PHYSICAL REVIEW VOLUME 93, NUMBER 4 FEBRUARY 15, 1954

Dislocations in Plastically Deformed Germanium

G. L. PEARSON, W. T. READ, JR., AND F. J. MORIN
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received November 3, 1953)

Both n- and p-type germanium rods were deformed plastically by bending. Etch pits were observed on the two active slip planes. Hall effect, conductivity, and lifetime were measured on both control and deformed samples. The results are consistent with the idea that edge dislocations in germanium are associated with acceptor-type energy levels in the middle or upper half of the gap.

BOTH n- and p-type germanium rods were deformed by bending into a radius of about 5 cm while heated to around 650°C. The samples were cleaned in KCN[1] and heated by passing a current through them in air—a method that introduces negligible "thermium."

In uniform plastic bending, the minimum-energy distribution of dislocations is determined by the curvature and the orientation of the crystal axes. The long dimension of the samples was $[1\bar{1}0]$ and the axis of bending $[110]$. Figure 1 is a micrograph showing etch pits on the (111) face. Vogel[2] and Gallagher[3] have shown that pits appear where dislocations meet the surface and are most easily seen on $\{111\}$ faces. As observed by Gallagher, the pits lie in rows along the traces of the two active slip planes $(\bar{1}11)$ and $(1\bar{1}1)$. The measured density of pits, about 3×10^6 cm^{-2}, is about a third of the minimum calculated from the curvature—a discrepancy that may be due to the difficulty of resolving closely spaced dislocations.

Measurements of conductivity, Hall effect, and lifetime were made on (1) a control, (2) a heated, and (3) a heated and deformed sample. In 15-ohm·cm p-type material deformation had a negligible effect on mobility and carrier density. Figures 2 and 3 show Hall mobility and conductivity for 15-ohm·cm n-type germanium containing arsenic impurity. The heating alone introduced about 3×10^{13} acceptor centers per cm^3. The results suggest that deformation introduces acceptor-type energy levels[4,5] lying in the middle or upper half of the gap. These levels are probably associated with the dangling bonds on edge dislocations; the unpaired dangling electron accepts another electron to form a pair. As extra electrons from the conduction band join the dislocation, the dislocation becomes a negatively charged line surrounded by a cylindrical region of positive space charge; thus the electrostatic potential is distorted in the vicinity of a dislocation.

The Hall angle was measured with both the current and magnetic field at right angles to the dislocations (Hall voltage parallel to the dislocations). Hall mobility was calculated by assuming that the electrons on the dislocation do not conduct. The mobility in the deformed sample of Fig. 2 in the range 15°–300°K is that which would result if the dislocations added (to the thermal

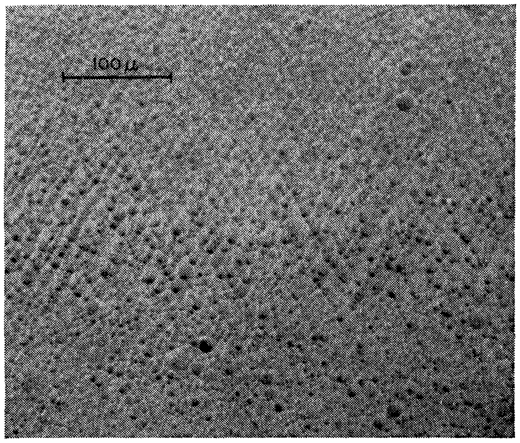

FIG. 1. Etch pits on (111) face of germanium crystal bent about $[110]$ axis.

