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Physics

Investigation of the Role of Negatively Charged Impurity Centers in Formation of Inverse Distribution of Photoelectrons; on a Coefficient of Hot Charge Carrier Trapping by Repulsive Impurity Centers

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ABSTRACT. The active medium with the inverse charge carrier population is known to form the basis of up-to-date semiconductor masers and lasers. This population can be created by various actions including electron generation and heating towards the conductivity region by means of electromagnetic radiation (photoheating). The objective of our studies was to find the conditions for formation of regions of hot photoelectron distribution when their lifetime is controlled by trapping by negatively and positively charged impurity centers for different energy relaxation mechanisms, both quasi-elastic and strongly inelastic. *© 2009 Bull. Georg. Natl. Acad. Sci.*

Key words: *inverse population, photoelectron distribution.*

To study the possibility of occurrence of the inverse distribution function at hot photoelectrons trapping by repulsive impurity centers it is, first of all, necessary to establish the analytical form of the energy dependence of the trapping coefficient $C(\varepsilon)$. For this purpose, a great bulk of the existing experimental data (essentially for Si and Ge), as well as theoretical results have been analyzed to calculate the trapping coefficient. It is clear that the repulsive center can trap an electron if the given impurity in the semiconductor generates at least two acceptor levels. For Si, such impurities are: Cd, Cu, Ni, Pt, Zn, and for Ge - Cu, Ag, Au, Ni, Pt. The recombination characteristics of the repulsive centers are most comprehensively studied for Ge. They are given in the Table.

For our further experiments, the charge carrier lifetime plays a significant role with respect to the given trapping mechanism. In the works existing to date it was believed without any argumentation that during the trapping by negatively charged impurity centers the free charge carrier lifetime is an increasing energy function. Our investigations have shown that it has a minimum point and accordingly, the increasing and decreasing regions. To vary the lifetime with respect to the given trapping mechanisms in the wide energy range, it is necessary to select a material and a corresponding impurity with high dissolubility values and trapping cross-sections. Ge has been selected. It is clear from the Table that the suitable impurities are Au and Cu as well as Pt, though there are not many experimental data for Pt. The ionization energies $Cu^{\equiv}$ (z=2), Au^{-} (z=1), $Au^{\equiv}$ (z=2), $Pt^{\equiv}$ (z=2) are respectively equal to E_c -0,26 ev, E_c -0,20 ev, E_c -0,04 ev and E_c -0,12 ev. Comparing the trapping processes by $Pt^{\equiv}$ and $Cu^{\equiv}$, one can state from physical considerations: during the trapping by $Pt^{\equiv}$ the electron must overcome a potential barrier lower than that during the trapping by $Cu^{\equiv}$. Therefore, for electrons with low energies (~26K) the probability of overcoming the barrier for $Pt^{\equiv}$ is higher than for $Cu^{\equiv}$. As for the trapping probability of the already tunneled electron, it is also higher for $Pt^{\equiv}$ than for $Cu^{\equiv}$. That is, the trapping cross-section by Pt must be higher than that by $Cu^{\equiv}$. With similar considerations for trapping by $Pt^{\equiv}$ and Au^{-} it can be concluded: for electrons

Table

Characterizing parameters of the repulsive centers in Ge (experimental data from [1 - 9]).

	Ge					
Impurity	z	λ (ev)	σ (cm^2)	C (T) ($cm^3 \cdot sec^{-1}$)	$\frac{C_{max}(E)}{C(T)}$	N_m (cm^{-3})
Au	1	E_c - -0,2	$3 \cdot 10^{-18}$ (30 K) 10^{-17} (77 K) $2 \cdot 10^{-16}$ (300 K)	$3 \cdot 10^{-12}$ (20 K) $9 \cdot 10^{-11}$ (77 K)	17 (20 K) 2.6 (77 K)	$>10^{16}$
	2	E_c - -0.04	$3 \cdot 10^{-19}$ (30 K)	$2 \cdot 10^{-12}$ (20 K)	1750 (20 K)	
Cu	1	E_υ + +0.32	$2 \cdot 10^{-17}$ (300 K)			$>10^{16}$
	2	E_c - -0.26	$4 \cdot 10^{-18}$ (25 K)	$9 \cdot 10^{-15}$ (30 K) 10^{-13} (71 K)	600(30K)	
Ag	2	E_c - -0.28	$5 \cdot 10^{-18} \ldots 10^{-16}$ (120 ...300 K)			$<10^{16}$
	3	E_c - -0.09	10^{-19} (80 K)			
Ni	2	E_c - -0.3	$5 \cdot 10^{-16}$ (300 K)		10(77K)	$<10^{16}$
Pt	2	E_c - -0.12	$6 \cdot 10^{-17} \ldots 2 \cdot 10^{-15}$ (26.2 ...77 K)	$6.3 \cdot 10^{-10}$ (26.2 K) $1.8 \cdot 10^{-8}$ (77 K)	315 (26.2 K) 8.4 (77 K)	$>10^{16}$
Cd	1	E_υ + +0.05	10^{-16} (160 K)			$<10^{16}$

