Effect Of Nuclear-Transmuted P-Type Silicon with Fast Neutrons on Electrophysical Properties

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ABSTRACT

The influence of defects induced by fast neutron irradiation on the carrier removal rate in reference p-Si <B> and neutron transmutation doped silicon (p-Si < B, P >) was investigated by the Hall effect and specific resistance techniques at room temperature. It is shown that the carrier removal rate is larger in p-Si < B, P >, than that of p-Si <B>. The barrier model was proposed for explanation of the observed effect.

Keywords: thermal and radiation defects, neutron-doped silicon, potential barrier, resistivity, charge carrier concentration and mobility, micro-heterogeneity, fast neutron fluence, Fermi level, A center, Hall effect, electrical resistivity

It is known that the accumulation of thermal and radiation (or impurity) defects in silicon, in most cases, leads to the occurrence of compensating defects. If the concentration of these defects becomes comparable with the initial concentration of charge carriers, then the radiation resistance of the electrophysical properties of compensated silicon increases [1]. Most researchers believe that the electrophysical properties of the compensated material are affected by the nature of radiation (or magnetic) defects, while other researchers consider the main contribution to increase the initial height of potential barriers (Δ) between high-resistance and low-resistance areas.

However, the effect of the contribution of potential barriers between low- and high-ohmic regions on the electrophysical properties of silicon under the influence of penetrating radiation remains insufficiently studied.

The aim of the work is to influence the height of the potential barrier between high-resistance and low-resistance regions on the radiation stability of the electrophysical properties of nuclear–doped silicon p-tipa (p-Si<B,P>).

P-type silicon with a specific resistance of 1 Ом·см ($p_o = N_B \approx 2 \cdot 10^{16}$ см$^{-3}$) was used as the starting material for the production of neutron-doped silicon.

The height of the potential barrier in the samples varied with a variation in the time of silicon doping with phosphorus impurities in the BBP-CM atomic reactor at $\varphi \approx 8 \cdot 10^{13}$ см$^{-2}$·с$^{-1}$. At the same time, the concentration of induced phosphorus atoms was calculated by the formula [2]:

$$N_P = 1{,}7 \cdot 10^{-4}\, \Phi,$$

where $\Phi = \varphi \cdot t$ is the flux of slow neutrons; φ- is the flux density of slow neutrons; t-is the irradiation time.

The annealing of radiation defects (after neutron doping) was carried out at a temperature of ~1270 K in air for ~ 30 min with subsequent cooling at a rate of (5÷10) deg/min.

Ohmic contacts on p-Si<B,P> were obtained by soldering the Sn+In alloy (50% +50%) at a temperature of ~ 400 K.

The height of the potential barrier between the hole–hole (p^{min} – p^{max}) transition in silicon samples was determined by known expressions [3÷5]:

$$\Delta = kT\ln\frac{p^{\max}}{p^{\min}} \quad \text{and} \quad \Delta = kT\ln\frac{\tau}{\tau_{o.}},$$

where $p^{max} = p_0\,(1+\frac{p^{\max}-p^{\min}}{2p_o}) - K)$ and $p^{min} = p_o\,(1-\frac{p^{\max}-p^{\min}}{2p_o} - K)$ – the maximum and minimum concentrations of charge carriers; $K = (N_P / p)$ is the degree of compensation, N_P - is the concentration of atoms of induced phosphorus, p_o– is the average concentration of charge carriers before irradiation; τ_o, τ – is the lifetime of the main charge carriers before and after thermal ignition in neutron-doped p-type silicon.

The parameters of the electro physical properties of the studied samples with various potential barriers are shown in the table.

Type and electro physical parameters of silicon samples

№№	Type of Samples	Resistivity ρ, Ом·см	Concentrations of charge carriersp, $см^{-3}$	Mobility of charge carriers μ, $см^2$ / В·с	The height of the potential barrier Δ, мэВ
11	p-Si<B>	9,8	$1{,}9\cdot10^{15}$	315	5
22	p-Si<B,P> $p_o \approx 2\cdot10^{16}$ $см^{-3}$	9,1	$2{,}3\cdot10^{15}$	280	23
33	p-Si<B>	1800	$1{,}3\cdot10^{13}$	280	10
44	p-Si<B,P> $p_o \approx 2\cdot10^{16}$ $см^{-3}$	1500	$1{,}5\cdot10^{13}$	275	115,7

It can be seen from the table that in the control p-Si<B> (samples №1 and №3) are almost homogeneous in conductivity, and nuclear-doped silicon (samples №2 and №4) are, on the contrary, heterogeneous.