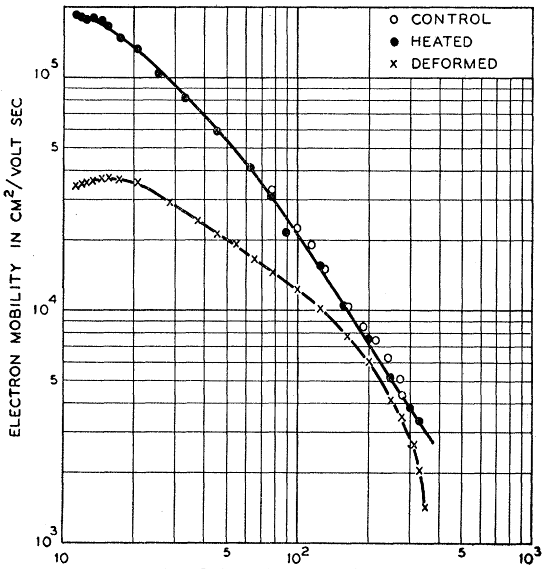

FIG. 2. Electron mobility *versus* temperature of (1) control, (2) heated, and (3) deformed germanium single crystal.

---

[1] R. A. Logan, Phys. Rev. **91**, 757 (1953).

[2] Vogel, Pfann, Corey, and Thomas, Phys. Rev. **90**, 489 (1953).

[3] C. J. Gallagher, Phys. Rev. **92**, 846 (1953).

[4] C. J. Gallagher, Phys. Rev. **88**, 721 (1952).

[5] W. C. Ellis and E. S. Greiner, Phys. Rev. **92**, 1061 (1953).

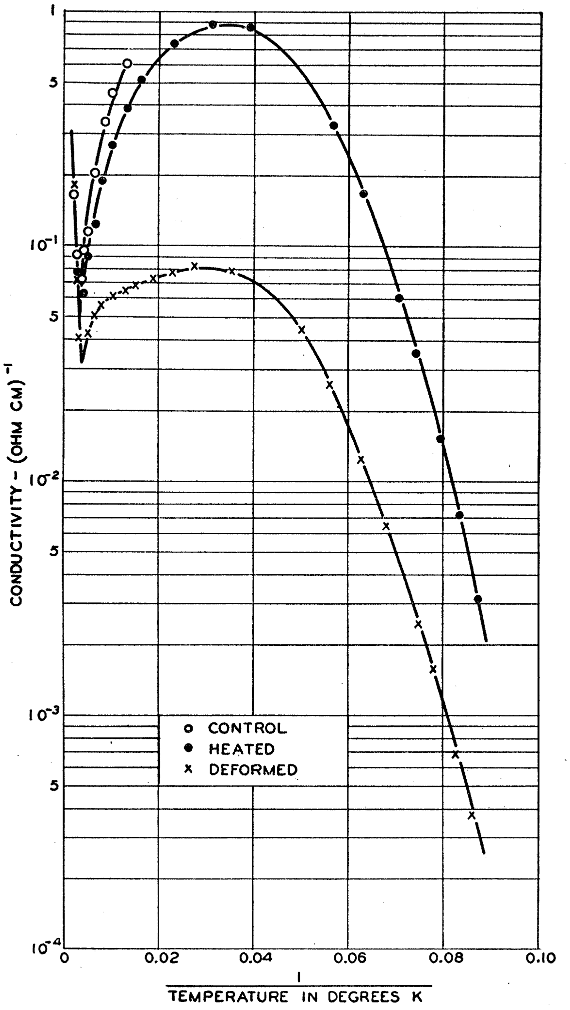

FIG. 3. Conductivity *versus* $1/T$.

