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AC Conductivity of Deformed Germanium Single Crystals at T = 4.2 K

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Dislocations introduced in semiconductor single crystals generate deep electronic states in the gap which form one-dimensional energy bands along the dislocation lines. Because dangling bonds can be charged by trapping electrons or holes, quasi-metallic conduction along the dislocations is expected. Plastic deformation produces a network of dislocations with only small unconnected segments of ideal behaviour. Therefore the conductivity of the dislocation core can only be obtained by special dc measurements /1, 2/ or from high frequency conductivity /3, 4/. The experiments must be performed at low temperature to exclude the conductivity caused by doping atoms in the bulk material; only ac measurements can avoid the contact difficulties setting in at low temperatures ($T < 60$ K). Using a dielectric model, considering the dislocation segments as parallel needle-like ellipsoids imbedded in homogeneous bulk material, the line resistance and typical segment length of the dislocations can be calculated from the ac conductivity over an extended frequency range /5/.

More or less parallel dislocations were introduced at 520 °C by four-point bending of parallelepipeds ([110], [001], and [1$\bar{1}$0]) cut from weakly compensated p-Ge single crystals ($N_A - N_D = 3.5\times10^{14}$ cm^{-3}). The main dislocation direction lay along the bending axis [1$\bar{1}$0], particular after compressing the bar in a second step parallel to the [110] direction at 500 °C. The disk-like samples (Φ = 7.6 mm, d = 1 mm) were cut out of the central part of the deformed crystal with the [1$\bar{1}$0] direction lying perpendicular to the plane of the disk.

The experiments were carried out in a special capacitance bridge /6/, designed similar to /7/. For that the specimen was placed in a capacitor, but isolated by thin teflon foil in order to avoid the problem of unknown contact

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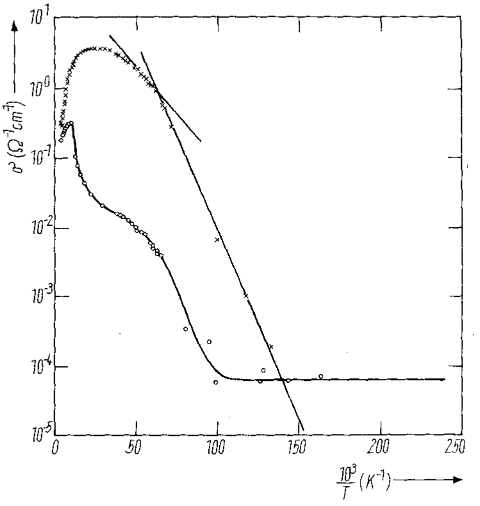

Fig. 1. Temperature dependence of the microwave conductivity σ(10.2 GHz) for p-type Ge single crystals ($N_A - N_D = 3.5x10^{14}\ cm^{-3}$); × undeformed, o deformed with $N_d = 7x10^7\ cm^{-2}$

properties at higher frequencies and lower temperature. The whole circuit was dipped in liquid helium including the diode for rectifying the balance signal which could be minimized by sliding a variable capacitor from outside. With this arrangement we were able to determine the conductivity and permittivity of deformed and undeformed Ge over a frequency range from 10 kHz to 600 MHz by measuring the minimum balance voltage and the value of the variable capacitor. In addition the microwave conductivity was measured in a cylindrical waveguide cavity at 10.2 GHz cooling down from room temperature to 4.2 K /8/.

The temperature behaviour of the microwave conductivity (Fig. 1) is significant for deformed p-type Ge with a high dislocation density of more than $10^7\ cm^{-2}$ /4/. Below 15 K the conductivity decreases proportionally to the activation energy for compensated crystals. While the conductivity of undeformed material decreases furtheron, the curve of the deformed sample bends at 10 K and becomes almost constant at a rather low value of $\sigma(T = 4.2\ K) = 7.5x10^{-5}\ (\Omega\ cm)^{-1}$. Fig. 2 shows the frequency dependence of the conductivity at T = 4.2 K. The conductivity of the control specimen increases with $\sigma \propto f^s$ and s = 0.2 until reaching the apparatus limit $\varepsilon'' = \sigma/2\pi f \varepsilon_0 = 10^{-3}$ (f frequency, $\varepsilon_0 = 8.85x10^{-12}$ As/Vm) at 50 MHz; perhaps a reference to impurity hopping conduction. The curves of the two deformed samples signify a typical relaxation behaviour. At frequencies below 300 kHz (respectively 2.5 MHz) the conductivity is approximately constant, but rises for higher frequencies with $\sigma \propto f^2$ and saturates near the microwave range with good agreement to the cavity measurement data. The relaxation frequency lies at 100 MHz (respectively 300 MHz). By increasing dislocation density the

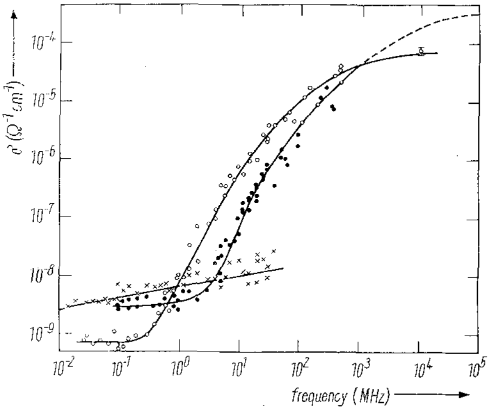

Fig. 2. Frequency dependence of the conductivity at T = 4.2 K for p-type Ge single crystals ($N_A - N_D$ = $= 3.5x10^{14}$ cm^{-3}); x undeformed, o deformed with $N_d = 7x10^7$ cm^{-2}, • deformed with $N_d = 2x10^8$ cm^{-2}

curve of the ac conductivity is shifted to higher absolute values and higher frequencies. The data were analysed in terms of a two-phase mixture model, discussed in detail in /5/. The line resistance ρ of the dislocation core is proportional to the inverse high-frequency conductivity times the dislocation density N_d. Assuming a core diameter of about 1 nm we can calculate the conductivity σ_c of the dislocation core. The relaxation frequency and the lower bending point give the segment length l and the bulk conductivity σ_b, which can be approximated by the conductivity at low frequencies. The results are summed up in Table 1.

The first results of Kveder et al. /7/ (p-Ge, $N_D = 2x10^{12}$ cm^{-3}, $N_d = 1x10^7$ cm^{-2}, ρ = 400 kΩ/nm, l = 9 μm) confirm the dependences to be pointed out. The line resistance of the dislocation core shows a decrease by increasing dislocation density. For all samples the core conductivity at 4 K lies in the metallic region. Because the dislocation network getting closer the segment length is approximately proportional to the dislocation density.

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Table 1

sample	1	2
N_d (cm^{-2})	$7x10^7$	$2x10^8$
ρ(kΩ/nm)	60	30
σ_c(Ω^{-1} cm^{-1})	$2.1x10^2$	$3.6x10^2$
l(μm)	1.2	0.7
σ_b(Ω^{-1} cm^{-1})	$7.0x10^{-10}$	$2.6x10^{-9}$

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