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TENSOELECTRICAL PROPERTIES OF ELECTRON-IRRADIATED n-Si SINGLE CRYSTALS[†]

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Tensoresistance at uniaxial pressure for electron-irradiated n-Si single crystals at room temperature has been studied. Silicon single crystals for research were doped with phosphorus, concentration N_d=2.2·10^{16} cm^{-3}, and irradiated by the electron flows of 5·10^{16} el./cm^2, 1·10^{17} el./cm^2 and 2·10^{17} el./cm^2 with the energy of 12 MeV. Measurements of tensoresistance and Hall constant were performed for the uniaxially deformed n-Si single crystals along the crystallographic directions [100] and [111]. Mechanisms of tensoresistance for the investigated n-Si single crystals were established based on the measurements of the tenso-Hall effect and infrared Fourier spectroscopy. It is shown that the tensoresistance of such single crystals is determined only by changes in the electron mobility under the deformation. In this case, the electron concentration will not change under the action of uniaxial pressure, because the deep levels of radiation defects belonging to the VO_i VO_iP complexes will be completely ionized. Ionization of the deep level of E_v+0.35 eV, which belongs to the defect of C_iO_i, under the deformation will not be manifested and will not be affect on the tensoresistance of n-Si. It is established that the anisotropy of electron scattering on the created radiation defects, which occurs at the uniaxial pressure along the crystallographic direction [100], is the cause of different values of the magnitude of tensoresistance of n-Si single crystals, irradiated by different electron flows. For the case of tensoresistance of the uniaxially deformed n-Si single crystals along the crystallographic direction [111], the dependence of its magnitude on the electron irradiation flow is associated with changes in the screening radius due to an increase in the effective electron mass. For the first time obtained at room temperature the increase of the magnitude of tensoresistance for the n-Si single crystals due to their irradiation by the electron flows of $\Omega \geq 1\cdot10^{17}$ el./cm^2 can be used in designing high uniaxial pressure sensors based on such n-Si single crystals with the higher value of tensosensitivity coefficient regarding available analogues. Such sensors will have increased radiation resistance and a wide scope of operation.
Keywords: n-Si single crystals, radiation defects, tensoresistance, electron irradiation, tenso-Hall effect, infrared Fourier spectroscopy, scattering anisotropy.
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Monocrystalline silicon is one of the promising materials for the manufacture of pressure sensors, which are used in many areas of science and technology, such as aerospace, cryo energy, nuclear and atomic power, instrument engineering and others [1-6]. The use of such sensors in these industries at the presence of radiation fields makes demands on the accuracy and stability of their parameters. The solution of these problems is possible due to the optimization of the performance of pressure sensors and the development of technologies for their production. Among the known methods of obtaining silicon and other semiconductor materials is metallurgical doping by the isovalent and rare earth impurities, impurity complexes and impurities with the deep levels [7-10]. However, these technologies have several disadvantages, such as limited solubility of doping impurities, which significantly narrows the range of possible concentrations of charge carriers, increasing the concentration of structural defects and reducing the degree of homogeneity of the material with increasing doping concentration. Another method of obtaining semiconductor materials with the necessary properties is the modification of these properties by radiation defects that are created in semiconductors under the irradiated with high-energy quanta or particles [8, 11]. In [12-14], the effect of gamma irradiation and annealing on the tensoresistive effect in n-Si single crystals was studied. It was established that the tensoelectrical properties of the investigated silicon single crystals are determined by the radiation defects belonging to A-centers [12, 13], or both A-centers and thermodonors [14]. However, the effect of these defects on the n-Si tensoresistance will be manifested only at temperatures slightly higher than the temperature of liquid nitrogen, and the energy levels of A-centers and thermodonors will be ionized at room temperature. This significantly narrows the scope of operation of pressure sensors that are manufactured based on such gamma-irradiated n-Si single crystals, as the use of gamma irradiation and thermal annealing technologies for this case does not allow to control the n-Si tensosensitivity at room temperature. Therefore, this work aimed to study the mechanisms of tensoresistance of electron-irradiated n-Si single crystals at the uniaxial pressure and establishing optimal electron irradiation conditions to increase the tensosensitivity of these single crystals at room temperature.

