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The influence of high energy irradiation on electrical and dissipative properties of silicon single crystals

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Behavior of internal friction δ and electric resistance in silicon single crystals with low dislocation density (10–100 cm^{-2}) has been studied during of bombardment with α-particles. Effect of strengthening has been found as well as change of direct hysteresis into reverse one in amplitude dependence of internal friction at increasing α-irradiation dose rate. The fact is explained by blocking of charged dislocations by radiation-induced vacancies and areas of charge separation formed due to secondary infrared irradiation.

Изучено поведение внутреннего трения δ и электрического сопротивления монокристаллов кремния с низкой плотностью дислокаций (10–100 см$^{-2}$) в процессе бомбардировки α-частицами. Выявлен эффект упрочнения и изменения прямого гистерезиса на обратный на амплитудной зависимости внутреннего трения при увеличении мощности дозы α-облучения. Это объясняется блокировкой заряженных дислокаций вакансиями радиационного происхождения и формирующимися вследствие вторичного инфракрасного излучения зонами расслоения заряда.

Semiconductors with diamond type lattice are used as functional material in solid-state electronics. The problem of great importance is how to provide mechanical and radiation resistance of products made from these materials. To solve that problem, the profound physical and chemical processes taking place in the substance under irradiation are to be researched. The study of these processes is especially urgent in case of irradiation by high-energy particles with low penetrating ability. This is connected both with nanotechnologies development in electronics and higher requirements to quality and surface radiation stability, and with the whole spectrum of secondary radiation effects increasing the depth of damaged substance layer which have still to be studied [1, 2].

When investigating secondary radiation effects in semiconductors, quite informative is a study of electrical and dissipative properties combination. Electrical resistance is rather sensitive to the appearance of new point effects, while internal friction (IF) informs us about charge state in structural defects, the damage accumulation rate and fatigue strength of the material as a whole under loading of different frequencies and amplitude [3].

The factor hindering the wide application of IF method to semiconductors with diamond type lattice is the high fragility thereof and necessity to strain rather thin samples (in case of weak penetrating irradiation).This is especially valid for silicon which is highly fragile. Thus, neither a problem of α irradiation influence on silicon mechanical relaxation processes, nor processes of inductive light fluxes in visible and infrared bands of electromagnetic radiation spectrum when primarily knocked out atoms are braked have been sufficiently studied to date [4]. So, the aim of this work was to study electrical and dissipative properties of silicon single crystals at different orientations immediately in the course of its irradiation with high energy α-particles.

The study object was high purity *p*- and *n*-Si which is used for epitaxial growing of silicon films in integrated circuit production. For samples with boron admixture (*p*-Si, $N_B > 10^{16}$ cm^{-3}) dislocation density was $N_d = 10$ cm^{-2} (when specific electrical resistance is $\rho = 0.5$ Ohm·cm). For samples with antimony admixture (*n*-Si, $N_{Sb} > 10^{17}$ cm^{-3}), $N_d = 100$ cm^{-2} (electrical resistance $\rho = 0.013$ Ohm·cm). Oxygen concentrations N_{O_2} were about 10^{16} cm^{-3} in both sample types. Silicon ingots were grown by the Czochralsky technique. From the ingots, plates shaped as disks of 410±20 μm thickness and 60 mm diameter were cut out perpendicularly to [111] crystallographic direction using an Almaz-6 machine, and then the plates were ground on both sides and polished. The damaged layer was removed from the plate surface by chemical and mechanical polishing. Obtained plates had mirror-like surface of 14th purity class. The single crystal samples shaped as 12 to 60 mm long and 5–6 mm wide strips were cut out from the discs along $<01\bar{1}>$ и $<\bar{2}11>$ directions.

The low frequency bending vibration method [2] was used to measure mechanical decrement. Specific electrical resistance ρ was determined by four-probe method. Plutonium sources with activity of $3.7 \cdot 10^7$ to $5.53 \cdot 10^7$ Bq were placed parallel to the surfaces of the samples to be bombarded by α-particles of about 5.1–5.5 MeV energy at the distance of 3–4 mm.

