

Recombination of Charge Carriers in Semiconductors and its Effect on Lifetime

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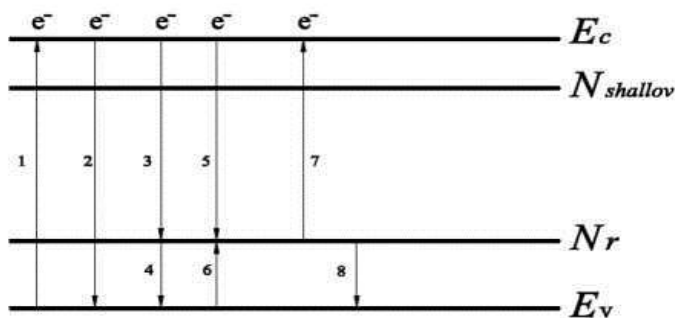
Abstract: This work has researched the recombination processes that occur in semiconductors and its effect on the lifetime of charge carriers. It has been shown that the rate of recombination under external influence depends on the concentration of non-balanced charge carriers. It has been argued that the recombination rate of interbranch radiation is greater in straight-zone semiconductors than in faulty-zone semiconductors, and that the lifetime of electrons and cavities is much larger in straight-zone semiconductors than in straight-zone semiconductors. The reasons why the lifetime of non-primary charge carriers increases with increasing temperature are explained.

Keywords: silicon, generation, recombination, carrier, trap, lifetime, semiconductor.

Introduction. Three types of recombination have been extensively studied in scientific publications [1-6]. There are three types of recombination by type of electronic transitions:

1. Interregional recombination.
2. Recombination through local centers.
3. Surface recombination.

In inter-zonal recombination, the transition from the electron conduction zone to the valence band loses energy equal to or greater than the band gap of the semiconductor (Figure 1, transition 2).



The transitions 1, 7, and 8 in the figure define the generation process, in which electrons pass from the valence band or through the energy levels generated by the inert atoms into the fission zone. Transitions 2, 3, and 6 define the recombination process, in which electrons pass from the conduction band to the valence band by releasing their energy.

Figure 1. Generation and recombination processes that can occur through local centers in silicon

In recombination, which occurs through local centers, the electron is captured by local centers before falling into the valence band, which is then recombined with a cavity in the valence band (Figures 3 and 4 transitions).

In recombination, which occurs through local centers, the energy levels generated by the kirindi atoms in the forbidden zone of the semiconductor play a role as recombination centers. The inclusion of deep-stage impurities (Au, Ni, Co, Pt, Ir, Rh, Cu) in semiconductor materials leads to a change in the concentration of charge carriers, which in turn leads to a change in the recombination rate [5,6]. Shallow surfaces in silicon do not affect the recombination process. Because such centers are in a fully ionized state.

Surface recombination is associated with technological processes, and this type of recombination often plays a crucial role in semiconductor devices. The surface of the semiconductor and the areas of the semiconductor in contact with other materials form a large number of recombination centers, as a break occurs at the boundary and between the atoms on the crystal surface and adjacent atoms.

Depending on the type of energy separation in the recombination process, recombination is divided into two types:

- 1) Radiation recombination.
- 2) Non-radiation recombination.

Radiation recombination is the process of annihilation of this electron-cavity pair, in which the released energy is irradiated in the form of photons.

In non-radiation recombination, the excess energy of the electrons is transferred to the crystal lattice or other particle.

[9] have studied the recombination processes that occur in induced semiconductors. By introducing an input into a semiconductor, its sensitivity to light can be increased or vice versa. This is due to the nature of the energy levels formed by the kirindi atoms in silicon. Second, the photosensitivity of semiconductor photocells is explained by the rate of recombination, which in turn depends on the concentration of non-balanced charge carriers and the lifetime of the charge carriers.

[10] studied the dependence of the rate of interbranch recombination on the structure of semiconductor zones. The feasibility of using faulty zonal semiconductors to make solar cells with high light sensitivity based on semiconductor materials has been justified.

