საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 4, №1, 2010
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 4, no. 1, 2010

Physics

Investigation of the Role of Negatively Charged Impurity Centers in Formation of Inverse Distribution of Photoelectrons.The Kinetics Equation and Formation of the Inverse Distribution Function

Esma Khizanishvili*, Zaur Kachlishvili*, Marina Khizanishvili*, Maia Gigauri*

* *I. Javakhishvili Tbilisi State University*

(Presented by Academy Member T. Sanadze)

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 study was to find the conditions for formation of regions of hot photoelectron distribution when their lifetime is controlled by trapping either negatively or positively charged impurity centers for different energy relaxation mechanisms, both quasi-elastic and strongly inelastic. *© 2010 Bull. Georg. Natl. Acad. Sci.*

Key words: *inverse population, photoelectron distribution.*

Let us consider a semiconductor at low temperatures ($T << \varepsilon_i$, ε_i is the ionization energy) where the external monochromatic radiation excites electrons with the ε_0 "throw up" energy in the conductivity region. This energy is much higher than the equilibrium. Later, the excited electrons recombine, pre-scattering part of their initial energy by acoustic lattice oscillations. Our task is to establish the type of the electron distribution function under the above-mentioned conditions when their lifetime is controlled by trapping by repulsive (negatively charged) impurity centers.

At high energies photoelectron "throw up" when the quasielasiticity condition is violated and the distribution is far from equilibrium, one can use the Fokker-Planck equation. In this case spontaneous radiation is proved to play a main role in the flow and the term describing the departure of electrons on a lower energy state is predominant. The integral has the form [1,2]:

$$J(\varepsilon) = \frac{\partial}{\partial \varepsilon}\left[\frac{g(\varepsilon)\varepsilon}{\tau_{ak}(\varepsilon)} f(\varepsilon)\right], \qquad (1)$$

where $f(\varepsilon)$ is the charge carrier distribution function, $\tau_{ak}(\varepsilon)$ is the acoustic phonon emission time:

$$\tau_{ak}(\varepsilon) = \frac{2\sqrt{2}E_1^2 m^{5/2}}{\pi\hbar^4\rho}\varepsilon^{-1/2}. \qquad (2)$$

Proceeding from the above, at high "throw up" energy in the stationary condition the kinetic equation will have the form:

$$\frac{\partial}{\partial\varepsilon}\left[\frac{g(\varepsilon)\varepsilon}{\tau_{ak}(\varepsilon)}f(\varepsilon)\right]-\frac{f(\varepsilon)g(\varepsilon)}{\tau_c(\varepsilon)}+I\delta(\varepsilon-\varepsilon_0)=0. \quad (3)$$

$f(\varepsilon)g(\varepsilon)/\tau_c(\varepsilon)$ is the term describing the number of recombined electrons per unit time, $I\delta(\varepsilon-\varepsilon_0)$ is the photoelectron generation velocity with the "throw up" energy ε_0; it is described by the δ functions, I is the number of "born" photoelectrons per unit time, $\tau_c(\varepsilon)=(N\sigma\upsilon)^{-1}$ is the photoelectron lifetime with respect to trapping by repulsive centers with the concentration N.

The accurate solution of equation (3) in different energy regions has different forms [1]. The studies have shown that in the $\varepsilon>\varepsilon_0$ region $f(\varepsilon)$ is a decreasing energy function and at high ε it passes into the Boltzmann distribution. And in the $\varepsilon<\varepsilon_0$ region,

$$f(\varepsilon)=f_1(\varepsilon)=\frac{CI\tau_{ak}(\varepsilon)}{g(\varepsilon)\varepsilon}\exp\left[-\int_{\varepsilon}^{\varepsilon_0}\frac{\tau_{ak}(\varepsilon)}{\tau_c(\varepsilon)\varepsilon}d\varepsilon\right], \quad (4)$$

C is found from the $f(\varepsilon)$ normalization condition.