A typical IF amplitude dependence (ADIF) curve for *n*-Si (Sb) (with orientation of normal voltage $\sigma \parallel <01\bar{1}>$ prior to irradiation is given in Fig. 1. Its general view corresponds to literature data [2, 5]. As to *n*-Si $<\bar{2}11>$, a more complex non-monotonous motion of amplitude dependence has been revealed containing a maximum. Its nature will be considered elsewhere. This work will look at the simplest case (Fig. 1).

Experimental studies of damping immediately in the course of irradiation with α-particles at flux density $5 \cdot 10^6$ particles· cm^{-2}·c^{-1} evidence a slope decrease of internal friction amplitude dependence (ADIF) (Fig. 1, curve *2*). The dose rate increase up to $7.6 \cdot 10^6$ cm^{-2}·s^{-1} has confirmed the same trend of ADIF decrease (Fig. 1, curve *3*). As ADIF in silicon is explained by admixture-dislocation interaction [5, 6], the trend to ADIF slope decrease is an evidence of fixation (blockage) of dislocations under irradiation. The substantial absence of ADIF shown by curve *3* proves a significant reduction of dislocation mobility and material strengthening.

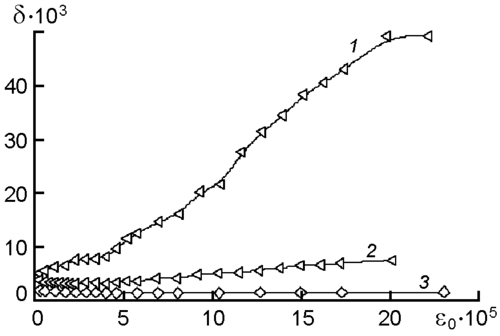

Fig. 1. ADIF of *n*-Si$_{<011>}$ single crystals prior to irradiation (*1*) and during irradiation with α-particles. Dose rate: $5 \cdot 10^6$ cm^{-2}·s^{-1} (*2*) and $7.6 \cdot 10^6$ cm^{-2}·s^{-1} (*3*).

Preliminary ADIF studies at loading/unloading prior to irradiation have shown that when the amplitude decreases, the ADIF curve lies higher, i.e. the well-known direct hysteresis is observed [2, 6]. However, under α-particle beam, as it has been found, the direct hysteresis changes to reverse one (Fig. 2). Anomalous curves of this type can be found in scientific literature but only seldom. A similar ADIF behavior in alkali halide crystals [7] has been explained by charged dislocations blockage by cation vacancy surroundings of Debye-Hueckel type. Thus, the ADIF slope reduction at increasing dose rates, a characteristic reverse hysteresis allows to suggest, along with the known literature data, a fixation of dislocations in silicon and its strengthening, perhaps due to sweeping of radiation-induced vacancies by charged dislocations.

Here, the movement of individual dislocation sections according to the known bending mechanism by small distances [5] is obviously blocked to a lesser degree, thus defining a stable, radiation-resistant, somewhat increased IF level at small amplitudes (Fig. 3).

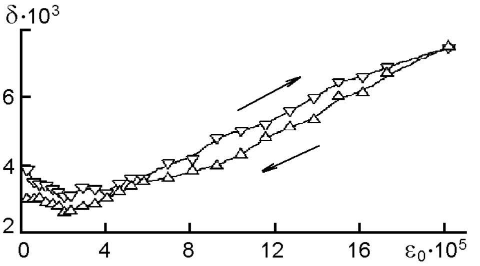

Fig. 2. Reversed ADIF hysteresis in *n*-Si<011> single crystals, obtained under α-particle beam ($5\cdot10^6$ particles$\cdot$cm$^{-2}\cdot$c^{-1}).

