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ATOMIC STRUCTURE AND NONELECTRONIC PROPERTTIES OF SEMICONDUCTORS

Electroplasticity of Undoped and Doped Silicon

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Abstract—A new technology of formation of dislocation dissipative structures in undoped and doped semiconductor crystals by the combined deformation, which makes it possible to control their elastoplastic properties, is suggested. New macroplastic properties of these crystals are found. From the obtained compression diagrams, various strain parameters are determined and surface microstructures of the obtained deformed samples are investigated. Possible physical explanations are proposed for the observed phenomenon.

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1. INTRODUCTION

In the last decade, special attention was paid to the effect of electroplasticity in crystals due to its wide applied significance [1]. The considerable contribution to the electroplasticity of metals creates a thermal pulse, which locally increases the temperature and results in dislocation mobility. The electric current used during the deformation of samples also produces a specific effect on structural defects [2], instead of only the thermal action on the crystal lattice. Therefore, the electroplastic deformation is, first of all, an increase in the plasticity and a decrease in resistance of the crystal to the deformation arising due to the nonthermal effect of the current on the plastic strain in the crystal [3]. Investigations of the magnitude of electroplastic effect, where the current density observed experimentally can be as high as 1000 A/mm^2, continued at a rapid pace [4, 5]. In this context, it seems to be of importance to study similar effects found in semiconductors. The electroplasticity effect discovered for germanium single crystals was considered in [6]. In this study, a similar effect was investigated for silicon single crystals.

2. EXPERIMENTAL

As the investigation objects, we selected undoped and boron-doped samples of p-type silicon single crystals with the resistivity $\rho_1 = 35$ kΩ m and $\rho_2 = 17$ Ω m in the form of parallelepipeds of 15 × 9 × 6 mm in size. One side was in parallel to the (110) plane, and two others were declined by 10° from (111) and (112) planes. The deformation was carried out along the (110) direction by the single-axis compression in vacuum at $T = 750$°C in the dynamic-load and creep modes. The shear stress varied from 0 to 25 MPa. The samples were heated by the direct-current flow with simultaneous heating by an external resistance furnace [combined plastic deformation (CPD)]. The current density amounted to 0.5×10^6 A/m^2. The voltage drop across the sample was 3 V. The released electric-current power amounted to 100 W. For the electron-microscopic investigation, the samples were first chemically etched for 1–2 min and then the obtained surface microstructures were investigated on the wide side of the sample by an SEM LEO 1450 scanning electron microscope. In this study, we investigated the macroplastic properties of the undoped and doped silicon under the CPD and, in this connection, revealed the features of the surface-microstructure formation. In addition, another purpose of this investigation was to clarify the CPD effect on the electrical properties of p-Si samples.

3. RESULTS

In Fig. 1, we show the experimental strain–shear-stress dependences σ(ε) for undoped and doped sili-

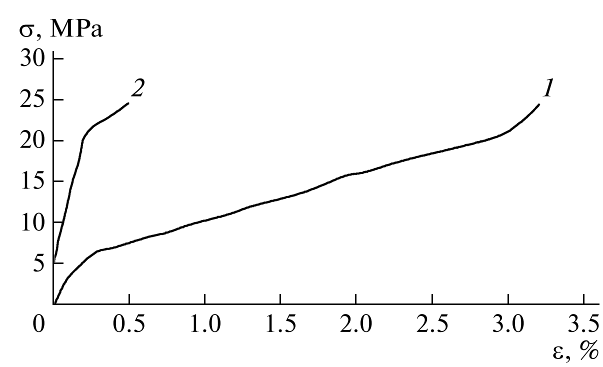

Fig. 1. Dependences of the shear-stress value σ on the strain value ε under conditions of the combined plastic deformation at $T = 750$°C for various samples of p-Si single crystals; (*1*) pure and (*2*) doped.

Quantitative characteristics of the deformation process

Sample	Coefficient of strengthening on portions of the dependence $\sigma(\varepsilon)$, $\gamma = d\sigma/d\varepsilon$, (MPa/%) %		Deformation rate on portions of the dependence $\sigma(\varepsilon)$, $\dot{\varepsilon} = d\varepsilon/dt$, s^{-1}		Strain value ε, %	
					dynamic mode	creep mode
Pure	1	16	1	2.4×10^{-5}	3.2	2.3
	2	5.3	2	7.8×10^{-5}		
	3	12				
Doped	1	73	1	4.8×10^{-6}	0.5	0.4
	2	14.6	2	2.3×10^{-5}		

