Investigation of the nature of the diode effect on dislocations in silicon

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(Submitted April 9, 1974)
Zh. Eksp. Teor. Fiz. 67, 1148–1160 (September 1974)

The current-voltage characteristics of *p-n* junctions are investigated in *n* silicon in which regions with hole-type of conductivity were produced not by doping but by introducing, via plastic deformation, physical acceptors in the form of centers bound to dislocations. It is shown that the junctions thus produced are gradual and the reverse current of the junction is determined by generation-recombination processes at deep centers in the space-charge region. It is suggested that the forward current is limited by the space charge. The activation energies of the acceptor centers responsible for compensation are determined from the temperature dependences of the reverse current in the dislocation junction and of the electric conductivity of the compensated material. The limits of conductivity inversion are determined for initial *n*-silicon with different resistivities and dislocation densities. The temperature region where rectification occurs is also determined. Various mechanisms of formation of the electrical characteristics of the deformed region and of the *p-n* junction are discussed by analyzing the structures of the centers bound to the dislocations, the positions of the energy levels that describe them, and the kinetics of their filling during high-temperature deformation and annealing.

INTRODUCTION

As is well known, the fundamental basis of the overwhelming majority of semiconductor devices is the rectifying electron-hole junction. Until recently, in fact, the only method of producing such a junction inside a crystal was to dope the material during its growth, fusing, diffusion, etc. It was recently observed [1] that rectifying p-n junctions in single-crystal silicon can be produced by a qualitatively new method, which obviates the need for the doping the initial crystal with impurities. Inversion of the n-type conductivity in local sections of silicon was attained by introducing dislocations via special plastic deformation.

An investigation of the nature of the diode effect based on dislocations is of considerable scientific and practical interest. The very first results have demonstrated the possibility of using dislocation p-n junctions for the development [2] of a uniquely simple method of producing semiconductor diodes that recover their properties after breakdown. This uncovers attractive prospects for complete automatization of semiconductor-device production. A study of the mechanism of formation, of the structure, and of the various characteristics of dislocation p–n junctions makes it possible not only to point out new ways of using these junctions in technology, but to obtain abundant and more profound information on the changes that occur in the spectrum of the electronic states in a semiconductor as a result of dislocations.

The study of the influence of dislocations on the electric properties of semiconductor single crystals has a long history [3-16]. The peculiar stress field produced around the dislocations causes bending of the energy bands. In the region of large deformation gradients there can appear discrete levels in the forbidden-band, as a result of a detachment from one of the energy bands. This effect can be particularly noticeable in the case of screw dislocations, since dislocations having an edge component of the Burgers vector are more strongly influenced by the electrostatic potential. Most authors believe that the decisive factor in the change of the electric properties of the semiconductor is the appearance of new electronic states at these dislocations, with the cores of which are connected broken (unsaturated) covalent bonds. Depending on the position of the Fermi level relative to the dislocation levels, the broken bonds can either capture additional electrons (acceptor action of the dislocations), or give up their electrons to the conduction band (donor action). If the distance between the captured electrons is small in comparison with the average distance between the chemical donors or acceptors (and also between the dislocations), then a cylindrical region of screening charge is produced around a charged dislocation line. The radius of this region is such that the absolute values of the charge per unit length are the same for the dislocation and for the cylinder. The bending of the majority-carrier current around the screening space charge determines the carrier scattering, meaning also the change of the mobility.

The experimental data obtained mainly in investigations of the Hall effect, the conductivity, and recombination radiation of germanium single crystals agreed qualitatively with the previously developed concepts, but were highly contradictory when compared, in particular, with the experimentally-determined positions of the dislocation levels. The observed divergence of the results could be due to the masking influence of the impurities, which change their state in the field of the dislocation microstresses, and also to the difference between the dislocation structures of the investigated samples. The main efforts of many experimenters were therefore aimed at investigating weakly doped samples containing a sufficiently low dislocation density, such that it was relatively easy to monitor the type of dislocation and to guarantee that the screening Read cylinders did not overlap, thus ensuring a clear-cut disclosure of the anisotropic effects and the validity of the developed theories.

