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Mechanically Stimulated Changes in Surface Electrical Conductivity of X-Irradiated Silicon Crystals

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ABSTRACT

Changes in the resistance of single crystals of p-type conductivity silicon under the action of mechanical loading were investigated in this research. Also, non-irradiated and pre-irradiated X-rays experimental samples were studied. It was found that at small deformation values when they are at the initial stage of the action of elastic deformation, a section forms and increases, on which the resistance practically does not depend on the applied mechanical load. In irradiated crystals, at small deformation values, electron generation processes dominate, which then recombine with the main carriers – holes. The consequence of such processes is the appearance of a maximum increase in electrical resistance at the initial stage of elastic deformation of experimental samples irradiated with X-rays. Charge carrier generation processes begin to dominate with further deformation. Such processes occur as a result of the release of acceptor centers from other complex defects, which are destroyed during the deformation of the Si crystal and captured by mobile dislocations. Thus, the processes of generation of charge carriers prevail over the processes of gettering and, accordingly, a mechano-stimulated decrease in the electrical resistance of p-Si samples occurs.

Keywords: X-ray irradiation, silicon, uniaxial deformation, dislocation.

INTRODUCTION

One of the most pressing problems of modern microelectronics is the formation of high-quality and reliable ohmic metal-semiconductor contacts. The structural perfection of the surface of the semiconductor's near-surface layer plays a special role in the formation of the contacts [1, 2]. Heat treatment of crystals in the process of forming the corresponding structures is accompanied by partial relaxation of local mechanical stresses, an annihilation of internode atoms, as well as aggregation of point and linear defects. Mechanical stress relaxation processes in planar contact structures make it possible to improve the structural perfection of the surface of materials (*p*-Si), which in turn ensures the formation of high-quality ohmic contacts on them [3].

Today, the greatest attention is paid to solving scientific and practical problems of creating a new generation of sensors and ejection radiating devices based on a closed silicon cycle [4]. At the present stage, significant theoretical and experimental material has been accumulated for studying the parameters and properties of silicon-based semiconductor structures [3–7]. At the same time, some issues with the influence of technological processing of experimental samples on the stability and reproducibility of their parameters after repeated exposure to external factors remain unresolved.

The redistribution of the concentration of charge carriers, and the evolution of structural defects in deformed and X-ray irradiated *p*-Si crystals is largely determined by the perfection of the starting material, the presence and mobility of dislocations, which are drains for charges and defects, especially in the near-surface region [8]. In addition, a surface with sprayed metal contacts is an effective getter for deep-level structural defects [9, 10]. The discrepancy between the parameters of the crystal lattices and the metal contact sprayed on it leads to the appearance of local mechanical stresses [11]. Radiation exposure of crystals and devices of semiconductor electronics is accompanied by the accumulation of charges on internal defects, changes in surface states, the formation of internal electric fields and fields in the semiconductor-dielectric contact area, and so on [6, 9]. These and other mechanical and radiation-stimulated effects stimulate changes in the electrophysical parameters of crystals. As a result, the effects deteriorate the operational characteristics of microelectronic devices [11, 12]. Therefore, the study of mechanical stress relaxation processes and their effect on changes in the electrophysical characteristics of Si crystals under the influence of external factors is relevant.

Materials and Methods

In this paper, single-crystal samples of *p*-type conductivity silicon grown by the Chokhralsky method are studied (ρ = 10 *Ohm·cm*), size 3.55×3.99×7.60 mm. Cutting, grinding and polishing of crystals was carried out according to the standard method. Before spraying the ohmic aluminum contacts (Al), the crystals were etched in an alkaline herbalist and washed in distilled water. The surface has been polished in a mixture of $HF+HNO_3$ acids (1:3) for 25 sec. Afterwards, the crystals were washed in methyl alcohol. Vacuum ($p = 10^{-3} Pa$) spraying of ohmic contacts (Al) on the crystal in the form of strips with a width of 2 mm was carried out on the plane (111) near the ends of the sample (Fig. 1). Gold microwires were welded to the Al strips by thermo-compression.

The samples were irradiated with X-rays using the URS-1.0 unit (U = 55 kV, I = 8 mA, W-anticathode). The distance between the source of X-rays and crystals was minimal (2 mm). The exposure dose was 492 R/min. The absorbed dose was increasing by 130 *Gy* in every 30 minutes [13]. Mechano-stimulated change in electrical conductivity $R(\sigma)$ the test samples were performed using the setup described in [13, 14].