In the general case, for any trapping mechanism and energy relaxation way, $f(\varepsilon)$ has the extreme point (ε_m) if the condition $\tau_{ak}(\varepsilon)/\tau_c(\varepsilon)=2$ is fulfilled. When the probability of extra energy losses is higher than that of free electron trapping, hot electrons first are thermolyzed and only afterwards are trapped by different impurity centers. In this case they do not form a non-equilibrium distribution function, since they have time to come into equilibrium with the lattice. If the trapping probability is higher than that of energy relaxation, this distribution is established and it can be inverse. Electrons have no time to be re-distributed on low energy levels. Assuming that the energy relaxation takes place during acoustic phonon scattering, the inversion condition for the distribution function takes the form [2]: $\tau_c(\varepsilon)<\tau_{ak}(\varepsilon)$.

In the first part of the present work a wide range of materials creating negatively charged trapping centers in Ge has been studied. The conclusion was made: only during trapping by $Au^{\equiv}$ and $Pt^{\equiv}$ centers the hot photoelectron lifetime $(\tau_c(\varepsilon))$ can be varied within a sufficiently wide range. Accordingly, to find inverse areas in the distribution function, in the energy region $\varepsilon<\varepsilon_0$, the function $f_1(\varepsilon)$ was studied for $Au^{\equiv}$ and $Pt^{\equiv}$ impurities at different values of ε_0 and N.

It was obtained that at high N and ε values, depending on $f_1(\varepsilon)$, there is a maximum point and $f_1(\varepsilon)$ up to this point is an increasing energy function. Hence, the states in this region are inversely populated.

At high "throw up" energies electrons start to emit intensively acoustic phonons, descending energetically to the value $\varepsilon_э$, below which $\tau_c(\varepsilon)<\tau_\varepsilon(\varepsilon)$. This suggests that electrons born with the energy $\varepsilon_0>\varepsilon_э$, first accumulate in the $\varepsilon_э$ region and only afterwards are trapped by repulsive centers. Under condition $\varepsilon_0>>\varepsilon_э$, the descent time does not depend on ε_0 and it is determined by the equation:

$$\tau(\varepsilon_э)=\left(\frac{1}{\sqrt{\varepsilon_э}}-\frac{1}{\sqrt{\varepsilon_1}}\right)\sqrt{2m}l_0=2\left(1-\sqrt{\frac{\varepsilon_э}{\varepsilon_0}}\right)\tau_{ak,\varepsilon}(\varepsilon_э) \quad (5)$$

The value $\varepsilon_э$ is defined by the N values and does not depent on ε_0. With increasing N, $\varepsilon_э$ shifts toward higher values and thereby the inversion area broadens.

In the inverse,j part of the distribution function the energy values are such that optical phonon radiation is possible. Therefore, we have in this region:

$$\tau_\varepsilon^{-1}=\tau_{ak,\varepsilon}^{-1}+\tau_{op,\varepsilon}^{-1} \quad (6)$$

where $\tau_{op,\varepsilon}$ is the energy relaxation time with optical phonon radiation [3]:

$$\tau_{op,\varepsilon}=\frac{\sqrt{2}\pi\hbar^4\rho S^2}{(m\hbar\omega_0)^{3/2}E_{1,op}^2}\left(\frac{\varepsilon}{\hbar\omega_0}-1\right)^{-1/2} \quad (7)$$

where $E_{1,op}$ is the deformation potential coefficient under optical scattering.

The results of the theoretical estimations carried out are given in Figs.1 and 2. It is clear from the figures that the optical phonon radiation only narrows the energy area where $f_1(\varepsilon)$ is inverse.

To summarize, we can state that the inversion in the $f(\varepsilon)$ dependence of photoelectrons can be observed in Ge $Pt^{\equiv}$ on repulsive centers at $N_{Pt}>10^{16}cm^{-3}$, and for $Au^{\equiv}$ with reasonable N values, the inversion will be weak in the narrow energy region.