EXPERIMENTAL RESULTS AND DISCUSSION

Measurements of tensoresistance and Hall constant were performed for the uniaxially deformed n-Si single crystals along the crystallographic directions [100] and [111]. The investigated silicon single crystals were doped by the

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phosphorus impurity, concentration N_d=2.2·10^{16} cm^{-3}, and irradiated by the electron flows of 5·10^{16} el./cm^2, 1·10^{17} el./cm^2 and 2·10^{17} el./cm^2 with the energy of 12 MeV at room temperature. The method of preparation of silicon samples and experimental measurements of tensoelectrical properties is described in detail in [15]. In [16], measurements of infrared Fourier spectroscopy have been conducted for these n-Si single crystals, irradiated by the electron flow of 1·10^{17} el./cm^2. It was found that the absorption lines with frequencies of 836 and 885 cm^{-1} correspond to the A-center (VO_i complex), and the absorption line with the frequency of 865 cm^{-1} - the C_iO_i complex. These defects are the main ones and determine the electrical properties of these single crystals. The activation energy of radiation defects for irradiated silicon by the electron flow of Ω=1·10^{17} el./cm^2, which is determined in this work based on Hall effect measurements turned out to be equal to $E_A = E_c - (0{,}107 \pm 0{,}005)$ eV, which corresponds to the A-center, additionally modified with impurity of phosphorus (VOiP complex). This allowed us to establish that VOiP complexes will be created under the irradiation of silicon in addition to VO_i complexes. The analysis of temperature dependences of electron concentration for irradiated silicon single crystals by the electron flows of 5·10^{16} el./cm^2, 1·10^{17} el./cm^2 and 2·10^{17} el./cm^2 showed that at room temperature the radiation defects belonging to A-centers, will be ionized, and the deep levels E_v+0,35 eV belonging to the C_iO_i defects will be filled with electrons. Also, these conclusions are in good agreement with our measurements of the IR absorption spectra for irradiated n-Si single crystals by the electron flows of 5·10^{16} el./cm^2 and 2·10^{17} el./cm^2 at room temperature (Fig. 1).

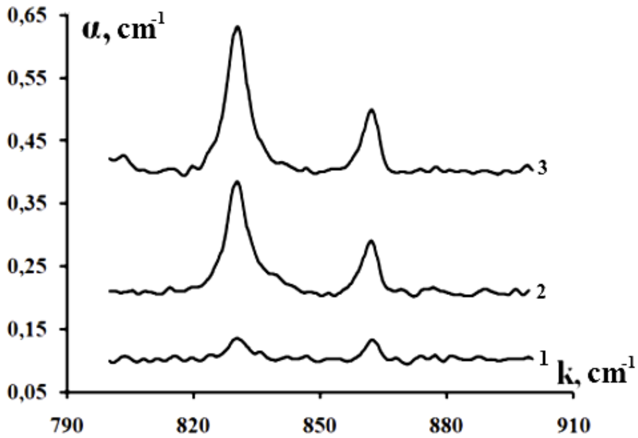

Figure 1. Absorption spectra at room temperature for irradiated n-Si single crystals by the different electron flows Ω, el./cm^2: 1 –5·10^{16}; 2 – 1·10^{17} [16]; 3 – 2·10^{17}.

As follows from Fig. 1, in the absorption spectrum of irradiated silicon there is no line 885 cm^{-1}, which corresponds to the negatively charged state of the A-center, and there are absorption lines 836 cm^{-1} (corresponds to the neutral state of the A-center) and 865 cm^{-1}. Therefore, only radiation defects belonging to the C_iO_i complex will be electrically active at room temperature. The increase in the area under the curves that correspond to these absorption lines indicates that the concentration of the considered defects increases with the increasing electron irradiation flow. This statement is also confirmed by the quantitative calculations conducted in [16].

Dependences of the tensoresistance for unirradiated and irradiated n-Si single crystals by the electron flows of 5·10^{16} el./cm^2, 1·10^{17} el./cm^2 and 2·10^{17} el./cm^2 at the uniaxial pressure along the crystallographic directions [100] and [111] at room temperature show in Fig. 2 and Fig. 3.

