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High-Stress Piezoresistance and Mobility in Degenerate Sb-Doped Germanium*

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The resistivity of germanium containing between $N=3\times10^{17}$ and 10^{19} antimony atoms per cc was measured at 1.2°K under uniaxial compressions of up to 10^{10} dyn cm^{-2}. These stresses are high enough to effect an observable saturation in the piezoresistance, that is, to transfer all electrons to a single conduction-band valley ([111] compression) or to two valleys ([110] compression). Two distinct ranges are observed in degenerate germanium: for $N<10^{18}$ cm^{-3} the mobility increases with N and shows impurity-band effects; for $N>10^{18}$ cm^{-3} the mobility decreases and ionized-impurity scattering is the dominant scattering process. The latter range is $N>3\times10^{18}$ cm^{-3} for large [111] compression. The resistivity was measured for current flowing parallel and perpendicular to the stress direction. The mobility anisotropy was found to be $\mu_\perp/\mu_\parallel=3.9\pm0.1$ for $N>4\times10^{18}$ cm^{-3}. This indicates that the mean free path is nearly isotropic. The mobility for electrons in 1, 2, and 4 valleys is compared with Csavinszky's partial-wave treatment of impurity scattering. The change of screening with the number of valleys was taken into account. Csavinszky's theory overestimates the N dependence and the magnitude of the scattering. This is attributed to the failure of the individual-scattering assumption.

I. INTRODUCTION

THE transport properties and the shape of the band edges in heavily doped (degenerate) semiconductors are not understood. Several recent experiments indicate rather significant deviations from the simple model which treats the doped semiconductor as a metal under residual resistance conditions. A negative longitudinal and transverse magnetoresistance[1] has been observed within a wide concentration range, the resistivity exhibits a temperature dependence[2] well below the degeneracy temperature, and the tunneling experiments[3] require for their explanation a sizeable number of tail states[4] extending far into the forbidden gap of the pure material. Other experiments, on the other hand, in particular the study of the piezoresistance,[5,6] the specific heat,[7] the magnetic susceptibility,[8] and the strain-induced birefringence,[9] are explained on the basis of the simple degenerate model.

The transport properties of multivalley semiconductors are complicated by the fact that the total mobility is composed of the anisotropic mobilities of each valley and that both intra- and intervalley scattering can occur, each process with a different anisotropy and different dependencies on energy and impurity concentration. It has been shown,[2,6] however, that by extending the piezoresistance measurements in degenerate germanium to stresses sufficiently high so that the electrons are transferred to two or a single conduction band valley depending on the stress orientation, the mobility anisotropy can be measured directly.

In this paper we report high-stress piezoresistance measurements in Sb-doped germanium at 1.2°K. The range of concentrations extends from 3×10^{17} to 9×10^{18} cm^{-3}. Uniaxial compressional stresses of up to 10^{10} dyn/cm^2 were used. These are sufficiently high to transfer all electrons into two valleys ([110] stress orientation) or one valley ([111] orientation). The resistivity was measured parallel and perpendicular to the stress orientation. Samples were also measured under [100] stress in order to test the homogeneity of the stress distribution and to determine the magnitude of small contributions to the piezoresistance which do not depend on the removal of the equivalence of the valleys.

Sb rather than As or P was chosen as donor element because its small central cell potential[10] yields an intervalley scattering which is negligible[11] in comparison with the intravalley scattering.

The results are compared with the ionized impurity scattering theory of Brooks and Herring[12] which is

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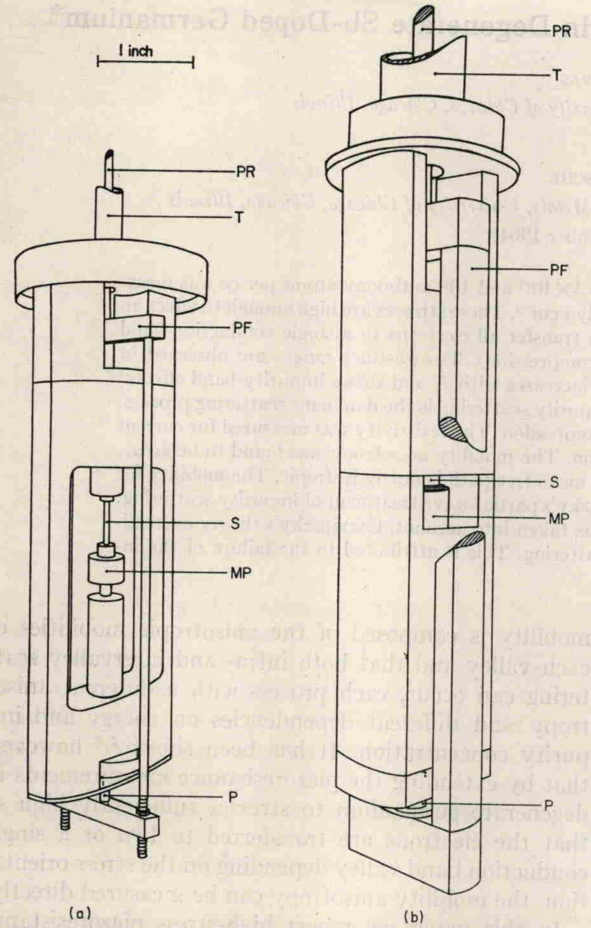