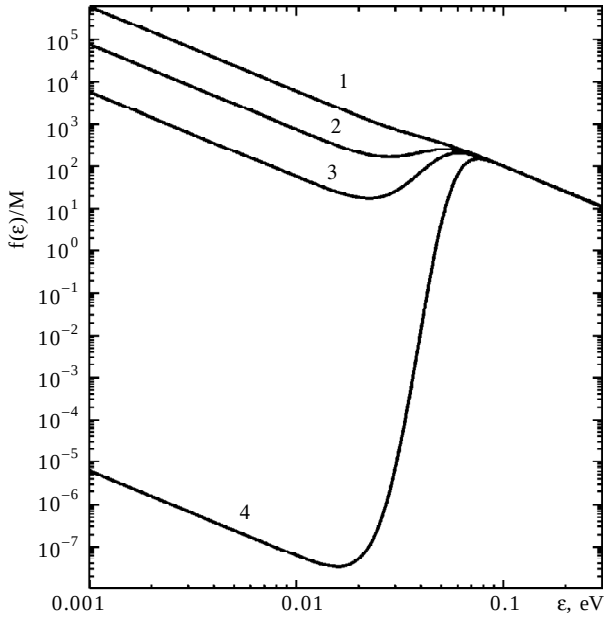

Fig.1. Distribution function in the Pt-doped Ge samples at different values of N_{Pt}.

1. - $N_{Pt}=10^{15}cm^{-3}$; 2. - $N_{Pt}=5\cdot10^{15}cm^{-3}$;
3. - $N_{Pt}=10^{16}cm^{-3}$; 4. - $N_{Pt}=5\cdot10^{16}cm^{-3}$;

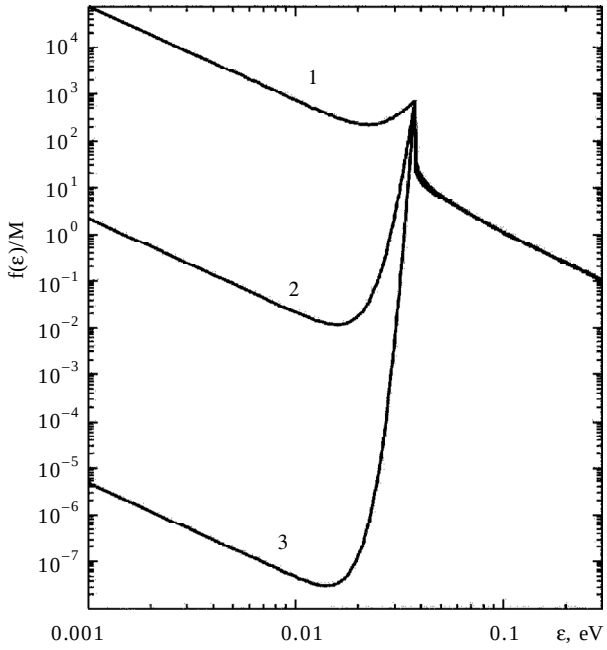

Fig. 2. Distribution function in the Pt-doped Ge samples at different values of N_{Pt} (with allowance for the process of scattering by optical phonons).

1. - $N_{Pt}=10^{16}cm^{-3}$; 2. - $N_{Pt}=5\cdot10^{16}cm^{-3}$; 3. - $N_{Pt}=10^{17}cm^{-3}$.

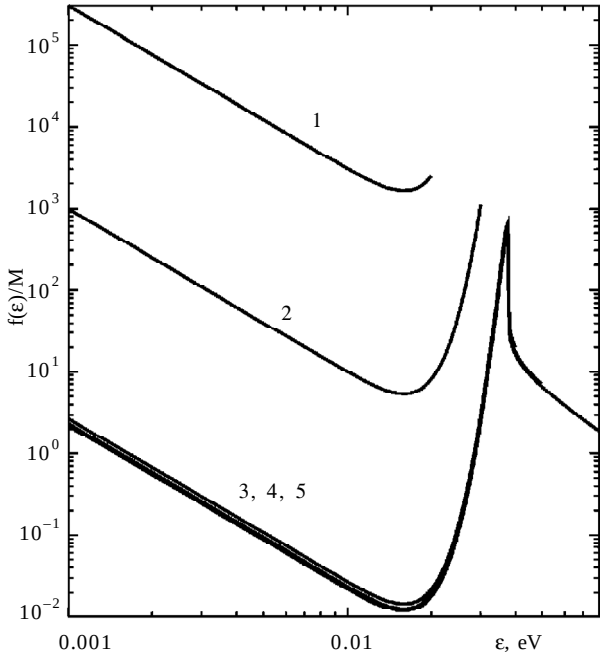

Fig. 3. Distribution function in the Pt-doped Ge samples at different values of N_{Pt} ($N_{Pt}=5\cdot10^{16}cm^{-3}$) at different ε_0 values.