con obtained under the CPD in dynamic mode. From these dependences, it can be seen that the run of curves radically differs. For the doped sample, a significant resistance of the crystal to deformation (see curve *2* in Fig. 1) is typical. The distinction between samples in purity also affects the strain parameters, such as the elastic limit, yield strength, and total strain value. As can be seen from the dependences $\sigma(\varepsilon)$, the presence of several step portions for the plastic deformation with various coefficients of strengthening γ (see table) is a characteristic feature of the sample-purity effect on the strain characteristics. In this case, we observe distinct alternation of them. For the doped sample, the constant coefficient of strengthening at initial portion 1 decreases stepwise at portion 2 (see curve *2* in Fig. 1). For an undoped sample, a somewhat different pattern is observed—γ increasing at the first portion is replaced by γ decreasing at the second portion, and then again by γ increasing at the third portion (table). In addition, the strain in an undoped sample much exceeds that in a doped sample. In Fig. 2, we show the increment ΔL for linear sizes during the deformation depending on the time *t* for *p* silicon. The strains ε at the same scale were determined from the formula

$$\varepsilon = \frac{\Delta L}{L} 100\%, \quad (1)$$

where L is the initial sample length.

The deformation rate $\dot{\varepsilon} = d\varepsilon/dt$ is expressed in units of [s^{-1}]. The displacement at $\Delta L = 300$ μm for curve *1* (Fig. 2) yields the strain $\varepsilon = 2\%$. Curves *1* and *2* of the dependence $\Delta L(t)$ (Fig. 2) are obtained simultaneously with the curves of the dependence $\sigma(\varepsilon)$ in the range of 0–25 MPa. As can be seen from Fig. 2, the deformation behavior of the crystal is also stepwise. The ratio between the deformation rates reaches 3 for different portions of curve *1*, and this ratio is ~4.8 for curve *2* obtained for the doped sample (table). If we compare the highest deformation rates between dependences *1* and *2*, the distinction amounts to ~3.5 times. In the doped crystals, the process of transformation of stationary dislocations into the mobile ones, which is additionally accelerated in the current-action mode, leads to the step change in the dislocation density. An increase in the dislocation density results in the motion delay due to the interaction with nearby opposite dislocations and impurities. For pure crystals, we observed no sharp increase in the dislocation density; consequently, no fast strengthening occurs.

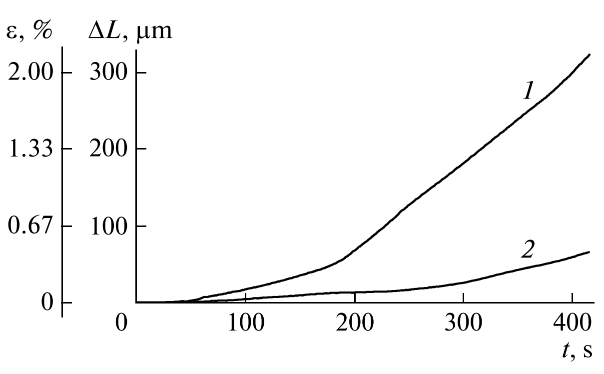

Fig. 2. Values of increment of linear sizes ΔL as functions of time *t* under conditions of the combined plastic deformation at $T = 750°C$ and the shear stress $\sigma = 0$–25 MPa for the samples: (*1*) pure and (*2*) doped. On the scale of ordinates, the strain values determined from Eq. (1) are shown.

4. DISCUSSION OF RESULTS

The obtained experimental dependences are characterized by a low yield stress, varying deformation strengthening coefficients and deformation rates on various portions, and also by the absence of "a high-temperature yield tooth" in contrast to [7], where the silicon samples were deformed under conditions of only hot plastic deformation (HPD). The total strain value for silicon samples subjected to the CPD action in this study considerably exceeds that for the same samples under HPD conditions. The direct electric current used in this study causes the relaxation of non-equilibrium dislocation groups (the blocked dislocation clusters, the rearrangement of clusters in slip lines, and the pinning of impurity to dislocations),

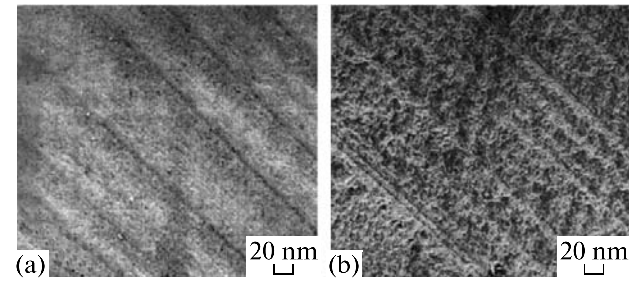

Fig. 3. Photographs of surfaces of *p*-Si samples under conditions of the combined plastic deformation: (a) pure and (b) doped.

