Microwave conductivity of n-type germanium with dislocations

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The microwave conductivity of n-type single crystal germanium with dislocations was investigated. Germanium samples with different dislocation densities and with different impurity concentrations were studied. The measurements were made at temperatures from 4.2 to 100 K. It was established that introduction of dislocations in n-type germanium single crystals leads to the appearance of a noticeable conductivity in the microwave band and to an increase in the dc conductivity in the low-temperature region. A substantial difference is observed between the temperature dependences of the microwave conductivities of n-type germanium and p-type germanium with dislocations. Possible conduction mechanisms are discussed.

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1. INTRODUCTION

The conductivity of plastically deformed silicon and germanium in the microwave band was investigated for the first time in Refs. 1–3. It was observed there that plastic deformation increases sharply the microwave conductivity of silicon[1,3] and of p-type germanium[2] at low temperatures. It was proposed[1-3] that the observed microwave conductivity is connected with the motion of the carrier along dislocation cores, when it might seem that all the electron (holes) should go over from the donors (acceptors) to the dislocations. Under conditions when all the carriers are on the dislocations, the most natural explanation is that the microwave conduction is via the dislocation mechanism. Another possible mechanism of microwave conduction may be hopping conduction over the impurities.[4] This mechanism was discussed in Ref. 2 and we shall discuss it again below. In the present study we have investigated the microwave conductivity of n-type germanium. It turned out that the microwave conductivities of deformed n- and p-type germanium differ qualitatively.

2. EXPERIMENTAL PROCEDURE

The measurements were performed on germanium samples of n type (doped with antimony) with a differential donor density N_d equal to 2×10^{13} cm^{-3}, 5×10^{12} cm^{-3}, and 3×10^{12} cm^{-3}. The deformation and the preparation of the samples are described in Ref. 2. The electric conductivity and the dc Hall effect in the temperature interval 4.2 – 300 K and the conductivity in the microwave band ($f=9\times10^9$ Hz) in the temperature interval 4.2 – 100 K were measured in the same manner as before.[2]

In the present study we came upon the need of investigating samples with a conductivity lower than in Ref. 2. To increase the senstivity of the apparatus, we modified somewhat the procedure for the measurement of the samples with the highest resistance. The investigated sample was placed in a pass-through resonator operating in the E_{010} mode, and the resonance curve was displayed on the oscilloscope screen. The sample was then taken out and a sapphire rod was advanced into the resonator to a position such that the resonator frequency resumed its previous value. A calibrated attenuator was then used to measure the change of the transmission coefficient of the resonator when the sample was replaced by the sapphire rod.

In addition, we measured the bandwidth of the resonator with the sapphire. The bandwidth of the resonator with the sample was calculated from formula $\Delta f=10^{\Delta/20}\Delta f_0$, where Δ is the change of the transmission coefficient in decibels and Δf_0 is the bandwidth of the resonator with the sample. The conductivity of the sample was calculated from the formula (see Ref. 5)

$$\sigma^{-1}=\frac{5.9\cdot10^{11}V_{\text{samp}}}{V_{\text{res}}(\Delta f-\Delta f_0)}\,[\Omega\cdot\text{cm}\,].$$

Here V_{res} is the volume of the resonator and V_{samp} is the volume of the sample. To measure the conductivity of the highest-resistance samples at $T=4.2$ K we used, besides a copper resonator, also a superconducting niobium resonator with $Q\sim10^5$. These steps have enabled us to measure samples with resistivity $\rho\leqslant10^4\Omega$-cm.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The measurements results are shown in Figs. 1–3. The letter d following a number means that the measurements were made with direct current; an asterisk indicates that according to the dc measurements of the

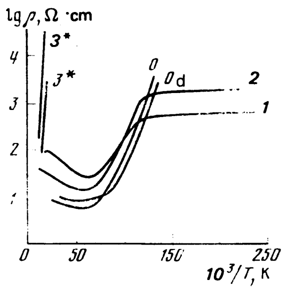

FIG. 1. Temperature dependences of the microwave resistivity of samples with chemical-donor concentration $N_d=3\times10^{12}$ cm^{-3} and with various dislocation densities: curve 0—without dislocations: $1-N_d=3\cdot10^5$ cm^{-2}; $2-N_d=2\cdot10^6$ cm^{-2}; $3-N_D=5\cdot10^6$ cm^{-2}.

