

Effect of Neutron Irradiation on Carriers Removal Rates in $n - Si \langle P, Rh \rangle$

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Abstract

Carrier removal rate in $n - Si \langle P, Rh \rangle$ with different doping rhodium concentrations were investigated under fast neutrons irradiation. It is shown that the rate of carrier removal increases with phosphorus atom concentration but decreases with rhodium atom concentration. Theoretical analysis on the base of kinetic equations has shown that standard scheme of quasichemical reactions taking into account the interaction between rhodium atoms, vacancies and self interstitial atoms could not explain the results of experiment. Therefore a new model based on the use of radiation to increase the barrier between regions of fluctuating impurity concentration has been proposed.

1. Introduction

Investigation of irradiation influence upon carrier removal rate gives us valuable information that is necessary to forecast radiation stability in semiconductor materials, and to explore the mechanisms of radiation processes. Although the carriers removal rate was studied carefully in [1-4], how deep levels impurities influence carriers removal rates in silicon remains unclear.

The aim of this work is investigation of rhodium impurity atoms influence on carriers-removal rate in silicon for various concentration of rhodium (Rh) doping.

2. Samples Preparation and Experimental Technique

N-Type silicon with $\rho = (0,8 - 8)\Omega \cdot cm$ (concentration of oxygen $\sim 5 \cdot 10^{17} cm^{-3}$ and dislocation density $\sim 10^4 cm^{-2}$) is used as initial substance. Rhodium doping was carried out via the thermodiffusion method over $\sim 20hr$ at 1300 - 1500 K followed by cooling at rate of $\sim 250K/minute$. Under this circumstance, electrically active concentration of rhodium M varies over the interval: $4 \cdot 10^{14} < M < 2 \cdot 10^{15} cm^{-3}$. The rate of neutron - induced removal of carriers ($\sim 10\%$) was investigated in silicon irradiated by fast neutrons ($10^{13} < \Phi_n < 5 \cdot 10^{14} cm^{-2}$) with energy spectrum $E \geq 0,1 MeV$ at the temperature $\sim 320K$. Carriers concentration has been measured at temperature $\sim 300K$.

3. Results and Discussion

Dependence of initial carriers removal rate in silicon, $\Delta n/\Delta\Phi = (n_0 - n)/(\Phi_2 - \Phi_1)$, on their initial concentration n_0 is shown in Fig. 1.

From Fig.1a it can be seen that the carriers removal rate in $n - Si\langle P, Rh \rangle$ (lines 1, 2, 3) is lower than in the control sample of $n - Si\langle P \rangle$ (line 4), in which $\Delta n/\Delta\Phi$ decreases with degree of compensation $K = N_a/n_0$ (where N_a is concentration of acceptors compensation centers; n_0 is concentration of main carriers). It was found that concentrations of compensating radiation centers in $n - Si\langle P, Rh \rangle$ (at $K < 0,2$) and in $n - Si\langle P \rangle$ samples practically do not differ.

Figure 1b represents the results of $\Delta n/\Delta\Phi$ dependence on electrically active rhodium atom concentration in silicon. For identical concentrations of Rh , the carriers removal rate decreases with reduction of initial phosphorus concentration P . It is in our point of view that carriers removal rate mainly depends on the materials degree of compensation (inhomogeneity degree) but not on the existence of sinks for V and I .

The authors of works [4, 5-7] have observed increase of radiational stability, i.e. decrease of carriers removal rate, with concentration of Ni, Co, Mn, Cu, S impurity in silicon. The decrease of carriers removal rate in samples $Si\langle Au \rangle$, $Si\langle Ni \rangle$, $Si\langle Co \rangle$, $Si\langle Mn \rangle$, $Si\langle Cu \rangle$, $n - Si\langle S \rangle$ was explained by transition of a part of electrically inactive impurity atoms into electrically active state due to interaction with vacancies (V) [4-6]. Additionally in recent years there have appeared works where increase of radiation stability is explained by the presence of sinks in doped silicon contributing to annihilation of vacancies created in the process of irradiation [7, 8].

These analysis results gives us the idea that any model to be constructed should describe the increase of $\Delta n/\Delta\Phi$ with phosphorus concentration of and with reduction of Rh concentration in silicon. For this purpose we constructed and analyzed the standard

scheme of quasichemical reactions taking place under irradiation:

$$\begin{aligned}
 dV/dt &= \lambda - k_1VI - k_2VP - k_3VM - V/\tau_v \\
 dI/dt &= \lambda - k_1VI - k_4IM - I/\tau_I \\
 dE/dt &= k_2VP & P \simeq const \\
 dD_1/dt &= k_3VM & M \simeq const \\
 dD_2/dt &= k_4VM
 \end{aligned} \tag{1}$$

where V, I, E, D and M are concentrations of various defects and impurities; k_j are quasi chemical reaction constants; λ are rates of V and I formation; $1/\tau_I$ and $1/\tau_v$ are probabilities of I and V disappearance at sinks; terms k_3VM and k_4IM describe interaction between M, V and I atoms, respectively; and term k_2VP describes interaction of V and phosphorus atoms.

