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Auger Recombination in Semiconductors

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ABSTRACT: The Auger recombinations occurring in semiconductors have been studied in this work. The theoretical and analytical data of Auger recombination processes in semiconductors with straight and complex bands are highlighted. The relationship between the rate of recombination and the structure of the bands of semiconductors has been studied. Expressions of the laws of conservation of energy and momenta are given for the processes of recombination of semiconductors with straight bands.

KEYWORDS: silicon, recombination, energy, momentum, impurity, semiconductor, lifetime, electron, hole, concentration

INTRODUCTION

The study of recombination processes is important for understanding the processes occurring in semiconductors and semiconductor devices. To date, three types of recombination have been widely studied [1-6]. These are radiative recombination, Auger recombination or impact recombination and Shockley-Reed-Hall recombination through deep surfaces.

Radiative recombination is the process of annihilation of an electron-hole pair, in which the released energy is emitted in the form of a photon.

Auger or shock recombination is a three-particle process in which the energy released during the annihilation of an electron-hole pair is transferred to a third particle.

In Shockley-Reed-Hall recombination, the processes of recombination in semiconductors occur through impurity centers.

The main mechanisms of Auger recombination are considered in this work [6]. On the basis of the Beatty-Landsberg-Blackmore model, the author investigated the dependence of the rate and lifetime of generation-recombination on the composition and temperature of the HgCdTe material of the n- and p- types.

In this work [7], we calculated the dependence of the concentration of charge carriers participating in radiative recombination on the pump intensity.

In the work of the author [8], the dependence of the recombination processes occurring in semiconductors on the structure of the semiconductor bands has been studied. The advantages of using indirect zonal semiconductors in the creation of solar cells are substantiated.

This article presents theoretical and analytical data on Auger recombination processes in semiconductors and the conclusions that follow from them.

Auger recombination in n-type semiconductors involves two electrons and one hole, while p-type semiconductors involve two holes and one electron. The Auger recombination rate is equal to

$$r_n = c_n n^2 p, \quad r_p = c_p p^2 n \qquad (1)$$

This expression shows that the recombination rate depends on the concentration of electrons and holes. Along with this, the rate of recombination in semiconductors also depends on the structure of the semiconductor bands.

Let us first consider the recombination processes occurring in direct-gap semiconductors (Figure 1a).

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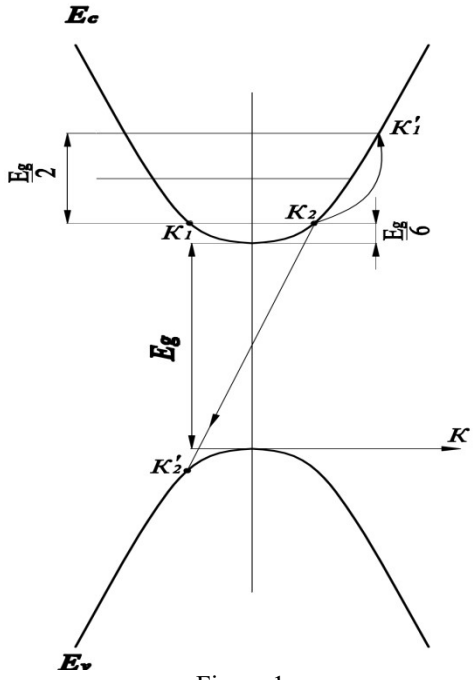

Figure 1a

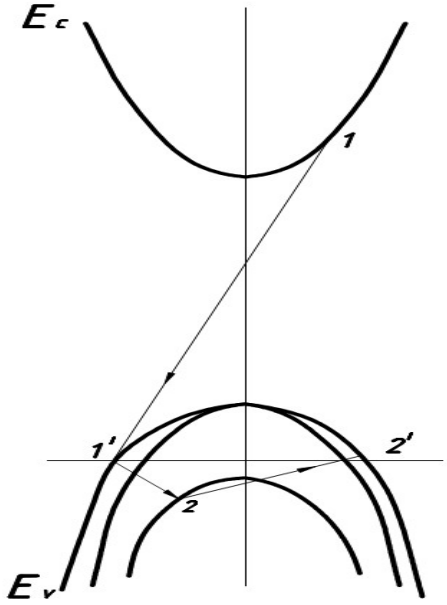

Figure 1b

Auger recombination processes in direct-gap semiconductors

It is known that the laws of conservation of energy and momentum are valid for all processes occurring in semiconductors. The laws of conservation of energy and momentum for this process are as follows.

The electron $\vec{k}_2$, giving its energy to a neighboring electron, recombines ($k_2^{`}$) with a hole in the valence band.