Further, these samples were irradiated with neutrons, in the horizontal channel of an atomic reactor, at a temperature of ~ 300 K. The efficiency of the formation of radiation defects (RD) was studied by measuring the Hall coefficient and resistivity at room temperature.

The results of the study are shown in Fig.1. As can be seen from the figure, in samples p-Si<B,P>, the carrier removal rate (curves 2 and 4) is higher than in control samples (curves 1 and 3) despite the same sample parameters (see Table 1).

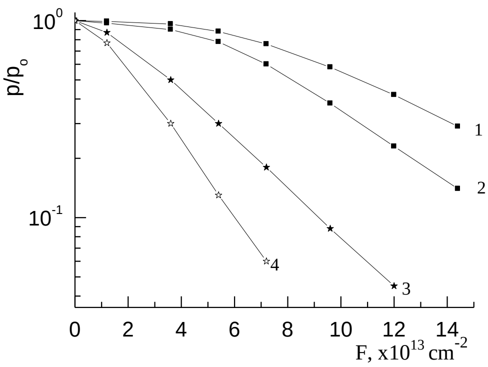

Fig. 1. Dependence of the relative change in the concentration of charge carriers in silicon on the fluency of fast neutrons: 1 – p-Si<B> (ρ = 9,8 Ом·см); 2– p-Si<B,P> (ρ = 8,6 Ом·см); 3 – p

–Si<P> (ρ = 1800 Ом·см) ; 4– p-Si<B,P> (ρ = 1500 Ом·см)

A barrier model is proposed to explain the observed effect. The essence of this model is as follows. It is known that when silicon crystals are grown, due to the uneven distribution of the main impurities of boron, oxygen and carbon impurities, low-resistance (p^{max})- and high-resistance (p^{min})- conduction regions are formed in the crystal volume [1]. The presence of contacts between these regions leads to an insignificant potential barrier Δ_o for charge carriers (see Table №1, 3). At the same time, the energy position of the Fermi level (E_f) for the p^{max} and p^{min} regions remains the same, and its position is determined by the p^{max} region [3, 6]. In [7], defects with ionization energies are formed in irradiated p-type silicon samples by neutrons: $E_1 = E_v + 0{,}28$ eV , $E_2 = E_v + 0{,}35$ eV , $E_3 = E_v + 0{,}40$ eV.

In our case, the Fermi level is $E_f \geq E_V + 0{,}20$ eV, so it was assumed that all observed donor levels of RD are completely ionized in p-Si<B> and p-Si<B, P> (based on the results shown in Fig.1). In addition, it was believed that the concentration of the main charge carriers – holes ($p = N_B$) is greater than the concentration of RD (N_{RD}), i.e. (p^{max}) > (N_{RD}).

At the initial stages of neutron irradiation, the p^{max} -region of the p-Si<B> crystal, practically without feeling the compensation of carriers, remain the same low resistance, and the p^{min} -regions of the crystal of the concentration of the main carriers of the hole decreases. I.e., due to the significant difference in the degree of compensation in p^{max} and p^{min} regions, irradiation leads to an increase in the initial height of the potential barrier ($\Delta_o \rightarrow \Delta$) between these regions (Figure 2b) and the sample becomes heterogeneous.

An increase in the fluence of neutron irradiation leads (to $\Delta_o \rightarrow \Delta$) and, in turn, to an increase in the degree of filling of the RD of the p^{min} –region, in this case E_1. At the same time, the released electrons (to fill E_1) from the p^{min} –region pass into the p^{max} –region, i.e. the increase of E_f begins. Ultimately (up to a certain irradiation fluency) in the valence band of the compensated (up to irradiation of homogeneous) material, the concentration of free holes remains virtually unchanged until the Fermi level changes in the p^{max}-region (Figure 2b),. As mentioned above in such an inhomogeneous material, it is mainly the p^{max}-region that is conductive. A similar effect was previously observed for n-Si<P> in [4].

