Spin-dependent conductivity along dislocations in Si

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A resonant change of the dislocation conductivity is observed in plastically deformed silicon at $T = 1.4$ K. This effect is assumed to be caused by the interaction of current carriers with previously unknown paramagnetic *Ch* centers on dislocations.

It may now be considered as firmly established that paramagnetic centers, which are chains of broken bonds in the nuclei of the dislocations (BBD), as well as different defects on dislocations, appear with plastic deformation in silicon crystals. These centers give a specific electron paramagnetic resonance signal (DEPR).[1,2] In addition to DEPR, an appreciable high-frequency electrical conductivity, which is related to the motion of electrons (*n*-type) and holes (*p*-type) captured by dislocations, is observed along dislocations in plastically deformed silicon.[3] In this connection, it would be of great interest to investigate the effect of the spin state of dislocation paramagnetic centers on the conductivity along dislocations. However, in unannealed crystals, where electrons and holes are captured primarily directly on BBD, we have not yet been able to observe this effect. In this paper we report the observation of spin-dependent conductivity in specimens annealed after deformation at 800–850 °C.

As follows from previously reported observations,[2] annealing of plastically deformed specimens at $T > 700$ °C leads to a weakening of the EPR signal of BBD chains right up to complete vanishing. We explain this by the reconstruction of the atomic structure of the nuclei of the dislocations, leading to closure of BBD. Deep electronic states, which are related directly to the presence of BBD, vanish at the same time. In this case, however, some one-dimensional bands, arising due to strong distortion of the crystal lattice around dislocations, can remain. Carriers, which are captured in these states, can also give a conductivity along dislocations and, since they have a spin, they must feel the spin state in the nuclei of the dislocations of paramagnetic defects. We assume that this is the phenomenon that we observed in our experiments.

We have investigated samples of *n*-type (2×10^{14} cm^{-3} and 10^{15} cm^{-3} P) and *p*-type (10^{13} cm^{-3} B) silicon, which were plastically deformed by 2–3% compression along [110] at 680 °C. The specimens were then annealed for 30 min at 800–850 °C.

The measurements were performed at $T = 1.4$ K. A sample was placed into a rectangular resonator (H_{102}) of a superheterodyne EPR spectrometer with a working frequency of $f_0 \simeq 9.5$ GHz. UHF (pump) power at a frequency of $f_p \simeq 18$ GHz was introduced into this resonator. The pump signal was prevented from reaching the receiving part of the EPR spectrometer with the help of a reflective filter. The resonator was carefully screened from IR radiation from the warm parts of the waveguide and from the cryostat. The specimen could be illuminated with a miniature incandes-

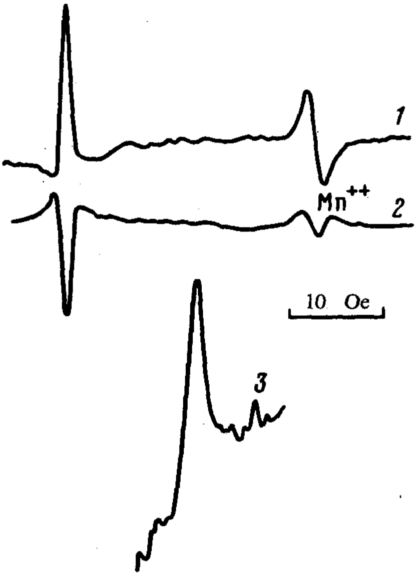

FIG. 1.

cent lamp. Modulations with an amplitude of 0.3 Oe at a frequency of 80 Hz could be superimposed on the static magnetic field H; this permitted recording the derivatives of the absorption and of the dispersion.

Figure 1 (curve 3) shows the derivative of the absorption of the high-frequency power at the frequency f_0 in the presence of 18 GHz pumping with H scanned near $H_H^{\rm res} \simeq 6$ kOe. The signal was not observed in the absence of pumping. It was established that the recorded signal (we will call it the *Ch* line) is not related to leakage of the pump power into the receiving channel or heating of the specimen; the *Ch* line appears only after the sample is illuminated by the lamp and the amplitude remains virtually constant for several hours after the light is switched off. The signal is observed only in samples with dislocations.

The observed signal is also observed in fields $H_0^{\rm res} \simeq 3$kOe, whether or not the 18-GHz pump is present. The signal decreases sharply when the sample is moved into the region of the rf magnetic field of the resonator, where the electric field at the working frequency f_0 is low.

Figure 1 shows the derivatives of the absorption (1) and of the dispersion (2) in a field $\simeq 3$ kOe. The magnitudes of the g-factor $H_H^{\rm res}/\gamma f_H$ and $H_0^{\rm res}/\gamma f_0$ coincide. The EPR line of the standard Mn^{++} in MgO is shown on the right.

