ROLE OF FREE CARRIERS SCREENING IN SHALLOW IMPURITY ELECTRIC FIELD BREAK DOWN IN SEMICONDUCTORS

O.Z. ALEKPEROV

Institute of Physics of Academy of Sciences of Azerbaijan Republic
370143, Baku, G. Javid avenue, 33

Free carriers capture to screened Coulomb potential in semiconductors are considered. It is established that with the decrease of the screening radius the capture cross section decreases drastically, and it equals to zero when $r_s \leq a_B{}^*$. On the basis of obtained result a new mechanism of shallow impurity electric field break down in semiconductors is suggested.

For correct consideration of the kinetic, photoelectrical and optical phenomena in semiconductors and semiconductor structure it is necessary to take into account the carriers capture to an attractive centres. One of these centres in semiconductor is negatively or positively charged shallow acceptors or donors, the potential of which is considered usually as Coulomb one. The capture of carriers to Coulomb centre in semiconductors was first considered by Lax [1] and corrected in [2]. In [2] the capture theory was developed for small and large concentrations of impurities. In the first case the capture occurs to isolated centres. In the second case, which characterised by overlapping of the effective capture orbits $(r_T = e^2/\chi\ kT)$ of neighbouring centres, it was supposed that the capture takes place to the wells of the potential fluctuations of impurities. This gives an essentially week dependence for the capture cross section (CCS) on centres concentration $(\sigma \sim N_D^{1/6})$ than that for isolated centre $(\sigma \sim N_D)$. However, the potential of the charged impurity in real semiconductors may be considered as a purely Coulomb in the week doping case only ($N_D^{1/3}\ \overset{\bullet}{a}_B\ <<\ 1$, where N_D is the shallow impurities concentration, $\overset{\bullet}{a}_B$ is an effective Bohr radius). With the increase impurity concentration the potential of charged centre differs from Coulomb one and as a result of screening by free electrons and charged impurities it transforms into the Yukawa type potential.

In this work we will consider the capture process in the case of high free carriers concentration n, when Debye screening of a Coulomb centre takes place. Such a situation can be realised in semiconductors at some circumstances:

- in the case of high concentration of impurity and at relatively high temperatures when kT is comparable with the shallow impurity ionization energy ε_i when the most of shallow impurities are ionized $(n \sim N_D)$;

- in both cases of small and high concentrations of impurities and low temperatures $(kT << \varepsilon_i)$, if sufficiently strong electric field would be applied of semiconductor. As it is known [2,3] the CCS would decrease under the electric field and as a result free electron concentration would increase [4]. As it will be shown in the case of strong free electron screening the CCS goes to zero.

We consider the capture of free carriers to potential of the form

$$U = -(e/\chi r)\exp(-r/r_s). \tag{1}$$

In (1) r_s is the Debye screening radius and it must be chosen as $r_s = \chi E_F/(6\pi n e^2)$ in degenerate case and as $r_s = r_s = \sqrt{\chi kT\ /\ (4\pi n e^2)}$ in the nondegenerate case, where $E_F = h^2 k_F^2/2m^*$, $k_F = (4\pi n^2)^{1/3}$, χ is dielectric constant and n is the free carrier concentration.

Similarly to Coulomb potential case the effective capture radius is determined from the equation

$$E = (e^2/\chi r)\exp(-r/r_s) \tag{2}$$

where E is the total energy of carrier.

To calculate the CCS we use the following expression [2]:

$$\sigma = (\pi h)^2/(2kTm^*)\left[\int_{-\infty}^{0}\exp(E/kTB^{-1}(E)\,dE\right]^{-1} \tag{3}$$

where

$$B(E) = \int \varepsilon\tau^{-1}(\varepsilon)\rho(\varepsilon)\delta[E - \varepsilon - U(r)]d\varepsilon d^3r \tag{4}$$

$$\rho(\varepsilon) = 8\sqrt{2}\pi(2\pi h)^{-3} m^{*3/2}\varepsilon^{1/2},\ \tau(\varepsilon) = 1_0\cdot(m^*/2\varepsilon)^{1/2},\ 1_0 = (\pi h^4\rho_0)/(2m^{*3}E_c^2) \tag{5}$$

E_c is the deformation potential constant, ρ is the crystal density, m^* is the carrier effective mass.

For $B(E)$ in this case we have:

$$B(E) = 8m^*/(\pi 1_0 h^3)\bullet r_S^3 E^2/6\bullet J(x\ ) \tag{6}$$

$$J(x) = 2x^3 + 12x(1 + x - e^{-x}) + 3x^2(e^{-x} - 1)e^x \tag{7}$$

where $x = r_1/r_s$, r_1 is the root of equation (2) for a given screening length r_s.