Brief analysis shows that the recombination processes occurring in semiconductors have not been sufficiently studied for their effect on the life of charge carriers.

Main part. The study of the phenomenon of recombination in semiconductors and its effect on life time is important for understanding the processes occurring in semiconductor devices and improving their physical characteristics. For example, the photosensitivity of semiconductor-based solar cells depends on the recombination rate. The rate of recombination depends on the concentration of non-balanced electrons and cavities, respectively.

In general, the concentration of non-balanced charge carriers is written as follows

$$\frac{\Delta n}{\Delta t} + diVj_n = G_n - R_n$$

$$\frac{\Delta p}{\Delta t} + diVj_p = G_p - R_p \tag{1}$$

here, Δn - and Δp - concentration of non-balanced charge carriers, j_n and j_p - current density, G_n and G_p - charge carrier generation rate, R_n and R_p - charge carrier recombination rate.

Recombination rate of charge carriers equals to $R_n = \frac{\Delta n}{\tau_n}$, $R_p = \frac{\Delta p}{\tau_p}$. In this case τ_n and τ_p are the lifetime of electrons and cavities.

When the recombination and generation of charge carriers are equal ($\Delta n = \Delta p$), the lifetime of non-balanced charge carriers can be written as $\tau = \tau_n = \tau_p$.

In this case, equation (1) generally takes the form $\frac{\Delta n}{\Delta t} = G_n - \frac{\Delta n}{\tau}$. It appears that the lifetime of non-balanced charge carriers depends on the concentration of non-balanced charge carriers.

In the process of recombination, the process of recombination varies depending on the release of energy relative to the initial and final energy state of the electron.

In "zone-by-zone" recombination, the electron passes directly from the conduction band to the valence band.

Under the influence of light, the electron passes from the valence band to the conduction band. In the process of recombination, the electron passes from the conduction band to the valence band due to the release of the received energy (Figure 2).

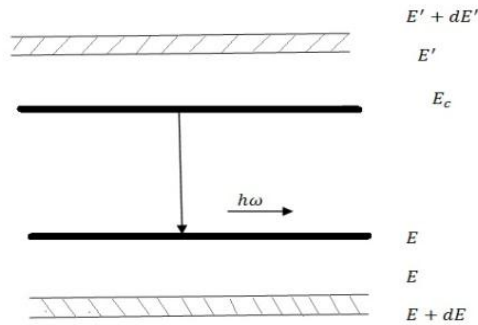


Figure 2. Occurring in semiconductors recombination phenomenon

The number of electrons in the conduction band with energy E^1 to $E^1 + dE^1$ is expressed as $N_c(E)f(E^1)dE^1$. For the valence band, this expression appears as $N_v(E)f(E)dE$. The more electrons in the conduction band and the more holes in the valence band, the greater the number of recombination and is expressed as follows,

$$dr = W(E^1, E)N_c(E)N_v(E)f(E^1)f(E)dEdE^1 \quad (2)$$

Fermi function of non-balanced charge carriers formed in semiconductors under external influence

$$f(E^1) = \left[\exp\left(\frac{F_n - E^1}{kT}\right) + 1 \right]^{-1}, \quad f(E) = \left[\exp\left(\frac{E - F_p}{kT}\right) + 1 \right]^{-1},$$

$$n = n + \Delta n = N_c \exp\left(\frac{F_n - E_c}{kT}\right), \quad p = p_o + \Delta p = N_v \exp\left(\frac{E_v - F_p}{kT}\right),$$

$$n \cdot p = n_o p_o \exp\left(\frac{F_n - F_p}{kT}\right) = n_i^2 \exp\left(\frac{F_n - F_p}{kT}\right)$$

$$\text{in that case, } f(E^1)f(E) = \frac{n \cdot p}{N_v \cdot N_c} e^{-\frac{E^1 - E_c}{kT}} e^{-\frac{E_v - E}{kT}}$$

