Dislocation microwave conductivity of germanium doped by thermal-neutron bombardment

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The dislocation microwave conductivity of germanium, discovered earlier, has now been studied in samples doped by thermal-neutron bombardment. This doping method made it possible to carry out measurements with a uniform dopant distribution and to establish the correlation between the microwave conductivity and the number of current carriers captured by dislocations.

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The introduction of dislocations in germanium single crystals gives rise to a new conductivity mechanism in the microwave range.[1–3] We will refer to this mechanism as the "dislocation conductivity."

At sufficiently low temperatures ($\leqslant 10$ K), at which there are no free carriers in the bands, the dislocation conductivity becomes predominant and can easily be observed experimentally. The magnitude of the dislocation conductivity turns out to depend on a doping of the sample with shallow donors or acceptors; this type of conductivity vanishes in undoped samples. It is currently believed[4] that this effect can be attributed to the capture of additional electrons or holes to dislocation states and to the motion of these carriers along segments of dislocation lines under the influence of the microwave field. In particular, it was shown in Ref. 3 that if the dislocation structure is anisotropic the dislocation conductivity will also be anisotropic. Despite the substantial progress in research on this topic, however, the experimental results of Refs. 1–3 are not sufficient for drawing a final conclusion about the mechanism for this conductivity. The best candidate is a dislocation mechanism, which has the microwave conductivity resulting from the motion along dislocation centers of carriers (electrons or holes) captured by dislocations. In this case, the dislocations may be regarded as one-dimensional conductors distributed over the volume of the crystal. On the other hand, the data of Refs. 1–2 do not completely rule out another mechanism, in which the dislocations would play a different role. During the plastic deformation of a crystal and a subsequent annealing[1] (at 460 °C and 700 °C, respectively), there may be a diffusion of shallow dopant impurities in the elastic fields of dislocations. There is thus the possibility in principle that regions with an impurity concentration several orders of magnitude above the average concentration might form near dislocations. (The germanium crystals used in Refs. 1–3 were both n- and p-type crystals with a shallow-impurity concentration $\sim 10^{13}$ cm^{-3}.) In this case, the carriers in the heavily doped regions that form might be degenerate, and this degeneracy might give rise to a microwave conductivity. It is clear that if it were found possible to prepare germanium samples with dislocations and with a definitely uniform distribution of shallow impurities, we would be in a position to choose between the alternative conductivity mechanisms.

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We have attempted to resolve the problem by using neutron bombardment to dope germanium.[5] During bombardment by thermal neutrons, some isotopes of germanium capture neutrons and become unstable, decaying into elements of groups III and V. The most important processes are

$$Ge^{70}(n, \gamma)Ge^{71} \xrightarrow[k]{11.4\ d} Ga^{71}, \qquad (1)$$

$$Ge^{74}(n, \gamma)Ge^{75} \xrightarrow[\beta]{82\ m} As^{75}. \qquad (2)$$

The first reaction gives rise to acceptors, and the second to donors. After capturing a neutron, the isotope Ge^{70} converts into the unstable isotope Ge^{71}, which in turn converts through K-capture (with a decay half-life of 11.4 days[5]) into Ga^{71}. Reaction (2) is a conversion of Ge^{74} into As^{75}, which occurs as follows: The isotope Ge^{74}, after capturing a neutron, converts into the radioactive isotope Ge^{75}, which converts in turn into As^{75} by β decay (with a half-life of 82 min). The decay half-lives are such that the donor concentration has reached its maximum value by the time the measurements are begun (2 or 3 days after the bombardment), while the acceptor concentration continues to rise for several months. The compensation is complete in 5.8 days, while the final ratio of acceptor and hole concentrations is $\sim 3:1$. The idea behind the experiments was to carry out the two operations of introducing the dislocations and doping the crystals in different orders. We introduced dislocations in single crystals of ultrapure n-type Ge (donor concentration $\sim 2 \times 10^{11}$ cm^{-3}). The procedures used for the deformation and subsequent annealing were similar to those described in Ref. 1. The dislocation concentration in most of the samples was $\sim 3 \times 10^6$ cm^{-2}. The samples did not exhibit a microwave dislocation conductivity after deformation; this result is attributed to the extremely low donor concentration in the original samples.[2] We then covered the samples with a protective layer of lead and bombarded them in a reactor channel (the ratio of thermal neutrons to fast neutrons was $\sim 300:1$). The bombardment time (8–20 min) was chosen to achieve a final added-acceptor concentration of 10^{13}–10^{14} cm^{-3}. Control samples were bombarded along with the deformed samples. After bombardment, the samples were annealed at ~ 500 °C for 7–8 h in order to remove the bombardment-induced structural defects, which result primarily from the fast neutrons present in the reactor beam. At first glance, this mandatory annealing step would seem to negate the advantage of the neutron-doping method, since there might be concern over whether shallow impurities might collect at dislocations during the annealing. However, this would be a legitimate concern only for donors; the acceptors have not yet had time to form in significant numbers by the end of the annealing step. When the measurements were begun, we were dealing with samples in which the donor concentration was 10^{13} cm^{-3} (we can say nothing about the uniformity of the donor distribution because of the annealing), and each day $\sim 10^{12}$ acceptors (Ga^{71}) per cubic centimeter formed. The acceptors form absolutely uniformly over the volume of the sample. The method used to measure the microwave conductivity is summarized in Ref. 3. In parallel with the measurements of the microwave conductivity at 4.2 K, we measured the dc Hall effect at 77 K and determined the donor and acceptor concentrations. Figure 1 shows the results of the Hall-effect measurements for a control germanium sample (a) and for a deformed sample (b), plotted against the time

