = N_t V(E)\sigma(E) \qquad (iii)$$

N_t is the concentration of doubly charged traps, $V(E)$ is the velocity of the electron and $\sigma(E)$ is the capture cross section. According to [1,10]

$$\sigma(E) = \tilde{\psi}(E)E^{\nu-1}\left[\exp\left(\frac{2mZe^2}{\varepsilon h^2 K}\right) - 1\right]^{-1},$$

where $\tilde{\psi}(E)$ is a slowly varying function, ν is a small negative number, Ze is the charge of the trap, ε is the dielectric constant and K is the wave vector of the incident electron. The last term in (*i*) describes the generation of electrons. When electrons are generated by a monochromatic light source with frequency Ω_0, this term can be written as [3,11]:

$$g(E) = I\delta(E - h\Omega_0 + E_{Au^{3-}}) \qquad (iv)$$

where I is proportional to the intensity of the incident photon flux, the ionisation cross section of triply charged gold centres Au^{3-} and their concentration $N_{Au^{3-}}$. $E_{Au^{3-}}$ is the energy level from which generation takes place.

Substituting by (*ii*), (*iii*) and (*iv*) in (*i*) one can write the kinetic equation in the dimensionless form:

$$\frac{d}{dx}\left[x^2\frac{df_0(x)}{dx} + x^2 f_0(x)\right] - AR(x)f_0(x) + G\delta(x - x_0) = 0, \qquad (1)$$

where

$$x = \frac{E}{K_0 T}, \quad x_0 = \frac{h\Omega_0 - E_{Au^{3-}}}{K_0 T}, \quad A = \frac{\tilde{\psi}(K_0 T)^{\nu} 1_{ac} N_t}{2mV_s^2},$$

$$R(x) = x^{\nu} \exp\left(\frac{-\gamma}{x^{1/2}}\right), \quad \gamma = \frac{2\pi Z e^2}{\varepsilon h V_T}, \quad G = \frac{I 1_{ac}}{2V_s^2}\left(\frac{x_0}{2mK_0 T}\right)^{1/2},$$

$$V_T = \left(\frac{2K_0 T}{m}\right)^{1/2}.$$

Using the substitution

$$f_0(x) = y(x) \exp(-x) \tag{2}$$

one can rewrite equation (1) in Euler's form:

$$\frac{d}{dx}\left[P(x)\frac{dy(x)}{dx}\right] - AQ(x)y(x) + G\delta(x - x_0) = 0 \tag{3}$$

where

$$P(x) = x^2 \exp(-x), \quad Q(x) = R(x) \exp(-x).$$

3. *The variational method*

The variational technique for the solution of the kinetic equation has been used by several authors [12–14]. In the present work we shall try to obtain a solution for equation (3) by a method based on the variational principle. This method is based on an appropriate choice of a trial function which satisfies the boundary conditions as the exact solution. The functional for equation (3) is then written down in terms of the trial function. From the conditions of minimum of the functional the variational parameters, in the trial function, are then determined. It can be seen [15] that the functional for equation (3) is

$$\mathcal{J}[y(x, x_0)] = \int_0^{\infty} dx \left[P(x)\left(\frac{dy(x, x_0)}{dx}\right)^2 + AQ(x)y^2(x, x_0) - 2Gy(x, x_0)\delta(x - x_0)\right]. \tag{4}$$

Together with the condition of balance, equating the number of generated and recaptured electrons:

$$G = A \int_0^{\infty} dx Q(x) y(x, x_0) \tag{5}$$

the functional (4) achieves its minimum for the exact solution.

The simplest trial function, which satisfies the conditions of continuity of the distribution function at the generation energy $x = x_0$, can be chosen in the form

$$y(x, x_0) = a + B\frac{R(x)}{x^2}$$

$$+ \theta(x - x_0)\left[C(x - x_0)^2 - G\left(\frac{(x - x_0)^2 R(x) \exp(x)}{x^4} + \int_{x_0}^{x} dx' \frac{e^{x'}}{x'^2}\right)\right], \tag{6}$$

where $\theta(x-x_0)$ is the unit step function

$$\theta(x-x_0) = 1, \quad x \geqslant 0$$
$$= 0, \quad x < 0.$$

Using condition (5) yields

$$a = G\left(\frac{A^{-1}+I_3+I_4}{I_0}\right) - B\frac{I_1}{I_0} - C\frac{I_2}{I_0},$$