RESULTS AND DISCUSSION

Fig. 2 shows curves of the mechano-stimulated dependence of changes in the electrical conductivity of a crystal on the number of elastic strain cycles. The analysis of the patterns of changes in these dependencies shows that in the initial section of the action of the deformation, a section of weak dependence of the change $R(\sigma)$ (the dependence of the electric resistance on the magnitude of the elastic mechanical deformation) emerges and increases up to the 10th cycle with each subsequent cycle of compression-extension, starting with the second one on the dependence curves $R/R_0=f(\sigma)$.

Analysis of the regularities of mechano-stimulated changes in the electrical conductivity of *p*-Si crystals shows that at the initial stage (~ 0.6 MPa) of the first elastic deformation (uniaxial compression along the direction of [$11\bar{2}$], parallel to the plane (111)), the value of R/R_0 practically unchanged (Fig. 2, curve 1). This dependence may be due to the deflection of dislocations fixed at the edges, as well as shielding the

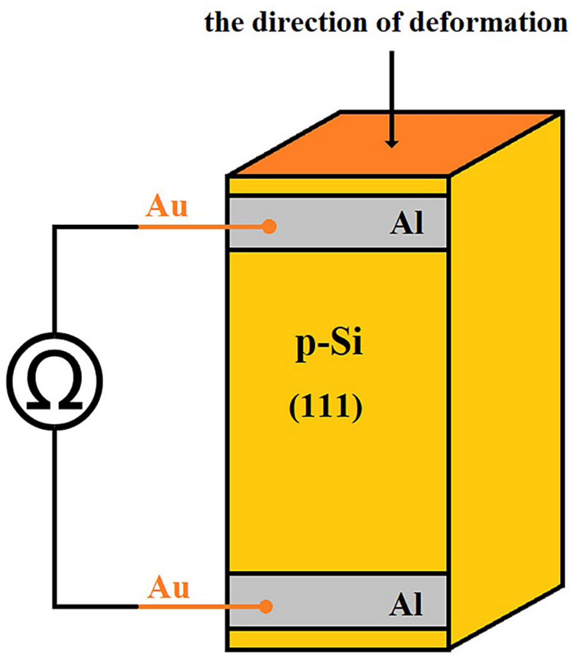

Figure 1. Schematic representation of the experimental sample.

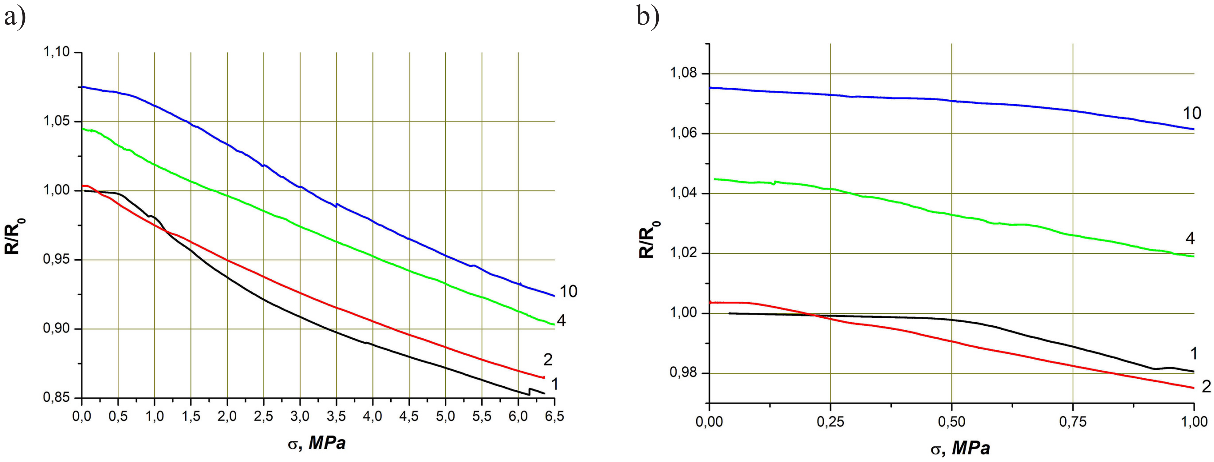

Figure 2. Mechano-stimulated change in the electrical conductivity of uniaxially elastically deformed crystals: 1, 2, 4, 10 – the cycles of elastic deformation (**Fig. 2**b – the initial deformation site is shown)

movement of charges by the stresses of internal contact fields due to the discrepancy between the parameters of the constant lattices Al and Si. Further uniaxial compression is accompanied by an exponential mechano-stimulated decrease in the resistance value, with the activation energy of the process commensurate with the energy of near-surface charge removal by dislocations with fixed ends.

