PECULIARITIES OF PIEZORESISTANCE OF γ-IRRADIATED *N*-SI CRYSTALS IN THE CASE OF SYMMETRIC POSITION OF THE DEFORMATION AXIS RELATIVE TO ALL ISOENERGETIC ELLIPSOIDS

A.V. FEDOSOV,[1] S.V. LUNIOV,[1] S.A. FEDOSOV[2]

[1]**Lutsk National Technical University**
(75, Lvivska Str., Lutsk 43018, Ukraine; e-mail: luniovser@mail.ru)

[2]**Lesya Ukrainka Volyn National University**
(13, Voli Ave., Lutsk 43025, Ukraine; e-mail: ftt@univer.lutsk.ua)

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The piezoresistance of γ-irradiated n-Si crystals is studied in the case where $X\|J\|[111]$. A change of the energy gap between the deep energy level E_C – 0.17 eV and the conduction band valleys in n-Si arising due to a uniaxial deformation along the crystallographic direction [111] is determined. It is shown that, for this crystallographic direction, the baric coefficient of a change of the energy gap is insignificant, since the shifts of the deepest level E_C – 0.17 eV and the conduction band valleys in n-Si under deformation are practically identical.

The study of peculiarities of the piezoresistance of γ-irradiated n-Si crystals in the case of a symmetric position of the deformation axis relative to all isoenergetic ellipsoids is interesting from both theoretical and cognitive viewpoints. A nonlinear, considerable in magnitude dependence $\frac{\rho_X}{\rho_0} = f(X)$ was obtained for n-Si in [1] in the case of large mechanical stresses at $X\|J\|[111]$. As the application of the mechanical stress X does not result in a relative shift of valleys in n-Si under conditions of these investigations, the presence of the piezoresistance in nonirradiated crystals at a constant concentration of charge carriers in the conduction band is explained by a change of the mobility due to an increase of the transverse effective mass $m_\perp$ under the simultaneous manifestation of the deformation-induced nonparabolicity of the C-band [1,2]. With regard for the fact that $m_\perp \sim X$, the authors of work [1] obtained the expression

$$\frac{\rho_X}{\rho_0} - 1 = a_0 X^2, \tag{1}$$

where a_0 is some constant depending on the mechanisms of scattering of charge carriers.

Taking the expressions for the resistivity of deformed and undeformed n-Si samples into account, we obtain

$$\rho_X = \frac{1}{en_e\mu_X}, \quad \rho_0 = \frac{1}{en_e\mu_0}, \tag{2}$$

where μ_X and μ_0 stand for the mobilities of charge carriers in deformed and undeformed n-Si, respectively, and n_e is the electron concentration in the conduction band. With regard for (2), relation (1) takes the form

$$\frac{\mu_0}{\mu_X} = 1 + a_0 X^2. \tag{3}$$

The effect of radiation-induced defects on the piezoresistance of n-Si under the condition $X\|J\|[111]$ was investigated, by using n-Si crystals grown by the Czochralski method with the resistivity $\rho_{300\ \mathrm{K}}$ =30 Ohm·cm and the initial concentration of charge carriers $n = 1.24 \times 10^{14}$ cm^{-3} and irradiated by γ-quanta from Co^{60} with a dose of 3.8×10^{17} quanta/cm^2 (Fig. 1).

As is known, γ-irradiation of silicon crystals with a high content of oxygen impurity results in the formation of radiation-induced defects having deep energy levels in the forbidden band (E_C – 0.17 eV) belonging to A-centers ("vacancy – interstitial oxygen" complex) [3].

In the case of γ-irradiated n-Si crystals with a deep energy level E_C – 0.17 eV, we have

$$\sigma_X^0 = \frac{1}{\rho_X^0} = en_\varepsilon\mu_X^0, \quad \sigma_0^0 = \frac{1}{\rho_0^0} = en\mu_0^0, \tag{4}$$

where σ_X^0, ρ_X^0, σ_0^0, ρ_0^0, μ_X^0, μ_0^0, n_ε, and n stand for the conductivity, resistivity, mobility, and concentration of charge carriers for γ-irradiated n-Si crystals, respectively; and the indices "X" and "0" denote deformed and undeformed semiconductors, respectively. According to [4], the electron concentration in the conduction band of a semiconductor with deep energy levels depends on the deformation in the following way:

$$n_\varepsilon = ne^{-\frac{\Delta E}{\alpha kT}}. \tag{5}$$

Here, ΔE is a change of the energy gap between the deep energy level and the conduction-band bottom, and α is the coefficient varying from 1 to 2 depending on the degree of occupation of the deep level.