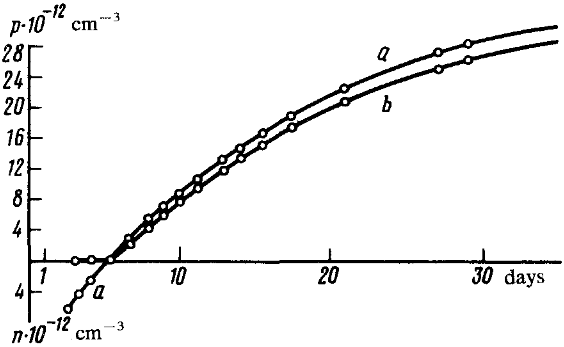

FIG. 1. Carrier concentration in the bands vs the time that has elapsed since the bombardment. The measurements were taken at 77 K. a—Control sample with an initial (prebombardment) shallow-donor concentration $\sim 2 \times 10^{11}$ cm^{-3}; b—sample with a dislocation concentration $\sim 3 \times 10^6$ cm^{-2}.

elapsed since bombardment. The difference in the behavior of curves a and b in Fig. 1 over the first 5 days is a consequence of the acceptor effect of the dislocations; the donor effect of the dislocations, in contrast, is not exhibited at 77 K at this dislocation concentration.[6] Figure 2 shows the measured microwave conductivity of a sample with dislocations at $T = 4.2$ K. The curve has a clearly defined minimum on the fifth day after the bombardment, i.e., at the time at which (as can be seen from Fig. 1a) the donors and acceptors introduced by the bombardment compensate for each other. The behavior here is precisely that which we would expect on the basis of Refs. 1 and 2 if we assumed that the dislocation conductivity in Refs. 1 and 2 were due to a motion of the current carriers along dislocations, rather than due to local clusters of the dopant. The initial decrease in the dislocation conductivity in Fig. 2 is ascribed to a decrease in the number of uncompensated donors and thus a decrease in the number of electrons which have been transferred from donors to dislocations. The subsequent increase in the microwave conductivity results from an increase in the number of holes captured by dislocations from acceptors. The dislocation conductivity reaches saturation when the "occupation" of dislocations by holes reaches a maximum, and the number of holes on the dislocations stops increasing, despite the continuing increase in the acceptor concentration in the volume of the sample. On the other hand, if we assume that the initial microwave conductivity of the sample results from the appearance, during the annealing, of regions in which the donor concentration is many orders of magnitude greater than the average concentration, then the subsequent appearance of acceptors distributed uniformly over the volume, with a concentration $\sim 10^{13}$ cm^{-3}, should not significantly alter the microwave conductivity.

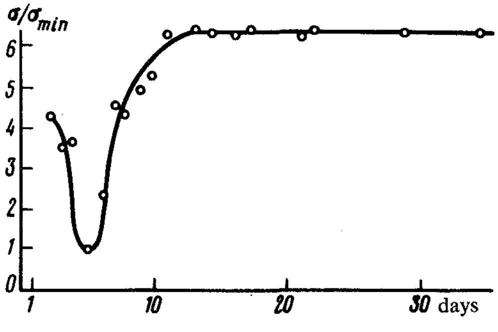

FIG 2. Microwave conductivity vs the time elapsed since the bombardment. The conductivity values are normalized to their minimum value $\sigma_{\min}$. The dislocation concentration in this sample was 3×10^6 cm^{-2}. The sample was bombarded by the same beam as the sample in Fig. 1.

In summary, we may say that we have been able to observe the dislocation conductivity in samples in which the dopant distribution (Ga^{71}) was definitely uniform. This observation is evidence in favor of the conductivity mechanism involving a motion along dislocation centers.

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