We solved this system (1) by the method of defects relaxation times hierarch.

We assumed that relaxation of interstitial atoms I , is the fastest process. Then $dI/dt = 0$ which gives

$$I = (\lambda\tau_I)/(1 + k_4M\tau_I) \simeq \lambda\tau_I \tag{2}$$

$$V = \lambda T_v(1 - e^{-t/T_v}) = \begin{cases} \lambda t & \text{at } t \ll T_v \\ \lambda T_v & \text{at } t \gg T_v \end{cases} \tag{3}$$

$$T_v = [k_1\lambda\tau_I + k_2P + k_3M + 1/\tau_v]^{-1} \tag{4}$$

$$\left. \begin{aligned}
 E &= \lambda k_2 T_v P t \\
 D_1 &= \lambda k_3 T_v M t \\
 D_2 &= \lambda k_4 \tau_I M t
 \end{aligned} \right\} (at \ t \gg T_v) \tag{5}$$

(While solving this system, relations (1) were used with the following initial conditions: at $t = 0, V = I = E = D_1 = D_2 = 0$).

Under irradiation carriers concentration decreases by the law:

$$n(t) = n_0 - [\alpha_E E + \alpha_{D_1} D_1 + \alpha_{D_2} D_2], \tag{6}$$

where n_0 is the initial concentration of carriers.

Then the carriers removal rate depends on concentration of phosphorus and rhodium by the law

$$\frac{dn}{d\phi} = \frac{dn}{Jdt} = \alpha_E \sigma_d N_o T_v P + \alpha_{D_1} k_3 \sigma_d N_o T_v M + \alpha_{D_2} \sigma_d N_o \tau_I M, \tag{7}$$

where J is the intensity of the irradiation, $\sigma_d N_o$ is the efficiency of Frankel's divided pairs production, α_j are constants depending on the type of center, capturing free electrons.

One can see from Eq. (7) that carriers removal rate increases with phosphorus concentration as with rhodium concentration (T_v depends on phosphorus and rhodium concentrations, Eq. 4) and there is no agreement between theory and experiment (Fig. 1a).

Hence, the standard model is not adequate to describe the real situation, of the above mentioned mechanism of decreasing carriers removal rate in compensated silicon (at $K > 0, 2$) and existence of identical rates of carriers removal in doped ($K < 0, 2$) and control silicon. Therefore the below model is proposed to explain $\Delta n/\Delta\Phi$ dependence in doped silicon. Silicon crystals grown by modern technology have areas of low conductivity n and areas of high conductivity n^+ due to inhomogeneity of the main doping impurity, atoms of phosphorus, in the $n - Si\langle P \rangle$ crystal volume, even with uniform distribution of compensating impurities after doping [9]. Due to existence of n^+ - and n_- areas in the $n - Si\langle P, Rh \rangle$ volume, $\Delta n/\Delta\Phi$ was observed to be considerably below the control $n - Si\langle P \rangle$ sample under fast neutron irradiation.

In Fig. 2, the barriers model is offered to explain the initial carriers removal rate decrease in compensated $n - Si\langle P, Rh \rangle$. Here, we take into account that in silicon rhodium atoms form centers with $E_1 = E_c - 0,32eV$ and $E_2 = E_c - 0,55eV$ [10] Fermi level position E_f in the n^+ area above E_1 and E_2 levels, which are completely filled with electrons. Compare with the n -area where the E_1 center is partially ionized and E_2 center is completely filled with electrons (Fig. 2a). In our case, the Fermi level position is the following: $0,2 < E_f < 0,28eV$; and under this conditions the compensating role of radiational centers $E(E_3 = E_c - 0,44eV)$, $A(E_4 = E_c - 0,18eV)$ centers and divacancy ($E_5 = E_c - 0,23eV$) [3, 11] is such that only the E_3 center takes part in carriers removal (E_4, E_5 centers do not participate in carriers removal). At initial stages under such conditions, the effect of irradiation compensation is much more appreciable for n -areas than for n^+ areas. As such, the Fermi level for n^+ - and n_- areas remains uniform, however its position is determined by the n^+ - area. Therefore, potential barrier between these areas is growing at the initial stages of irradiation due to essential difference of compensation rates of conductivity in n^+ - and n_- areas with $\Delta_0 \rightarrow \Delta$ (see Fig. 2b). The growth of barrier $\Delta_0 \rightarrow \Delta$ results in an increase of ionized E_1 -centers concentration in the n -area (see Fig. 2). Under these conditions, electrons that percolate into the n^+ - area from the n -area are seized by deep radiational centers E_3 . As a result, at the conductivity zone of inhomogeneous material, concentration of free carriers remains practically stable, if the position of the Fermi level does not change considerably in the n^+ -area under irradiation, as far as in such inhomogeneous material the n^+ - area is basic for carrier current [12].