where

$$I_0 = \int_0^\infty R(x)e^{-x}dx, \quad I_1 = \int_0^\infty \frac{R^2(x)e^{-x}}{x^2}\,dx,$$

$$I_2 = \int_{x_0}^\infty (x-x_0)^2 R(x)e^{-x}dx, \quad I_3 = \int_{x_0}^\infty (x-x_0)^2\frac{R^2(x)}{x^4}\,dx,$$

$$I_4 = \int_{x_0}^\infty R(x)e^{-x}\int_{x_0}^x dx'\,\frac{e^{x'}}{x'^2}\,dx.$$

The variational parameters B and C are determined from the conditions

$$\frac{\partial}{\partial B}\mathcal{I}[y] = 0, \quad \frac{\partial}{\partial C}\mathcal{I}[y] = 0. \tag{7}$$

Inserting expression (6) for the trial function in the functional (4) it can be shown that conditions (7) yield

$$B = G\frac{T_1+AT_2+A^2T_3}{D_1+AD_2+A^2D_3}, \quad C = G\frac{L_1+AL_2+A^2L_3}{D_1+AD_2+A^2D_3}, \tag{8}$$

where

$$T_1 = i_1\left(\frac{I_2}{I_0}+i_2\right) - i_4(i_3-\psi(x_0)),$$

$$T_2 = i_1i_7+i_2i_6-i_9(i_2-\psi(x_0))-i_4i_8, \quad T_3 = i_6i_7-i_8i_9.$$

$$D_1 = i_4i_5-i_1^2, \quad D_2 = i_5i_9+i_4i_{10}-2i_1i_6, \quad D_3 = i_9i_{10}-i_6^2,$$

$$L_1 = i_2(i_3-\psi(x_0))-i_5\left(\frac{I_2}{I_0}+i_2\right),$$

$$L_2 = i_6(i_3-\psi(x_0))+i_1i_8-i_5i_7-i_{10}\left(\frac{I_2}{I_0}+i_2\right), \quad L_3 = i_6i_8-i_7i_{10}.$$

$$i_1 = \int_0^\infty P(x)\psi'(x)\zeta'(x)dx, \quad i_2 = \int_0^\infty P(x)\eta'(x)\zeta'(x)dx$$

$$i_3 = \int_0^\infty P(x)\eta'(x)\psi'(x)dx, \quad i_4 = \int_0^\infty P(x)\zeta'^2(x)dx$$

$$i_5 = \int_0^\infty P(x)\psi'^2(x)dx, \quad i_6 = \int_0^\infty Q(x)\psi(x)\zeta(x)dx$$

$$i_7 = \int_0^\infty Q(x)\eta(x)\zeta(x)dx, \quad i_8 = \int_0^\infty Q(x)\eta(x)\psi(x)dx$$

$$i_9 = \int_0^\infty Q(x)\zeta^2(x)dx, \quad i_{10} = \int_0^\infty Q(x)\psi^2(x)dx$$

$$\psi(x) = \frac{R(x)}{x^2} - \frac{I_1}{I_0}, \quad \zeta(x) = (x-x_0)^2\theta(x-x_0) - \frac{I_2}{I_0}$$

$$\eta(x) = \left(\frac{A^{-1}+I_3+I_4}{I_0}\right) - \theta(x-x_0)\left\{\frac{(x-x_0)^2R(x)e^x}{x^4} + \int_{x_0}^{x} \frac{e^{x'}}{x'^2}\,dx'\right\}.$$

Assuming that electrons are generated in the passive energy region [16] $\left(x \leqslant x_m = \dfrac{hw_0}{K_0T}\right.$, $hw_0 = 0.035$ eV is the optical phonon energy$\Big)$, so, for convenience, the upper limit of all the above integrals is approximated to be x_m.

Numerical calculations using the IBM 1620 computer have been performed. The obtained values are given in Table I for $T = 77$ K.

