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Relation between structure inhomogeneities and relaxation processes in excited silicon crystals

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The part played by electric current pulses in formation of residual electroplastic effect and the "electric memory" effect in dislocation-containing silicon crystals has been investigated. The character of the observed effects has been found to be defined by parameters of electronic excitation and to result from relationship between the charge state and its relaxation in motionless and mobile dislocations.

Исследована роль импульсного электрического тока в формировании остаточного электропластического эффекта и эффекта "электрической памяти" дислокационных кристаллов кремния. Установлено, что характер найденных эффектов регулируется параметрами электронного возбуждения и обусловливается связью между зарядовым состоянием и его релаксацией в неподвижных и подвижных дислокациях.

Both experimental studies and theoretical principles of nonequilibrium processes are now in progress [1, 2]. The processes resulting in semiconductor memory associated with the appearance of nonequilibrium stimulated conduction (SC) or residual conduction (RC) as well as the long-time conduction relaxation (LCR) in semiconductors are under intense investigation. The slow RC relaxation (or its essential absence) is elucidated by hindered recombination of the current carriers that may take place in the following cases: (i) the presence of macroscale potential barrier separating spatially the recombining carriers; (ii) capture of one carrier by deep attachment levels; and (iii) transition into a quasi-nonequilibrium state in the extrinsic band. The carrier transfer into the RC state occurs in the intrinsic conduction band or in the extrinsic one; the drift potential barriers are taken into account, too.

The presence of a potential relief in samples exhibiting SC (or RC) is confirmed by a number of additional facts. In most cases, the samples showing such properties are subjected preliminarily either neutron irradiation or a special doping, or heat treatment in a specified atmosphere. All those influences favor the formation of inhomogeneities. Some other treatments that form inhomogeneities in the sample and simultaneously impart the SC and LCR thereto are also worth to note. Those include generation of dislocations by plastic straining, formation of structure distortions and inhomogeneities by laser treatment, etc. The potential barriers appear, in particular, due to macrodefects. Such defects include, for example, intercrystallite boundaries, dislocations together with their surroundings, accumulations of point defects (clusters), segregation of alien phases as metallic and dielectric particles, finally, the doped region boundaries and the sample surface. There are also data on recombination in elementary Ge and Si semiconductors containing dislocations and on the influence of Coulomb dislocation barrier due to an excess charge at dislocations on the major and minor carrier lifetime [3–5]. The scientific activity in investigations of the long-time relaxation of structure defect charge states is explained by the hope that these investigations favor the understanding of the memory effect in semiconductors.

Consideration of literature data on LR and RC allows to suppose that non-equilibrium electron states may arise in dislocation-containing Si crystals under electric current pulses. These non-equilibrium electron states are connected with the presence of space charge about the dislocation as well as with effect of the Coulomb dislocation barrier. The investigations of the current pulse effect can be intended to create preconditions for revealing the charge state of defects (including dislocations) as well as revealing the relaxation processes of that charge state. That is, the "electric memory" of defects can be revealed through the non-equilibrium process study.

Our suggestions were confirmed in experiment. So, in [6], we have observed effects similar to the RC ones. The essence of the effects revealed consists in what follows. If silicon crystals are subjected first to a combined electric and mechanical pulse to tear off the dislocation from its start position and then the mobile dislocations are exposed to continued mechanical stresses only, the charge relaxation can be observed as well as changes in the dislocation kinetics and dynamics related thereto, that is, the "electric memory" and residual electroplastic effect (REPE) on mobile dislocations.

The matters related to the effect of direct electric current on motionless dislocations are of interest. To that end, we carried out experiments with motionless dislocations. Silicon crystals with introduced dislocations were exposed first to electric current pulses at different density values j of 10^5 to 10^6 A/m^2 and duration τ_{imp} of 10^{-4} to 10^2 s; as the electron excitation was over, mechanical stress $\sigma = 63.5$ MPa was applied. The preliminary treatment of silicon crystals containing dislocations with electric current pulses resulted in a considerable (100 %) hardening of surface layers under the following mechanical loading (Figure). According to [7, 8], a strong hardening due to illumination or electric field application (photo- or electroplastic effects) is connected with changes not only in the crystal structure but also in electron subsystem.