Before the recombination process, the electron energy has the following form:

$$E_c(k_1) = E_g + \frac{\hbar^2 k_1^2}{2m_n},\ E_c(k_2) = E_g + \frac{\hbar^2 k_2^2}{2m_n} \qquad (2)$$

After the recombination process, the electron energy looks like this:

$$E_c(k_1^{`}) = E_g + \frac{\hbar^2 k_1^{`2}}{2m_n},\quad E_V(k_2^{`}) = -\frac{\hbar^2 k_2^{`2}}{2m_p} \qquad (3)$$

In this case, the law of conservation of energy is written as follows:

$$2E_g + \frac{\hbar^2 k_1^2}{2m_n} + \frac{\hbar^2 k_2^2}{2m_n} = E_g + \frac{\hbar^2 k_1^{`2}}{2m_n} - \frac{\hbar^2 k_2^{`2}}{2m_p} \qquad (4)$$

The momentum conservation law is written as follows:

$$k_1 + k_2 = k_1^{`} + k_2^{`} \qquad (5)$$

The probability of the presence of electrons in the conduction band at k_1

$$f(E_c(k_1)) = \frac{n}{N_c} e^{-\frac{\hbar^2 k_1^2}{2m_n k_0 T}}$$

$$f\left(E_V(k_2^{`})\right) = \frac{p}{N_V} e^{-\frac{\hbar^2 k_2^{`2}}{2m_p k_0 T}}$$

Using these expressions, we get the following

$$f(E_c(k_1)\, f(E_c(k_2)) \cdot (1 - f\left(E_V(k_2^{`})\right) = \frac{n^2 p}{N_c^2 N_V} exp\left\{-\left[\frac{\hbar^2(k_1^2+k_2^2)}{2m_n} + \frac{\hbar^2 k_2^{`2}}{2m_p}\right]/k_0 T\right\} \qquad (6)$$

If $m_n = m_p$ and $k_2^{`} || (k_1 + k_2)$, $k_2^{`} = \frac{k_1 k_2 - \frac{E_g m_n}{\hbar^2}}{|k_1+k_2|^2}(k_1^2 - k_2^2)$ according to the relation (6) auger recombination rate occurs with the highest probability.

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$k_1 = k_2 = k_0$, $|k_0| = \frac{1}{3}(\frac{E_g m_n}{\hbar^2})^{1/2}$ is the condition for maximizing the expression (6). Applying these relations, expression (6) can be written as follows.

$$f(E_c(k_1)\, f(E_c(k_2)) \cdot (1 - f\left(E_V(k_2^{`})\right) = \frac{n^2 p}{N_c N_V} \exp\left(-\frac{E_g}{2k_0 T}\right) \qquad (7)$$

In this case, electrons located above $E_g/2$ take part in the recombination.

If $m_n \neq m_{p,}\ E(k_1) = E(k_2) > E_{co}$, then

$E_1 = E_2 = E_{co} + \frac{E_g \theta^2}{(1+3\theta+2\theta^2)}$, while $\theta = \frac{m_n}{m_p}$, in this situation $E_{VO} - E_2^{`} = \frac{E_g \theta}{1+3\theta+2\theta^2}$ electrons located above $E_g/6$ take part in the recombination.

If $m_n = m_p$; then $E_1 = E_2 = E_C + \frac{E_g}{6}$, at $m_n \ll m_p$ becomes $E_1 = E_2 = E_{CO}$. П In this state, the electrons of the upper valence band and the lower conduction band participate in Auger recombination. In the position of thermodynamic equilibrium, 2 electrons and 1 hole take part in Auger recombination. The recombination rate is then expressed as

$$r = \frac{8\pi^2 \beta e^4 \hbar^2 |I_1 I_2|^2 \theta^{3/2} n^2 p \exp\left(-E_g \theta/(1+\theta) k_0 T\right.}{(4\pi\varepsilon)^2 m_n^2 (k_0 T)^2 E_g (1+\theta)\sqrt{2(1+2\theta)}} \qquad (8)$$

Here $I_1 = \int u_C^*(k_1 r) u_V(k_1^{`} r) d^3 r$

$I_2 = \int u_V^*(k_2 r) u_C(k_2 r) d^3 r$ Bloch function integral.

Evaluating the expression (8), if $\beta = 3, \theta = 1, |I_1 \cdot I_2| \approx 10^{-2}$, the recombination coefficient is $c_n = 10^{-28}\left(\frac{10}{\varepsilon}\right)\left(\frac{m_o}{m_n}\right)^2\left(\frac{1\,eV}{E_g}\right)\left(\frac{300}{T}\right) e^{-\frac{E_g}{2k_0 T}}$.

For *InSb* at $E_g = 0{,}3eV, m_n = m_p$, and $n = 10^{15}\ cm$, $c_n = 10^{-30}\ cm/sec$. The lifetime of charge carriers is

$$\tau = \left(\frac{E_g}{k_0 T}\right) exp\left(\frac{(1+2\theta)E_g}{(1+\theta)k_0 T}\right).$$

Let us now consider the Auger recombination process in complex-gap semiconductors. It is known that semiconductors Si, Ge, AsGa belong to complex-gap semiconductors, since their valence bands consist of three networks (Fig.2).