TABLE I

$v = -1$		$v = -2$		$v = -3$	
$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$
T_1 $3.318 \cdot 10^{-7}$	$1.559 \cdot 10^{-7}$	$6.783 \cdot 10^{-8}$	$3.550 \cdot 10^{-8}$	$1.463 \cdot 10^{-8}$	$5.132 \cdot 10^{-9}$
T_2 $3.235 \cdot 10^{-13}$	$1.287 \cdot 10^{-13}$	$1.842 \cdot 10^{-14}$	$5.656 \cdot 10^{-15}$	$7.488 \cdot 10^{-16}$	$1.575 \cdot 10^{-16}$
T_3 $3.990 \cdot 10^{-20}$	$9.559 \cdot 10^{-21}$	$4.872 \cdot 10^{-22}$	$8.786 \cdot 10^{-23}$	$4.335 \cdot 10^{-24}$	$5.184 \cdot 10^{-25}$
L_1 $4.480 \cdot 10^{-13}$	$2.150 \cdot 10^{-13}$	$2.352 \cdot 10^{-14}$	$1.381 \cdot 10^{-14}$	$2.059 \cdot 10^{-15}$	$1.163 \cdot 10^{-15}$
L_2 $1.602 \cdot 10^{-19}$	$1.715 \cdot 10^{-19}$	$4.838 \cdot 10^{-21}$	$2.362 \cdot 10^{-21}$	$8.625 \cdot 10^{-23}$	$3.626 \cdot 10^{-23}$
L_3 $2.080 \cdot 10^{-26}$	$2.664 \cdot 10^{-26}$	$1.793 \cdot 10^{-28}$	$8.420 \cdot 10^{-29}$	$7.168 \cdot 10^{-31}$	$2.641 \cdot 10^{-31}$
D_1 $2.089 \cdot 10^{-13}$	$8.833 \cdot 10^{-14}$	$1.286 \cdot 10^{-14}$	$4.892 \cdot 10^{-15}$	$1.017 \cdot 10^{-15}$	$3.788 \cdot 10^{-16}$
D_2 $1.602 \cdot 10^{-19}$	$6.337 \cdot 10^{-20}$	$2.283 \cdot 10^{-21}$	$7.446 \cdot 10^{-22}$	$3.533 \cdot 10^{-23}$	$9.887 \cdot 10^{-24}$
D_3 $2.080 \cdot 10^{-26}$	$7.513 \cdot 10^{-27}$	$7.482 \cdot 10^{-29}$	$2.108 \cdot 10^{-29}$	$2.645 \cdot 10^{-31}$	$6.042 \cdot 10^{-32}$
I_0 $7.066 \cdot 10^{-7}$	$7.066 \cdot 10^{-7}$	$2.006 \cdot 10^{-7}$	$2.006 \cdot 10^{-7}$	$6.271 \cdot 10^{-8}$	$6.271 \cdot 10^{-8}$
I_1 $5.476 \cdot 10^{-13}$	$5.476 \cdot 10^{-13}$	$3.467 \cdot 10^{-14}$	$3.467 \cdot 10^{-14}$	$2.787 \cdot 10^{-15}$	$2.787 \cdot 10^{-15}$
I_2 $4.947 \cdot 10^{-7}$	$1.936 \cdot 10^{-7}$	$1.015 \cdot 10^{-7}$	$3.853 \cdot 10^{-8}$	$2.099 \cdot 10^{-8}$	$7.695 \cdot 10^{-9}$
I_3 $2.463 \cdot 10^{-14}$	$9.507 \cdot 10^{-15}$	$1.052 \cdot 10^{-15}$	$3.793 \cdot 10^{-16}$	$4.635 \cdot 10^{-17}$	$1.536 \cdot 10^{-17}$
I_4 $1.607 \cdot 10^{-6}$	$1.017 \cdot 10^{-6}$	$3.396 \cdot 10^{-7}$	$2.072 \cdot 10^{-7}$	$7.250 \cdot 10^{-8}$	$4.243 \cdot 10^{-8}$