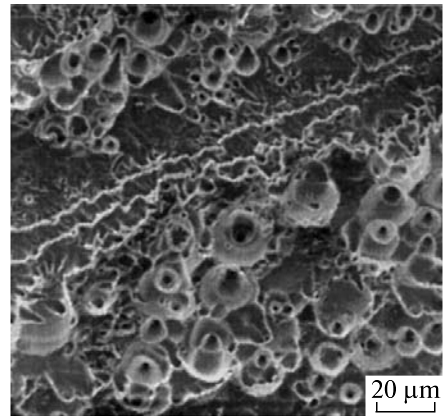

Fig. 4. Helicoidal dislocations propagating along the direction [110] in the doped *p*-Si single crystal.

which is accompanied by a macroplastic deformation. The dc density stimulates the displacement of charged dislocations capturing free electrons. However, the sensitivity of different samples to the electric field under the CPD proves to be different. The smooth shape of the compression curve for pure silicon may be related to a gradual propagation of strain through the crystal bulk [8]. For doped silicon, we observed a sharp transition from the linear compression portion to the dependence region corresponding to an intense strain. At the microscopic level, this means the transition from an individual to multiple slip accompanied by the generation, annihilation, and diffusion of defects in the mode of the directed high-energy flux.

The features of the structural relief formed in the sample bulk by the deformation defects representing the systematic features of formation of plastic wave fronts are shown in Fig. 3. The pure-sample surface was characterized by the presence of one slip-band system (Fig. 3a). For the doped sample, we observed the mutually orthogonal slip-band systems on the surface (Fig. 3b). Their penetrability is indicative of the fact that the dislocations start to play the role of the deformation-strengthening source. During the investigations, we also determined various quantitative characteristics: the slip direction for the primary and secondary bands and the distance between slip bands. These characteristics enable us to assess how the crystallographic shear bands are formed during the deformation. The band width amounts to about 40 μm, the direction of their primary slip is oriented under the angle of 75° to the compression axis for both samples, whereas the secondary-slip orientation for the doped sample continues under an angle of 55° with respect to the primary-slip direction (Fig. 3b). The formation of large crystallographic shears in the crystals under deformation represents an example of dynamic dissipative system of strongly interacting dislocations, in the evolution of which the effects of spatial and time self-organization [9] manifest themselves. Due to the capture of impurities by individual vacancies in the doped single crystal, they disappear [10]. Because of undersaturation of the crystal with vacancies, the dislocations are forced to creep and screw dislocations become helicoidal at such a process (Fig. 4).

The structural modifications caused by the plastic deformation at various load speeds resulted also in a sharp change in physical properties. The deformation leads to the displacement of energy levels in the semiconductor; to the redistribution of charge carriers between them; and, finally, to the change in electrical characteristics of the semiconductor [11]. As the measurements showed, the resistivity in the plastically deformed semiconductors increases differently in comparison with the initial crystal: 25 times for the pure silicon sample and 5 times for the doped one. One feature is the same for both pure and doped silicon: the resistivity measured along the compression axis proves to be lower than that measured in the transverse direction. For example, this difference amounts to 12 times for the pure sample and only 5 times for the doped one. It can be seen that this difference between the resistivity along and across pure samples proves to be almost 2.5 times higher with increasing deformation. It determines the anisotropic properties of such a crystal. The lifetime of minority charge carriers decreases stronger in pure samples than in the doped ones. The dislocations manifesting the acceptor properties and simultaneously carried away by the dynamic flow of electrons have time to generate the recombination centers due to which the lifetime of minority charge carriers decreases.

5. CONCLUSIONS

As a result of our investigations, we established that it is impossible to achieve a considerable strain value under conditions of hot plastic deformation at temperature and pressure identical with those under combined plastic deformation. The possibility of considerably reducing the shear-stress value and the elastic-region size appeared under the CPD in contrast to the HPD. We revealed appreciable distinctions in the plasticization of pure and doped silicon samples subjected to CPD action. The significant resistance to the plastic deformation takes place in doped single crystals, and the plastic deformation proceeds more efficiently in pure silicon single crystals. The CPD action on the semiconductor structure resulted in increasing of its resistivity in comparison with that of the initial sample. In this case, the resistivity decreases more strongly in the longitudinal direction, i.e., in the direction of the sample-compression axis, than in the transverse direction. Obviously, such a mechanism of the structure formation may have potential for developing the technologies of low-temperature processing of semiconductor crystals for the preparation, for example, of semiconductor pressure sensors.

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