FIG. 1. Compression apparatus for (a) longitudinal and (b) transverse measurements. PR = pulling rod, T = support tubing, PF = pulling frame, S = sample, MP = movable piston, P = pin pushing the movable piston upwards.

based on the Born approximation and the more accurate partial-wave analysis of Csavinszky.[13] In both cases the change of the screening parameter with the change of the number of valleys as discussed by Robinson and Rodriguez[14] was taken into account. In both theories the scattering anisotropy was treated on the assumption of an isotropic scattering cross section.

II. STRESS APPARATUS AND CRYOSTAT

Germanium can be subjected to very large elastic strains without breakage if the surface is smooth and free of cracks. The presence of soldered leads on the surface increases the probability of breaking, but strains of the order of 10^{-2}, that is, uniaxial compressional stresses of 10^{10} dyn/cm^2, can safely be applied. The part of the stress apparatus holding the sample is shown schematically in Figs. 1(a) and 1(b) for longitudinal and transverse piezoresistance measurements, respectively. In both cases uniaxial compression is achieved by pulling the lower end of the sample upwards, holding the upper end fixed against the support of a stainless steel tubing. The pulling frame hangs on a thin stainless rod from one side of a beam balance which is on top of the cryostat but still inside the helium chamber. This construction has several advantages. First the larger tubing being under compression and the inner rod being under tension, the dimensions can be chosen so that the heat flux to the lower parts of the cryostat is very small. The inner rod would have to be much thicker to support large compressions without bending. Second, friction is eliminated by avoiding the passage of the pulling rod through a vacuum tight seal.

The compression frame of Fig. 1(a) is machined out of Invar. The ends of the sample, which has a cross section of about 0.8 mm^2 and a length of 2 cm, are cemented with Epoxy Resin into brass cups. For electrical insulation, these are placed into thin nylon cups and tightly fitted into the end holes of the movable pistons of the compression frame. Rotation of the pistons while the Epoxy is setting assures very good alignment of the sample.

The frame of Fig. 1(b) for transverse measurements is made of hardened stainless steel. The gliding surfaces of the piston and of the hole are chrome plated and polished. In this case the sample rests with its long axis perpendicular to the stress axis and is insulated by thin mica sheets from the upper surface of the compression frame and the top of the piston. These two surfaces are of hard permalloy. They were polished optically flat and parallel. For the transverse measure-

TABLE I. Sample characteristics.

Sample	N (10^{18} cm^{-3})	E_{F_0}[a] (eV)	$E_{F_{sat}}$[b] (eV)	μ_0 at 1.3°K[a] (cm^2 sec^{-1} V^{-1})	μ_{sat} at 1.3°K[b] (cm^2 sec^{-1} V^{-1})
Sb-C-a	0.320	0.00303	0.0048	809.5	326
Sb-C-b	0.845	0.0058	0.0093	1127	517
Sb-C-1	1.10	0.00693	0.0111	1097	500
Sb-C-2	2.47	0.0119	0.0190	1077	510
Sb-C-3	3.96	0.0163	0.0262	973	468
Sb-C-4	5.07	0.0194	0.0310	925	459
Sb-C-5	8.38	0.0270	0.0430	848	469
Sb-F-a	0.282	0.0028	0.00705	719	56.2
Sb-F-b	0.657	0.0049	0.0123	1057	144.5
Sb-F-1	1.13	0.00705	0.0180	1056	164
Sb-F-2	1.60	0.00895	0.0227	1093	201
Sb-F-3	2.47	0.0109	0.0305	1103	219
Sb-F-4	4.27	0.0171	0.0440	1003	233
Sb-F-5	5.24	0.0199	0.0500	938	221
Sb-F-6	7.00	0.0240	0.0605	867	215
Sb-G-1	4.01	0.0164	0.0422	1046	969
Sb-G-2	4.12	0.0169	0.0430	1047	970
Sb-G-3	4.84	0.0190	0.0480	864	827
Sb-G-4	8.74	0.0282	0.0714	850	794
Sb-H-1	8.38	0.0270	0.0430	845	719

[a] The subscript 0 stands for zero stress.
[b] The subscript "sat" stands for saturation.

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