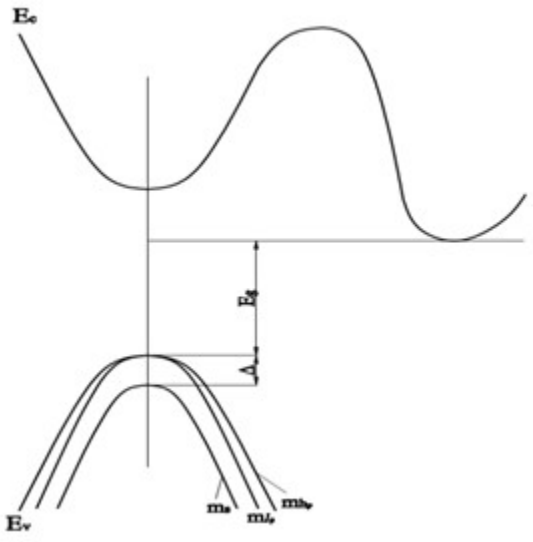

Figure 2

Auger recombination in complex-gap subconductors

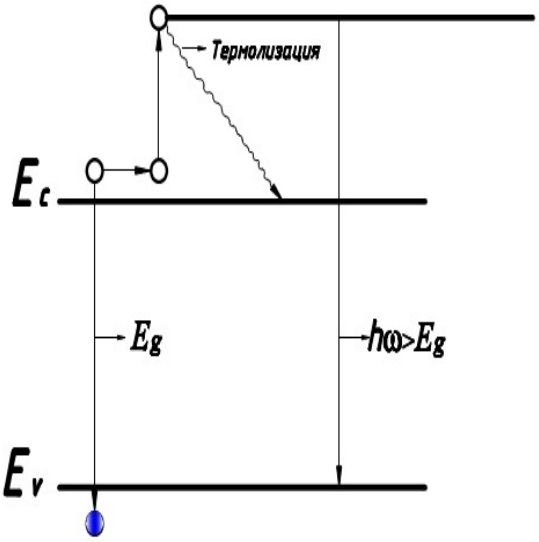

Figure 3

One kind of Auger recombination

In this case, the recombination processes depend on the ratio of the distance Δ to the band gap of the semiconductor E_g and the networks of the valence band.

If $\Delta > E_g$, mutual optical conductivity between electron networks makes almost no contribution to Auger recombination. At $\Delta = E_g$, the conduction of electrons between networks makes a large contribution to Auger recombination.

In direct-gap semiconductors Auger recombination occurs as follows (Fig.1b). The first electron recombines with the 1^ ` hole, the 1^` hole transfers its excess energy to the 2nd hole and it can go into the 2^ ` state. In this case, the required minimum energy is

$$E_{min} = \frac{2m_{np}+m_n^*}{2m_{hp}+m_n^*-m_s}(E_g - \Delta) \qquad (9)$$

Due to the value of the variable $E_g - \Delta$ the energy of activation of Auger recombination will be in the interval $0 < E \leq \frac{E_g}{2}$.

Conclusion

Thus, the following physical phenomena were observed in Auger recombination.

1. In the Auger recombination process, with an increase in the concentration of the majority charge carriers, the lifetime of the minority carriers decreases. In the expression $\tau_p = \frac{1}{n}$, $\tau_n = \frac{1}{p}$ for *Ge* in the type of n at $n = 10^{17} cm^{-3}$, $equal\ to\ \tau_n = 50 - 60\ mks., \tau_p = 1\ mks.$.
2. $\tau \sim \frac{1}{T}$, – that is, with an increase in temperature, the lifetime of charge carriers decreases.
3. With the introduction of impurities into semiconductor materials, the recombination rate increases sharply, that is r = $\frac{\Delta n}{\tau_n}$,
4. With a decrease in the concentration of charge carriers in any way, the rate of radiative recombination decreases, which shows a decrease in the radiation intensity $r_{излуч} = \gamma_n np$. With a decrease in concentration, a decrease in radiation intensity is called a luminescence-concentration decrease. As the temperature rises, the kinetic energy of the electrons increases, and the probability of Auger recombination increases.
5. In semiconductors with indirect bands, the recombination rate is relatively lower than direct band semiconductors.
6. An electron that has entered into recombination with a hole transfers its excess energy to a neighboring electron. Electrons that have received excess energy are called hot electrons and they transfer their energy to the crystal lattice in a short time, this phenomenon is called thermolization (Fig. 3) for $2E_g > h\omega_{нур} \geq E_g$, $h\omega_{нур} \approx 2E_g$ (Ge).

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