1. - e_0=0,02 eV; 2. - e_0=0,03 eV; 3. - e_0=0,05 eV;
4. - e_0=0,08 eV; 5. - e_0=0,1 eV.

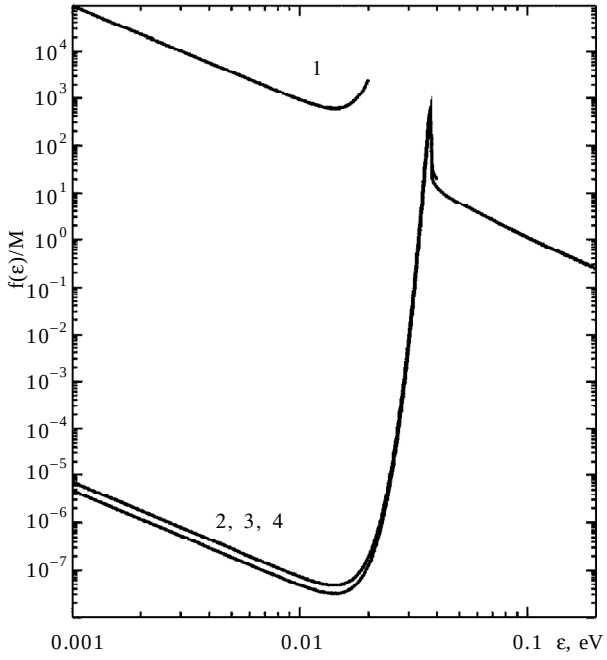

Fig. 4. Distribution function in the Pt-doped Ge samples at different values of N_{Pt}. ($N_{Pt}=5\cdot10^{17}cm^{-3}$) at different ε_0 values.

1. - e_0=0,02 eV; 2. - e_0=0,08 eV; 3. - e_0=0,1 eV;
4. - e_0=0,15 eV.

The work has been supported by the Georgia National Science Foundation (Grant № GNSF/ST06/4-014).

ფიზიკა

უარყოფითად დამუხტული მინარევული ცენტრების როლის გამოკვლევა ფოტოელექტრონების ინვერსიული განაწილების ფორმირებაში; კინეტიკის განტოლება და ინვერსიული განაწილების ფუნქციის ფორმირება

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

* *ი. ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი*

(წარმოდგენილია აკადემიკოს თ. სანაძის მიერ)

მოცემულ ნაშრომში ჩვენი გამოკვლევების მიზანს წარმოადგენდა ცხელი ფოტოელექტრონების ინვერსიული განაწილების ფორმირების პირობების დადგენა, როდესაც მათი სიცოცხლის ხანგრძლივობა კონტროლდება უარყოფითად დამუხტულ მინარევულ ცენტრებზე ჩაჭერით, ენერგიის რელაქსაციის სხვადასხვა მექანიზმებისას: როგორც კვაზიდრეკადი, ასევე ძლიერად არადრეკადი.

თეორიულმა გამოთვლებმა გვიჩვენეს, რომ Ge-ში მხოლოდ $Au^{\equiv}$ და $Pt^{\equiv}$ ცენტრებზე ჩაჭერისას შეიძლება ცხელი ფოტოელექტრონების სიცოცხლის დროის ვარირება ენერგიის ფართო დიაპაზონში. განაწილების ფუნქციის ინვერსიულობა Ge-ში $Pt^{\equiv}$-ის ($N_{Pt}>10^{16}$ სმ $^{-3}$-სას) განმზიდავ ცენტრებზე გაბნვისას შეიძლება დამზერილ იქნეს ენერგიის საკმაოდ ფართო არეებში. ხოლო $Au^{\equiv}$-სათვის, N-ის დასაშვებ მნიშვნელობებზე, ინვერსია იქნება სუსტი ენერგიის ვიწრო არეებში.

REFERENCES

1. *Yu.P. Ladyzhinski* (1969), FTT, **11,** 8: 2282.
2. *E.B. Goldgur, R.I. Rabinovich* (1984), FTT, **26**, 6: 1705.
3. *V.F. Gantmakher, I.B. Levinson* (1984), Current carrier scattering in metals and semiconductors. M. (in Russian).
4. *Z.S. Kachlishvili, N.M. Makharadze, F.G. Chumburidze* (1989), Soobshcheniya AN GSSR, **139** (in Russian).

Received December, 2008