The studies of specific electric resistance changes at the moments of onset, end, as well as during the irradiation process indicates correctness of the approach being developed. In the course of irradiation, the electric resistance increases monotonously, indicating the accumulation of defects in the material. At the moments of irradiation onset and end, practically no substantial changes of specific electrical resistance ρ are observed in semiconductor with electronic conductivity. Relative determination error of ρ is ±0.3 %. A different situation has been observed in case of silicon with hole conductivity (Fig. 3). At the irradiation onset and end, the conductivity jumps have been noticed. At the moment of irradiation cessation, those jumps look unusually (Fig. 3, dashed line *2*).

The electric resistance dropped first by about 1.5 % during the first 60 seconds. Then it restored to the original value approximately in 170 s. Later, a slower process went on. Electrical resistance grew with gradual slowing down of gain rate, becoming practically constant in about 1200 s from the moment of source removal.

It is known that the major dislocation motion mechanism in deep potential relief of Payerls, that is characteristic of crystals with diamond-type lattice, is thermally activated generation of single bends from the surface and their diffusion along the dislocation segment [5]. As the obtained results show, this process is blocked by α-irradiation. Moreover, it is blocked irreversibly, as after α-irradiation source removal, the ADIF slope increased (dislocations became more active). However, it is to note that α-irradiation source was located on the one side of the sample (Fig. 4). In this case, origin of bends should occur on the other side of the sample and no dislocation blocking (decrease of ADIF) would be noticed (or at least it would be insignificant).

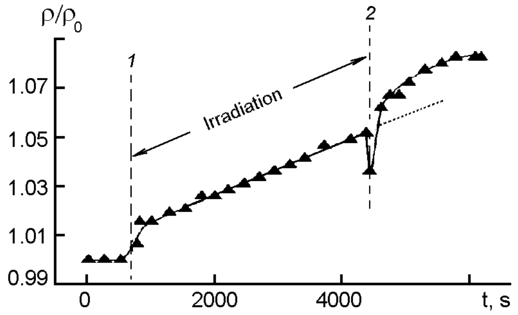

Fig. 3. Dependence of specific electric resistance p on irradiation time and relaxation effects in *p*-Si-<011> at dose rate $5\cdot10^6$ particles$\cdot$cm$^{-2}\cdot$c^{-1} ($\rho_0 = \rho$ at $t = 0$).

Considering the fact that α-irradiation has a low penetrating capability (about 7–9 μm at mentioned α-particle energy) and cannot directly block the origin of dislocations at the reverse side of the sample ($h = 410$ μm), it is necessary to clarify the effect mechanism.

During silicon irradiation with α-particles [8], introduction of one 5.1 MeV α-particle produces about 3.1 MeV as electromagnetic irradiation in near infrared spectral range. Silicon is transparent to infrared light with wavelength higher than 1 μm. Thus, a fraction of α-particle energy is absorbed in the semiconductor surface layer, creating irreversible structural changes therein. Another energy fraction of the penetrated α-particle is spent to generate and emit electromagnetic waves in infrared spectral range.

When light quantum energy exceeds 1.12 eV (band gap width in silicon at 300 K [9]), generation of charge carriers due to ionization of silicon atoms in caused by internal photoeffect. Along with that, the carrier generation is more probable due to ionization of admixture atoms located in the lattice sites, since it requires an order lower activation energy than the width of Si band gap. The Sb donor level energy is only 0.039 eV, and boron atom acceptor level is 0.045 eV [9].

According to [9], dislocations in *n*-type crystals behave as linear negative charge. Electrostatic interaction between ionized atoms resulting from α-particles bombardment and charged dislocations results in formation of complexes indestructible in the course of cyclic straining. Judging from the time of conductivity relaxation, a long-term relaxation of carriers could be suggested. Moreover, n-Si irradiation does not change the type of energy carriers, consequently, there are no significant conductivity jumps. Electric resistance increase during the irradiation process is obviously explained by accumulation of point defects like displaced atoms, active centers, defect clusters, etc. Peculiarities of conductivity behavior at irradiation cessation evidence the formation of volume defects from electrically active admixtures which causes spatial separation of major and minor carriers, in accordance with [1]. The existence of such defects is controlled by long-term relaxation with characteristic time of a thousand seconds and becomes the main reason for dislocation blockage in the process of small-amplitude straining at IF measurements when the fluctuation period is fractions of a second.