Measurements of samples containing a high dislocation density, at which overcompensation could be obtained, are extremely scanty.[14-16] The situation realized in this case is qualitatively different from that described above: the Read cylinders overlap and the semiconductor can be regarded as uniformly "doped" by physical acceptors (donors) connected with the dislocations. Although there are no developed theoretical models for this case, its investigation is of particular interest. First, in the process of overcompensation there should occur a considerable change in the position of the Fermi level relative to the dislocation levels. This should determine the possibility of observing a richer manifestation of the changes of the carrier energy spectrum of the semiconductor under the influence of the dislocations than in the case of crystals with few dislocations. Second, application of the large arsenal of methods developed for the study of the characteristics of p-n junctions to the investigation of "dislocation" electron-hole junctions produced at the boundary between the deformed and dislocation-free matrices uncovers new possibilities for the analysis of the electronic states connected with the dislocations.

We present in this paper the results of an investigation of the current-voltage characteristics of dislocations p-n junctions and of the conductivity of silicon that is overcompensated as a result of its dislocation levels. The dependences of the forward and reverse currents on the voltage and on the temperature are determined, and the region of existence of the diode effect in the silicon crystal with different contents of doping impurities and dislocations is established. The structure of the p-n junction is described and the mechanism of its formation is analyzed.

EXPERIMENTAL PROCEDURE

The initial samples for the investigation were cut from dislocation-free silicon single crystals of n-type, doped with phosphorus while grown by the Czochralski method. Unless specially stipulated, we used crystals with initial resistivity 100 Ω-cm at room temperature.

We investigated the current-voltage characteristics with samples subjected to local plastic deformation produced with an indentor [17] or by three-point bending. The deformation with a concentrated load was effected at 820°C. A four-face diamond indentor under a load of 2 kg was pressed into the sample {111} surface, which measured $10 \times 4 \times 1$ mm and had edges oriented along ⟨110⟩, ⟨112⟩, and ⟨111⟩, respectively.

The crystals subjected to bending were plane-parallel plates measuring $10 \times 3 \times 0.5$ mm. The bending axis ⟨110⟩ was perpendicular to the longest edge, and the broad face was oriented parallel to {100}. The samples were deformed for 3—5 minutes at 850°C under a load of 3 kg on the central support (a corundum rod) whose wedge-shaped edge of which was in contact with the crystal. The distance between the lower supports was 6 mm. After deformation, the sample assumed the form of a dihedron with angle between faces approximately equal to the apex of the corundum wedge. The transition region had a curvature radius ~ 1 mm. The plastically deformed region, with dislocation density 10^8—10^{10} cm^{-2}, was localized under the central support and penetrated through the crystal in the form of a column of width 1 mm. The electric contacts were welded to the deformed section and to the dislocation-free matrix. They were made of In, Au, and Au + 0.04% Sb.

An investigation of the influence of dislocations on the electric conductivity of the deformed region was made either with $3 \times 0.5 \times 0.5$ mm samples cut from the bent crystals, or with prisms deformed by compression at constant load. In the latter case, the samples measured $8 \times 3 \times 3$ mm and the edge orientations were ⟨111⟩, ⟨112⟩, and ⟨110⟩. The compression axis was parallel to the ⟨110⟩ direction. The deformation was carried out at 700°C in an argon medium or in air for 30 minutes at a pressure 10 kg/mm^2. The attained average dislocation density was ~ 10^9 cm^{-2}. In all cases the samples were cooled together with the oven to 400°C. After deformation, and also before the measurements, the samples were chemically polished in the standard solution (1 HF + 7 HNO_3).

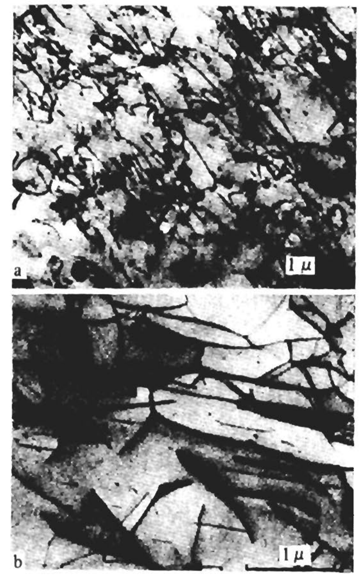

FIG. 1. Typical electron microgram of dislocation structure: a—overall view, the start of the formation of the cellular structure is observable; b—fragment of dislocation structure at large magnification. A large number of dipoles and dislocation loops is observed.

