Investigation of high-frequency conductivity of dislocations in silicon

V. A. Grazhulis, V. V. Kveder, V. Yu. Mukhina, and Yu. A. Osip'yan

Institute of Solid State Physics, USSR Academy of Sciences

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An investigation of *p*-type silicon crystals (10^{13} boron atoms/cm^3) containing dislocations, in the temperature interval $T \leq 150\,^\circ\mathrm{K}$, has revealed a sharp increase of the high-frequency conductivity $\sigma(\omega)$ of the crystals at the frequencies $f = 9.5 \times 10^9$ and $f = 3.3 \times 10^{10}$ Hz compared with the dc conductivity $\sigma(0)$, with a ratio $\sigma(\omega)/\sigma(0) > 10^7$. The conductivity $\sigma(\omega)$ depends little on the temperature and increases with increasing frequency, whereas $\sigma(0)$ depends exponentially on the temperature with an activation energy $E_0 = 0.44$ eV. It is concluded in the paper that the anomalously large high-frequency conductivity of deformed crystals is due to conductivity along dislocations.

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An investigation of the properties of conducting one-dimensional systems,[1] such as the system of dislocations in covalent crystals[2,3], is of considerable interest. In the case of dislocations with edge components, the conductivity along the nuclei can be realized both as a result of trapped carriers and as a result of the electrons of the broken bonds. The character of the conductivity depends essentially on the form of the energy spectrum[4] and also on the disturbances of the translational symmetry along the dislocations. One can expect here an appreciable difference between the dc conductivity and the conductivity at high frequency.[5]

We report below experimental results that illustrate the abrupt increase of the microwave conductivity $\sigma(\omega)$ of weakly-doped silicon crystals containing dislocations, in comparison with the conductivity of the same crystals at $\omega = 0$, and also the singularities of the behavior of $\sigma(\omega)$ with changing temperatures. The procedure for sample preparation in measuring $\sigma(0)$ and the Hall effect were described by us earlier.[4] To be able to observe the dislocation conductivity directly and to exclude the contribution of the hopping conductivity over the impurities we have investigated in the present study pure single-crystal silicon containing $\sim 10^{13}$ cm^{-3} boron atoms (Fig. 1).

The samples were deformed by bilateral compression at a stress $\tau \approx 9.6$ kg/mm^3 and temperature 700 °C. The strain in strongly deformed crystals reached 4%; the dislocation density, estimated from the intensity of the ESR signal[3,6] ranged in the deformed samples from 5×10^7 to 5×10^8 cm^{-2}. The measurements of $\sigma(\omega)$ were carried out at frequencies $f = 9.5\times10^9$ Hz and 3.3×10^{10} Hz. The conductivity was determined from the change of the Q of a microwave resonator into which the sample was introduced. It was assumed the conductivity is proportional to the microwave losses in the sample. We used both a copper and a superconducting (niobium) resonator. The latter was evacuated and the temperature of the sample, which was glued to a sapphire rod passing through an opening in the bottom of the resonator, was varied with the aid of a heater placed on the external end of the sapphire rod.

The Q was determined by measuring the half-width of the resonance curve of the resonator. We used in this case a system similar to that of[7], which produced narrow ($\sim$5 kHz wide) frequency markers. As low Q we measured the coupling coefficient of the resonator, and at high Q ($\gtrsim 5\times10^4$) we measured the damping of the oscillations in the resonator following a pulse from the microwave generator.

Figure 1 shows the temperature dependences of the density and mobility of the carriers for the initial deformed samples. In a sample with dislocations, the carrier density in the valence band depends on the temperature exponential-

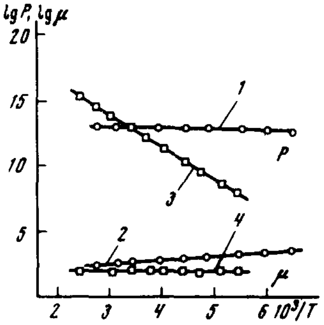

FIG. 1. Dependence of the hole density (P) and of their mobility in the initial sample (circles) and in a sample deformed with a strain 1.6% (squares).

