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High-Stress Piezoresistance in Degenerate Arsenic-Doped Germanium*

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The resistivity of germanium containing between $N=4\times10^{17}$ and 10^{19} arsenic atoms per cc was measured at 1.2°K under uniaxial compressions of up to 10^{10} dyn cm^{-2}. The piezoresistance fails to saturate near the stress at which one expects essentially all electrons to have been transferred to a single conduction band valley ([111] compression) or to two valleys ([110] compression). Saturation is approached at much higher stresses. The resistivity was measured for current flowing parallel and perpendicular to the stress direction. For $N>10^{18}$ cm^{-3}, the mobility anisotropy was found to be $\mu_\perp/\mu_\parallel=4\pm0.4$, 5 ± 0.6, and 6 ± 0.5 for the 4-, 2-, and 1-valley cases, respectively. The mobility ratio $\mu_\parallel(\mathrm{Sb})/\mu_\parallel(\mathrm{As})$ increases from about 1.5 to 1.9 as the electrons are transferred from 4 valleys to 1 valley. Evidence for the presence of tail states in As-doped germanium and the significance of the large central impurity cell potential of As donors for the interpretation of the piezoresistance are discussed.

I. INTRODUCTION

BY applying large shear stresses it is possible to change a multivalley semiconductor or one with degenerate bands into a simple semiconductor in which the charge carriers are confined to one region in k space which has a simple ellipsoidal shape. This method has been used recently for the determination of deformation potentials,[1,2] and for studying the effect of stress on the impurity wave functions in n-Ge,[3] and p-Ge.[4] In degenerate n-Ge this method allows the direct measurement of the mobility anisotropy of the carriers in one conduction band valley.[5,6] Having this parameter one might try to treat the semiconductor like a metal under residual resistance conditions and obtain information about the mobility and its dependence on energy and impurity concentration which can be compared with theory.[6] In the case of Sb-doped degenerate germanium fairly good agreement was found between the experimental results of two different laboratories.[5,6] However, rather large discrepancies were found[6] between these results and theoretical calculations of ionized impurity scattering based on an individual scattering model.[7]

The experimental situation is much less certain in the case of As-doped degenerate germanium. The mobility anisotropy of a single valley has not been measured directly and very different values are obtained from this quantity by different authors depending on the model used for interpreting the experimental results.[5,8]

The case of As-doped Ge is more complicated than that of Sb-doped Ge because of the much larger central cell potential, which gives rise to the valley-orbit splitting of the isolated donor impurity levels of the As donors.[1] This important difference between Sb and As donors in germanium is apparent in many experiments. The large magnitude of intervalley scattering[9] and of the impurity-assisted interband tunneling[10,11] and the presence of a negative magnetoresistance effect[12] at high doping levels in As-doped Ge are indications of the effect of the large central cell potential of the As donors.

In order to evaluate the validity of the different models used for the description of As-doped degenerate germanium, we have extended the piezoresistance measurements to higher stress values and higher As concentrations and obtained the mobility anisotropy directly by measuring the resistivity parallel and perpendicular to the valley axis. The range of As concentrations extends from 4×10^{17} to 10^{19} cm^{-3}. Uniaxial compressional stresses of up to 10^{10} dyn/cm^2 along the [111] and the [110] axes were used. The piezoresistance measurements were carried out at 1.2°K.

II. EXPERIMENTAL DETAILS AND RESULTS

The stress apparatus, the cryostat, and the sample preparation are the same as those used for Sb-doped

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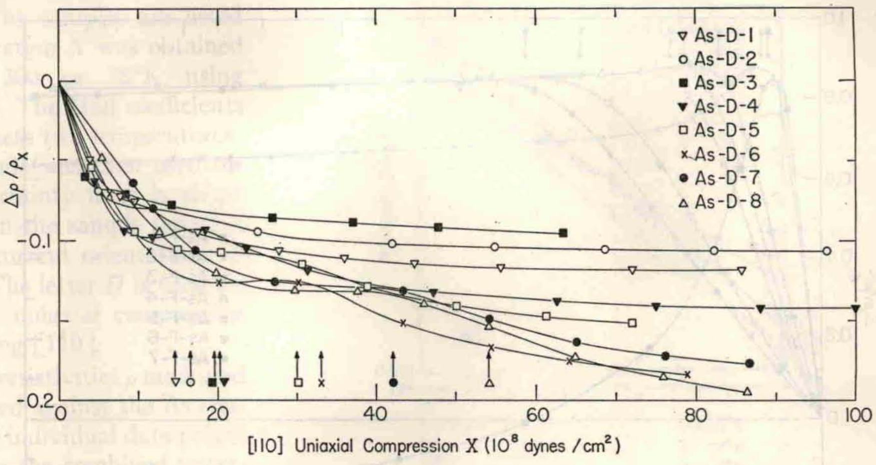