The dislocation structure of the deformed crystal was investigated by electron microscopy. The average density of the dislocations in the sections with inverted type of conductivity ranged from 10^8 to 10^{10} cm^{-2}. The dislocation structure in the investigated samples was in general inhomogeneous and corresponded to the structure observed (see [18]) on the initial sections of the creep curves during the stage when the deformation rate of the silicon decreases. It was the result of shear-formation processes that proceeded along several intersecting slip planes. The onset of a cellular structure, due to interlacing of the dislocations, is already noticeable. Inside the cells and in the interlacings one observes numerous dipoles of small height as well as loops. The dislocation lines remain linear only in small sections, and the bent shape predominates. Several examples of the observed dislocation-structure elements are shown in Fig. 1.

The current-voltage characteristics were investigated either with the aid of a "characterograph," or plotted point by point using the standard circuit. At low temperatures, the reverse currents were registered with a digital electrometer. The electric conductivity was measured by a dc four-contact method in the temperature interval 100—460°K. The Hall measurements were made also with direct current, using a electrometer with a dynamic capacitor in the field range 3—6 kOe and temperature range 200—290°K. The type of conductivity of the material was determined also from the sign of the thermoelectric power. The samples were annealed in air.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Current-Voltage Characteristic of Dislocation p-n Junction

The dislocation-induced diode effect was observed in n-Si crystals deformed with an indentor. However, when a p-n junction is produced in this manner, difficulties arise when it comes to varying the geometric characteristics of the junctions in the inverted region. Our investigations have shown that a rectifying p-n junction can be obtained with any method of deformation that ensures an abrupt boundary of the high-dislocation-density region. In particular, when the three-point bending described in the preceding section is used, it is possible to obtain a macroscopically flat p-n junction shape, rather than spherical as in the case of an indentor. By varying the dimensions of the samples and the distances between the supports, it was possible to vary the thickness of the inverted section and the area of the p-n junction. The general form of the room-temperature current-voltage characteristics of dislocation junctions (DJ) whose p-region was obtained by deforming with a concentrated load and by bending is shown in Fig. 2. At the chosen conditions, p-n junctions obtained by different deformation methods have close energy parameters. The entire discussion that follows pertains to DJ obtained by the two indicated methods.

A. Reverse-biased p-n junctions. The reverse branch of the current-voltage characteristic is shown in log-log scale in Fig. 3. It is easy to see that the reverse current (I_{rev}) varies with voltage U like $I_{rev} \sim U^{1/\gamma}$, where γ ranges from 2.9 to 3.3 for most investigated junctions. This value of γ indicates that the DJ are continuous, i.e., the "excess" concentration of the physical acceptors varies linearly, and the reverse current is a generation-recombination current determined by the generation processes on the deep centers in the space-charge region.

It is known (see [19]) that the generation-recombination (gr) centers are the most effective if they are energywise located near the center of the forbidden band. Therefore if the material contains gr centers with

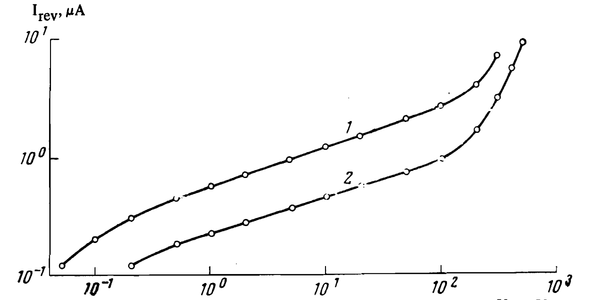

FIG. 3. Reverse branch of current-voltage characteristics of junctions: 1—spherical, 2—flat.

different positions in the forbidden band, then I_{rev} of the junction is determined only by those centers that lie closest to the center of the forbidden band.

The position of the deepest gr level can be determined by measuring the temperature dependence of the reverse current at different fixed values of U_{rev}. These measurements were performed on p-n junctions obtained by deformation with a concentrated load, and are shown in Fig. 4. It turns out that I_{rev} increases exponentially with increasing temperature: $I_{rev} \sim \exp(-\Delta E_1/kT)$, where $\Delta E_1 = 0.4$ eV. A comparison of the results with the data on the temperature dependence of the electric conductivity of the deformed region, presented in the second section, offers evidence that the gr level lies in the lower half of the forbidden band, 0.4 eV above the top of the valence band.