With regard for (3), (4), and expression (5) for the electron concentration in a deformed semiconductor with deep levels, we obtain

$$\frac{\rho_X^0}{\rho_0^0} = (1 + aX^2)e^{\frac{\Delta E}{\alpha kT}} = f(X), \tag{6}$$

where $\Delta E = \frac{d(\Delta E)}{dX}X$.

Let us expand the function $f(X)$ in a Taylor series in the neighborhood of some point X_1 in the linear approximation:

$$f(X) \cong f(X_1)+$$

$$+\left[\frac{2aX_1 f(X_1)}{1 + aX_1^2} + \frac{f(X_1)}{\alpha_1 kT}\frac{d(\Delta E)}{dX}\right](X - X_1). \tag{7}$$

In this approximation, the values of the coefficients α for two close points X_1 and X_2, for which $X_2 = X_1 + \Delta X$, where $\Delta X \ll X_1$, can be considered equal. Then we can write

$$f(X_2) \cong f(X_1)+$$

$$+\left[\frac{2aX_1 f(X_1)}{1 + aX_1^2} + \frac{f(X_1)}{\alpha_1 kT}\frac{d(\Delta E)}{dX}\right](X_2 - X_1). \tag{8}$$

According to (6), we have

$$\frac{\frac{d(\Delta E)}{dX}}{\alpha_1 kT} = \frac{\ln\frac{f(X_1)}{1+aX_1^2}}{X_1}.$$

This substitution yields the expression allowing one to determine the constant a (at some fixed temperature T):

$$f(X_2) \cong f(X_1)+$$

$$+\left[\frac{2aX_1 f(X_1)}{1 + aX_1^2} + f(X_1)\frac{\ln\frac{f(X_1)}{1+aX_1^2}}{X_1}\right](X_2 - X_1). \tag{9}$$

Taking (5) and (6) into account, we can write down the expression for the concentration of charge carriers in n-Si under the condition $X\|J\|[111]$ in the presence of deep energy levels in the forbidden band:

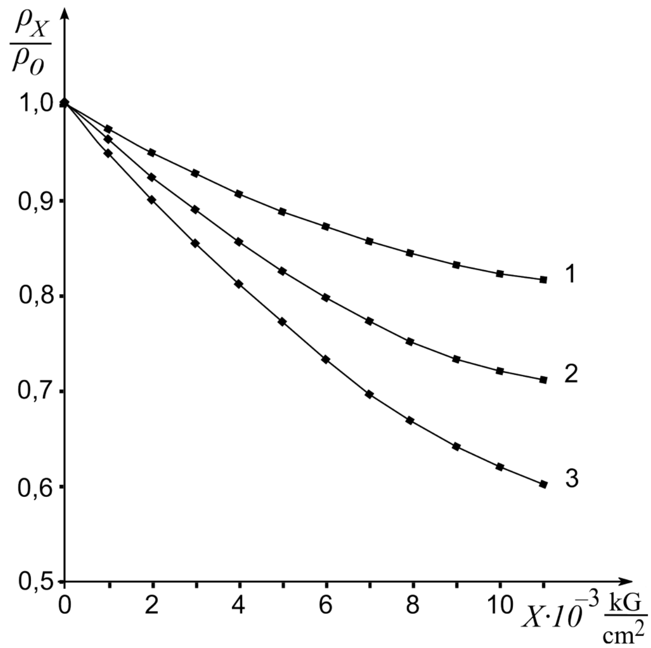

Fig. 1. Dependences $\frac{\rho_X}{\rho_0} = f(X)$ after γ-irradiation of n-Si crystals with the dose $\Phi = 3.8 \times 10^{17}$ quanta/cm^2 in the case where $X\|J\|[111]$ at different temperatures T: *1* – 150, *2* – 130, *3* – 77 K

$$n_\varepsilon = n\frac{1 + aX^2}{f(X)}. \tag{10}$$

Let us differentiate (5) with respect to X:

$$\frac{dn_\varepsilon}{dX} = -\frac{n}{\alpha kT}e^{-\frac{\Delta E}{\alpha kT}}\frac{d(\Delta E)}{dX}. \tag{11}$$

