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# EFFECT OF UNIAXIAL STRESS ON InSb TUNNEL JUNCTIONS

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**Abstract**—The deformation potential constants of heavily doped InSb have been determined by applying uniaxial stress to $p$–$n$ tunnel junctions formed below the surface of rectangular InSb bars. Stress applied parallel to the major axes of these bars and parallel to the junction plane resulted in a linear decrease in tunnel current as a function of stress. The percentage decreases were $24{\cdot}5\times10^{-3}$, $9{\cdot}5\times10^{-3}$ and $4{\cdot}5\times10^{-3}\,\mathrm{cm^2kg^{-1}}$ for stress applied parallel to [010], [$1\bar{1}0$], and [111] directions respectively. The observed changes in tunnel currents are attributed to a decrease in the tunnel probability produced by a shift in the conduction band edge relative to that of the valence band. Our data is consistent with a hydrostatic deformation potential of $-10$ eV, and valence band deformation potentials $b=-1{\cdot}3$ eV and $d=-7{\cdot}4$ eV.

## 1. INTRODUCTION

Quantum mechanical tunneling between oppositely doped regions of a semiconductor diode has been used extensively to reveal various physical properties of the materials. For example, the general features of the energy gap have been studied via the electron–phonon interaction [1, 2] while the presence of defect or tailing states has been postulated to account for the excess current [3]. Hydrostatic pressure [4] and uniaxial stress have been used to alter the energy gap and hence to modify the barrier transmission probability. In Ge tunnel diodes, in the bias range where direct tunneling dominates Fritzsche and Tieman [5] observed that the change in tunnel current was proportional to the stress. Payne [6] has deduced the deformation potentials of Ge by relating the shift in the electron–phonon interaction energy, revealed by tunneling, to the applied stress. Long and Hulme [7] have used the theory developed by Pikus and Bir [8] to account for the observed change in tunnel current when [100] stress was applied to Ge tunnel diodes.

This paper deals with the effect of uniaxial stress on InSb tunnel junctions. Changes in the tunnel current as a function of stress are related to the change in energy gap through the compliance coefficients and the deformation potentials of the conduction and valence bands. Experimental techniques and results are presented and analyzed using Kanes [9] theory of tunneling and the theoretical results of Bir and Pikus [10].

## 2. EXPERIMENTAL

Specimens were prepared by diffusing Cd at 500°C for 60 hr into degenerate $n$-type ($N_d = 5\times10^{17}\,\mathrm{cm^{-3}}$) bars (12 mm long × 2 mm wide × 1 mm thick) of InSb. The major axis of the bars were aligned within 1° of either the [111], [$1\bar{1}0$] or [010] directions with the normal to the 2 mm wide face lying in the [$1\bar{1}0$], [111] or [100] directions, respectively. A closed tube diffusion process was used, each ampoule containing three specimens, one of each orientation, and the diffusion source. The latter consisted of 100 $\mu$g of a 10 per cent solution of Cd in In. Diffusion in preference to alloying was used as the means to form the junctions for a number of reasons: Firstly, it is possible to produce similar junctions on any crystallographic plane, since the diffusion coefficient is independent of orientation whereas crystal regrowth, in the case of alloying, exhibits facets [16]. Secondly, metallic inclusions in the alloying process contribute to local stress inhomogeneity and this leads to anomalously high stress effects [7]. Finally, experiment indicates that it is difficult to achieve sufficient overcompensation using conventional alloying procedures [19].

Five junctions were formed below the surface of the 2 mm wide face of each of the bars, by lapping the diffused surface until it coincided with the surface of shallow, flat bottomed pits which had been cut into this face before diffusion. Ohmic contacts were made to the diffused region using 1 ml dia. Au wire and In balls.

