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Stress Effects on Impurity-Induced Tunneling in Germanium*

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The effects of uniaxial compression and of hydrostatic pressure on the impurity-induced interband tunneling current in germanium tunnel junctions have been studied experimentally at 4.2°K. The diodes were formed on (100) and (110) faces of arsenic-doped germanium bars. The stress coefficients of the tunnel current were measured at fixed forward and reverse bias voltages. The experiments show that the part of the electron wave function responsible for impurity-induced tunneling is not associated with a particular conduction-band valley. Some structure in the bias dependence of the shear stress coefficients near zero bias remains unexplained. This structure does not appear in the hydrostatic-pressure coefficient.

I. INTRODUCTION

THERE are three distinctly different interband tunneling processes[1–4] in semiconductors: (i) direct tunneling between states having the same value of the crystal momentum k, (ii) phonon-assisted tunneling between states of different k, and (iii) impurity-induced tunneling. This last tunneling process again occurs between states of different k, but in this case the difference in crystal momenta of the initial and final electron states is supplied by impurities or defects.

All three tunneling processes can be observed in Ge or Si tunnel junctions in different bias ranges.[3–5] In Ge, the relative amount of phonon-assisted and impurity-assisted indirect tunneling depends strongly on the donor element.[6,7] The fraction of impurity-induced tunneling increases with increasing magnitude of the central cell potential of the particular donor element. In Sb-doped germanium, impurity-induced tunneling is almost completely negligible with respect to phonon-assisted tunneling, and the reverse is true for As- and P-doped Ge.

Recently[8,9] many details of the direct and the phonon-assisted indirect tunneling processes have been uncovered by measuring the bias dependence of the effect of pressure and shear stress on the tunneling current in Sb-doped germanium tunnel diodes. The absence of impurity-induced tunneling in these samples made it possible to get some clear answers concerning the other processes.

The work discussed here on As-doped tunnel diodes complements the previous work in that the impurity-induced tunneling current in these samples completely dominates the phonon-assisted components.

There are several questions concerning this mode of tunneling that can be answered by stress experiments. In particular, it has been shown[8] that the presence or absence of a large positive shear stress coefficient for current I along [1$\bar{1}$0] and compressional stress along

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1 L. Esaki, Phys. Rev. **109**, 603 (1958).
2 E. O. Kane, J. Appl. Phys. **32**, 83 (1961).
3 H. Holonyak, Jr., I. A. Lesk, R. N. Hall, J. J. Tiemann, and H. Ehrenreich, Phys. Rev. Letters **3**, 167 (1959).
4 J. V. Morgan and E. O. Kane, Phys. Rev. Letters **3**, 466 (1959).
5 R. N. Hall and J. H. Racette, J. Appl. Phys. **32**, 2078 (1961).
6 R. N. Hall, in *Proceedings of the International Conference on Semiconductor Physics, Prague, 1960* (Academic Press Inc., New York, 1961), p. 193.
7 Y. Furukawa, J. Phys. Soc. Japan **15**, 1903 (1960).
8 H. Fritzsche and J. J. Tiemann, Phys. Rev. **130**, 617 (1963).
9 H. Fritzsche and J. J. Tiemann, *Proceedings of the International Conference on the Physics of Semiconductors, Paris, 1964* (Academic Press Inc., New York, 1965), p. 599.

[110] can be used to decide whether or not an electron tunnels from a particular (111) valley in the conduction band.

This paper reports measurements at 4.2°K of the stress-tunneling coefficients $\Pi=\Delta I/IX$ and $\Pi_p=\Delta I/I3p$ of germanium tunnel junctions containing As concentrations of 1.5×10^{19} cm^{-3}. The direction of the tunnel current was parallel to [001] or [1$\bar{1}$0]; the orientation of the uniaxial compression was along [100] or [110].

II. DEFINITION OF THE STRESS-TUNNELING COEFFICIENTS

We restrict our discussion to the first-order stress effects on tunnel junctions placed (i) on a (001) crystallographic plane so that the tunnel current flows along [001] and (ii) on a (1$\bar{1}$0) plane with the current along [1$\bar{1}$0].