The change in resistivity during deformation can occur both due to changes in mobility and electron concentration. As is known [12], the decrease in electron mobility of the unirradiated silicon single crystals at the uniaxial pressure along the crystallographic direction [100] occurs due to the redistribution of electrons between two minima of the conduction band with lower mobility, which descend down, and four minima with higher mobility, which ascend up on the energy scale under the action of deformation. That is, mobility in this case becomes anisotropic. The decrease in electron mobility of n-Si at the uniaxial pressure along the crystallographic direction [111] is associated with the increase in the effective mass of electrons during the transformation of a two-axis isoenergetic ellipsoid of rotation in the three-axis and the emergence of non-parabolicity of the silicon conduction band under the deformation [15].

In [15], it was established that changes in the electron mobility under the uniaxial pressure for the same n-Si single crystals with radiation defects are also associated with the additional mechanisms of electron scattering, which are not manifested for unirradiated n-Si single crystals. In so doing, the electron concentration during deformation increases due to the reduction of the ionization energy of the VO_i and VO_iP complexes. These two reasons will determine the tensoresistance of irradiated n-Si single crystals at an uniaxial pressure. It should be noted that in [15] studies of the tensoelectrical properties of electron-irradiated n-Si single crystals were performed for the temperature range 130-300 K. According to the temperature dependences of the electron concentration and infrared Fourier spectroscopy measurements [16], the energy levels of VO_i and VO_iP complexes will not be ionized at the temperatures T<250 K and will contribute to the changes in the electron concentration under the deformation and, accordingly, to the tensoresistance of the irradiated Si. In our case, these defects will be ionized and will not affect the tensoresistance n-Si at room temperature. The change in the electron concentration under the action of deformation is possible only due to the ionization of the C_iO_i complex, which will not be ionized at room temperature. Therefore, to interpret the obtained results of tensoresistance, presented in Fig. 2 and Fig. 3, the measurements of tenso-Hall effect have been conducted. In Fig. 4 shows the dependences of the Hall constant for unirradiated and irradiated n-Si single crystals by the electron flows of $5\cdot10^{16}$ el./cm^2, $1\cdot10^{17}$ el./cm^2 and $2\cdot10^{17}$ el./cm^2 on the uniaxial pressure along the crystallographic directions [100] and [111] at room temperature.

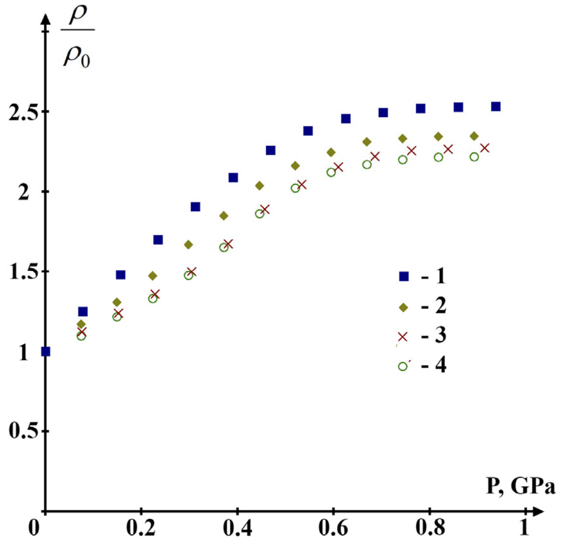

Figure 2. Dependences of tensoresistance at the uniaxial pressure along the crystallographic direction [100] for irradiated n-Si single crystals by the different electron flows Ω, el./cm^2: $1 - 2\cdot10^{17}$, $2 - 1\cdot10^{17}$ el./cm^2, 3 – 0, $4 - 5\cdot10^{16}$.