FIG. 4. Transverse piezoresistance as a function of [110] compressional stress with current along [1$\bar{1}$0] at 1.2°K for As-doped germanium (arrangement D). The arrows indicate the saturation stress for undistorted parabolic bands.

large stresses. This decrease is considerably larger than that observed in orientation F: about 0.1 compared to about 0.04 for case F (see Fig. 2). Also, the curves in Fig. 4 show a tendency to saturate followed by a subsequent decrease of $\Delta\rho/\rho$. The fact that the change of $\Delta\rho/\rho$ beyond X_s is larger for orientations G and D than for F and C, respectively, is consistent with Koenig's explanation[5] for this effect: If localized electron states remain associated with the valleys moving upwards with stress, then these immobile electrons transfer into the lowered valley or valleys at stresses larger than X_s. An electron originating from such levels will contribute a larger increase in conductivity for current orientations in the high mobility directions (cases G and D) than for the low mobility orientation (cases F and C). Furthermore, more immobile electrons become available beyond X_s when 3 valleys are moved up by stress (cases F and G) than when 2 valleys are raised (cases C and D). The absence of the decrease of $\Delta\rho/\rho$ beyond the onset of saturation in Sb-doped Ge would then imply that the number of such localized states is negligible for that material.

It is instructive to point out the differences and similarities of the two donor elements Sb and As in germanium with regard to their effects on the mobilities and the piezoresistance effects. Figure 6 shows the low-stress piezoresistance coefficient Π_{44} as a function of Sb and As concentration. Our values are in fair agreement with those of Katz and Koenig.[5] They are significantly larger, however, than the extrapolation into the high concentration range of the results of Nakamura and Sasaki.[16]

Figure 7 shows for Sb[6] and As donors the concentration dependence of the zero stress mobility (4-valley case) and of the mobility components parallel and perpendicular to the respective stress directions for the 2- and 1-valley cases. The results were obtained at 1.2°K from the resistivities in the very high stress limit under the assumption that the carrier concentration is not changed by the stress.

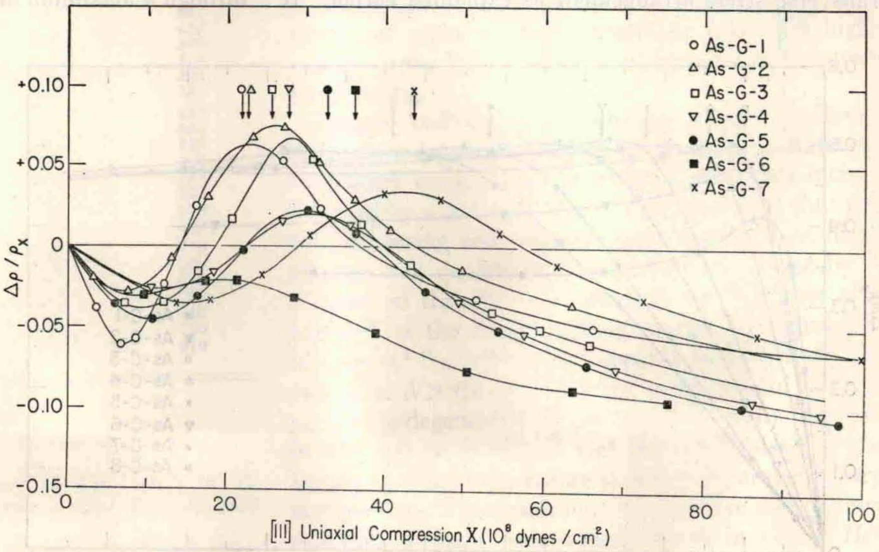

FIG. 5. Same as Fig. 4 for [111] compressional stress (arrangement G).

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