Substituting (6) and (7) into (3) we obtained an expression for CCS

$$\sigma_0/\sigma = 2/(kT)^2 \bullet (e^2/\chi r_s)^3 \int_0^{\infty} \exp(-E/kT)/(E^2 J(x)) \bullet dE \quad , \tag{8}$$

where $\sigma_0=(4\pi/3l_0)\bullet(e^2/\chi kT)$ is the CCS in the Coulomb potential case.

The results of numerical calculation at $T=4.2$ K for GaAs (curve 1) and Ge (curve 2) with parameters $m^*=0.067m_0$, $\chi=12,5$ and $m^*=0,082\ m_0$, $\chi=16$, correspondingly, are shown in Fig.1.

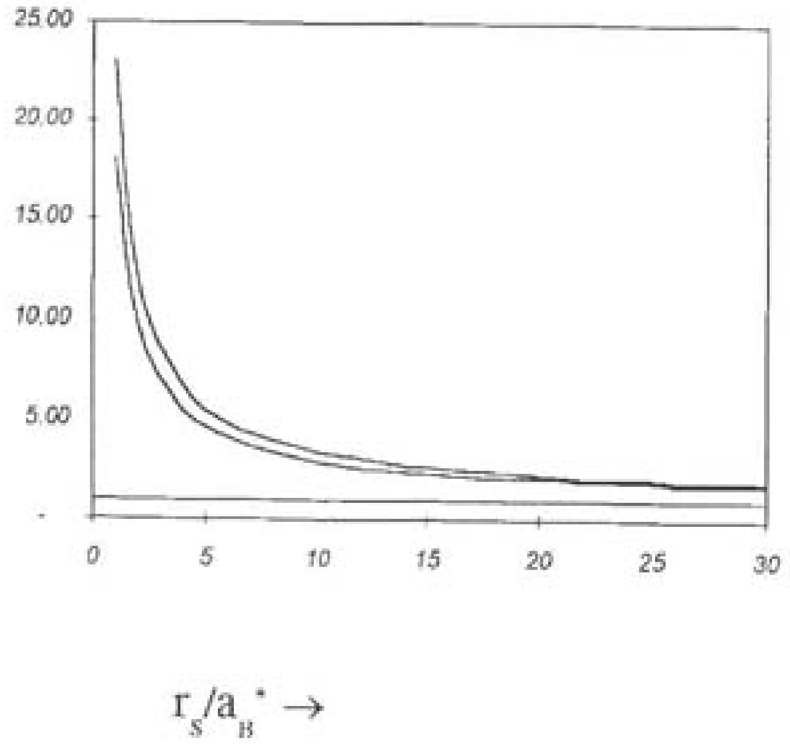

Fig.1. Dependence of σ_0/σ on screening radius r_S/a_B^*:
1 - for GaAs; 2 - for Ge; 3 - Coulomb potential case.

It is easy to show that when $r_s\rightarrow\infty$ for CCS from (8) the Coulomb potential case may be obtained. Note, that the screened potential (1) in contrast to Coulomb one has finite number of bound states and when $r_s \le a_{B^*}$ has no any bound states at all -they pass into the continuous bands [5,6]. It is obvious that in the absence of bound states CCS must be equal to zero for such centre. But, as it is seen from Fig.1, when $r_s \le a_{B^*}$ the CCS in comparison with Coulomb potential case decrease no more than 20 and 25 times for Ge and GaAs correspondingly. This means that the diffusive method used for CCS calculation in [2] and in this work becomes inapplicable at small screening lengths, when the number of discrete states are small. In this case the capture process can not be considered as a diffusive lowering of carriers through energetic states of impurity. Note, that owing to this the values of σ/σ_0 would be higher than those presented by curves 2 and 3 not only for $r_s \le a_{B^*}$.

Thus, we obtain the simple result -the more the screening the less is the capture coefficient, and when $r_s \le a_{B^*}$ it equals to zero. It is obviouse that the analogous result must be obtained for the coefficient of thermic ionisation from impurity states, because of lowering of ionisation energy ε_1 from them, when screening is strong (ionisation probability $w_1 \sim \exp(-\varepsilon_1/kT)$). Now we will consider some consequences of obtained result.