It can be stated that the gr centers are connected either with the intrinsic point defects produced by plastic plastic deformation (these should become annealed by deformation process itself[20,21]), nor with impurities that enter the crystal during the production of the contacts (the level of the gold that is fused with the silicon is 0.64 eV away from the valence band[22]). Since the $E_1 = 0.4$ eV level does not appear in any experiments on control (initial, dislocation-free) samples that have been subjected to the same treatment as the deformed sample, it can also be stated that the centers responsible for its appearance are connected with the dislocations. Of course, the dislocation can produce here two effects: the dislocation levels can either capture the electrons directly, or else complexes based on dislocations, including also intrinsic point defects, can participate in this process.

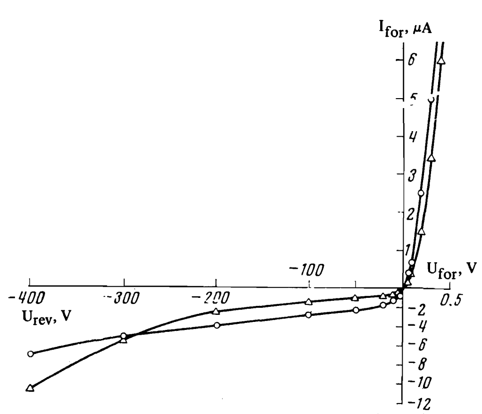

FIG. 2. General form of current-voltage characteristics of dislocation junctions obtained by deformation with a concentrated load (O, spherical junction) and by bending (△, flat junction); T = 300°K.

The relation $I_{rev} \sim U^{1/3}$ holds in the interval $U_{rev} \sim 0.5$—100 V. At higher voltages, the current increases strongly with increasing voltage (Fig. 5); this increase can be described by the function $I_{rev} \sim e^{\alpha U}$, where $\alpha \approx (10^{-2}$—$10^{-3})$ V. This indicates that electric breakdown takes place above 100 V. It can be due to impact ionization, the probability of which is quite high, since the values of the junction thickness obtained in investigations by a probe method range from 20 to 70 μ. However, impact ionization does not lead to formation of cascade breakdown, apparently because the defects produced by the plastic deformation greatly lower the electron mean free path.

B. Forward-biased p-n junction. It is known that for ordinary (defusion or alloyed) p-n junctions in silicon, the forward current is connected with the voltage by the exponential relation $I_{for} = I_0 \exp(qU/mkT)$, where m = 1

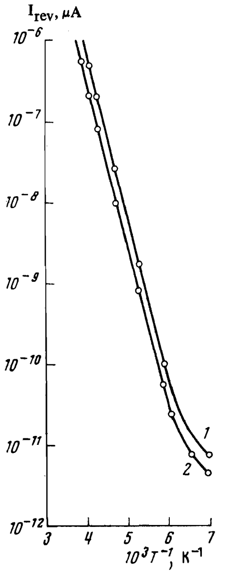

FIG. 4

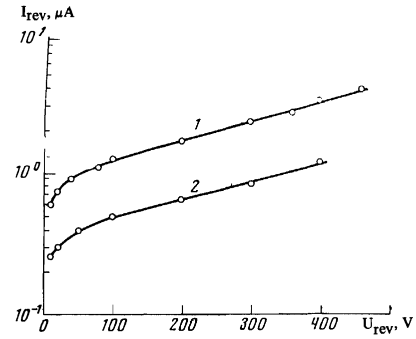

FIG. 5

FIG. 4. Temperature dependence of the reverse current: 1—U_{rev} = 9 V, 2—U_{rev} = 1 V, A = 0.4 eV.

FIG. 5. Reverse characteristic in the region of high U_{rev}: 1—spherical junction, $\alpha = 3.1 \times 10^{-3}\ V^{-1}$; 2—flat junction, $\alpha = 3.0 \times 10^{-3}\ V^{-1}$.

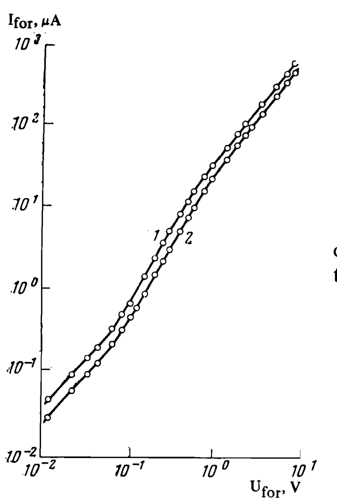

FIG. 6. Forward characteristics of dislocation junction: 1—flat junction, 2—spherical junction.