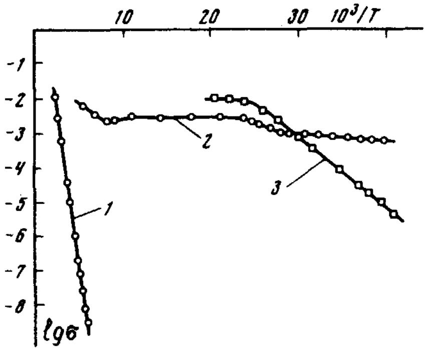

FIG. 2. Dependence of the conductivity on the temperature: 3) $\sigma(0)$ and $\sigma(\omega)$, frequency 9.3 GHz, 1) $\sigma(0)$—dc conductivity of sample with strain 1.6%, 2) conductivity $\sigma(\omega)$ of the same sample (strain 1.6%) at 9.3 GHz.

ly with an activation energy $E_0 = 0.44$ eV, and at temperatures below 100°K it becomes $< 10^8$ cm^{-3}. Figure 2 shows the temperature dependences of the specific conductivity for a sample with dislocations and for the initial sample, determined both with direct current and at a frequency 9.5 GHz. As seen from the figure, the specific conductivity of the deformed sample at 9.5 GHz exceeds by more than seven orders of magnitude the dc specific conductivity of the same sample, whereas for the initial crystal to two conductivities are equal. Attention is called to the fact that in the temperature region $T < 10$°K the microwave conductivity $\sigma(\omega)$ depends little on the temperature, but at $T = 30$—40°K a rather sharp decrease of $\sigma(\omega)$ is observed. At $T < 30$°K the conductivity $\sigma(\omega)$ decreases exponentially with an activation energy $E \lesssim 5$ meV.

Figure 3 shows plots of $\sigma(\omega)$ at frequencies 9.5 and 35 GHz for a sample with dislocations. The conductivity $\sigma(\omega)$ increases with increasing frequency, and a decrease of E_ω with increasing ω can be noted.

It must be emphasized that the aforementioned region of sharp decrease of $\sigma(\omega)$ is located in approximately the same temperature range (30—40°K) where the minimum of free-carrier mobility is observed in deformed strongly doped silicon samples,[4] and there is also a deviation from the Curie law in the temperature dependence of the magnetic susceptibility of the dislocation spin system and an anomalous behavior of the spin-relaxation times.[3]

An analysis of the experimental results shows that the observed high microwave conductivity in deformed silicon crystals is due to conductivity along the

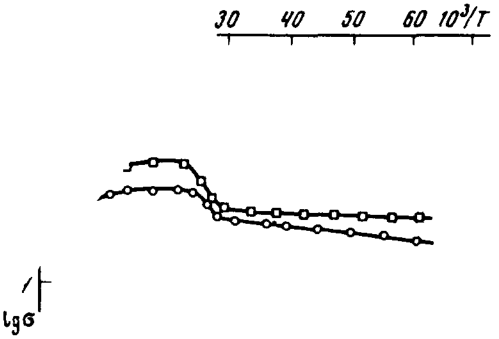

FIG. 3. Temperature dependence of the conductivity $\sigma(\omega)$ of a sample with strain 1.9%: ○—frequency 9.3 GHz, □—33 GHz.

dislocation cores. The question of the appearance of accompanying defects and the choice of the optimal regime for introducing the dislocations was investigated by us earlier.[3,4,6] We indicate here only that annealing the investigated samples at $T = 500\,^\circ\mathrm{C}$ does not change significantly the parameters of the investigated crystals, nor is the effect of sample aging observed.

We propose to study the observed phenomena in greater detail in the future.

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