TABLE II

	$\nu = -1$		$\nu = -2$		$\nu = -3$	
	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$
T_1	$-1.103 \cdot 10^{-10}$	$3.085 \cdot 10^{-12}$	$-2.586 \cdot 10^{-12}$	$1.983 \cdot 10^{-13}$	$2.667 \cdot 10^{-13}$	$1.149 \cdot 10^{-14}$
T_2	$-2.254 \cdot 10^{-17}$	$2.604 \cdot 10^{-20}$	$-7.989 \cdot 10^{-20}$	$1.220 \cdot 10^{-22}$	$-2.476 \cdot 10^{-22}$	$6.661 \cdot 10^{-25}$
T_3	$-1.158 \cdot 10^{-24}$	$-2.819 \cdot 10^{-27}$	$-2.704 \cdot 10^{-28}$	$-3.923 \cdot 10^{-31}$	$-5.934 \cdot 10^{-32}$	$-4.891 \cdot 10^{-25}$
L_1	$1.147 \cdot 10^{-17}$	$3.444 \cdot 10^{-18}$	$1.479 \cdot 10^{-19}$	$4.408 \cdot 10^{-20}$	$2.492 \cdot 10^{-21}$	$7.417 \cdot 10^{-22}$
L_2	$9.600 \cdot 10^{-25}$	$1.857 \cdot 10^{-25}$	$6.791 \cdot 10^{-28}$	$1.255 \cdot 10^{-28}$	$6.450 \cdot 10^{-31}$	$1.172 \cdot 10^{-31}$
L_3	$1.045 \cdot 10^{-32}$	$1.939 \cdot 10^{-33}$	$4.517 \cdot 10^{-37}$	$7.399 \cdot 10^{-38}$	$2.802 \cdot 10^{-41}$	$4.227 \cdot 10^{-42}$
D_1	$1.630 \cdot 10^{-21}$	$3.952 \cdot 10^{-23}$	$2.108 \cdot 10^{-23}$	$5.057 \cdot 10^{-25}$	$3.551 \cdot 10^{-25}$	$8.507 \cdot 10^{-27}$
D_2	$1.219 \cdot 10^{-28}$	$2.303 \cdot 10^{-30}$	$9.392 \cdot 10^{-32}$	$1.564 \cdot 10^{-33}$	$9.612 \cdot 10^{-35}$	$1.463 \cdot 10^{-36}$
D_3	$1.206 \cdot 10^{-36}$	$2.457 \cdot 10^{-38}$	$6.037 \cdot 10^{-41}$	$9.516 \cdot 10^{-43}$	$4.192 \cdot 10^{-45}$	$5.506 \cdot 10^{-47}$
I_0	$3.334 \cdot 10^{-10}$	$3.334 \cdot 10^{-10}$	$4.973 \cdot 10^{-11}$	$4.973 \cdot 10^{-11}$	$8.162 \cdot 10^{-12}$	$8.162 \cdot 10^{-12}$
I_1	$7.769 \cdot 10^{-19}$	$7.767 \cdot 10^{-19}$	$1.004 \cdot 10^{-20}$	$1.004 \cdot 10^{-20}$	$1.687 \cdot 10^{-22}$	$1.887 \cdot 10^{-22}$
I_2	$4.078 \cdot 10^{-11}$	$1.359 \cdot 10^{-12}$	$2.933 \cdot 10^{-12}$	$7.296 \cdot 10^{-14}$	$1.722 \cdot 10^{-13}$	$3.929 \cdot 10^{-15}$
I_3	$2.539 \cdot 10^{-21}$	$8.064 \cdot 10^{-23}$	$1.076 \cdot 10^{-23}$	$2.339 \cdot 10^{-25}$	$4.781 \cdot 10^{-26}$	$6.885 \cdot 10^{-28}$
I_4	$1.612 \cdot 10^{-7}$	$9.528 \cdot 10^{-8}$	$9.442 \cdot 10^{-9}$	$4.922 \cdot 10^{-9}$	$5.636 \cdot 10^{-10}$	$2.628 \cdot 10^{-10}$

For $T = 20$ K the results of numerical calculations are given in Table II. For small values of A corresponding to trap concentration $N_t \approx 10^{15}\,\mathrm{cm}^{-3}$ the variational parameters B and C in (8) will be independent of A, in this case we have for the distribution function

$$f_0(x, x_0) = \frac{G}{A}\left[I_0^{-1}e^{-x} + A\left\{\tilde{a} + \tilde{B}\frac{R(x)}{x^2}\right.\right.$$

$$\left.\left. + \theta(x-x_0)\left(\tilde{C}(x-x_0)^2 - \frac{(x-x_0)^2 R(x)e^x}{x^4} - \int_{x_0}^{x}\frac{e^{x'}}{x'^2}\,dx'\right)\right\}\exp(-x)\right], \qquad (9)$$

where

$$\tilde{a} = \frac{I_3 + I_4}{I_0} - \frac{I_1}{I_0}\frac{T_1}{D_1} - \frac{I_2}{I_0}\frac{L_1}{D_1}, \quad \tilde{B} = \frac{T_1}{D_1} \quad \text{and} \quad \tilde{C} = \frac{L_1}{L_1}.$$

The numerical values of the parameters $\tilde{a}$, $\tilde{B}$ and $\tilde{C}$ for $T = 77$ K are given in Table III. For $T = 20$ K the results for the parameters $\tilde{a}$, $\tilde{B}$ and $\tilde{C}$ are given in Table IV.

