Plastic Deformation of Germanium and Silicon

C. J. GALLAGHER
General Electric Research Laboratory, Schenectady, New York
(Received June 18, 1952)

Single crystals of germanium and silicon have been plastically deformed at elevated temperatures. Germanium becomes ductile above 500°C, and silicon requires temperature above 900°C. At temperatures below 600°C, germanium exhibits an induction period at constant load. Deformed germanium, originally *n*-type, remains *n*-type. The resistivity is increased by deforming, and the lifetime of photo-injected carriers is drastically reduced.

PLASTIC deformation has been observed in single crystals of germanium. Deformation occurs in the temperature range above 500°C with applied stresses of the order of several kg/mm². The temperature range is well below the melting point of 941°C. The specimens studied were single crystal bars of *n*-type germanium of approximately 1-mm square cross section, with a purity corresponding to a resistance range of 2- to 20-ohm cm. These bars were bent and also subjected to tension. Right angle bends can be obtained over a length of 6 mm without fracture. Strains of 0.06 have been measured in tensile specimens subjected to stresses of 2 kg/mm² at 600°C. Slip lines have been observed in both bent and tensile specimens. A typical tensile specimen is shown in Fig. 1. These slip lines are in 111 planes, as might be expected from the packing in the diamond-type cubic lattice of germanium. The slip direction has not yet been definitely established. In

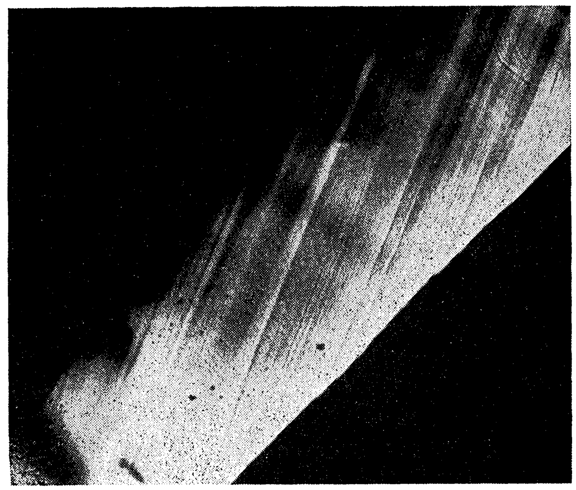

FIG. 1. A typical tensile specimen of Ge.

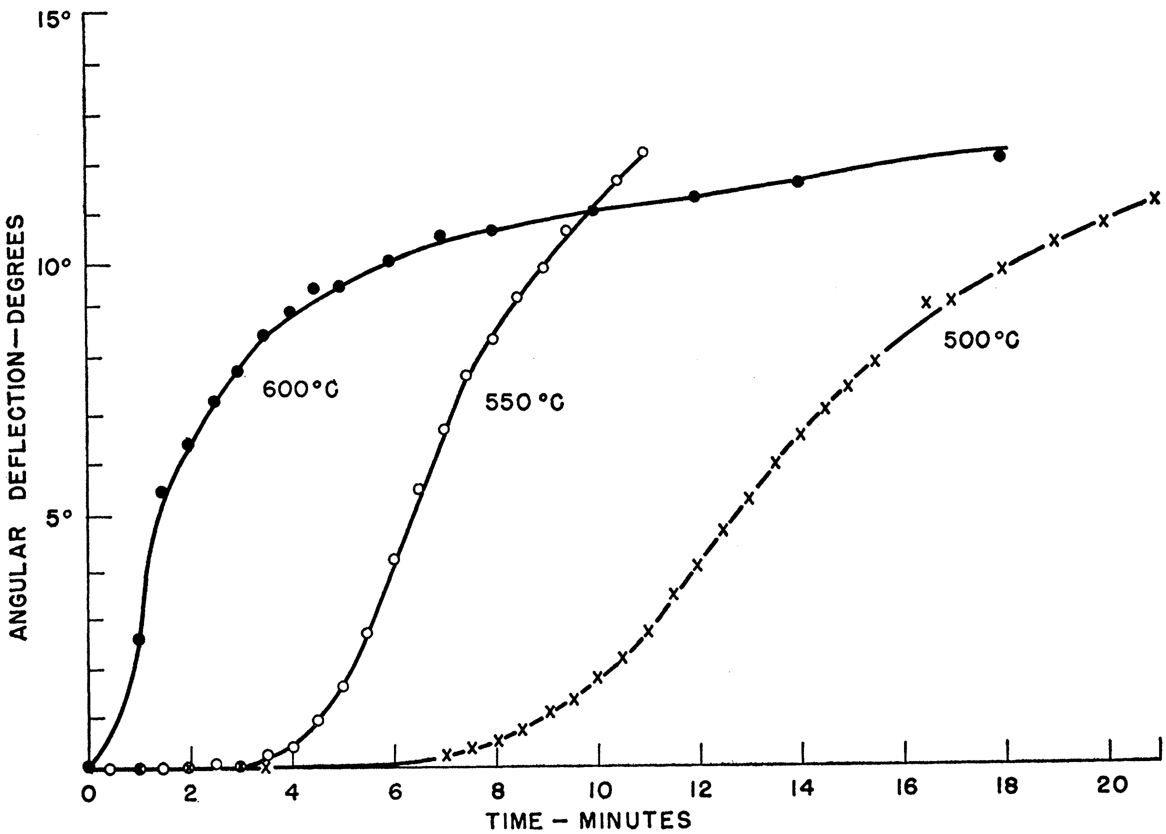

FIG. 2. Angular deflection of a Ge bar as a function of time, at three temperatures.

several specimens, two sets of slip lines have been observed intersecting at angles corresponding to 111 planes. The slip lines disappear when the specimen is etched. Laue patterns of the deformed regions of bent specimens show asterism, but the material retains its single crystal character over the range of strain observed. When larger specimens are bent drastically, audible clicks can be heard.

