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Effect of Elastic Strain on Interband Tunneling in Sb-Doped Germanium*

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The effects of uniaxial compression and of hydrostatic pressure on the direct and indirect tunneling processes in germanium tunnel diodes have been studied experimentally under forward and reverse bias at 4.2°K and compared with Kane's theory. The diodes were formed by alloying indium doped with $\frac{3}{8}\%$ gallium on (100) and (110) faces of germanium bars containing an antimony concentration of $5.5\times10^{18}/\mathrm{cm}^3$. The first order change of the tunneling current with stress was measured at fixed bias voltages. For biases smaller than 8 mV the current is direct and not affected by the relative shifts of the (111) conduction band valleys. In the bias range of indirect tunneling the anisotropic tunneling from the (111) valleys was observed in agreement with theory. In the range of direct tunneling to the (000) conduction band the current change is correlated with the stress induced change of the direct band gap and of the energy separation between the (111) and (000) conduction bands. This separation was found to be 0.160 ± 0.005 eV at zero stress in agreement with optical measurements on degenerate germanium. Some details of the bias dependence of the pressure effect including some fine structure at small biases remain unexplained.

I. INTRODUCTION

As a result of extensive experimental and theoretical efforts, the main features of the tunneling process in Esaki tunnel diodes[1] have been clearly established. However, since it is difficult to assess the validity of some of the simplifying assumptions and approximations which underlie our present theoretical understanding of this process, it is not clear to what extent the existing theories[2,3] should explain the finer details of the experimental observations. This problem is particularly difficult to resolve because tunnel diodes can only be made in highly impure materials. This fact

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precludes the possibility of ever performing a tunnel diode experiment under very ideal conditions. It is hoped that some of these difficulties can be alleviated by performing a series of experiments upon each diode. In this paper we discuss measurements of the effect of hydrostatic pressure and of uniaxial compression on the tunneling current of germanium tunnel diodes at helium temperatures. A subsequent paper will report the temperature dependence of the tunneling current of the same diodes.

The effects of elastic strain will strongly depend on the effective-mass anisotropies and on the deformation potentials of the relevant band extrema. Most of these quantities are known for germanium.[4] Furthermore, in germanium, two types of tunneling have been observed,[5,6] and theoretical expressions for both types have been derived.[3] These two tunneling processes are (1) direct tunneling and (2) indirect or phonon-assisted tunneling. The relative proportion of the current carried by these two processes depends on the temperature, the bias voltage, and on whether As, P, or Sb is used as the donor impurity.[5] Although the mechanism is not understood theoretically at present, direct tunneling predominates in As- and P-doped diodes at all temperatures and biases. In Sb-doped diodes, on the other hand, one observes at helium temperatures several distinct bias regions in which one or the other of these processes is dominant. This material has the advantage that both direct and indirect tunneling are observable in separate bias ranges in a single diode.

This is important because there is considerable experimental uncertainty as regards the details of the impurity distribution within the junction itself. By measuring both types of tunneling in one sample, this uncertainty does not affect the conclusions. Antimony-doped germanium tunnel diodes have the additional advantage that the unambiguously direct tunneling to the (000) minimum in the conduction band is much more clearly observed.[6,7]

The main effect of elastic strain on the tunneling current arises from the shifts in energy of the conduction band valleys with respect to the valence band. Hydrostatic pressure causes all of the conduction band valleys to rise in energy, but the (000) valley moves faster than the (111) valleys.[8] In addition, shear stress can shift the (111) valleys with respect to one another.[9] These effects can be quantitatively calculated by applying deformation potential theory to the expressions for the tunnel current derived by Kane.[3] The calculated behavior is in good qualitative agreement with the main features of the experimental data.

II. THEORETICAL CONSIDERATIONS

According to Kane's theory,[3] the tunneling current flowing from a single valley in the conduction band to the valence band is given by

$$I_d = C_d D_d \exp(-\alpha) \quad \text{with} \quad \alpha = \lambda_d E_g^{3/2} m^{*1/2}/F, \qquad (1)$$

when the transition is direct, i.e., when the conduction and valence band extrema occur at the same wave number **k**. It is given by

$$I_i = C_i D_i \exp(-\beta) \quad \text{with} \quad \beta = \lambda_i (E_g \pm \hbar\omega)^{3/2} m^{*1/2}/F, \qquad (2)$$

when the transition is indirect, i.e., when the band extrema occur at different **k**. In Eq. (2) $\hbar\omega$ is the energy of the phonon needed to conserve wave number in the tunneling process. The upper sign is for p to n tunneling (reverse bias), the lower sign for n to p tunneling (forward bias).

In Eqs. (1) and (2), E_g is the appropriate band gap; $m^* = (1/m_{hx} + 1/m_{ex})^{-1}$ is the reduced effective mass in the tunneling direction. The quantities C and λ are given by Kane. The average junction field is given by

$$F = [2\pi n^* (E_g + \zeta_n + \zeta_p - eV)/\kappa]^{1/2}, \qquad (3)$$

where $n^* = np/(n+p)$ is the reduced doping constant, κ is the dielectric constant, ζ_n and ζ_p are the Fermi level penetrations into the conduction band and the valence band, respectively, and E_g is the smallest band gap. The phonon energy has to be considered also in the density of states factor D_i as will be discussed later. The density of states factor is given in Kane's notation by

$$D = \int [1 - \exp(-2E_s/\bar{E}_\perp)][f_1(E_1) - f_2(E_2)] dE. \qquad (4)$$

When there is more than one valley in the conduction band, or more than one valence band, the total current will be a sum over all combinations of conduction band and valence band extrema which can contribute. Because of the exponential dependence on the reduced mass appearing in Eqs. (1) and (2), however, this sum for germanium can be reduced to only those transitions which involve the light hole band. Furthermore, since the conduction band valleys in germanium are quite anisotropic, and since the tunneling probability depends only on the effective mass along the direction of tunneling,[10] the current contributions of the four (111) valleys will, in general, be different.

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[10] The tunneling direction for isotropic effective masses is along the direction of the electric field (perpendicular to the plane of the junction). For an anisotropic effective mass, the tunneling direction lies between the electric field direction and the direction of minimum effective mass. We have assumed that in all cases the tunneling direction coincides with the electric field; so we have slightly overestimated the nonequivalence of the valleys.