According to the data of works [5–7],

$$\frac{d(\Delta E)}{dX} = \text{const}. \tag{12}$$

The value of the derivative $\frac{dn_\varepsilon}{dX}$ at some point X_1 is equal to the tangent of the tangent slope angle for the plot of the function $n_\varepsilon = f(X)$. Then the derivative $\frac{dn_\varepsilon}{dX}$ at the point X_1 can be presented as

$$\left.\frac{dn_\varepsilon}{dX}\right|_X = \text{tg}\beta_1. \tag{13}$$

According to (5), (11), and (12),

$$\frac{d(\Delta E)}{dX} = -\frac{\alpha_1 kT}{n_\varepsilon(X_1)}\text{tg}\beta_1. \tag{14}$$

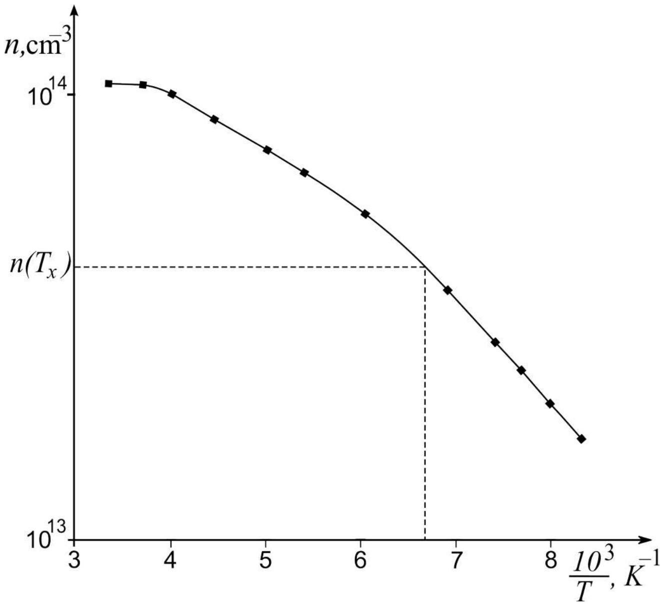

Fig. 2. Temperature dependence of the concentration of charge carriers in n-Si irradiated by γ-quanta with a dose of 3.8×10^{17} quanta/cm^2

Then, for two different values X_1 andX_2, expression (14) yields

$$\frac{\alpha_1 tg\beta_1}{n_\varepsilon(X_1)} = \frac{\alpha_2 \mathrm{tg}\beta_2}{n_\varepsilon(X_2)}. \qquad (15)$$

It is shown in [6, 8] that the dependence of the concentration at temperatures $T \geq T_x$ has the form $n \sim \exp\left(-\frac{E_0}{2kT}\right)$. In the case of low temperatures $T < T_x$, the energy in the exponent is the total activation energy of a level, and T_x stands for some characteristic temperature determined experimentally from the temperature dependence of the concentration of charge carriers. Then $\alpha = 1$ at $T < T_x$. According to (15),

$$\frac{\alpha_1}{n_\varepsilon(X_1)}\mathrm{tg}\beta_1 = \frac{\alpha_2}{n_\varepsilon(X_2)}\mathrm{tg}\beta_2, \qquad (16)$$

where $tg\beta_0$ is the tangent of the tangent slope angle for the plot of the function $n_\varepsilon = f(X)$ at the point X_0, where $n_\varepsilon(X_0) = n(T_x)$. In accordance with (14) and (15), the variation of the energy gap between the deep level E_ε and the lower valleys of the conduction band under deformation ($T =$ const) is equal to

$$\frac{\alpha_1}{n_\varepsilon(X_1)}\mathrm{tg}\beta_1 = \frac{\mathrm{tg}\beta_0}{n_\varepsilon(X_0)}. \qquad (17)$$