(2) integrating the equation:

$$r = \int dr = \iint W(E, E^1)N_c(E^1)N_v(E)f(E^1)f(E)dEdE^1$$

this expression provides complete recombination. $r_F = \gamma \cdot n \cdot p$ (3). Here γ - recombination

coefficient

$$\gamma = \frac{1}{N_c N_v} \int_{E^I=E_c}^{+\infty} \int_{E=-\infty}^{E_v} W(E^I, E) N_c(E^I) N_v(E) e^{-\frac{E^I-E_c}{kT}} e^{-\frac{E_v-E}{kT}} dE dE^I$$

$$r_o = \gamma_r n_o p_o \tag{4}$$

recombination in the dark in the absence of external influences.

The recombination rate observed only under external influence is obtained by subtracting from (3) to (4).

$$\begin{aligned} r &= r_F - r_o = \gamma_r [(n_o + \Delta n)(p_o + \Delta p) - n_o p_o] = \\ &= \gamma_r [n_o p_o + n_o \Delta p + p_o \Delta n + \Delta n \Delta p - n_o p_o] = \gamma_r (\Delta n p_o + \Delta p n_o + \Delta n \Delta p) \end{aligned} \tag{5}$$

Hence, the rate of recombination that occurs under external influence depends on the concentration of non-balanced charge carriers. To reduce the rate of volumetric recombination in semiconductor materials, it is necessary to protect it from radiation or reduce its sensitivity to radiation.

Recombination affects the lifespan of charge carriers. Let us first consider the recombination processes that take place through local centers. It is known that the recombination rate of inter-zonal radiation is greater in straight-zone semiconductors than in faulty-zone semiconductors. The lifetime of electrons and cavities is much longer in faulty zonal semiconductors. E.g. for Si $\tau = 3$ sec., For Ge equals to $\tau = 0,43$ sec. The lifetime of the charge carriers changes several times when silicon-deep inclusions are introduced. E.g. Si and Ge to Ni, Au such as deep surface-forming inclusions $N = 10^{15} \text{ cm}^{-3}$ residence time when the amount is entered from 10^{-3} decreases to $10^{-8}-10^{-9}$ sec.

Average residence times in the conduction band of electrons and in the valence band of cavities

$$\tau_n = \gamma_n (N_r - n_r) \cdot n, \tau_p = \frac{1}{\gamma_p \cdot n_r} \tag{6}$$

here, n_r - the concentration of centers occupied by electrons. Coefficients of capture of electrons and cavities by the holding center is represented by holding cuts γ_n and γ_p :

$$\gamma_n = S_n \vartheta, \gamma_p = S_p \vartheta \tag{7}$$

The typical magnitudes of the charge-carrying sections of the atoms of germanium and silicon compounds are given in Table 1 (all data are given in 10^{-16} cm^2 units).

As can be seen from the table, the inputs shown are multi-charged, and their levels change with the change in charge state when shallow inputs are introduced. In this case, the holding of the charge carrier of the center of gravity reaches to cut 10^{-12} cm^2 , the neutral center is around 10^{-16} cm^2 , and the center of repulsion is $10^{-18} - 10^{-20} \text{ cm}^2$.

Table 1. Charge holding sections of germanium and silicon incorporated surfaces.

Introductions	For German	Cuts	
Au	$S_n^1 = 1$	$S_n^- = 2$	$S_p^- = 100$
Cu	$S_n^- = 0,5$	$S_n^- = 0,36$	$S_p^- = 0,04$
Zn	$S_n^- = 3 \cdot 10^{-5}$		
Ni	$S_n^0 = 1$	$S_n^- = 6$	$S_p^- = 100$

Fe	$S_n^0 = 10$	$S_p^- = 30$	$S_p^- = 100$
Co	$S_n^0 = 10$		$S_p^- = 100$
Ag	$S_n^0 = 0,6$	$S_n^- = 1$	$S_p^- = 50$
	For silicon		
Au	$S_n^+ = 30$	$S_n^0 = 5$	$S_p^0 = 20$
Fe	$S_n^+ \geq 10$	$S_p^0 = 3$	

The release of electrons due to thermal motion (Fig. 1, transition 7) is the reverse process of the capture of charge carriers by the handles. The distribution of the energies of the charge carriers in the unbalanced state in both dark and light in the absence of nausea in the zones does not differ from the distribution in the equilibrium state. Therefore, recombination quantities are the same for charge carriers in the unbalanced state and in the equilibrium state.