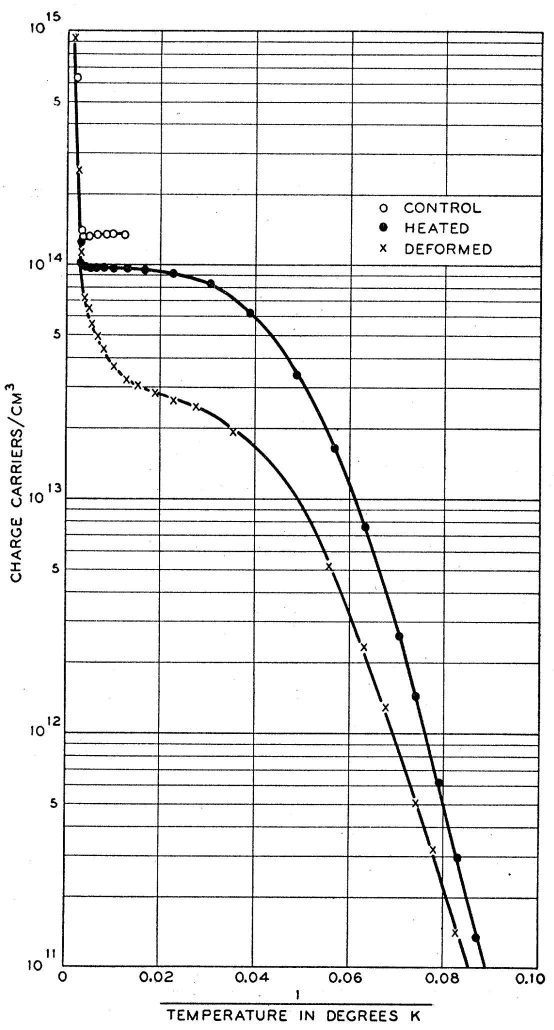

FIG. 4. Electron density *versus* $1/T$.

scattering of the control) scattering with a constant mean free path of 9.5×10^{-5} cm.

In the high-temperature range of Fig. 2 the difference between the two curves may be due to the fact that the space charge around a dislocation distorts the streamlines; this could give an apparent reduction in mobility even when the effect of the dislocations on mean free time is negligible. Such distortion of the streamlines affects both Hall angle and conductivity in the same way and therefore introduces no error into the calculation of carrier concentration, Fig. 4, which is found from the ratio of conductivity to Hall angle.

Because the dislocations are charged, even a density of dislocations of the order of 10^7 cm^{-2} can have a relatively large effect on mobility, especially at low temperature. It is planned to publish a detailed analysis of scattering from a charged dislocation in a later paper. It will also be shown in a later paper that the occupation of dislocation-acceptor centers is governed by Fermi statistics only when the fraction of centers occupied is negligibly small—of the order of 10^{-5} in the present case. As the temperature is lowered below room temperature, the fraction steadily increases and reaches a maximum of about 0.1 near the absolute zero of temperature. The data of Fig. 4 is consistent with a single energy level about 0.2 ev below the conduction band.

The number of dislocations required to explain the conductivity and Hall effect data is 2 to 3 times the minimum value, 10^7 cm^{-2}, calculated from the curvature.

As reported by Gallagher,[4] deformation drastically reduces minority carrier lifetime in both *n*- and *p*-type germanium; typical values were 300μsec in the control, 50μsec in the heated, and less than 1μsec in the heated and deformed sample.

We wish to thank W. Shockley for his helpful discussions, E. E. Thomas for preparing the micrograph, and W. W. Feldman and J. P. Maita for assistance with the experimental measurements.

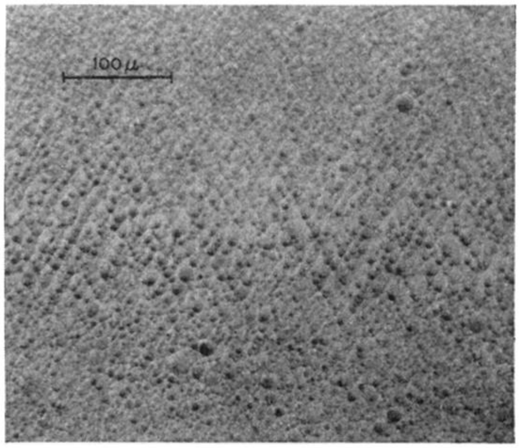

FIG. 1. Etch pits on (111) face of germanium crystal bent about [110] axis.