Asymmetry of dislocation mobility in semiconductors

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An asymmetry has been observed in the mobility of individual dislocations in silicon and germanium single crystals. As a result, reversal of the stress changes the dislocation velocity substantially, by up to two orders of magnitude.

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Since Frenkel[1] first calculated the resistance of a crystal lattice to shear plastic deformation and thus initiated the dislocation hypothesis, this problem has been one of the most fundamental problems in the physics of strength and plasticity. Decades later, a rigorous theoretical analysis[2,3] has been developed for the motion of unextended dislocations in a Peierls potential relief, but a comparison of the theoretical predictions with experimental data reveals several fundamental discrepancies.[4] In efforts to resolve these discrepancies it has been suggested that point defects may change the way in which double kinks form and expand[5,6] and that there is a stacking fault at the center of an extended dislocation.[7,8] In an effort to sort out the effects of these mechanisms, we have studied how a reversal of the glide direction affects the velocity v of individual dislocations in semiconducting single crystals. This study has revealed an asymmetry in the dislocation mobility.

The dislocation velocities were measured by the method of Refs. 9 and 10 in samples cut from dislocation-free bars of n-type germanium and silicon with resistivities in the range 50–100 Ω · cm. The samples were tetrahedral prisms with edges of 1.5, 4, and 35 mm along the $[1\bar{1}1]$, $[\bar{1}12]$, and $[110]$ directions. Semihexagonal dislocation half-loops 600–800 μm in diameter were first introduced into the crystal by a four-support bending around the $[\bar{1}12]$ axis at an elevated temperature T. Chemical etching revealed the places at which the 60° and screw regions of the half-loops emerged at the $\{111\}$ surface. Special experiments revealed no indication of a spontaneous contraction of these very large half-loops under the influence of image forces and linear tension, even over times much longer than the total time of the subsequent heat treatments. From these starting positions the dislocations were moved in the direction corresponding to expansion of the half-loop; then the crystal was cooled and again subjected to etching, and distance between the etching pits at the initial and final positions of the dislocations was measured. The sample was then reheated and subjected to stresses of the opposite sign, which caused the half-loop to contract. After cooling and etching, the distances traveled by the dislocations in the opposite direction were measured.

Figure 1 shows histograms of the distances traveled by 60° dislocations in silicon

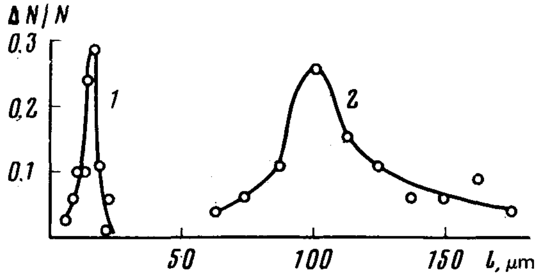

FIG. 1. Distribution of 60° dislocations with respect to distance traversed in silicon. 1—During expansion of the half-loops; 2—during contraction of the half-loops. $T=650°$ C, $\tau=0.5$ kgf/cm².

under the influence of tangential stresses $\tau=0.5$ kgf/mm² of opposite signs at $T=650°$ C for a loading time $t=20$ min; these histograms were constructed from measurements of the motion of 80 dislocations. We see that the reversal of direction was accompanied by substantial increases in not only the average distance traveled by the dislocations but also the dispersion of the distance distribution. Study of the dependence of the average range of the dislocations on the loading time (Fig. 2) showed that the difference was due to a sharp increase (from 1.4×10^{-6} to 10^{-5} cm/s) in the dislocation velocity along the direction corresponding to the contraction of the half-loop. When the reversal cycle was repeated, i.e., upon a switch from contraction to expansion of the half-loops, the ratio of the dislocation velocities along the two directions remained nearly the same.

The asymmetry in the dislocation mobility was observed for 60° and screw regions of half-loops in both initially extended and initially compressed regions of the sample. The difference between the dislocation velocities in opposite glide directions was found to be very sensitive to the magnitude of the stress, the temperature, and the conditions during the heat treatment of the crystal before the stress reversal. If the reversal was imposed without cooling the sample, the asymmetry increased significantly. In germanium at $T=450°$ C with $\tau=0.5$ kgf/mm², for example, the contraction velocity for the half-loop exceeded its expansion velocity by a factor of 100 in this case. If instead the sample was cooled before the τ reversal, the change in ν was by a factor of only ten.

The observed effect is not determined by a change in the order of the partial dislocations forming the 60° total dislocation. The effect is also observed for screw dis-

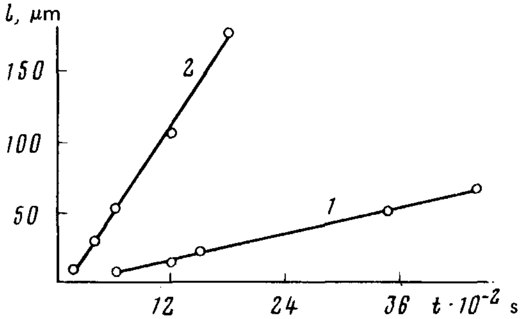

FIG. 2. Dependence of the average distance traveled by 60° dislocations in silicon on the time over which the load is applied. 1—During expansion of the half-loops; 2—during contraction. $T=650°$ C, $\tau=0.5$ kgf/cm².

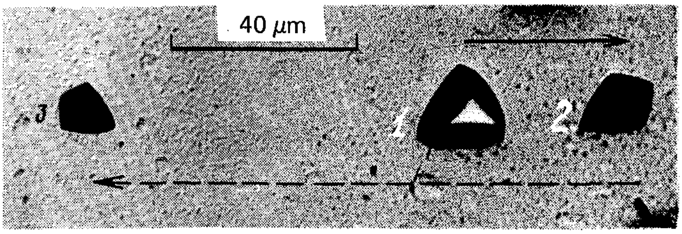

FIG. 3. Arrangement of etching pits in a silicon sample etched after the reversal of the glide of a 60° dislocation. The arrows show the dislocation glide directions. The time required for the motion from the starting position (1) toward the right to the turning point (2) was 32 min; the time of the motion toward the left to the final position (3) was 20 min.

locations split into identical 30° partial dislocations. During expansion of the half-loops, the velocities of 60° dislocations with partial dislocations in the opposite orders differed by only 20–30%. The mobility asymmetry is caused primarily by the change in the state of the crystal in terms of point defects near the dislocation and in regions adjacent to the marked part of the glide plane. As it moves, a dislocation collects impurities, and we found direct evidence of these processes in these crystals. After the etching of samples which had not been cooled or etched before the reversal, an etching pit was found at the dislocation turning point (Fig. 3). This pit was caused by a part of the impurity atmosphere which was stripped off the dislocation at the instant at which ν was increased, according to x-ray topographic measurements. A one-dimensional set of point-defect complexes formed from this atmosphere and served as a line defect, which could be detected in ways other than by etching. Experiments by the method of Ref. 11 showed that this line defect leads to the formation of a voltage-current characteristic of the diode type for the interface of germanium with a metal microprobe positioned at an etching pit caused at the dislocation turning point not by the dislocation but by a local excess of an acceptor impurity. At high temperatures and high stresses the asymmetry essentially disappeared. These facts, as well as the increase in the dispersion of the distance distribution (Fig. 1), can easily be explained on the basis that the point-defects state of the crystal has a definite effect on the dislocation mobility.

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