The lifetime of electron cavity pairs in the process of irradiated recombination can be calculated. As known, the recombination coefficient γ_r can be expressed in the following form using the recombination effective section S_{eff} .

$$\gamma_r = S_{eff} \bar{v} \tag{8}$$

Here \bar{v} is the average heat rate of electrons. Living time of couples in an unbalanced state

$$\tau = \frac{\Delta n}{r_n} = \frac{\Delta n}{\gamma_r(np - n_0p_0)} = \frac{1}{\gamma_r(n_0 + p_0 + \Delta n)} \tag{9}$$

Given that $n_0p_0 = n_i^2$ in equilibrium, we determine that the product obtained from expression (7) on n_0 or (p_0) is equal to zero, and that τ is maximal in a particular semiconductor when $n_0 = p_0$.

$$\tau_{max} = \tau_i = \frac{1}{2\gamma_r \cdot n_i} \tag{10}$$

For Germani T=300 K, $r_0 = 2,8 \cdot 10^{19} \text{ cm}^{-3} \cdot \text{sec}^{-1}$. From

$$\gamma_r = \frac{r_0}{n_i^2} = \frac{2,8 \cdot 10^{19}}{5,6 \cdot 10^{34}} = 0,5 \cdot 10^{-15} \frac{\text{cm}^3}{\text{sec}}$$

The average thermal velocity of electrons at T = 300 K is about $\bar{v} \cdot 10^7 \text{ cm} / \text{sec}$.

$S_{eff} = \frac{\gamma_r}{\bar{v}} = 10^{-21} \text{ cm}^2$. For Ge (10) maximum living time calculated from the formula

$$\tau_i = \frac{1}{2\gamma_r \cdot n_i} = 0,43 \text{ sec}.$$

The values calculated at room temperature for several specific semiconductors are given in Table 2.

Table-2

Semiconductor	T, K	R, $\text{cm}^{-3} \text{ sec}^{-1}$	n, cm^{-3}	γ , $\text{cm}^3 \text{ sec}^{-1}$	τ , sec.	S, cm^2
Diamond	295	$4,0 \cdot 10^{-66}$	$6,68 \cdot 10^{-28}$	$8,96 \cdot 10^{-12}$	$8,35 \cdot 10^{+37}$	$9,48 \cdot 10^{-19}$
Si	290	$9,2 \cdot 10^{+4}$	$7,16 \cdot 10^{+9}$	$1,88 \cdot 10^{-15}$	$1,48 \cdot 10^{+3}$	$1,87 \cdot 10^{-22}$
Ge	300	$2,85 \cdot 10^{+13}$	$2,33 \cdot 10^{+13}$	$5,25 \cdot 10^{-14}$	$4,09 \cdot 10^{-1}$	$5,5 \cdot 10^{-21}$