$E_c - E_\upsilon$ =0,67 -for Ge

Z - the center charge

λ – the ionization energy of the generated center

σ - the trapping cross-section

$C(T)$ – the trapping coefficient

$C_{max}(E)/C(T)$ – the ratio of the maximum value of the trapping coefficient in the electric field to its thermodynamic value.

N_m – the dissolubility value.

with relatively high energies (77K) the probabilities of overcoming the barrier for $Pt^{\equiv}$ and $Au^{=}$ will not strongly differ from each other, but during the trapping by $Au^{=}$ the tunneled electron must lose more energy than by $Pt^{\equiv}$, therefore, the trapping cross-section for $Pt^{\equiv}$ might be higher than that for $Au^{=}$.

The comparison of the results (see Table) for $Au^{=}$, $Pt^{\equiv}$ and $Cu^{\equiv}$ proves the correctness of the above considerations. Hence, the trapping cross-section (coefficient) must be a function of the charge state of the impurity center (z) and the energy trapping level (λ).

In many works, to explain the experimental results for the temperature dependence of the trapping coefficient, the following formula [10] is used:

$$C(T) = C_0 e^{-\left(\frac{T_0}{T}\right)^{\frac{1}{3}}}, \qquad (1)$$

where $T_0 = 27\pi^2 W_B$, $W_B = \frac{me^4}{2\chi^2\hbar^2} z^2$ is the Bohr center energy, χ is the dielectric permittivity. In (1) an explicit form of C_0 is not given. And for our purposes it is very important.

In [11] it was supposed that the probability of energy losses during tunneling is $\sim \varepsilon^P$ ($p<0$, ε is the electron energy). In [12] it was proved that the probability of a multi-phonon trapping of the tunneled electron is $\sim \exp\left(-\frac{\varepsilon}{\varepsilon_1}\right)$, where ε_1 is the oscillation quantum energy. According to [13], the differential trapping coefficient can be written in the form:

$$C(\varepsilon) = 2\pi \cdot \sqrt{\frac{W_B}{\varepsilon}} \cdot \left(e^{2\pi\sqrt{\frac{W_B}{\varepsilon}}} - 1 \right)^{-1} \cdot e^{-\frac{\varepsilon}{\varepsilon_1}}., \qquad (2)$$

On the other hand, taking into account the results of [14], after calculating we obtain:

$$C(\varepsilon)=B(\lambda,z)\cdot\sqrt{\frac{W_B}{\varepsilon}}\cdot\left(1+\frac{\varepsilon}{|\lambda|}\right)^{-2}\cdot\left(e^{2\pi\sqrt{\frac{W_B}{\varepsilon}}}-1\right)^{-1}\cdot e^{\frac{(\varepsilon+|\lambda|-a_\lambda)^2}{\delta^2}}, \quad (3)$$

where $B(\lambda,z)=\dfrac{27\pi^3\hbar^2}{m^{\frac{3}{2}}\sqrt{2W_B}}\left(\dfrac{E_C W_B}{\lambda^2}\right)\left(\dfrac{\hbar\omega_C}{Ms^2}\right)^{\frac{1}{2}}$, $\hbar\omega_C$ is the Debye phonon energy, E_c is the deformation potential constant, M is the elementary cell mass, s is the sound velocity, a_λ and $\delta^2=\delta_0{}^2\left[1+\varphi_c(T)\right]$ are defined in [14], $\varphi_c(T)$ is the Debye function.

At low temperatures ($T<\lambda$), calculating $C(\lambda,T)$ by the "pass" method, we obtain from (3):

$$C(\lambda,T)=B(\lambda,z)\cdot\sqrt{\frac{16\pi}{3}}\cdot\left(\frac{W_B\pi}{T^*}\right)^{\frac{2}{3}}\cdot e^{-\left(\frac{T_0}{T^*}\right)^{\frac{1}{3}}-\sigma}, \quad (4)$$

where $\sigma=\dfrac{\left(|\lambda|-a_\lambda\right)^2}{\delta^2}$, $\dfrac{1}{T^*}=\dfrac{1}{T}+\dfrac{1}{\varepsilon_{01}}$,

$\varepsilon_{01}=\dfrac{\delta^2}{2\left(|\lambda|-a_\lambda\right)}$.