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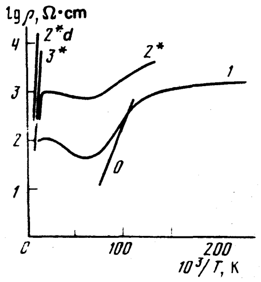

FIG. 2. Temperature dependences of microwave resistivity of samples with chemical-donor concentration $N_d = 5\times10^{12}$ cm^{-3} and with different dislocation densities: curve 0—without dislocations; 1 – $N_D = 2\cdot10^6$ cm^{-2}; 2* – $N_D = 6\cdot10^6$ cm^{-2}; 3* – $N_D = 2\cdot10^7$ cm^{-2}.

Hall effect the sample is overcompensated (i.e., it turned into p-type after plastic deformation).

The main results consist in the following:

1. In the low-temperature region (4–7 K) the microwave conductivity of a number of deformed samples exceeds by many orders of magnitude both the dc conductivity of the same samples and the microwave conductivity of the undeformed samples (Fig. 1, curves 1 and 2; Fig. 2, curve 1; Fig. 3, curves 1–3). We shall henceforth call the microwave conductivity of deformed samples in the range 4–7 K "dislocation conductivity" for short.

2. Dislocation conductivity is characterized by weak temperature dependence, and increases with increasing temperature. A similar temperature dependence of microwave conductivity was observed also in deformed p-Ge at relatively low dislocation densities.[2]

3. The dislocation conductivity decreases with increasing dislocation density N_D and vanishes at sufficiently large N_D, i.e., it becomes less than $10^{-4}\Omega$-cm; this changes the qualitative temperature dependence of the dc and microwave resistances in the entire temperature interval (100–4.2 K). The dependence of the dislocation conductivity on the dislocation density differed substantially from that in deformed p-Ge, where the dislocation conductivity increased with increasing N_D and did not vanish at sufficiently large N_D.

The indicated singularities of the DC were observed

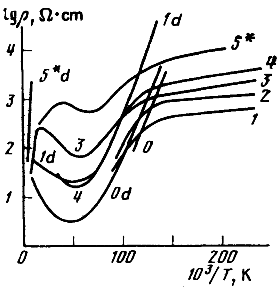

FIG. 3. Temperature dependences of the microwave resistivity of samples with chemical-donor concentrations $N_d = 2\cdot10^{13}$ cm^{-3} and different dislocation densities; curve 0—without dislocations; 1 – $N_D = 2\cdot10^6$ cm^{-2}; 2 – $N_D = 6\cdot10^6$ cm^{-2}; 3 – $N_D = 9\cdot10^6$ cm^{-2}; 4 – $N_D = 1\cdot10^7$ cm^{-2}; 5* – $N_D = 2\cdot10^7$ cm^{-2}.

in samples from three different ingots, i.e., they did not depend on the differential donor concentration (whose range of variation, to be sure, was not very large) or on uncontrollable features of different ingots.

We discuss first the dependence of the microwave conductivity of the samples on the temperature. In the initial dislocation-free crystals, the conduction is due to electron motion in the conduction band. The conductivity is the product of the electron mobility by their concentration. The resistance of such samples has a characteristic minimum in the region of 20 K (curves 0 and 0d in Fig. 1). The resistance is decreased when the temperature is raised from 4.2 because of excitation of electrons from the donors into the conduction band, and the further increase at $T > 20$ K is due to the decrease of the free-electron mobility.

We consider now crystals with dislocations. It is known that dislocations in n-Ge crystals act as acceptors.[6] The maximum number of electrons that the dislocations can capture from the donors is determined by the maximum filling coefficient f. For n-Ge at $T \sim 4.2$ K we have $f \approx 0.1$.[6] If the dislocation concentration is N_D, then the density of the electrons trapped by the dislocations will be $c^{-1}fN_D$, where c is the distance between the broken bands in the dislocation core. At low dislocation density, such that $c^{-1}fN_D < N_d$ (N_d is the concentration of the chemical donors), neutral donors remain in the volume of the crystal. With increasing temperature, the electrons from these donors are excited into the conduction band. The dc resistance is determined completely by these electrons and has also a characteristic minimum in the region of 20 K. By way of example, Fig. 3 shows the dependence of the dc resistance of sample 1d ($N_d = 2.3\times10^6$ cm^{-2}, $N_d = 2\times10^{13}$ cm^{-3}).