TABLE III

	$\nu = -1$		$\nu = -2$		$\nu = -3$	
	$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$
$\tilde{a}$	-0.323	-0.595	-0.144	-0.763	-0.161	-0.302
$\tilde{B}$	$1.588 \cdot 10^6$	$1.765 \cdot 10^6$	$5.272 \cdot 10^6$	$7.257 \cdot 10^6$	$1.439 \cdot 10^7$	$1.354 \cdot 10^7$
$\tilde{C}$	2.144	2.433	1.828	2.823	2.024	3.071

TABLE IV

	$\nu = -1$		$\nu = -2$		$\nu = -3$	
	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$
$\tilde{a}$	$2.193 \cdot 10^{+2}$	$2.513 \cdot 10^{+2}$	$-1.569 \cdot 10^{+2}$	$-1.080 \cdot 10^{+2}$	-94.56	-37.70
$\tilde{B}$	$-6.769 \cdot 10^{10}$	$7.805 \cdot 10^{+10}$	$-1.226 \cdot 10^{-11}$	$3.921 \cdot 10^{+11}$	$7.511 \cdot 10^{+11}$	$1.351 \cdot 10^{+12}$
$\tilde{C}$	$7.036 \cdot 10^{+3}$	$8.713 \cdot 10^{+4}$	$7.016 \cdot 10^{+3}$	$8.717 \cdot 10^{+4}$	$7.017 \cdot 10^{+3}$	$8.718 \cdot 10^{+4}$

The second term in the squared bracket in (9) represents the effect of electron capture on the energy distribution.

4. The capture rate ratio

Using the obtained distribution (9), the capture rate ratio

$$C_n/C_M = \frac{\int_0^\infty f_0(x, x_0)R(x)dx}{\int_0^\infty f_0(x, x_0)x^{1/2}dx} \cdot \frac{\int_0^\infty e^{-x}x^{1/2}dx}{\int_0^\infty R(x)e^{-x}dx}$$

has been calculated, where C_M is the capture rate when the distribution of electrons is Maxwellian.

Case I:

For trap concentrations $N_t < 10^{15}$ cm^{-3}. The results for $T = 77$ K and $T = 20$ K are given in Tables V and VI, respectively.

TABLE V

	$\nu = -1$		$\nu = -2$		$\nu = -3$	
	$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$	$x_0 = 3.5$	$x_0 = 4$
$\left(\frac{C_n}{C_M} - 1\right) \times 10^{-20} N_t$	0.66	0.80	0.29	0.36	0.09	0.17

TABLE VI

	$\nu = -1$		$\nu = -2$		$\nu = -3$	
	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$	$x_0 = 12$	$x_0 = 16$
$\left(\frac{C_n}{C_M} - 1\right) \times 10^{-17} N_t$	0.32	0.40	0.12	0.16	0.06	0.08