and m = 2 respectively for the diffusion and recombination currents. For the dislocation p-n junctions, however this dependence does not describe the experimental data: the experimental values plotted in coordinates log I_{for} and ($U_{for}q/kT$) do not fall on straight lines with slope 1 or 0.5. A plot of $I_{for}(U_{for})$ in a log-log scale is shown in Fig. 6. We see that the variation of the forward current in the voltage interval 0–10 V can be described by a power law function, $I_{for} \sim U^{\beta}$. At low forward voltages we have $I_{for} \sim U^1$. The current then increases in near-quadratic fashion, $I_{for} \sim U^{1.8}$. In the third section, the exponent decreases to 1.3. This dependence of the forward current on the voltage suggests that the current flowing through the DJ in the forward direction is space-charge limited (SCLC).

It is quite probable that for dislocation junctions in which the depletion region is broad enough (up to 100 μ) and has high resistivity, the conditions favor the appearance of SCLC, namely, the time of flight of the carriers through the depletion region is equal to the dielectric relaxation time [23]. This assumption allows us to regard the DJ actually as an analog of a p-i-n structure, in which the injecting contacts are junctions of the n-i and p-i type.

We can propose the following qualitative description of the main physical processes that determine the form of the forward characteristic of the dislocation p-n junction. At low voltages ($U_{for} \le 0.1$ V), the concentration of the injected carriers is small and the currents are described by the free carriers. In this region of U_{for}, Ohm's law $I = en\mu U/L$ is satisfied (e is the electron charge, n is the free-carrier density, μ is the drift mobility, and L is the width of the i-region. With increasing density of the injected carriers, the currents begin to be limited by their own space charge. In the ideal case, this process is described by the Mott-Gurney law $I = 9\epsilon\mu e U^2/8L^3$ (ϵ is the dielectric constant of the medium). The deviation from the Mott-Gurney law observed for dislocation transitions (in the interval of U_{for} from 0.1 to 1 V) does not fit the known concepts concerning the dependence of μ on the field intensity E under the strong-field conditions. If the scattering is due predominantly to phonons, then the drift velocity is [24] $v = \mu E_0^{1/2} E^{1/2}$, and the current-voltage characteristic should be described by an expression in the form $I_{for} \sim \epsilon\mu E_0^{1/2} U^{3/2}/L^{5/2}$. It follows therefore that in our case the field dependence of the mobility does not manifest itself as yet. Therefore, to explain the second section of the experimental curve it is necessary to assume an additional mechanism for the inelastic scattering of the carriers in the material containing the dislocations.

The assumption that injection currents flow through a DJ connected in the forward direction is confirmed in experiments performed at low temperatures. In the interval 150–200°K, the forward branch of the current-voltage characteristic reveals singularities analogous to those that appear either as a result of double injection [25] or in the presence of complete filling of the traps [23], which in our case are of dislocation origin.

The slower growth of the current in the third section (at U > 1 V) is apparently connected with the low injection ability of the contacts.

C. Region of existence of rectification effect. From the practical point of view, considerable interest attaches to a determination of the singularities of the variation of the current-voltage characteristics of a dislocation junction with changing temperature, and also to the boundaries where the type of conductivity becomes inverted and where rectification takes place (rectification coefficient ≥ 10) in silicon with different resistivity and dislocation density. Investigations of this type were carried out with samples having resistivities from 0.01 to 1000 Ω-cm, deformed with a constant load. At a dislocation density 10^9–10^{10} cm^{-2}, the inversion of the type of conductivity from n to p occurs in samples with resistivity $\rho < 3\Omega$-cm. However, in samples with $\rho < 3\Omega$-cm at room temperature there is no rectification. It appears only when the crystal is cooled to 100–150°K. At a temperature ≥ 100°C there is no diode effect in samples with any resistivity and any dislocation density. Measurements of the thermoelectric power have shown that the absence of rectification at high temperatures is not connected with the absence of inversion, since the p-type conductivity in the deformed region of the crystal is preserved. These facts can be explained on the basis of the earlier results with allow-

