ACTIVATION ENERGY OF TECHNOLOGICAL THERMODONORS IN TRANSMUTATION DOPED GAMMA IRRADIATED N-Si(P)

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Temperature dependence of Hall coefficient in neutron transmutation doped (NTD) n-Si(P) crystals was measured and the activation energies of high temperature technological thermodonors were determined. Tensoeffect mechanisms in high uniaxially strained NTD γ-irradiated n-Si(P) were examined in order to explain the behaviors of the experimental dependencies.

Introduction

In earlier works, the characteristic peculiarities of the tensoeffect behaviors in NTD n-Si(P) were attributed to the availability in the volume of crystals of high temperature thermodonors, (see, for example [1]). Obviously, thermodonors in NTD n-Si(P) were generated in oxygen containing crystals during high temperature technological annealing which is normally carried out at 800-850°C for 1-2 hours in order to remove radiation-induced damages of the crystalline lattice after irradiation of the silicon ingots in a nuclear reactor.

In this report, results on the Hall-effect measurements and tensoeffect investigations are analyzed for neutron-transmutation doped n-Si(P) and silicon crystals doped by phosphorus from the melt. In order to detect the energy states of the technological thermodonors and radiation-induced defects in crystals irradiated by different doses of gamma-quanta from a ^{60}Co source. The original installation for experimental investigation of physical properties of solids under high uniaxial pressure [2] was used to measure tensoresistivity (TR), tenso-Hall effect (THE), temperature dependencies of conductivity, TR and THE current-voltage characteristics (ICV).

Results and discussion

Typical resistivity dependencies versus pressure taken at T=78 K for two silicon crystals doped from the melt and neutron-transmutation doped are shown in Fig.1.

The saturation of the resistivity-pressure dependencies for the n-Si crystals doped by phosphorus from the melt is characterized by the resistivity saturation in the range of strain-induced complete electrons redistribution between Δ_1-minima of conduction band (curves 1, 3, Fig.1). This occurs if energy splitting of Δ_1-values caused by uniaxial pressure corresponds to the criterion $\delta\varepsilon >> kT$ [3]. For n-Si uniaxially deformed in the [001] direction the energy splitting of Δ_1-valleys can be written as [4]:

$$\delta\varepsilon = \frac{\Xi_u X}{C_{11} - C_{12}}, \qquad (1)$$

where Ξ_u=9.3 [5] is deformation potential constant, X is the uniaxial pressure, C_{11}, C_{12} are elastic constants of monocrystalline silicon.

Taking into account that in n-Si crystals doped by phosphorus from the melt the tensoresistivity saturation measured at T=78 K occurs at X≈0.7 GPa, the ratio of $\delta\varepsilon/kT$ is approximately equal to ten. Thus, the electrons concentration in the "upper" Δ_1-valley of nondegenerate silicon crystals uniaxially deformed in the [001] direction is approximately $5 \cdot 10^{-5}$ from the concentration of electrons in the "lower" Δ_1-valley at X=0,76 GPa (see Eq. (1) in Ref. [6]).

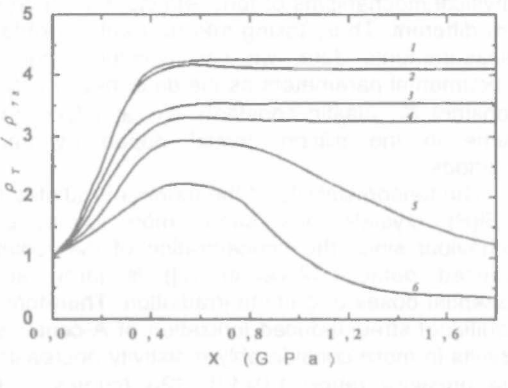

Fig.1. Normalized resistivity ρ_x/ρ_0 as a function of uniaxial stress for n-Si(P) crystals doped from the melt (curves 1, 3) and NTD n-Si(P) (curves 2, 4, 5, and 6). Dose of γ-irradiation (quanta/cm^2): (1-4) 0, (5) (2.1×10^{17}), (6) 8×10^{17}