The junctions selected for this study showed little or no tunneling in the forward direction. The perfection of the junctions was assessed by studying the ratio of the reverse tunnel current in the presence of a longitudinal and transverse magnetic field. Junctions were discarded if the tunnel current was relatively insensitive to the magnetic field orientation even through it displayed an apparent normal $I$–$V$ characteristic. Measurements of the magnetic field dependence as a function of field strength, orientation, and reverse bias permitted determination of the tunnel exponential $\beta E_g^{3/2}$, and its bias dependence. The results of this method were compared with those obtained by matching Kane's tunneling expression to the reverse $I$–$V$ characteristic $(-10^4\text{A/cm}^2 < I < 0)$. Both tests were applied to all junctions and only those yielding consistent values were used for stress studies. Further details of the methods and results are reported in Ref. [11].

Uniaxial compressive stress was applied to the specimen via a jig, lever and weight system similar to that described by Balshev[12]. The jig was composed of a fixed upper piston and a lower piston free to move in an accurately polished bore. Alignment of the major axis of the specimen with the axis of the jig was ensured by careful adjustment during the process of attaching brass cups to each end of the specimen. The assembly was then placed in the stressing jig and separate current and voltage leads were attached to each junction on the bar.

The stress dependence of the reverse current was studied since it is not complicated by the presence of excess and diffusion currents as is the forward current. Figure 1 illustrates a typical reverse $I$–$V$ characteristic with stress as a parameter. All junctions studied with stress parallel the [010] direction showed similar fractional decreases in current. Differing fractional changes were observed for stress in the [1$\bar{1}$0] and [111] directions. The fractional reduction in current as a function of stress for the three orientations studied are summarised in Fig. 2. The stress dependence of the fractional reduction in tunnel current was independent of reverse current density in the range 0–$10^3$A/cm$^2$. For convenience in the later analysis the data presented in Fig. 2, corresponds to a reverse bias of 50 mV and current densities of about 100A/cm$^2$.

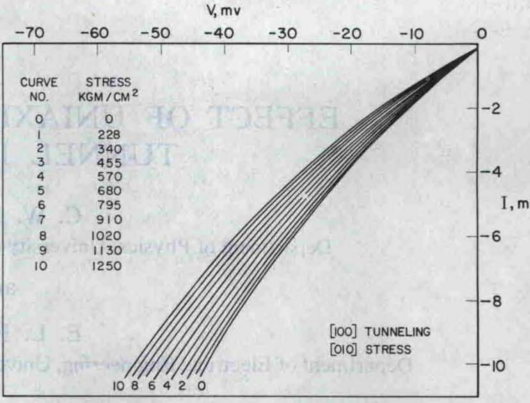

Fig. 1. Typical $I$–$V$ reverse characteristics with stress as a parameter.

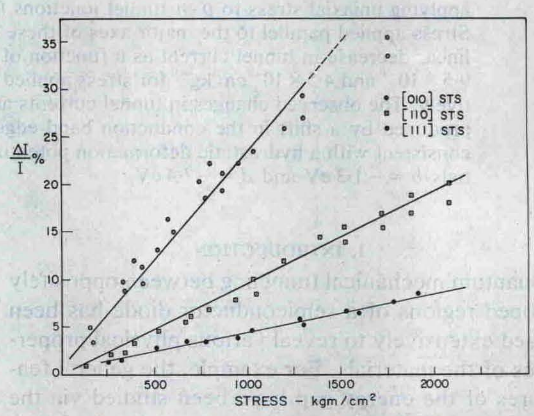

Fig. 2. Percentage change of reverse current at fixed bias as a function of stress for three stress orientation.

Sensitive d$I$/d$V$ and d$^2I$/d$V^2$ studies performed at the same time failed to reveal any stress dependent fine structure that would correspond to the lifting of the $\Gamma$ point degeneracy of the valence band. Studies at Helium (4.2°K) and nitrogen (77°K) temperatures were essentially identical. No evidence of Landau splitting was found for fields of up to 120 kG, and temperatures of 1·8–4·7°K.

The slope of the linear low stress region of the data of Fig. 2 gives percentage decreases in current of $24{\cdot}5 \times 10^{-3}$cm$^2$/kg for $\chi \| [010]$, $9{\cdot}5 \times 10^{-3}$cm$^2$/kg for $\chi \| [1\bar{1}0]$ and $4{\cdot}5 \times 10^{-3}$cm/kg for $\chi \| [111]$. For stress greater than approximately $10^{+3}$kg/cm$^2$ the slopes decrease slightly.