As for formula (2), it follows that:

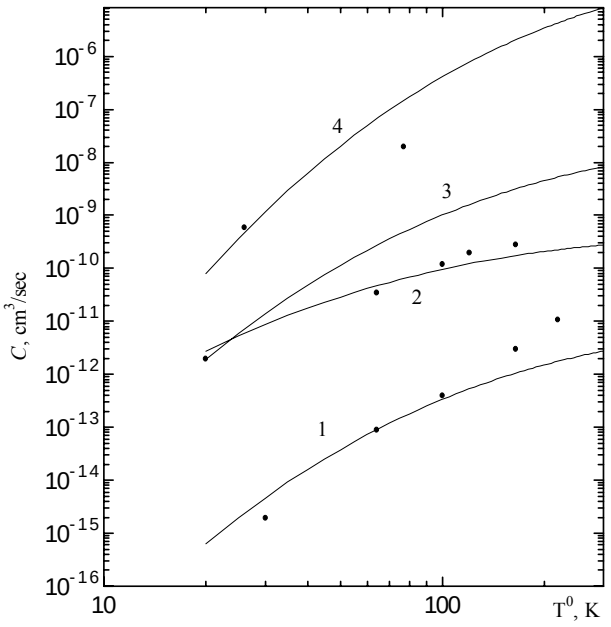
$$C(\lambda,T)=C_1\sqrt{\frac{16\pi}{3}}\left(\frac{W_B\pi}{T^*}\right)^{\frac{2}{3}}\cdot e^{-\left(\frac{T_0}{T^*}\right)^{\frac{1}{3}}} \quad (5)$$

where $\dfrac{1}{T^*}=\dfrac{1}{T}+\dfrac{1}{\varepsilon_1}$, and C_1 is a certain constant.

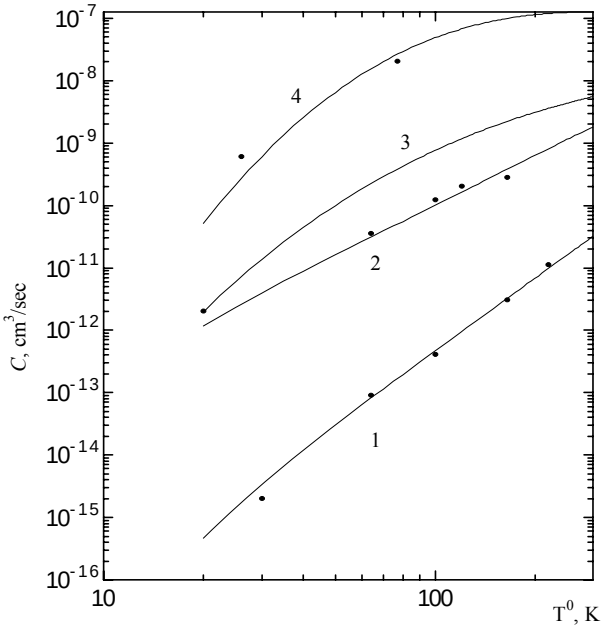
The temperature dependence coincides with the results of (3). At $T<\varepsilon_1(\varepsilon_{01})$ $T^*=T$ and $C(\lambda,T)$ is the increasing function of T, and at high T, $T^*=\varepsilon_1(\varepsilon_{01})$, and $C(\lambda,T)$ becomes saturated. However, as shown by the analysis of numerous experimental data (see Table), the trapping coefficient must have a maximum both according to its temperature and field (<10^3 v/cm) dependences [8, 11]. Hence, formula (4) and (5), obtained by the "pass" method, describe the experimental data only at low temperatures and electric fields. To have a full picture, it is necessary to perform numerical integration of formulas (2) and (3) in a wide temperature range. The obtained results are given in Figs.1 and 2. The estimations were carried out both in the simple temperature (Fig.1a,1b) and heating electrical field (Fig.2a,2b) regimes in the electron temperature approximation.

It should be mentioned that $C(\lambda,T)$ dependences obtained from (3) describe the experimental maximum points with the inclusion of the heating electric field much better. They are very sensitive to a_λ and δ^2 parameters. δ^2, in its turn, is a temperature function, and ε_{01} increases with T. Moreover, the change in the trapping coefficient depending on λ and z is perfectly described by the expression $B(\lambda,z)$.