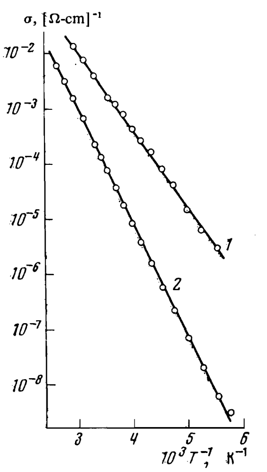

FIG. 7

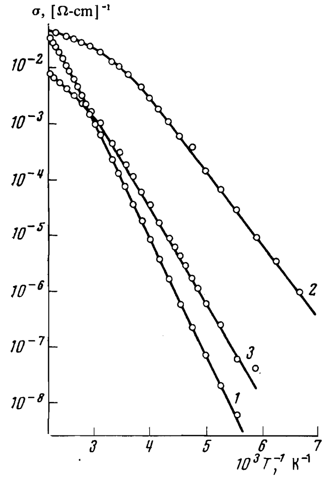

FIG. 8

FIG. 7. Temperature dependence of the conductivity of silicon deformed by bending—curve 1 ($\Delta E = 0.27$ eV) and by compression—curve 2 ($\Delta E = 0.44$ eV).

FIG. 8. Effect of annealing on the temperature dependence of the conductivity of compression-deformed silicon: 1—immediately after deformation (p-type), $\Delta E = 0.44$ eV; 2—annealing for 2.5 hr at 750°C; 3—after annealing for 15 minutes at 900°C.

ance for the difference in the temperature dependence of the forward and reverse dislocation-junction currents. As noted above, I_{rev} is determined by generation processes at deep levels in the depletion region. Lowering of the temperature leads to a decrease in the rate of generation of the carriers, and this should lead to a decrease in the reverse current. At the same time, when the temperature is lowered, the resistance of the deformed region increases (see Fig. 7), and with it also the width of the junction and the reverse current, since the latter is proportional to the width. In both cases the current increases or decreases exponentially, but the stronger dependence of the generation rate leads ultimately to a resultant decrease of I_{rev}. With increasing temperature, to the contrary, I_{rev} increases, mainly because of the increased rate of generation, and at a certain temperature it becomes equal to the forward current and the rectification disappears completely.

Investigations of the values of the dislocation density at the rectification boundaries have shown that for crystals with resistivity $\gtrsim 100$ Ω-cm the inversion takes place at a dislocation density $\geq 2 \times 10^7$ cm^{-2}. Inversion of crystals with lower resistivity takes place at higher dislocation densities.

2. Investigation of the Electric Conductivity of the Deformed Region

To determine the characteristics of the centers connected with dislocations, an investigation was also made of the temperature dependence of the electric conductivity of deformed crystals with a high dislocation density ($\gtrsim 10^9$ cm^{-2}), at which the initial material was entirely overcompensated and had p-type conductivity. Hall measurements were made on a few samples in order to monitor the mobility; these measurements have shown that the mobility of the holes in silicon having high dislocation density changes very little in the temperature interval 200—300°K (by not more than 2—3 times). It can therefore be assumed that the change of the conductivity is determined mainly by the change in the carrier density. It must be emphasized, however, that the level activation-energy values presented below are somewhat altered if account is taken of the temperature dependence of the mobility.

Figure 7 shows typical temperature dependences of the electric conductivity of deformed samples. We see that the electric conductivity varies with temperature like $\sigma = \sigma_0 \exp(-E/kT)$. The activation energies ΔE are equal to 0.44 and 0.27 eV for samples deformed by compression and by bending, respectively. In the control (undeformed) samples subjected to heat treatment at the deformation temperatures, and also in samples deformed by four-point bending at 800°C up to a dislocation density 10^5 cm^{-2}, no change whatever was observed in the electric conductivity in comparison with the the initial sample. Measurements of the electric conductivity performed both on the entire sample and on parts cut from the middle of the sample yielded identical results. Consequently, the inversion of the type of conductivity is not due to diffusion from the surface. Thus, an investigation of samples containing no p-n junction also confirms that when n-Si is deformed to a dislocation density 10^8—10^{10} cm^{-2} there are introduced into the volume of the material deep centers, which determine its conductivity and can serve as effective generation-recombination centers. An estimate of the concentration of the centers in accordance with the formulas for an overcompensated semiconductor[26] yields values 10^{16}—10^{17} cm^{-3}.

Attention is called to the difference between the activation energies of the levels connected with centers introduced by plastically deforming silicon by compression and by bending. The construction features of the insulations and the difference between the sample dimensions have made it necessary to perform experiments at different deformation durations and different temperatures, in order to obtain crystals having equal dislocation densities. To assess the influence of these parameters on the resultant change in the energy spectrum of the carriers, experiments were performed aimed at studying the effect of annealing on the electric conductivity of the samples. Figure 8 shows the measured temperature dependence of the electric conductivity of samples deformed by compression and annealed at different temperatures and durations.