In the samples p-Si<B,P> (№ 2 and 4) before exposure to neutron irradiation, there are micro uniformities in conductivity compared to p-Si<B> (see Table and Fig.2). To compare the carrier removal rate in both types of samples (p-Si<B,P> and p-Si<B> the Fermi level of these samples were almost the same before irradiation) the concentrations of the RD arising during irradiation, including the disordering region, were considered the same. Under these conditions, it can be said that the charge state of radiation defects in the high-resistance p^{min} region differs significantly with respect to the Fermi level. In the p-Si<B> p^{min} region, the Fermi levels are lower than the RD levels, and in p-Si<B,P> between E_1 and E_2 (see Fig.2b and 3b). Therefore, in the p^{min} region, the filling of RD electrons occurs faster (i.e., the transition of electrons from the p^{min} region to the p^{max} region in nuclear–doped silicon is faster than in the control (due to $\Delta_o^{p\text{-}SiB,P>} > \Delta_o^{p\text{-}Si<B>}$) with the same neutron fluence (Table and Fig. 1), respectively, the rate of carrier removal in nuclear-doped silicon increases (Fig.1).

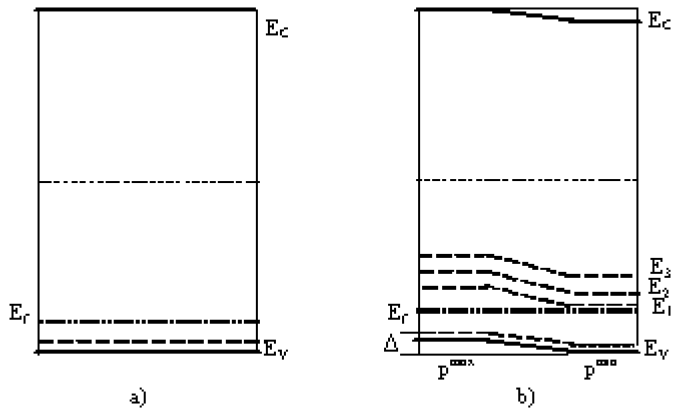

Fig.2. Models of inhomogeneous p^{max} and p^{min} -regions in p-type silicon before (a) and after neutron irradiation (b): $E_1 = E_v$ +0,28 eV , $E_2 = E_v$ + 0,35 eV and $E_3 = E_v$ + 0,40 eV.

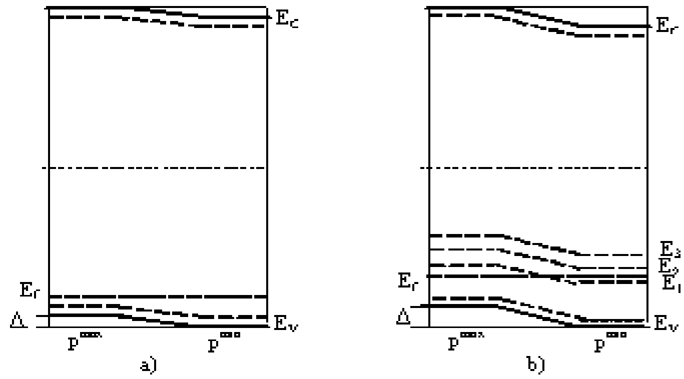

Fig.3. Models of inhomogeneous p^{max} and p^{min} - regions formed in nuclear–doped silicon: before (a) and after neutron irradiation (b): $E_1 = E_v$ +0,28 eV, $E_2 = E_v$ +0,35 eV and $E_3 = E_v$ +0,40 eV.

Conclusions

It was revealed that after irradiation with fast neutrons, the rate of removal of the main carriers in p-Si<B,P> is significantly higher than in the control p-Si<B>, which is due to the presence of micro-uniformity in conductivity before irradiation.

A model is proposed to explain the effect of neutrons on increasing the rate of removal of charge carriers in p-Si<B,P> samples (dynamics of potential barriers and changes in the degree of filling of the RD in the p ^{min} region) compared to p-Si<B>.

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