Removing the load from the crystal and holding it at 300 *K* for twelve days in a vacuum chamber (10^{-2} mm Hg) without illumination is accompanied by a return of the initial resistance value R_0 almost to the original (original) value.

In the second cycle of uniaxial compression, the plot of the initial constant value of the mechano-stimulated change R/R_0 decreases from 0.6 to 0.08 *MPa*, and the further course of the curve $R/R_0=f(\sigma)$an almost linear function is described.

The difference in dependencies $R/R_0=f(\sigma)$ is explained by the mechano-stimulated generation of electrons and their subsequent partial recombination with the main charge carriers (holes) in the near-surface layer of the crystal, which leads to an almost unchanged value R/R_0 at the initial stage of deformation. Further course of curves $R/R_0=f(\sigma)$ indicates that the efficiency of generating mechanically stimulated electrons with subsequent recombination begins to dominate, as a result of which the hole concentration decreases. In the first strain cycle, the concentration of mechanically stimulated electrons is slightly higher than in the second, so the efficiency of electron-hole recombination is higher and the rate of decrease in the value is higher R/R_0 it is also larger (exponential). In the second cycle, dislocation deformations remove electrons from larger depths of the Crystal volume, so the efficiency of electron-hole recombination is slightly lower.

It should also be noted that ten compression-decompression cycles lead to an increase in the residual resistance of the sample in the total amount of ΔR = 13.4%, and the resistance of the test sample consists of the resistance of the bulk crystal and the resistance of the near-surface layer of the semiconductor-metal contact. In the area of the near-surface crystal layer where the Al film is deposited, due to the discrepancy between the parameters of the Al and Si lattices, a region of the crystal stress state is formed under the aluminum film. Under the action of the strain potential due to the discrepancy between the parameters of the Al and Si lattices, the value of electrical conductivity in the near – surface layer of the crystal increases and, as a rule, by 50–70% the mobility of charge carriers increases [13, 15–16]. In addition, the metal film deposited on the Si surface contributes to the formation of a site in the near-surface layer, which is an effective getter for deep-level structural defects [9, 13]. Such defects can be impurity atoms moved from the sample volume to the near-surface region, Si atoms that leave the lattice nodes at interstitial positions, and vacancies generated at such outputs [11]. Mechano-stimulated rearrangement of the defective state of the crystal and its near-surface layer leads to an increase in the capture centers of charge carriers with an increase in the number of deformation cycles. Therefore, at the initial stage of each subsequent strain cycle, the area ($\sigma_1 = 0 \div 0.15$ *MPa* and $\sigma_2 = 0 \div 0.70$ *MPa*) low-variable dependence $R(\sigma)$.

When the magnitude of the mechanical load increases after the area of insignificant *R(σ)* dependence, the processes of generation of the main charge carriers prevail over the processes of their gettering. Under the deformation of a crystal, defected complexes are destroyed and, as a result, acceptor centers are released, which are captured by mobile dislocations afterwards. The consequence of such processes is a mechanically stimulated decrease in the electrical resistance of *p*-Si samples.

The regularities of changes in the electrical conductivity of *p*-Si crystals during uniaxial elastic compression and expansion can be explained by a mechanically stimulated change in the band structure since the proportion of fast charge carriers increases during compression and decrease during expansion.

The effect of X-irradiation on experimental *p*-Si samples is accompanied by the generation of electrons and radiation defects, the evolution and healing of structural defects. These processes occur and are implemented with different probability at different time intervals and different values of radiation doses and the degree of deformation.

For unirradiated crystals, the initial region of elastic uniaxial deformation is dominated by electron generation processes, which then recombine with the holes present in the sample. The consequence of these processes is that the value of resistance of p-Si crystals increases at small amounts of mechanical load (Fig. 3).

For irradiated crystals, the increase in resistance under deformation occurs due to the generation of electrons that are localized on shallow donor centers. Under the action of deformation, such electrons are captured by mobile dislocations and carried to the near-surface area of the crystal, where they are then recombined with holes – the main charge carriers. Irradiation of the samples with X-rays and their subsequent deformation leads to a decrease in the value of the residual resistance ΔR from 13.4% to 10.6%. This can be caused by the simultaneous action of two opposite factors: electron generation and electron-hole recombination. It is known [10, 17–18] that X-irradiation of *p*-Si crystals leads to an increase in the dislocation path by about 3–4 times. In this case, the effect of increasing the mileage increases with an increase in the absorbed radiation dose, that is, there is a radiation-plastic effect.