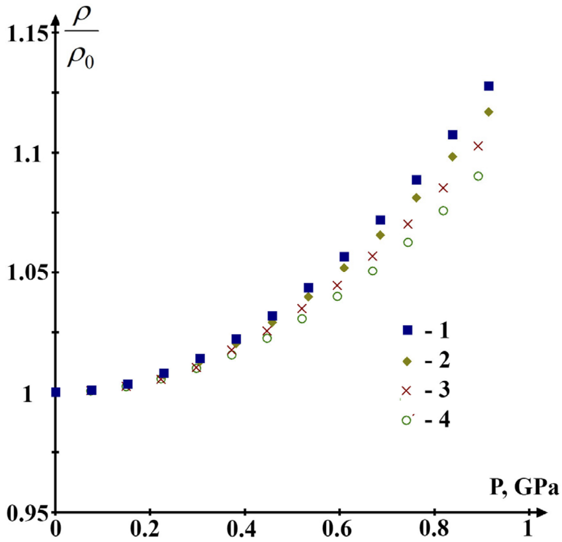

Figure 3. Dependences of tensoresistance at the uniaxial pressure along the crystallographic direction [111] for irradiated n-Si single crystals by the different electron flows Ω, el./cm^2: $1 - 2\cdot10^{17}$, $2 - 1\cdot10^{17}$ el./cm^2, 3 – 0, $4 - 5\cdot10^{16}$.

The value of the Hall constant does not depend on the orientation of the uniaxial pressure, so curves 1 and 2, 3 and 4, 5 and 6, 7 and 8 in Fig. 4 coincide at the deformation along the crystallographic directions [100] and [111] for the same electron irradiation flows.

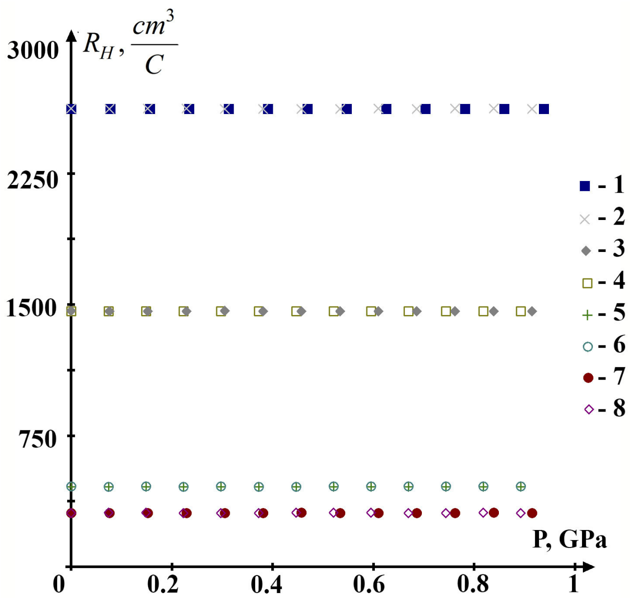

Figure 4. Dependences of the Hall constant on the uniaxial pressure along the crystallographic directions [100] and [111] at room temperature for irradiated n-Si single crystals by the different electron flows Ω, el./cm^2:
1, $2 - 2\cdot10^{17}$; 3, $4 - 1\cdot10^{17}$; 5, $6 - 5\cdot10^{16}$; 7, 8 – 0.

As follows from Fig. 4, the Hall constant does not depend on the uniaxial pressure for both unirradiated and irradiated silicon samples. This is explained by the fact that at room temperature ionization of the deep level of E_v+0,35 eV belonging to the C_iO_i defect will not be manifested under the action of deformation. In this case, the radiation defects corresponding to the VO_i and VO_iP complexes will be ionized and will not in any way affect the changes in the electron concentration during deformation, in accordance with the Fig. 1 and obtained in [16] of the temperature dependences of electron concentration. Therefore, the presence of tensoresistance for irradiated n-Si single crystals, as well as for unirradiated ones, will be determined only by changes in the electron mobility at uniaxial pressure. Also, a characteristic feature of the dependences of the tensoresistance (Fig. 2 and Fig. 3) is the increase in the magnitude of the tensoresistance for the flows of $\Omega \geq 1\cdot 10^{17}$ el./cm^2. To quantitatively explain this feature, the relative decrease of Hall mobility for undeformed and uniaxially deformed n-Si single crystals was estimated. The relative decrease in Hall mobility with the increasing magnitude of the electron flow can be represented as follows:

$$\alpha = \frac{\mu_h(0) - \mu_h(\Phi)}{\mu_h(0)} \cdot 100\% , \qquad (1)$$

where $\mu_h(0)$ is the Hall mobility for unirradiated silicon single crystals; $\mu_h(\Omega)$ is the Hall mobility for irradiated silicon single crystals by the flow Ω.

Table presents the calculated values of the relative decrease of Hall mobility for undeformed and uniaxially deformed n-Si single crystals with increasing electron irradiation flow (values of uniaxial pressures for elastically deformed n-Si single crystals, for which assessments were conducted, are presented in parentheses).