Te	300	$3,0 \cdot 10^{+20}$	$5,93 \cdot 10^{+15}$	$8,53 \cdot 10^{-12}$	$9,88 \cdot 10^{-6}$	$8,95 \cdot 10^{-10}$
GaP	300	$4,0 \cdot 10^{-13}$	2,73	$5,37 \cdot 10^{-14}$	$3,41 \cdot 10^{-12}$	$5,63 \cdot 10^{-21}$
GaAs	294	$1,2 \cdot 10^{+3}$	$1,29 \cdot 10^{+6}$	$7,21 \cdot 10^{-10}$	$5,37 \cdot 10^{+2}$	$7,64 \cdot 10^{-17}$
GaSb	300	$2,2 \cdot 10^{+14}$	$9,6 \cdot 10^{+11}$	$2,39 \cdot 10^{-10}$	$2,58 \cdot 10^{-3}$	$2,51 \cdot 10^{-17}$
InP	298	$6,0 \cdot 10^{+6}$	$6,9 \cdot 10^{+4}$	$1,26 \cdot 10^{-9}$	$5,75 \cdot 10^{+1}$	$1,33 \cdot 10^{-16}$
InAs	298	$5,8 \cdot 10^{+19}$	$8,26 \cdot 10^{+14}$	$8,5 \cdot 10^{-11}$	$7,12 \cdot 10^{-6}$	$8,94 \cdot 10^{-18}$
InSb	295	$1,03 \cdot 10^{+22}$	$1,5 \cdot 10^{+16}$	$4,58 \cdot 10^{-11}$	$7,28 \cdot 10^{-7}$	$4,84 \cdot 10^{-18}$

As can be seen from the table, the g_r recombination coefficient for GaAs, GaSb, InP, InAs, and InSb compounds with a correct zonal structure is several times greater than for faulty zonal semiconductors. Calculations show that in semiconductors other than silicon, γ_r increases with decreasing temperature, which in turn leads to a decrease in lifetime.

The lifetime of non-primary charge carriers depends on temperature. This can be seen in the example of silicon with n-type conductivity, with a recombination handle lying in the upper area of the restricted zone. At very low temperatures, the recombination handles become filled with electrons. In this case, the first stage of recombination takes place quickly and the survival time is not large. As the temperature rises, the Fermi level shifts to the lower side, and the recombination handle moves closer to the energy level. It turns out that not all handles are filled with electrons, which means that not all handles can hold holes in a semiconductor. Therefore, the residence time increases with increasing temperature.

The allowable energy levels that are formed between the forbidden zone of silicon due to defects in the crystal composition are referred to as traps.

The lifetime of electrons is determined by the following formula

$$\tau_n = \frac{1}{\gamma N[1-K(E_i)]} \quad (11)$$

where, is the concentration of N-handles, $N[1 - K(E_i)]$ – concentration of empty handles, $K(E_i)$ - the probability that the electron is in the middle of the band gap.

It's also time to live for the pits

$$\tau_p = \frac{1}{\gamma NK(E_i)} \quad (12)$$

as long as it is in view.

Surface surfaces are also actively involved in recombination processes, affecting the lifetime of electrons and cavities. It should be noted that the experimental value of the residence time also depends on the surface treatment condition. To evaluate the surface recombination process, the surface recombination rate S is entered.

Consider a semiconductor with an E_s energy center in the forbidden zone (Figure 3). Let a flat Δn and Δp concentration of excess charge carriers be formed in the semiconductor throughout its entire volume. For charge carriers in the unbalanced state, the presence of recombination centers on the surface of the semiconductor results in a flow of electrons and

holes directed to the surface:

$$\frac{j_n}{e} = -S_n \Delta n, \frac{j_p}{e} = -S_p \Delta p \quad (13)$$

where S_n and S_p are the rates of recombination of electrons and cavities on the surface in the corresponding form.

In equilibrium, the total current directed to the surface is zero, which means that the currents of electrons and holes are equal to each other.

