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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. The reasons why the lifetime of non-primary charge carriers increases with increasing temperature are explained.*

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

1. 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:

- Interregional recombination.
- Recombination through local centers.
- 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).

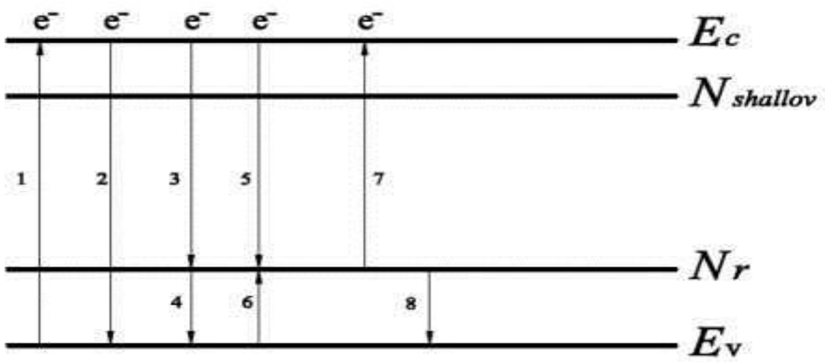

Figure 1. Generation and recombination processes that can occur through local centers in silicon

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.

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 shaved 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.

Alikulov M.N. in "The effect of recombination processes on the photosensitivity of semiconductor colar cells" [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 shaved 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.

Alikulov M.N. [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.

2. Materials and methods. 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

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

$$\frac{\Delta p}{\Delta t} + diVj_p = G_p - R_p \quad (1)$$

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.

3. Results. 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).

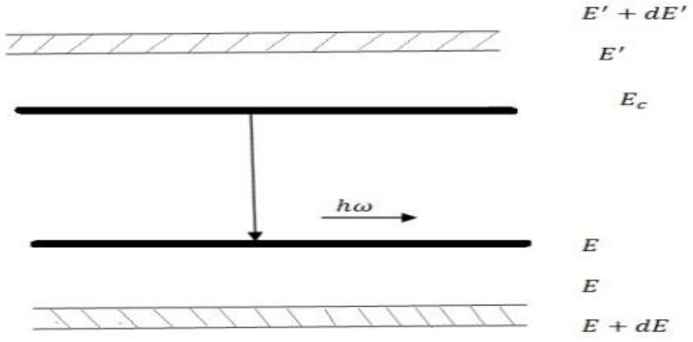

Figure 2. Occurring in semiconductors recombination phenomenon

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

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

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

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

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

(2) integrating the equation:

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

this expression provides complete recombination.

$$r_F = \gamma \,.\, n \,.\, p \quad (3)$$

Here γ - recombination coefficient

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

$$r_o = \gamma_r \, n_o \, p_o \quad (4)$$

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).

$$r = r_F - r_o = \gamma_r\left[(n_o+\Delta n)(p_o+\Delta p)-n_o p_o\right]=$$

$$= \gamma_r\left[n_o p_o + n_o\Delta p + p_o\Delta n + \Delta n\Delta p - n_o p_o\right] = \gamma_r(\Delta n p_o + \Delta p n_o + \Delta n \Delta p) \quad (5)$$

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.

4. Discussion. 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 τ= 3 sec., For Ge equals to τ= 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 $N = 10^{15}\ cm^{-3}$ 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

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

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:

$$\gamma_n = S_n\vartheta,\ \gamma_p = S_p\vartheta \quad (7)$$

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}.

$$\gamma_r = S_{eff}\overline{\vartheta} \quad (8)$$

Here $\overline{\vartheta}$- is the average heat rate of electrons. Living time of couples in an unbalanced state

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

Given that $n_0 p_0 = n_i^2$ 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 $n_0 = p_0$.

$$\tau_{max} = \tau_i = \frac{1}{2\gamma_r \cdot n_i} \quad (10)$$

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

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

The average thermal velocity of electrons at T = 300 K ‾th is about $\overline{\vartheta}\ 10^7\ cm$ / sec.

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

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

The values calculated at room temperature for several specific semiconductors are given in Table 1.

Table 1.

Semiconductor	T, K	R, $cm^{-3}\ sec.^{-1}$	n, cm^{-3}	γ, $cm^3 sec.^{-1}$	$\tau, sec.$	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

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

as long as it is in view.

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

5. Conclusion.

- The rate of recombination increases sharply when deep-layered incisions are introduced into silicon.
- The residence time depends on the concentration of the handles. As the defects in the semiconductor crystal increase, the lifetime decreases.
- As long as the residence time depends on the concentration of impurities.
- The lifetime depends on the temperature, i.e., as the temperature increases, the lifetime of non-balanced charge carriers increases.
- 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.
- The rate of recombination due to external influences depends on the concentration of non-balanced charge carriers.

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