An exponential decrease of resistivity of NTD n-Si(P) (curves 2,4, Fig.1) we attribute to the strain-induced ionization of thermodonor states [1, 6] which must be generated in oxygen containing crystals under technological heat-treatment at 800°C for 2 hours. Since the concentration of thermodonors for the mentioned annealing conditions is about $5 \cdot 10^{17}$ м$^{-3}$, the exponential a few percent decrease of resistivity in the range of uniaxial pressure 0.6-1.2 GPa is observed in n-Si crystals with phosphorus concentration $N_P \geq 1 \times 10^{19}$ m^{-3} (curves 2, 4 in Fig.1).

Therefore, in order to determine the influence of the thermodonor states availability on the tensoresistivity behavior, a more sensitive method of tensoeffect mechanisms identification [1] was used.

This method in fact adopts the procedure of the shear deformation potential constant Ξ_u determination [5]. By this method it was established that in the uniaxially deformed NTD n-Si(P)crystals the deviation of the logarithm of the electrons concentration ratio for the "upper" and "lower" Δ_1-valleys increases when phosphorus dopant concentration decreases . Thus, taking into account the two facts (1) a lower phosphorus concentration in NTD silicon corresponds to a lower dose of slow neutron irradiation and (2) conditions of annealing are approximately similar for all neutron-irradiated NTD n-Si(P) crystals the features of the $\lg(n_2/n_1)=f(X)$ dependence may be explained by the increasing of the thermodonors influence on the physical properties of pure silicon. Indeed, in the NTD silicon at the phosphorus concentration $N_p<1\times10^{19}$ m^{-3} the technological thermodonors may be considered as a codopant. Therefore, for high resistivity NTD n-Si(P, TD) the both decreasing of the oxygen content in crystal volume and annealing procedure optimization is undoubtedly necessary.

Note, that the deviation of the logarithm of the electrons concentration ratio dependence on X from linearity does not implies the change of the Ξ_u constant in NTD silicon in comparison to the n-Si doped by phosphorus from the melt since the physical mechanisms of tensoeffects in both crystals are different. Thus, taking into account the obtained measurements data, we can conclude that such fundamental parameters as the deformation potential constant Ξ_u, elastic constants C_{11} and C_{12} are the same in the silicon crystal doped by various methods.

The tensoresistivity of the gamma-irradiated NTD n-Si(P) crystals has some more characteristic behaviour since the concentration of the radiation-induced defects (A-center [7]) is large at the essential doses of gamma-irradiation. Therefore, the additional strain-induced ionization of A-center state results in more considerably resistivity decreasing in the pressure range 1.0÷1.8 GPa (curves 5, 6 In Fig.1). Obviously, the essential strain-induced change of the total concentration of electrons in gamma-irradiated silicon crystals excepts the application of the mentioned above method for the description of the physical mechanism of tensoeffects in this case.

In order to determine the technological thermodonors activation energy the measurements of temperature dependence of the Hall effect in slightly doped by slow neutron irradiation silicon were performed. Temperature dependencies of the normalized Hall-coefficient for neutron transmutation doped by phosphorus silicon are shown in Fig. 2. Obviously, only for slightly doped specimen (curve 3 in Fig. 2, specimen 3 NTD in Table 1) the Hall effect measurements allow to determine the activation energy of thermodonor states with acceptable accuracy.

It was found that two activation energies of thermodonor states can be assigned to the thermodonors generated in oxygen containing Chochralski grown silicon crystals and annealed under mentioned above conditions, namely: $\varepsilon_{a1}=(78\pm1.5)$ meV and $\varepsilon_{a2}\approx180$ meV.