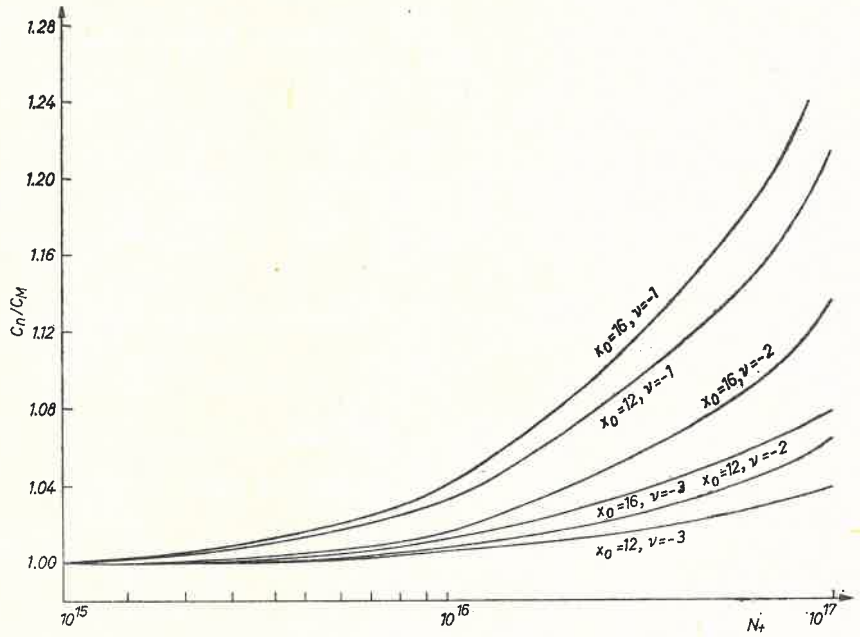

Fig. 1. Variation of capture rate ratio with trap concentration $T = 20$ K

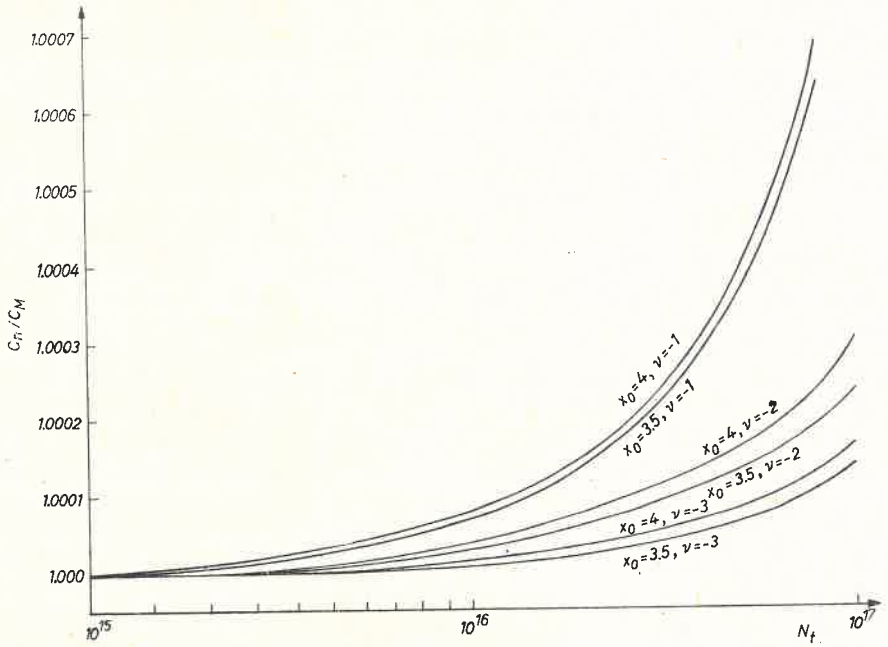

Fig. 2. Variation of capture rate ratio with trap concentration $T = 77$ K

Case II:

For trap concentrations $N_t > 10^{15}$ cm^{-3} the second and third terms in the numerator and denominator in expressions (8) become comparable to the first term. Therefore, the values of the variational parameters B and C will depend on the parameter A. In this case the part of the distribution function, representing the effect of electron capture will nonlinearly depend on the parameter A.

The results of numerical calculations for the capture rate ratio in this case are shown in figures 1 and 2 for lattice temperatures $T = 77$ K and $T = 20$ K, respectively.

5. *Discussion*

Using the variational technique in solving the kinetic equation, the solution is obtained in the form of a sum of two parts (equation (9)). The first part (Maxwellian part) is an exponential function of energy. The second part of the solution (additional part) depends on energy in a more complicated way. This part of the distribution represents the effect of electron capture on the energy distribution of electrons. It is shown that, for small trap concentrations N_t, the additional part is small and linearly proportional to N_t. With the increase of N_t the additional part of the distribution becomes more effective and nonlinearly dependent on N_t. It is important to underline that N_t must not exceed certain limit, at which the semiconductor is considered highly doped one.

The capture rate ratio has also been calculated using the obtained distribution function. The results show that this ratio increases with an increase of N_t and when the lattice temperature is lowered.

We notice from the figures that the higher the energy of the electron, the higher the value of its capture rate. This is attributed to the fact that electrons with higher energy can more easily surmount the barrier, surrounding the negatively charged trap. It is important to underline that if electrons are generated with energies $E > \hbar w_0$ i.e. in the active region [16], then after emitting optical phonons they fall in the passive region with energy $E < \hbar w_0$ as those considered in our study.

From the results it is also shown that the higher the energy-loss mechanism parameter $|v|$ the smaller the capture rate. This indicates that, on the other hand, electrons with lower energies loose their energy quicker and become captured.

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