Conclusion

Thus, investigating carriers removal rates in $n - Si\langle P, Rh \rangle$, we found the anomaly where carriers removal rates decrease with rhodium atoms concentration under fast neutrons irradiation. The standard analysis with kinetic quasichemical reactions taking into account the interaction between rhodium, vacancies and self-interstitial atoms could not explain the results of experiments. Therefore a model of potential barrier growth between n^+ - and n_- areas under irradiation had been proposed, giving qualitative explanation of the dependence observed in experiment.

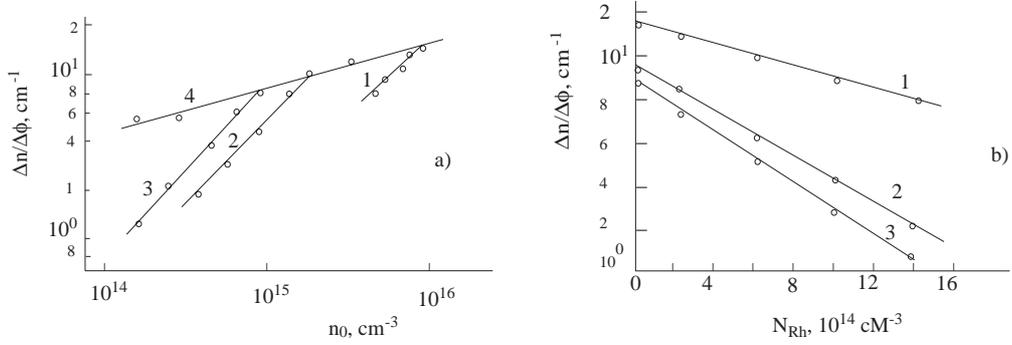


Figure 1.(a) The initial carrier removal rates dependence on initial concentration (n_0, cm^{-3} : 1- $\sim 8.10^{15}$; 2- $\sim 1, 2.10^{15}$; 3- $\sim 8.10^{14}$; 4- $(0, 2-8).10^{15}$) in $n-Si\langle P, Rh\rangle$ (1-3) and $n-S\langle P\rangle$ (4) after irradiation.

Figure 1.(b) The carriers removal rates dependence on rhodium centers concentration of (n_0, cm^{-3} : 1- $\sim 8.10^{15}$; 2- $\sim 1, 2.10^{15}$; 3- $\sim 8.10^{14}$) in $n-Si\langle P, Rh\rangle$.

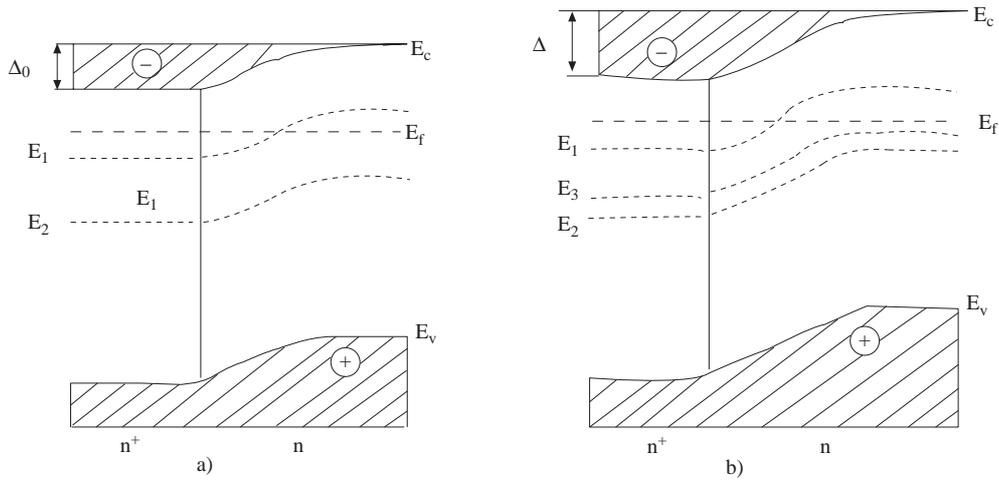


Figure 2. The barrier model of n^+ and n areas occurrence in compensated silicon: a- before and b- after irradiation.

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