The temperature dependence of the resistance in the microwave band of the samples with low dislocation densities ($c^{-1}fN_D < N_d$ takes a different form (curves 1, 2 in Fig. 1; 1 in Fig. 2, 1–4 in Fig. 3). The resistance of these samples also goes through a minimum at $T \sim 20$ K, but with further decrease of temperature ($T < 7$ K) the resistance remains practically unchanged. This causes the resistance in the microwave band, even at very low temperatures, to be small, and the conductivity relatively high. This is precisely the temperature interval in which the dislocation conductivity predominates.

The unexpected circumstance is that with increasing N_D the value of the dislocation conductivity decreases (curves 1–4 in Fig. 3). Obviously, there exists a region of N_D ($\sim10^5$ cm^{-2}) in which the dislocation conductivity increases with increaasing N_D. This follows from the fact that the conductivity of samples without dislocations is exceedingly small at $T \sim 4$ K. We, however, have not yet succeeded in producing samples with small N_D and with sufficiently homogeneous dislocation distribution. At sufficiently large N_D (such that $c^0fN_D > N_d$), the dislocations are capable of capturing more electrons than are present on the donors, and the type of conductivity of the crystal is reversed (it becomes overcompensated). In such samples, with increasing temperature, the electrons from the valence band are projected to the dislocation level and the holes produced in the valence band are responsible for both the dc and the microwave conductivity (curves 3*d and 3* in Fig. 1). The slopes of the curves are determined by the depth of the dislocation level, ~0.1 eV below the top of the valence band. We observed no dislocation conductivity in these samples.

In the intermediate region, when N_D exceeds only slightly the value needed for overcompensation of the sample ($c^{-1}fN_D \gtrsim N_A$), the following picture is observed. Direct-current measurements show that the sample is already overcompensated, i.e., it has p-type conductivity. At the same time the temperature dependence of the resistance in the microwave band reveals a characteristic minimum, and dislocation conductivity is observed. Thus, for example, dc measurements of the Hall effect and of the electric conductivity have shown that the samples are overcompensated (curves 5* and 6* in Fig. 3 and 3* in Fig. 2). By way of illustration we show the temperature dependences of the dc resistance of the samples 2*d in Fig. 2 and 5*d in Fig. 3. The same dependences have a different appearance in the microwave band—see curves 2* in Fig. 2 and 5* in Fig. 3. In our opinion, these results indicate that after plastic deformation the sample becomes inhomogeneous. This is the result of either inhomogeneous distribution of the dislocations in the sample volume, or as the result of a redistribution of the chemical donors in the course of the plastic deformation. It is possible that both mechanisms are actually in operation.

The inhomogeneity in the distribution of the donors and (or) dislocations can cause the entire crystal to be broken up into regions wherein overcompensation has already taken place in some regions, but not in others. It is also clear that such a breakdown of the sample is most probable if N_D exceeds insignificantly the value needed for overcompensation of the sample under conditions of a strictly homogeneous distribution of the donors and the dislocations. The breakdown of the sample into regions causes the results of the dc and microwave conductivity measurements to be different, even if the possible variance of the conductivity is neglected. In the case of the microwave measurements, all the sample regions contribute, and the dominant contribution is that of the low-resistance regions. Therefore curves 2* in Fig. 2 and 5* in Fig. 3 can be explained in the following manner. In the interval $T < 6$ K the dislocation conductivity predominates. When the temperature is raised the still non-overcompensated n-type regions first begin to conduct. The electrons from these regions are excited into the conduction band from shallow donor levels and cause the conductivity of the sample. Finally, when the sample temperature reaches 100 K, the overcompensated p-type region begin to contribute to the conductivity. In these regions the conductivity is effected by the holes excited into the valence band from deep dislocation levels.