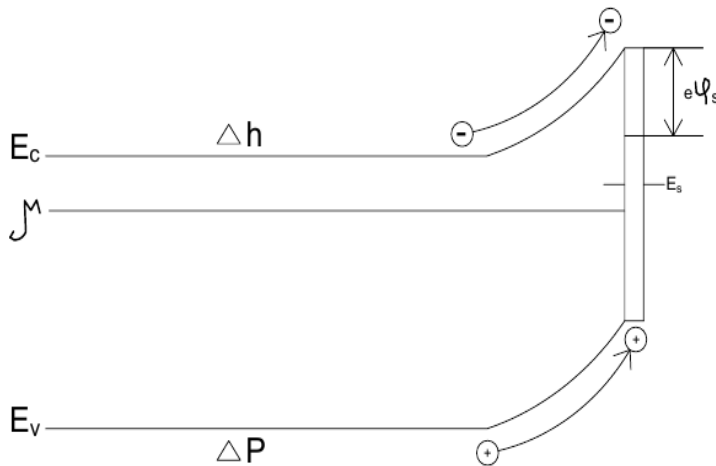


Figure 3. Recombination through surface conditions

The number of charge carriers recombination on a unit surface per unit time, i.e., the surface recombination rate

$$r_s = \frac{j_n}{e} = \frac{j_p}{e} = s_n \Delta n = s_p \Delta p \quad (14)$$

From this:

$$s_n = \frac{r_s}{\Delta n}, s_p = \frac{r_s}{\Delta p} \quad (15)$$

here s_n and s_p refers to the percentage of recombined carriers per unit time on the unit surface. if $\Delta n = \Delta p$, will be $s_n = s_p = s$. According to the diode theory of rectification of a semiconductor-metal contact, the current density of the pores directed to the surface

$$j_{p1} = \frac{1}{4} e \vartheta_{ps} p_s \quad (16)$$

ϑ_{ps} -average speed of cavities, p_s - volumetric concentration of pits. The R_s fraction of pores from the surface returns, and the flow of pores generated on the surface is also volume-oriented. Full density of surface-oriented pits:

$$j_{p2} = \frac{1}{4} e \vartheta_s p_s R_s \quad (17)$$

In equilibrium $j_{p1} = j_{p2} + j_{ps}$. From

$$\frac{1}{4} \vartheta_s p_{s0} = \frac{1}{4} \vartheta_s p_{s0} R_s + \frac{j_{ps}}{e} \quad (18)$$

$$\text{and the difference in currents } r_{s0} = \left(\frac{j_{ps}}{e}\right) = \frac{1}{4} \vartheta_s (1 - R_s) p_{s0} \quad (19)$$

(19) the expression is an expression of the surface recombination rate. (19) If we apply the expression to an unbalanced but stationary state:

$$r_s = \left(\frac{j_{ps}}{e}\right) = \frac{1}{4} \vartheta_s (1 - R_s) p_s \quad (20)$$

From expressions (19) and (20):

$$r = r_s - r_{s0} = \frac{1}{4} \vartheta_s (1 - R_s) \Delta p_s \quad (21)$$

$$\text{here } r = s \Delta p_s, s = \frac{1}{4} \vartheta_s (1 - R_s)$$

In the steady state, the surface recombination and generation rates are mutually equal. When

$R_s = 0$, will be $s = \frac{1}{4} \vartheta_s$. The surface recombination rate limits the rate at which charge carriers in the unbalanced state are delivered from the volume to the surface by diffusion. Depending on how the surface is treated, S will have a wide range of values. For Ge, Si, GaAs, etc., its maximum value is 10^5 cm / sec.

In general, surface recombination can occur through fast or slow cases. However, the relaxation time of slow cases is large, so in practice recombination goes through fast cases.

Using the above expressions, it is possible to draw the following conclusions about the causes affecting the life of non-balanced charge carriers.

Conclusion

- 1) The rate of recombination increases sharply when deep-layered incisions are introduced into silicon.
- 2) The residence time depends on the concentration of the handles. As the defects in the semiconductor crystal increase, the lifetime decreases.
- 3) As long as the residence time depends on the concentration of impurities.
- 4) The lifetime depends on the temperature, i.e., as the temperature increases, the lifetime of non-balanced charge carriers increases.
- 5) Calculations show that in semiconductors other than silicon, the recombination coefficient g_r increases with decreasing temperature, which in turn leads to a decrease in life.
- 6) The rate of recombination due to external influences depends on the concentration of non-balanced charge carriers.

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