For previously irradiated *p*-Si crystals with X-rays, in which the localization of electrons occurs on shallow acceptor centers, relaxation processes are characteristic even at room temperature (293 K) and a duration of 18–24 hours. We believe that these relaxation processes are triggered by the movement of dislocations by means of climbing. This mechanism of movement of dislocations is very probable since the speed of dislocations increases significantly in silicon crystals under the action of X-irradiation. The consequence of such relaxation processes is that the irradiated crystal (D = 312 Gy) behaves like a non-irradiated (initial) sample under uniaxial elastic deformation.

Irradiation of experimental samples with X-rays is also manifested in the fact that the characteristic maxima on the compression and decompression curves (Fig. 3) begin to manifest themselves more clearly. This means that some of the electrons generated by X-irradiation can also be

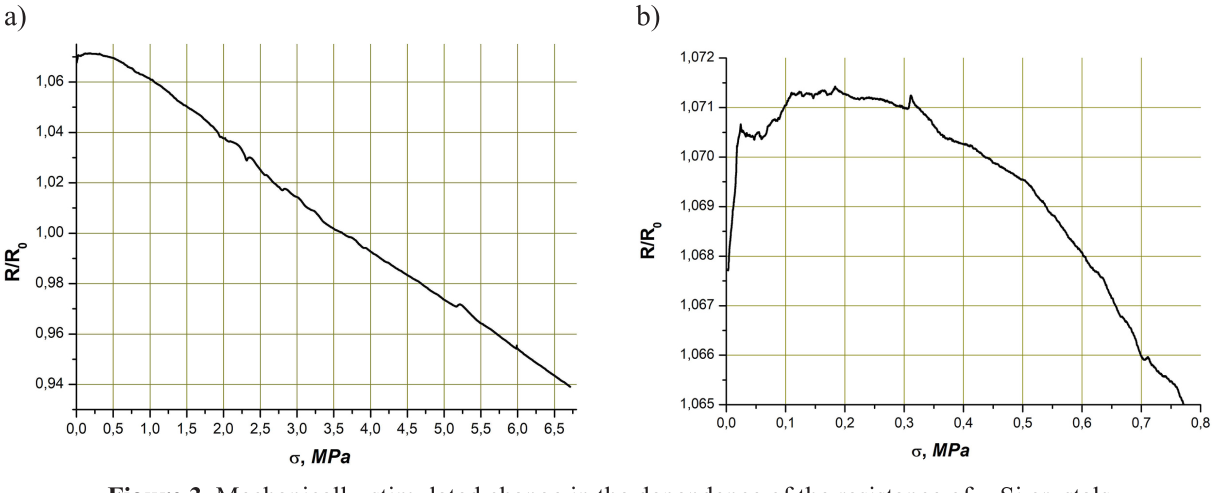

Figure 3. Mechanically-stimulated change in the dependence of the resistance of *p*-Si crystals irradiated with X-rays (D = 312 Gy) (in Fig. **3**b – the initial section is shown)

localized on more stable complex lattice defects formed as a result of repeated deformation cycles, and are released from them when certain values of mechanical stresses are reached, which can activate these defects, increasing their effect on certain patterns of changes in electrical conductivity.

CONCLUSIONS

For irradiated p-Si crystals, the increase in electrical resistance due to deformation is caused by electron generation processes. These electrons are captured by mobile dislocations and carried to the surface layers of the crystal. Then the electrons recombine with the available main charge carriers – holes. Once the recombination processes are completed, the resistance changes of the irradiated samples depend on the action of the mechanical load described by the same regularities as for non-irradiate crystals.

Point defects and more complex crystal lattice defects accumulate in the experimental crystals with an increase in the number of compression-decompression cycles of elastic deformation. Due to the movement of dislocations, such defects form clusters of different sizes, which leads to the formation of internal mechanical stresses. Corresponding macrodefects can localize charges, and dislocations can transfer electrons to the crystal surface under uniaxial compression. In the process of sample decompression, mobile dislocations and dislocation loops can move charges in the opposite direction: from the surface inside the crystal. The appearance of characteristic maxima on the dependence curves of $R(\sigma)$ may indicate the beginning of irreversible changes in the crystal structure that occurred under the action of deformation.

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