For a junction on a (001) plane of a crystal having cubic symmetry, there are two independent constants which describe the first-order stress dependence of the tunnel current. We shall call these A and B. Here $A=\Delta I/IX$ for a uniaxial compression X lying in the junction plane, as shown in Fig. 1, and $B=\Delta I/I3p$ for hydrostatic pressure p. The relative current change for uniaxial compression normal to the (001) plane is then

$$\Delta I/I=(B-2A)X. \tag{1}$$

For a junction placed in a (1$\bar{1}$0) plane, there are three independent coefficients C, D, and E. C and D are explained in Fig. 1 and E is the hydrostatic pressure coefficient for the tunneling direction [1$\bar{1}$0]. Calling Φ the angle between the compression axis and the [001] direction, the relative current change due to a uniaxial compression lying in the (1$\bar{1}$0) plane is then

$$\Delta I/I=[C+(D-C)\cos^2\Phi]X. \tag{2}$$

The corresponding quantity for a compressional stress normal to the (1$\bar{1}$0) plane is

$$\Delta I/I=(E-C-D)X. \tag{3}$$

III. EXPERIMENTAL DETAILS AND RESULTS

The tunnel junctions were formed by alloying indium dots doped with $\frac{3}{8}$% gallium at 540°C on opposite faces of single-crystal germanium bars containing an arsenic concentration of 1.5×10^{19} cm^{-3}. The diameter of a typical diode dot was about 0.05 cm after the etching process which removes the perimeter of the junctions. Uniaxial compressional stress varying between 5×10^7 and 5×10^8 dyn/cm² was applied parallel to [110] or [100] at helium temperatures. The stress coefficients averaged over the two opposed diodes (to eliminate the effects of flexure of the bar) were independent of stress in this range. The cryostat and stressing apparatus have been described before.[10] The hydrostatic pressure measurements were extended up to $p=7\times10^7$ dyn/cm².

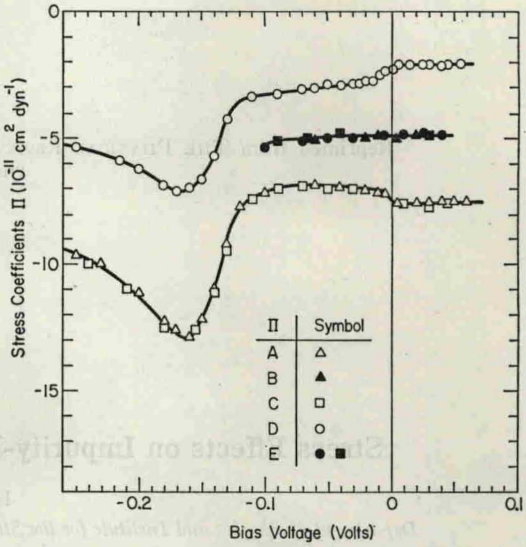

FIG. 2. Stress coefficients for uniaxial compression and hydrostatic pressure for As-doped Ge tunnel junctions as a function of bias voltage at 4.2°K. Note the factor $\frac{1}{3}$ in the definition of the hydrostatic-pressure coefficients B and E.

Figure 2 shows the bias dependence of the various stress coefficients defined in the previous section at 4.2°K. In contrast to the observations on Sb-doped germanium diodes,[8] these As-doped diodes do not exhibit the large positive shear stress contribution to the coefficient D. The stress coefficients A and C are found to be almost identical. The same is true for the pressure coefficients B and E. One further observes that the pure shear component $D-E$ for the orientation I[1$\bar{1}$0], X[110] is nearly identical in magnitude but of opposite sign to the pure shear component $(C-E)$ for this orientation or $(A-B)$ for the orientation I[001], X[100].

The bias dependence of the pressure coefficients B and E of these As-doped functions does not show the structure which was found[9] in the case of Sb-doped junctions. This is to be expected since the structure found in those cases is associated with the threshold voltages for phonon-assisted tunneling, and this process contributes only negligibly to the tunneling current in As-doped junctions. One observes, however, a change of the stress coefficients A and C and an opposite change of D at zero bias which is not present in the bias dependence of the pressure coefficients B and E. Thus

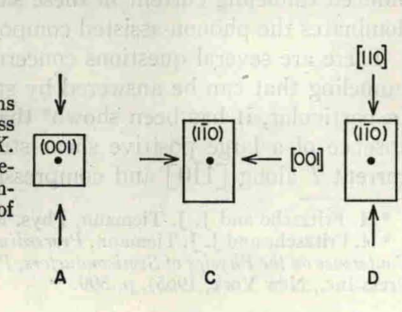

FIG. 1. Definitions of the uniaxial stress coefficients $\Delta I/IX$. The arrows represent uniaxial compressional stress of unit magnitude.

[10] M. Cuevas and H. Fritzsche, Phys. Rev. 137, A1847 (1965).