At the lower end of the temperature range, the deformation exhibits a time delay or induction period of the order of minutes. When a constant load is applied at constant temperature, the time delay decreases with increasing temperature, as shown in the curves of Fig. 2. Each curve represents the angular deflection *versus* time for a bar, 1 mm square, clamped at one end and loaded with 100 grams at a point 1 cm distant. Above 600°C, the time delay was too short to be observed with the loading method used.

The electrical behavior of the deformed material is of interest, particularly in view of results obtained by other workers on the effect of heat treating germanium.[1,2] It has been found that *n*-type germanium heated above 550°C and then quenched to room temperature is left with a permanent increase in resistivity and a decrease in carrier lifetime, probably due to the introduction of acceptor-type defects. A similar effect is found with deformed germanium. For bent specimens, the resistivity is higher in the region of bending, and the lifetime of photo-injected carriers is considerably lower. The germanium, originally *n*-type, was still *n*-type after deformation. Work is in progress to determine possible relations of defects introduced by deformation to those introduced by heat treatment.

Silicon single crystals have also been plastically deformed at temperatures above 900°C with somewhat higher stresses than for germanium. Slip lines have been observed along [111] planes. The writer is indebted to F. H. Horn for furnishing silicon crystals.

[1] Fuller, Theurer, and van Roosbroeck, Phys. Rev. **85**, 678 (1952).
[2] W. DeSorbo and W. C. Dunlap, Jr., Phys. Rev. **83**, 879 (1951).

PHYSICAL REVIEW VOLUME 88, NUMBER 4 NOVEMBER 15, 1952

The Plasticity of Silicon and Germanium

FREDERICK SEITZ
University of Illinois, Urbana, Illinois

(Received July 28, 1952)

A qualitative analysis of Gallagher's measurements of plastic flow in germanium and silicon is made. It is reasonable to suppose the slip occurs by motion in {111} planes of dislocations having a Burger's vector equal to an allowed translation in the $(1\bar{1}0)$ direction. It is suggested, following current thought, that the observed temperature-dependent incubation time for plastic flow is related to the freeing by thermal fluctuations of locking points of the Cottrell type associated with the broken bonds which occur along nearly pure screw dislocations that have a small edge component. It is proposed that foreign atoms reside at the broken bonds in normal materials. A discrepancy in the coefficient of the Boltzmann factor indicates, however, that these concepts cannot be applied in the most simple form. The analogy between Gallagher's measurement and those of Kramer and Maddin in β-brass is pointed out.

I. DISLOCATIONS IN LATTICE

THE recent work of Gallagher[1] on plastic flow in germanium and silicon provides a remarkable insight into the ductility of materials in general, as well as of valence crystals. In brief Gallagher has found that germanium and silicon become ductile in the vicinity of 500°C and 900°C, respectively. Slip occurs in {111} planes with the production of well-developed slip bands for stresses somewhat above 10^8 dynes/cm². One of the most interesting features of the flow process is the occurrence of an incubation time. From Gallagher's data for germanium one concludes tentatively that this incubation time τ satisfies an equation of the following kind:

$$\tau=\tau_0 \exp(Q/RT), \quad (1)$$

where $\tau_0=10^{-5}$ second and Q is about 28,000 cal/mole.

It is interesting to see to what extent Gallagher's observations can be explained in terms of the present concepts of dislocation theory. The simplest assumption to make is that the active dislocations move in slip planes of the {111} type and possess a Burger's vector equal to an allowed translational distance of the $(1\bar{1}0)$ type in such planes. Neighboring slip planes of the {111} type, which are also common cleavage planes, are linked by valence bonds which run normal to the planes. Since these bonds would be broken and not reformed if a dislocation whose Burger's vector is not an allowed translation were to pass across the slip plane, it seems highly unlikely that the active dislocations break into partial components[2] as is possible in close-packed cubic or hexagonal lattices, where the

[1] C. J. Gallagher, Phys. Rev. 88, 721 (1952).
[2] R. D. Heidenreich and W. Shockley, *Conference on the Strength of Solids* (Physical Society, London, 1948).

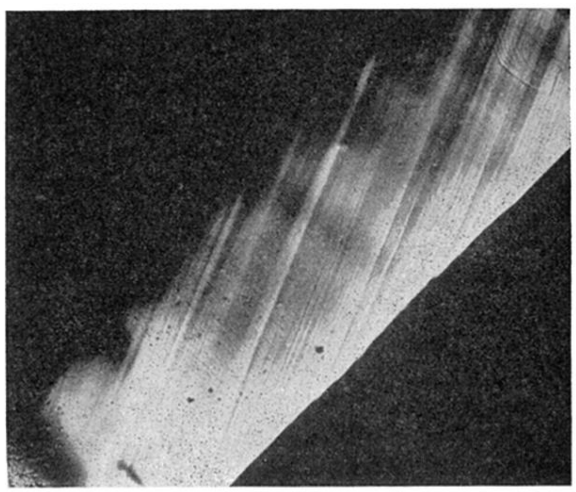

FIG. 1. A typical tensile specimen of Ge.