From the analysis of Figs. 1 and 2 it can be concluded: only during the trapping by $Au^{\equiv}$ and $Pt^{\equiv}$ cen-



a)



b)

Fig. 1.

Temperature dependences of the trapping coefficient obtained by formula (2). 1 - $Cu^{\equiv}$; 2 – $Au^{=}$; 3 – $Au^{\equiv}$; 4 - $Pt^{\equiv}$. (dots denote the corresponding experimental data)

Temperature dependences of the trapping coefficient obtained by formula (3) 1 - $Cu^{\equiv}$; 2 – $Au^{=}$; 3 – $Au^{\equiv}$; 4 - $Pt^{\equiv}$. (dots denote the corresponding experimental data)

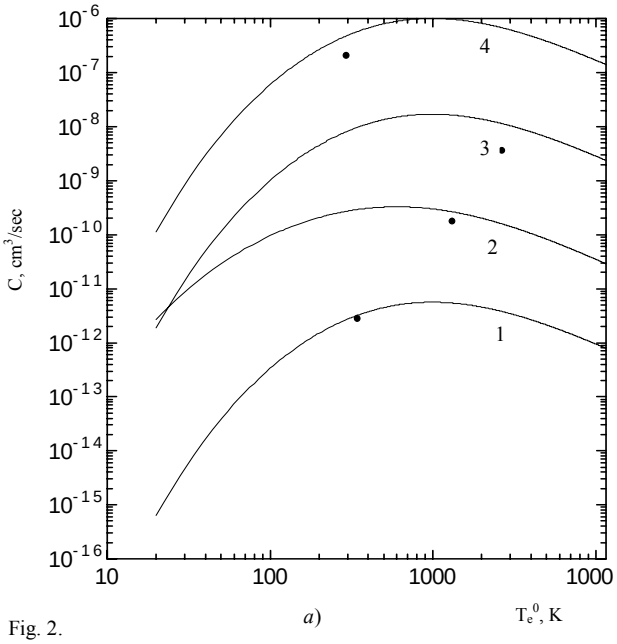
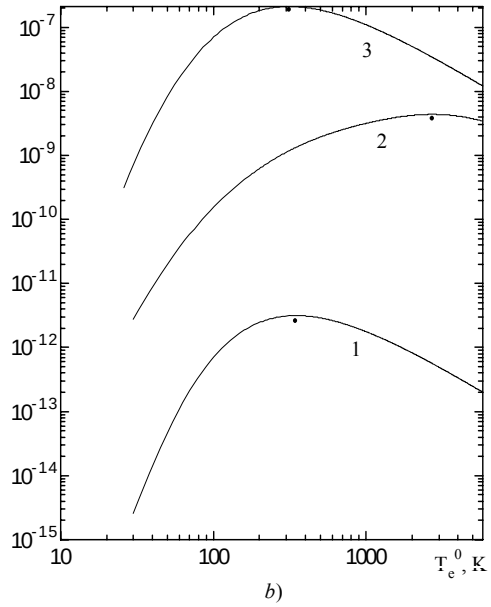


Fig. 2.

Temperature dependences of the trapping coefficient obtained by formula (2). Dots denote the corresponding experimental data.

1 - $Cu^{=}$; 2 – $Au^{=}$; 3 – $Au^{=}$; 4 - $Pt^{=}$.



Temperature dependences of the trapping coefficient obtained by formula (3). Dots denote the corresponding experimental data.

1 - $Cu^{=}$; 2 – $Au^{=}$; 3 - $Pt^{=}$

ters the lifetime of hot photoelectrons, (τ_c), can be varied within a wide spectral range and for the trapping coefficient expression (3) should be used.

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ფიზიკა

უარყოფითად დამუხტული მინარევული ცენტრების როლის გამოკვლევა ფოტოელექტრონების ინვერსიული განაწილების ფორმირებაში; მუხტის მატარებელთა ჩაჭერის კოეფიციენტი განმზიდავ მინარევულ ცენტრებზე გაბნევისას

ე. ხიზანიშვილი, ზ. ქაჩლიშვილი, მ. ხიზანიშვილი, მ. გიგაური

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(წარმოდგენილია აკადემიკოს თ. სანაძის მიერ)

როგორც ცნობილია, თანამედროვე ნახევარგამტარული ლაზერებისა და მაზერების მუშაობის საფუძველს წარმოადგენს ნახევარგამტარული აქტიური გარემო, მუხტის მატარებელთა ინვერსიული დასახლებით. ასეთი დასახლების შექმნა შესაძლებელია სხვადასხვა სახის ზემოქმედებით. მათ შორისაა ელექტრონების გენერაცია

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