In dc measurements, the resistance is determined by the highest-resistance sections of the current circuit. It appears that the flow of current from contact to contact in these samples (curves 2* in Fig. 2 and 5* in Fig. 3) was through the overcompensated p-type regions, and the n-type regions are not observed in these measurements.

If we take this point of view, then, in summarizing, we can state that the dislocation conductivity is observed only in undercompensated samples or in inhomogeneous samples with undercompensated regions.

We now discuss the possible dislocation-conductivity mechanisms. As already noted in Ref. 2, the most probable dislocation conductivity mechanisms are hopping conduction over the impurities and conduction along the dislocation core. According to the first of these models, plastic deformation produces local clusters of impurities (in this case, donors); since hopping conduction is extremely sensitive to the impurity concentration,[4] these clusters are capable of explaining the dislocation conductivity. It is not quite clear how to explain within the framework of this model the measured conductivity of p-Ge.[2] The second model, which seems most realistic to us, explains consistently the experiments on p-type germanium.[2] However, to be able to explain our present results within the framework of this model, we must assume that the spectrum of the carriers on the dislocations consists of several bands, and definite assumptions must be made concerning the carrier mobilities in these bands. The scheme proposed to explain from a unified point of view the results of measurement of n- and p-type germanium is the three-band scheme (Fig. 4). Assume that the electron dislocation spectrum consists of three bands. Let the first band be completely filled when the dislocation is neutral, and let the second and third bands be empty. The assumption we must make is that the carrier mobility in the second band is negligibly small compared with the mobilities in the first and third bands. In this model all the results find a consistent explanation. In particular, if a dislocation is introduced into a p-type crystal, some of the electrons go off from the first dislocation band to chemical acceptors, and the microwave conductivity observed in this case can be attributed to motion of the holes in the first band.

We consider now a dislocation in an n-type crystal. If the number of dislocations is small (the degree of smallness is determined by the concentration of the chemical donors), then the electrons that move over to the dislocation from the donors will be located in both the second and third bands, and the conductivity is due in this case to electron motion in the third band. With increasing number of dislocations all the additional electrons are in the second band and no conductivity will be observed. A similar three-band dislocation-

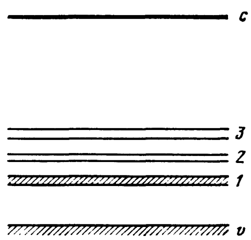

FIG. 4. Proposed energy level scheme of dislocations in germanium.

band scheme explains also the results on the dislocation conductivity of silicon.[1,3]

The experimental data presently at our disposal still do not allow us to draw a definite conclusion concerning the dislocation conductivity mechanism. Yet it is clear that the question of existence of conduction along a dislocation core is of great interest. We propose therefore to study the dislocation conductivity further. It seems promising to study samples with more perfect dislocation structures and doped with deep donors. This doping should exclude the hopping-conduction mechanism. On the other hand if the observed microwave conductivity is due to motion of electrons on dislocation cores, then its value should not depend on the type of centers that deliver the electrons to the dislocations.

[1]V. A. Grazhulis, V. V. Kveder, V. Yu. Mukhina, and Yu. A. Osip'yan, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 164 (1976) [JETP Lett. **24**, 142 (1976)].

[2]Yu. A. Osip'yan, V. I. Tal'yanskiĭ, and S. A. Shevchenko, Zh. Eksp. Teor. Fiz. **72**, 1543 (1977) [Sov. Phys. JETP **45**, 805 (1977)].

[3]V. A. Grazhulis, V. V. Kveder, and V. Yu. Mukhina, Phys. Status Solidi A **44**, 107 (1977).

[4]B. I. Shklovskiĭ, Fiz. Tekh. Poluprovodn. **6**, 1197 (1972) [Sov. Phys. Semicond. **6**, 1053 (1973)].

[5]A. A. Brandt, Issledovanie dielektrikov na SVCh (Investigation of Dielectrics at Microwave Frequencies), Fizmatgiz, 1963.

[6]W. T. Read, Jr., Philos. Mag. **45**, 775 (1954).

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