We will discuss the low temperature shallow impurity electric field breakdown (LTSIEFB) phenomenon in semiconductors. From the first observations of LTSIEFB [7] up to now [8], it is believed that this phenomenon is only due to impact ionisation of neutral impurities by free electrons as a result of theirs heating under an external electric field. Our result allows to put forward an alternative mechanism for LTSIEFB, which explains all peculiarities of CVC of semiconductor, including "candle"-like increase of current, and "S"-like form of CVC at breakdown electric field. According to this mechanism with the increase of electric field the concentration of free carriers n will increase, because of decrease of capture coefficient α and increase of ionisation coefficient β. The value of n in electric field would be established by balance condition between capture and thermic ionization - $n\alpha N_D^+ = \beta N_D^0$ (N_D^0-neutral and $N_D^+ = N_A + n$ charged donor concentrations)

$$n(E) = N_D^0(E)\ /\ N_D^+(E) \bullet \beta(E)\ /\ \alpha(E\ . \tag{9}$$

At some electric field, which is very close to the breakdown one, the value of n would be so much that the screening of charged impurities will take place. From this moment an avalanche increase of free carrier concentration will begin, owing to their screening influence on CCS decrease, and as a result of this further increase of $n(E)$, and so on. Thus $n(E)$, and as well as

$$j(E)=en(E)\mu(E)E \tag{10}$$

- dependences will have "candle"-like increase with electric field. Note, that LTSIEFB takes place at low temperatures when the dominant scattering mechanism of carriers are charged impurities. This means that owing to the screening of charged impurities potentials the mobility of carriers $\mu(E)$ at the breakdown electric field will increase, and as a result of this CVC would have "S"-like character. Screening induced $\mu(E)$ increase causes an additional (besides of $n(E)$) current increase in candle-like region of CVC. Note, that it was already established from cyclotron resonance line shape investigations of n-GaAs that free carriers screening of charged impurities is strong at the breakdown electric fields [9,10]. For LTSIEFB there is no need in condition $r_s = a_B^*$, when total screening of impurity states occurs. First of all such a condition means all neutral shallow impurities to be ionised in semiconductor. But as it was shown from Hall measurements [11] at breakdown electric field in n-Ge only 5%, and from plasma shift of cyclotron resonance line in n-GaAs [12] at electric fields 3-times greater than breakdown one only about 40% of neutral impurities were ionised. On the other hand the condition $r_s = a_B^*$ corresponds also to Mott transition which occurs at sufficiently high impurity concentration- $N_D^{1/3} a_B^* \approx 0.25$ and in this case all impurity electrons are in conduction band [13]. Hence LTSIEFB must disappear at very high concentrations of impurities. Note, that according to screening mechanism of LTSIEFB it must disappear in the low impurity concentration case also, which can be determined from the condition $r_s = r_T = e^2/\chi kT$. So that according to supposed mechanism LTSIEFB takes place only at neutral impurity concentrations $(kT/e^2)^3 \cdot 1/4\pi < N_D^0 < (0.25/a_B^*)^3$. For n-GaAs this condition requires $5\cdot10^{11}\,cm^{-3} < N_D^0 < 2\cdot10^{16}\,cm^{-3}$. In the next work I will give an experimental evidence which contradicts to impact ionisation model and confirms the above given mechanism of LTSIEFB in n-GaAs. The equality of CCS to zero when $r_s \le a_B^*$ may be considered as one of the Mott transition reasons in semiconductors.

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O.Z. Ələkbərov

DAYAZ AŞQARLARIN ELEKTRİK SAHƏSİNDƏ BOŞALMASINDA SƏRBƏST YÜKDAŞIYICILARIN EKRANLAŞDIRMASININ ROLU

Yarımkeçiricilərdə sərbəst yükdaşıyıcıların ekranlaşmış kulon mərkəzində tutulması araşdırılır. Tutulmanın en kəsiyi ekran-laşma radiusunun azalması nəticəsində kəskin surətdə kiçilir və $r_s=a_B^*$ qiymətində sıfra bərabər olur. Alınmış nəticə əsasında yarımkeçiricilərdə dayaz aşqarların elektrik sahəsində boşalmasının yeni mexanizmi verilir.

О.З. Алекперов

РОЛЬ ЭКРАНИРОВАНИЯ СВОБОДНЫМИ НОСИТЕЛЯМИ ПРИ ЭЛЕКТРИЧЕСКОМ ПРОБОЕ МЕЛКИХ ПРИМЕСЕЙ В ПОЛУПРОВОДНИКАХ

Исследуется захват свободных носителей на экранированный Кулоновский центр в полупроводниках. Показано, что сечение захвата существенно уменьшается с уменьшением радиуса экранировки и равно нулю когда $r_s=a_B^*$.

На основе полученных результатов предлагается новый механизм электрического пробоя мелких примесей в полупроводниках.

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