Since the tensoresistance for unirradiated and irradiated n-Si single crystals, as established above based on the analysis of the Hall constant dependences (Fig. 4), will be determined by changes in the electron mobility, then

$$\frac{\rho(P)}{\rho(0)} = \frac{\mu(0)}{\mu(P)} . \qquad (2)$$

As follows from the Table, the relative decrease in electron mobility for undeformed n-Si single crystals irradiated by the electron flow of $5\cdot 10^{16}$ el./cm^2 is greater than for uniaxially deformed. This explains, according to (2), the decrease of the value of the tensoresistance $\frac{\rho(P)}{\rho(0)}$ under irradiation for these single crystals relative to the unirradiated silicon single crystals.

Table. Relative decrease of the Hall mobility of undeformed and uniaxially deformed n-Si single crystals.

Electron irradiation flow of Ω, el./cm^2	Relative decrease of Hall mobility α, %		
	Undeformed silicon single crystals	Uniaxially deformed silicon single crystals along the crystallographic direction [100]	Uniaxially deformed silicon single crystals along the crystallographic direction [111]
$5\cdot 10^{16}$	2.7	0.5 (0.89 GPa)	1.3 (0.89 GPa)
$1\cdot 10^{17}$	5.4	8 (0.82 GPa)	6 (0.84 GPa)
$2\cdot 10^{17}$	7	16.6 (0.86 GPa)	8.4 (0.84 GPa)

For irradiated n-Si single crystals by the electron flows of $1\cdot 10^{17}$ el./cm^2 and $2\cdot 10^{17}$ el./cm^2 the situation, according to Table, changes to the opposite. In this case, the relative decrease in the electron mobility and, accordingly, the value of a tensoresistance for the uniaxially deformed n-Si single crystals increases with increasing electron irradiation flow. Such features of the dependences of electron mobility on the irradiation flow for undeformed and uniaxially deformed n-Si single crystals along the crystallographic direction [100] can be explained by the influence of the mobility anisotropy factor that arises in silicon for this deformation orientation. As is known [12], for undeformed silicon single crystals the electron mobility

$$\mu = \frac{1}{3}\mu_{\parallel} + \frac{2}{3}\mu_{\perp} , \qquad (3)$$

where $\mu_{\perp}$ and $\mu_{\parallel}$ is the electron mobility across and along the axis of the ellipsoid.

Electrons will be in two minima of the conduction band with less mobility $\mu_{\parallel}$ at the strong uniaxial pressures along the crystallographic direction [100]. In doing so, the sensitivity of the mobility μ and $\mu_{\parallel}$ to the influence of electron irradiation will be different, which explains the data in Table 1 and the dependence of tensoresistance for the uniaxially deformed n-Si single crystals along the crystallographic direction [100]. Mobility anisotropy will not be arise at the uniaxial pressure along the crystallographic direction [111]. But in this case the effective mass of electrons increases. The increase in the effective mass leads to changes in the screening radius, which, in turn, impact on the potential energy of the electron's interaction with the scattering centre and, accordingly, the electrons mobility. Such scattering centres for electrons in irradiated silicon single crystals are impurity phosphorus ions and created radiation defects. The change in the electron scattering conditions during deformation, in this case, is the cause of different dependences of the Hall mobility on the electron irradiation flow for undeformed and uniaxially deformed n-Si single crystals. These dependencies will determine the features of the tensoresistance of uniaxially deformed n-Si single crystals along the crystallographic direction [111] for different electron irradiation flows (Fig. 3).