Table 1. Parameters of the investigated crystals doped by various methods

Sample	Φ, ×10^{17} (quanta/ [illegible])	$k=N_a/N_d$	N_a, ×10^{14}cm^{-3}	N_d, ×10^{14} (cm^{-3})	$n_e=N_d-N_a$ ×10^{14} (cm^{-3})	$N_i=N_d+N_a$ ×10^{14} (cm^{-3})	μ_{78}, (cm^2/V×s)	ρ_{78}, ($\Omega\cdot$cm)
1		0.32	0.096	0.3	0.202	0.4	20800	15
2(NTD)	0	0.25	0.058	0.228	0.17	0.29	21300	17
3(NTD)	0	0.05	0.01	0.2	0.2	0.2	21500	1050
4(NTD)	0	0.52	0.62	1.2	0.58	1.84	20500	5.3
5	0	0.28	0.28	1.0	0.72	1.3	19100	4.55
6	0	0.9	2.4	2.7	0.28	5.13	14500	15.5
7	0	0.2	0.28	1.4	1.12	1.7	17600	3.2
8(NTD)	0	<0.0	≈0.01	3.2	3.2	3.2	16200	1.23
8a	1.36	0.05	0.15	3.2	3.0	3.35	14600	1.43
8b	1.76	0.27	0.86	3.2	2.34	4.1	14200	1.9
8c	2.1	0.8	2.53	3.2	0.63	5.7	12900	7.75
9(NTD)	0	0.01	≈0.01	7.2	7.2	7.2	14470	0.63
9a	8	0.94	6.8	7.2	0.4	14.0	4750	32.8

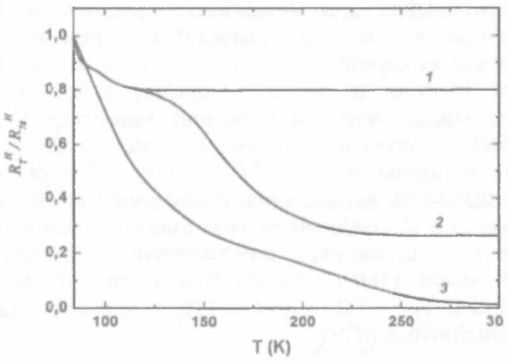

Fig.2 Normalized Hall-coefficient $R_T^H\ /\ R_{78}^H$ as a function of temperature for NTD n-Si (P): 1,2 samples 8 NTD and 8c respectively; 3 – 3 NTD in Table 1.

Note, that the temperature dependence of Hall-coeficient for pure NTD n-Si crystal in the range 78 K-300 K is determined completely by thermal activation of the technological thermodonor states. (curve 3 in Fig.2).

Conclusions

On the basis of the analysis of transport phenomena measurements data in transmutation doped γ-irradiated silicon the influence of the both radiation induced defect states (P, A-centers) and high temperature technological thermodonors on the tensoeffects behaviors was examined. Some fundamental parameters and characteristics of the n-Si(P) crystals doped by various methods are compared. The reasons of the features difference of these crystals are discussed.

The developed methods of the physical mechanisms identification of a tensoeffects in extremely strained silicon crystals were verified. Two activation energies of technological thermodonor states in Czochralski grown silicon crystals were determined for NTD silicon annealed at T=800°C for 2 h.

References

1. *Budsulyak S.I., Venger E.F., Dotsenko Yu.P., Ermakov V.M., Kolomoets V.V., Machulin V.F., Panasjuk B.I., Khivrich V.I.* // Reports of Ukrainian NASU. - 2000. - №9, - P.79.
2. *Ermakov V.M., Kolomoets V.V., Suss B.A., Rodionov V.E.* Patent of Russia. 2040785
3. *Ermakov V.M., Kolomoets V.V., Panasjuk B.I., Rodionov V.E.* // In Proc. of the 20th Internat. Conf. of the Physics of Semiconductors. Thesaloniki, Greece, 1990. - V.3. - P. 1803
4. Herring C. // Bell Syst. Tech. Journ.- 1955. - V.34. - P.237.
5. *Baranskii P.I., Dahovskii I.V., Kolomoets V.V. at al.* // Fiz. Tekh. Poluprov. - 1976. – V.10(7). - P. 1387–1389.
6. *Budzulyak S.I., Dotsenko Yu.P., Ermakov V.M. at al.* // Physica B. – 2001. – V.308 – 310. - P. 12-16.
7. *Watkins G.D., Corbert J.W.* // Phys. Rev. 1961. - V.121. - P. 1001.