The experiments have shown that annealing at temperatures below the deformation temperature (700°C) cause practically no change in the electric conductivity of the samples. In crystals annealed at 750°C, an increase of the hole density is observed with increasing annealing duration, as well as a gradual decrease of the activation energy from 0.44 to 0.27 eV after 20 minutes of annealing, and further annealing at this same temperature did not change the activation energy (Fig. 8, curve 2). When the annealing temperature is raised above 800°C, the hole density decreases, and the activation energy increases to approximately 0.4 eV (Fig. 8, curve 3).

It follows from the foregoing results that plastic deformation produces in silicon at least two acceptor centers responsible for the appearance of the levels $E_V + 0.27$ eV and $E_V + 0.44$ eV. The filling of these levels and their relative contributions to the electric characteristics of the crystals can differ significantly depending on the temperature and the time of the deformation (or on the subsequent annealing) of the sample.

The results of the study of the kinetics of the electric conductivity of deformed samples can be explained by assuming that donor centers are also produced in the silicon as it becomes deformed. In a compression-deformed sample, the $E_V + 0.27$ eV level is completely filled with electrons supplied by these donor centers, and this level makes no contribution to the electric conductivity. At 750°C, the donor centers are annealed, while the acceptor centers responsible for the $E_V + 0.27$ eV level become depleted and begin to determine the temperature dependence of the electric conductivity. In samples deformed by bending, this process took place apparently during the course of the deformation. With increasing temperature, the shallower acceptor levels ($\Delta E = 0.27$ eV) begin to be annealed, and the electric-conductivity activation energy increases to 0.4 eV. These results correlate with data on the temperature dependence of the inverse currents through the p-n junction.

CONCLUSION

Thus, the presented experimental results indicate that plastic deformation of n-type silicon crystals produces in the crystal of a system of acceptor and donor centers that are bound to the dislocations and cause, under certain conditions, inversion of the type of conductivity of the initial material.

The resultant dislocation p-n junction is continuous and constitutes a structure based on n-Si with shallow donor levels, in which the p region is obtained by overcompensation through the introduction into the initial material of deep acceptor centers connected with the dislocations. The generation-recombination processes at the centers responsible for the existence of the deepest acceptor level determine the reverse currents through the p-n junction. The electric conductivity of the deformed crystal is controlled by the acceptor centers, the levels of which are closest to the top of the valence band. Their relative contribution to the formation of the electric characteristics of the sample can be easily varied by annealing at different temperatures and durations.

This behavior, in our opinion, can be naturally attributed to the possibility of the formation of elaborate complex centers at the dislocations. Even in the earliest papers (see, e.g., [3]) it was proposed that uncompensated electron bonds in the dislocation core can lead to the appearance of either donor or acceptor levels. Subsequently, however, on the basis of investigations of strongly doped n-type semiconductors (as compared with the concentration of the broken bonds), only the possibility of acceptor action of the dislocation was considered for a long time. Investigations of germanium and silicon[11,13,27] of p-type have shown that, depending on the temperature, the dislocations can serve as the supply of either donor or acceptor centers. In a material overcompensated by plastic deformation, such as investigated in this paper, both donor and acceptor action of dislocations seems to appear simultaneously. In such crystals, the distance between the charged centers is comparable with the distance between the dislocations. The broken bonds can become saturated on account of electrons that are detached from the "dangling" bonds of the atoms in the cores of the neighboring dislocations, or even in one and the same dislocation. The possibility of such realignments in the dislocation core increases even more if account is taken of the latest results of electron-microscope investigations of the dislocation structure in silicon and germanium[28,29], which have demonstrated the presence of splitting of the 60° and screw dislocations, a fact that greatly increases the number of broken bonds in the core. The formation of elaborate donor-acceptor complexes readily explains the features of the recombination luminescence in plastically deformed semiconductors[8] in the absence of conductivity along the dislocations. It is also obvious that the kinetics of the formation of the centers can be made more complicated by the redistribution and by the changes in the state of the impurities, including those that are electrically neutral in the initial crystal, in the field of the dislocation microdeformations. It is quite probable that a rational utilization of the features of the energy spectrum of deformed semiconductors will make it possible in the future to develop devices capable of operating in a wide temperature range.

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Translated by J. G. Adashko
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