Figure 2 shows the anisotropy of the position of the *Ch* line for three different directions of rotation of the crystal (the axis of rotation $\vec{\Omega}$ was perpendicular to H). The solid curves show the computed dependences corresponding to the g tensor with $g_{11} = 1.9915 \pm 5 \times 10^{-4}$, $g_{22} = 2.0064 \pm 5 \times 10^{-4}$, $g_{33} = 2.0159 \pm 5 \times 10^{-4}$, whose principal axes have in the coordinate system of the crystal, [100], [010], and [001], the

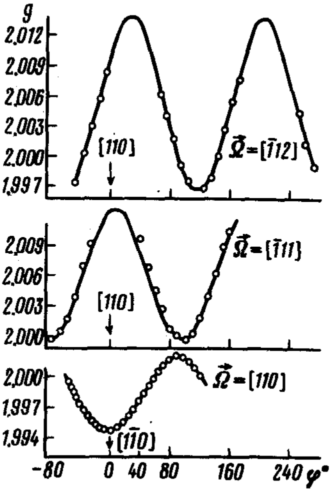

FIG. 2.

directional cosines $\eta_1 \simeq (0.38; -0.9; -0.2)$, $\eta_2 \simeq (0.32; -0.06; 0.94)$, and $\eta_3 \simeq (0.87; 0.43; -0.25)$. It was established that the amplitude of the *Ch* line changes drastically when the crystal is rotated, and the line essentially disappears when $\mathbf{E}_{f0} \perp [1\bar{1}0]$, where E_{f0} is the rf electric field. (We note that $\mathbf{E}_{f0} \| \mathbf{H}$). Figure 3 is an example of the relative amplitude of the line when the crystal is rotated around the [110] line; the solid curve corresponds to $A/A_{\max} = 0.83\cos^2\varphi + 0.1$. The curve was drawn by the method of least squares. Here φ is the angle between the $[1\bar{1}0]$ direction and $\mathbf{E}_{f0} \| \mathbf{H}$. The width of the line in this case remains essentially unchanged.

The results presented above in our opinion indicate that the observed *Ch* line is related to the resonant change of the one-dimensional or quasi-one-dimensional conductivity of several objects, lying along the $[1\bar{1}0]$ direction. At 1.4 K, in the absence of

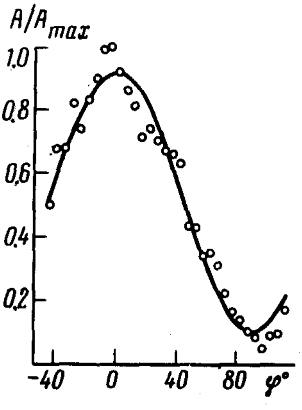

FIG. 3.

illumination, these objects can have a conductivity only if they are related to electronic energy bands lying in the forbidden band of silicon.

The observed effect is apparently related to the interaction of current carriers, which move along such quasi-one-dimensional objects, with some paramagnetic centers (*Ch* centers) localized on or in close proximity to these objects. It would be reasonable to assume that these conducting entities are dislocations that lie along $[1\bar{1}0]$, such as the 90° partial dislocations.

It should be noted that in Ref. 4 a series of lines, which appear after the sample is illuminated and whose phase is opposite to the usual EPR lines, was observed in Ge with dislocations during a study of the EPR. In principle, an EPR signal with an opposite phase can be obtained when the conditions of slow passage are violated.[5] It is more likely, however, that an analogous effect was observed in Ref. 4.

The recorded derivatives of the absorption and of the dispersion correspond to $\partial\epsilon''/\partial H$ and $\partial\epsilon'/\partial H$, where $\epsilon = \epsilon' + i\epsilon''$ is the dielectric constant of the sample. As follows from Fig. 3, we have $(\partial\chi'/\partial H)/(\partial\epsilon'/\partial H) < 0.1$ The same can also be said of $(\partial\chi''/\partial H)/(\partial\epsilon''/\partial H)$, where $\chi = \chi' + i\chi''$ is the magnetic susceptibility of the sample, which varies resonantly in the usual EPR. Working from this fact and from the magnitude of the signal, the number of paramagnetic centers is estimated to be $N_{Ch} < 10^{13}$ cm^{-3}.

From preliminary measurements, the magnitude of the signal $\partial\epsilon''/\partial H$ and $\partial\epsilon'/\partial H$ increases with decreasing power down to $P_{\text{microwave}} \simeq 10^{-7}$ W ($H_{\text{microwave}} \simeq 10^{-3}$ Oe).

An analysis of the line shape shows that the signs of $\partial\epsilon'/\partial H$ and $\partial\epsilon''/\partial H$ coincide. If the conducting parts of the dislocations are represented in the form of very elongated ellipsoids with length l, radius r, and conductivity per unit length s, then according to Ref. 6 such a synchronous change in ϵ' and ϵ'' accompanying a change in the magnitude of S is possible only if $2\pi\epsilon_0\epsilon_b f_0 l^2 >, \kappa S$, where $\epsilon_0\epsilon_b$ is the dielectric constant silicon, and $\kappa = 6/\pi[\ln(l/r) - 1]$. Thus the conducting parts must be very long. The same conclusion can also be reached from the fact that at least one *Ch* center must be present in an interval of length l.

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