CONCLUSIONS

Studies of the tenso-Hall effect and infrared Fourier spectroscopy have made it possible to establish the mechanisms of tensoresistive effect at the uniaxial pressures along the crystallographic directions [100] and [111] for electron-irradiated n-Si single crystals at room temperature. Dependences of the resistivity of the investigated n-Si single crystals on the uniaxial pressure are determined only by the change in the electron mobility. The electron concentration does not depend on the uniaxial pressure, because the deep levels of radiation defects belonging to the VO_i and VO_iP complexes will be completely ionized. Ionization of the deep E_v+0.35 eV level belonging to the C_iO_i defect will not occur under the action uniaxial pressure at room temperature. Dependence of the tensoresistance on the electron irradiation flow at uniaxial pressure along the crystallographic direction [100] is explained by the deformation-induced anisotropy of electron scattering on the created radiation defects. This leads to an increase of the scattering efficiency of electrons on radiation defects and, accordingly, to a greater relative decrease of electron mobility for the uniaxially deformed n-Si single crystals relative to undeformed n-Si single crystals. The increase in the value of the tensoresistance of uniaxially deformed n-Si single crystals along the crystallographic direction [111] at the flows of $\Omega \geq 1\cdot 10^{17}$ el./cm^2 is associated with changes in the screening radius due to the increase in the effective electron mass and, according, of the conditions of their scattering on radiation defects during deformation. In [17], it was found that the magnitude of the tensoresistance of silicon, uniaxially deformed along the crystallographic direction [100], can vary depending on the relative contribution of f- and g-transitions to intervalley scattering. In this case, the increase in the tensoresistance and, accordingly, the tensosensitivity of n-Si single crystals is achieved by reducing the temperature. Need for an additional cooling system with the aim of increasing tensosensitivity and the temperature calibration of pressure sensors, manufactured on the basic of such silicon single crystals, significantly complicates their structure, increases cost and reduces the scope of operation. Also, the use of doping technologies by the donor or acceptor impurities does not increase the tensosensitivity of silicon at room temperature [18]. In our case, such an increase in the tensosensitivity of n-Si can be achieved only by increasing the flow of electron irradiation, which is an advantage. Therefore, the obtained results can be used in the design of high uniaxial pressure sensors based on irradiated n-Si single crystals with the predetermined coefficient of tensosensitivity.

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ТЕНЗОЕЛЕКТРИЧНІ ВЛАСТИВОСТІ ОПРОМІНЕНИХ ЕЛЕКТРОНАМИ МОНОКРИСТАЛІВ n-Si

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Досліджено тензоопір при одновісному тискові для опромінених електронами монокристалів n-Si при кімнатній температурі. Досліджувані монокристали кремнію були леговані домішкою фосфору, концентрацією N_d=2,2·10^{16} см^3, та опромінювались потоками електронів 5·10^{16} ел./см^2, 1·10^{17} ел./см^2 та 2·10^{17} ел./см^2 з енергією 12 МеВ. Вимірювання питомого опору та сталої Холла проводились для одновісно деформованих вздовж кристалографічних напрямків [100] та [111] монокристалів n-Si. На основі вимірювань тензо-холл-ефекту та інфрачервоної Фур'є-спектроскопії були встановлені механізми виникнення тензорезистивного ефекту для досліджуваних монокристалів n-Si. Показано, що тензоопір для даних монокристалів визначається лише змінами рухливості електронів при деформації. При цьому концентрація електронів не залежить від одновісного тиску, оскільки глибокі рівні радіаційних дефектів, що належать комплексам VO_i VO_iP, будуть повністю іонізованими. Іонізація глибокого рівня $E_V + 0{,}35$ еВ, що належить дефекту C_iO_i, за рахунок деформації не буде проявлятися та впливати на тензоопір n-Si. Встановлено, що анізотропією розсіяння електронів на утворених радіаційних дефектах, яка виникає при одновісному тискові вздовж кристалографічного напрямку [100], є причиною різної величини тензоопору опромінених різними потоками електронів монокристалів n-Si. Залежність величини тензоопору одновісно деформованих вздовж кристалографічного напрямку [111] монокристалів n-Si від потоку електронного опромінення пов'язана зі змінами радіуса екранування за рахунок зростання ефективної маси електронів. Вперше одержане при кімнатній температурі зростання величини тензоопору монокристалів n-Si за рахунок опромінення потоками електронів $\Phi \geq 1 \cdot 10^{17}$ ел./см^2 може бути використане для конструювання сенсорів високого одновісного тиску на основі таких монокристалів n-Si з більшим значенням коефіцієнта тензочутливості відносно наявних аналогів. Такі сенсори матимуть підвищену радіаційну стійкість та широку сферу експлуатації.

Ключові слова: монокристали n-Si, радіаційні дефекти, тензоопір, електронне опромінення, тензо-холл-ефект, інфрачервона Фур'є-спектроскопія, анізотропія розсіяння.