As one can see from Fig. 2, the peculiarity of the dependence $n = f\left(\frac{10^3}{T}\right)$ consists in the transition from the

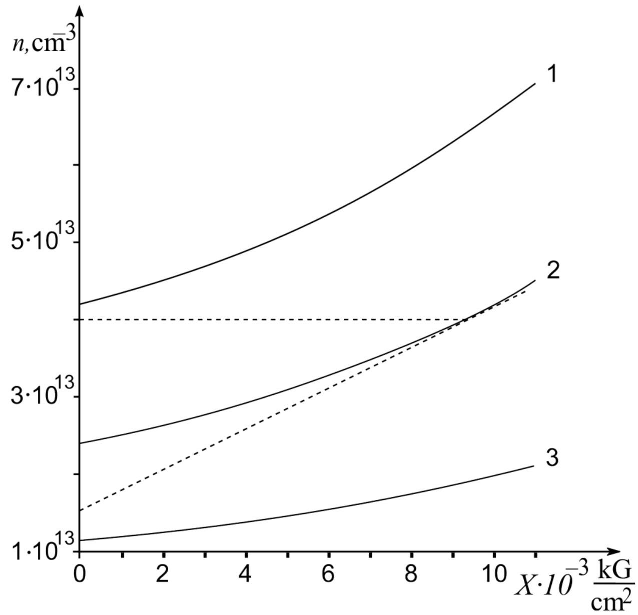

Fig. 3. Dependences $n_\varepsilon = f(X)$ after γ-irradiation of n-Si crystals with the dose $\Phi = 3.8 \times 10^{17}$ quanta/cm^2 under the condition $X \parallel J \parallel [111]$ at different temperatures T: *1* – 150, *2* – 130, *3* – 77 K

"complete" slope of the level $E_\mathrm{C} - 0.17$ eV at temperatures $T < T_x$ to the "half" one at $T \geq T_x$. According to Fig. 2, the characteristic temperature of the transition T_x =148 K, and the corresponding concentration $n(T_x) \cong 4 \times 10^{13}$ cm^{-3}.

Figure 3 presents the dependences $n_\varepsilon = f(X)$ in the case where $X \| J \| [111]$ at different temperatures, where n_ε was determined by the data on piezoresistance according to (10). The change of the energy gap between the deep level $E_\mathrm{C} - 0.17$ eV and the bottom of the conduction band in n-Si calculated per every 10^3 kG/cm^2 is equal to $(0.68 \pm 0.03) \times 10^{-3}$ eV. As one can see, the baric coefficient of a change of the energy gap for the given crystallographic direction is inessential. It is explained by the fact that, under deformation of n-Si along the crystallographic direction [111], the shifts of conduction band valleys and the deep level $E_\mathrm{C} - 0.17$ eV are practically identical [5].

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ОСОБЛИВОСТІ П'ЄЗООПОРУ γ-ОПРОМІНЕНИХ КРИСТАЛІВ n-Si У ВИПАДКУ СИМЕТРИЧНОГО РОЗМІЩЕННЯ ОСІ ДЕФОРМАЦІЇ ВІДНОСНО ВСІХ ІЗОЕНЕРГЕТИЧНИХ ЕЛІПСОЇДІВ

А.В. Федосов, С.В. Луньов, С.А. Федосов

Р е з ю м е

Досліджено п'єзоопір γ-опромінених кристалів n-Si за умови, коли $X\|J\|[111]$. Визначено величину зміни енергетичної щілини між глибоким енергетичним рівнем E_C – 0,17 еВ і долинами зони провідності n-Si при одновісній деформації вздовж кристалографічного напрямку [111]. Показано, що для даного кристалографічного напрямку баричний коефіцієнт зміни енергетичної щілини є незначним, оскільки зміщення самого глибокого рівня E_C – 0,17 еВ і долин зони провідності n-Si при деформації є практично однаковими за величиною.