A careful analysis of the obtained results on electrical resistance change at the moments of irradiation onset and cessation for silicon with different conductivity types as well as differences between relaxation sections in n- and p-Si after irradiation cessation enables us to propose a model of volume defect (cluster) structure in p-Si with charge separation, schematically shown in Fig. 4. In this model, the cluster envelop is formed by major carriers (holes) while the cluster nucleus is formed by minor carriers (electrons). During α-particle irradiation process, the secondary infrared irradiation generates (due to photoeffect) photoelectrons, which recombine with major carriers (holes). This decreases concentration of major carriers (holes) and supports a moderate level of electrical resistance. The irradiation cessation results in a rather sharp decrease of electrical resistance (quick relaxation) as a result of decrease of recombination processes role and increase in major carrier concentration (Fig. 3, dotted line *2*).

The presence and character of long-term relaxation following quick (recombination) relaxation is an evidence of the fact that it is just negative charge that accumulates inside the cluster. The excessive non-balanced fundamental carriers (holes) located outside the cluster envelope must penetrate into straining area overcoming the electrostatic potential barrier to return the system into balanced state. The height of this barrier will define the relaxation time. It is essential that in the course of long-term relaxation, the electrical resistance grows (Fig. 3, above the dotted line *2*), since the concentration of major carriers (holes) gradually goes down as they recombine with cluster nucleus electrons.

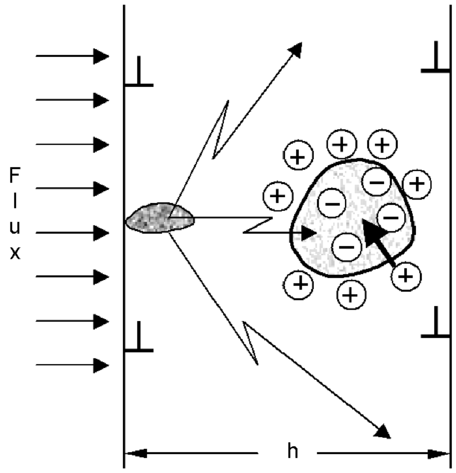

Fig. 4. Disturbance areas in p-Si plate of thickness h.

Thus, a strengthening is observed immediately in single silicon crystal samples with low dislocation density (10–100 cm^{-2}) bombarded with α-particles when measuring internal friction. The strengthening increases as the dose rate rises up to $7.6 \cdot 10^6$ particles/($cm^2 \cdot c$) and gradually disappears when irradiation is over. The strengthening is accompanied by weak anormalous (reversed) hysteresis of damping amplitude dependence. A mechanism of strengthening effect under irradiation has been proposed based on blockage of charged dislocations by areas of charge separation as a result of volume photoeffect under the influence of α-induced infrared irradiation near surface to which silicon is transparent. Investigation concerning influence of α-particle irradiation onset and end moments on silicon conductivity shows that this conductivity changes in time, which is a manifestation of volume photoeffect with memory elements. Peculiarities of electrical resistance relaxation in Si with different conductivity type at the moments of α-particle bombardment cessation show that areas of radiation-induced deviations formed during irradiation are caused by space separation of major and minor carriers.

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Вплив високоенергетичного опромінювання на електричні і дисипативні властивості монокристалів кремнію

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Вивчено поведінку внутрішнього тертя δ і електричного опору монокристалів кремнію з низькою щільністю дислокацій (10–100 см$^{-2}$) у процесі бомбардування α-частками. Виявлено ефект зміцнення і зміни прямого гістерезису на зворотній на амплітудній залежності внутрішнього тертя при збільшенні потужності дози α-опромінення. Це пояснюється блокуванням заряджених дислокацій вакансіями радіаційного походження і зонами розшарування заряду, які формуються у результаті вторинного інфрачервоного опромінення.