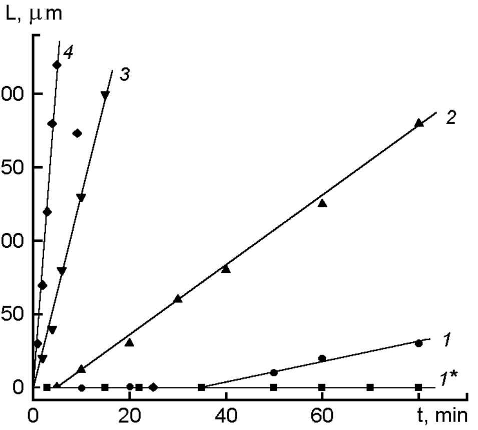

Fig. Dependence of dislocation mean free path on the duration of 63 MPa mechanical stress action at 823 K for initial silicon samples (*1*) and those passed by electric current at the density j (A/m^2): $1\cdot10^5$ (*2*), $5\cdot10^5$ (*3*), $1\cdot10^6$ (*4*). The samples 2, 3, and 4 were deformed in stationary mode, the current action duration being equal to that of mechanical loading. The sample 1* was deformed in pulse mode, the deforming was carried out after the sample treatment by current pulses.

The presence of broken dislocation bindings in the dislocation nucleus causes electron capture at those bindings, rise of the dislocation energy level E_d in the semiconductor band gap and electric charge appearance along the dislocation. The E_d level ascends due to Coulombian electron repulsion thereat as its electron occupancy increases and attains very fast the chemical potential μ value; then its occupancy process ceases. According to [9], this limitation results in low values of experimental occupancy coefficient for motionless dislocations as compared to mobile ones.

The dislocation charge q is known to be connected with the occupancy coefficient f by the relation $qb/e = f$ (where the dislocation charge q is normalized to the electron charge e and multiplied by the distance b between the broken bindings). Thus, the motionless dislocation charge can be supposed to be lower than that of mobile ones. Assuming that the radius of the Reed cylinder surrounding a dislocation (R_{shield}) is defined by the occupancy coefficient and the density of local extrinsic centers with energy E_t ($R_{shield} \sim (f/\pi na)^{1/2}$, where n is the center density), the following conclusion can be drawn. Since the motionless dislocations are characterized by the occupancy coefficient of dislocation broken bindings (DBB) f much lower than that of broken bindings of mobile ones, the shielding radius of motionless dislocations will be smaller than that of mobile ones. Considering two characteristic distances of an extrinsic center from a dislocation, R_1 and R_2, associated with different DCC occupancy extents, the following conclusion has been made in [9]: If the radius R_1 answers to a low f value and R_2, to high f, that is, if $R_1 < R_2$, then the electron transition probability from the extrinsic center to the dislocation exceeds the reverse process probability.

Applying the conclusions from [9] to our experimental results, it can be supposed that when a current acts on silicon crystals with motionless dislocations, the shielding radius of those dislocations is such that, starting from a certain value $\le R_{shield}$, the electron transition probability from the impurity to the dislocation becomes close to 1. This will result in a considerable increase of the dislocation charge and the corresponding increase of the Coulomb barrier. Perhaps that is why the motionless dislocations became unable to motion when treated with electric current. Other suppositions can be made on the current effect on motionless dislocations.

The dislocation mobility depends on the electric field configuration near their nuclei. In the case of motionless dislocations, in the opinion expressed in [10], the piezopolarization may be of importance for the dislocation nucleus charge. It can be assumed that the surface layer hardening of silicon crystals due to previous current action may be associated with mechanism mentioned in [10]. The store of electric excitation ("electric memory") is due to the presence of deep capturing states in the crystal volume. Both motionless dislocations and point defects may be such states. Thus, a change in the charge state of stable defects is characteristic for the hardening effects observed by us. The hardening effects caused by the "electric memory" storage are independent of the value and duration of the electric pulse acting previously on the motionless dislocations. The conservation time of that "memory" is essentially endless (the spontaneous relaxation processes are absent).

Thus, the pulsed electric current, being an excitation method of the electron subsystem, can be used to vary the silicon crystal strength. It has been established in experiment that previous treatment of silicon crystals by short electric current pulses results in appearance of residual electroplastic effect at the following crystal straining. For motionless dislocations, in contrast to mobile ones, the charge relaxation time is independent of the electron excitation parameters (the pulse density and duration).

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Зв'язок між структурними неоднорідностями і релаксаційними процесами в збуджених кристалах кремнію

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Досліджено роль імпульсного електричного струму у формуванні залишкового електропластичного ефекту та ефекту "електричної пам'яті" дислокаційних кристалів кремнію. Встановлено, що характер виявлениех ефектів регулюється параметрами електронного збудження і обумовлюється зв'язком між зарядовим станом і та його релаксацією у нерухомих і рухомих дислокацій.