## 3. DISCUSSION

The reduction in tunnel current at fixed bias can be explained on the basis of a reduction in the tunnelling probability. For most purposes the tunnel current is adequately described by the two band, uniform field model of Kane. For reverse bias this may be expressed as

$$I = \frac{qm^*}{36\hbar^2}\,\text{A.P.}\left(\frac{\bar{E}}{2}\right)D \tag{1}$$

where

$$P = \exp\left(-\beta E_g^{3/2}\right)$$

$$\beta = \pi m^{*1/2}/2\sqrt{2}\hbar qF$$

$$\bar{E} = \sqrt{2}\hbar qF/(\pi^2 m^* E_g)^{1/2}$$

$$D = qV + \left(\frac{\bar{E}}{2}\right)\left\{\exp\left(-\frac{2\delta_n}{\bar{E}}\right)\right.$$

$$+\exp\left(-\frac{2\delta_p}{\bar{E}}\right)$$

$$\left.-2\exp\left(-\frac{qV+\delta_n+\delta_p}{\bar{E}}\right)\right\}$$

$$m^* = 2m_c m_v/(m_c + m_v).$$

The quantity $P$ in equation (1) is the tunnel probability for an electron with zero transverse momentum. For a given junction structure $\beta$ depends upon $m^*$, the dielectric constant, the doping concentrations and profile of the junction. $\bar{E}$ is a measure of the limiting energy of electrons having transverse momentum and an appreciable tunnel probability. For the junctions studied $\bar{E}$ is approximately 10 meV. The parameter $D$ is a joint density of states function which may be approximated by $qV$ for bias voltages much greater than $\bar{E}/2q$. In Kane's two band model $m_c$ and $m_v$ are isotropic effective masses for the conduction and light hole band respectively and $\delta_n$ and $\delta_p$ are the fermi energies in the $n$ and $p$ sides of the junction measured from the conduction and valence band edges respectively. The junction area is $A$, and $F$ is the effective junction field. The other symbols have their usual meaning.

Approximating $D$ with $qV$, we may express (1) as

$$I = CE_g^{-1/2}\exp\left(-\beta E_g^{3/2}\right) \tag{2}$$

where

$$C = \frac{\sqrt{2}m^{*1/2}q^2VFA}{72\pi\hbar^2}.$$

In addition to changes in the energy gap induced by stress, the constant energy surfaces are warped, and the valence band degeneracy at the $\Gamma$ point is lifted. In the present study no evidence could be found for the splitting at the $\Gamma$ point and it is assumed that the smearing of the band edges, arising from the heavy doping levels necessary, was sufficient to mask these effects. Such effects should be second order compared with the effects due to changes of $E_g$ and we proceed in the manner suggested by Long and Hulme[7]. Fractional changes in tunnel current may then be expressed as

$$\frac{1}{I}\left(\frac{\mathrm{d}I}{\mathrm{d}\chi}\right) = -\frac{1}{2}\left[1 + 3\beta E_g^{3/2}\right]\frac{1}{E_g}\left(\frac{\mathrm{d}E_g}{\mathrm{d}\chi}\right). \tag{3}$$

In (3) $\chi$ is the stress and is negative for compression, and $E_g$ and $I$ are the energy gap and tunnel current in the absence of stress. From previous studies on these junctions[11] we find we may express

$$\beta E_g^{3/2} = (10 \pm 0{\cdot}5)(1 + 5{\cdot}88\,V)^{0{\cdot}63}.$$

The anisotropy in the fractional decrease in tunnel current with stress can be accounted for on the basis of the work of Bir and Pikus. At the centre of the Brillouin zone the change in energy gap with stress may be expressed in terms of the compliance coefficients, $S_{ij}$, and the deformation potentials. For stress parallel [010] it is given by

$$\frac{\mathrm{d}E_g}{\mathrm{d}\chi} = K - b(S_{11} - S_{12}). \tag{4}$$

Similarily for stress parallel [111]

$$\frac{\mathrm{d}E_g}{\mathrm{d}\chi} = K - \frac{d}{2\sqrt{3}}S_{44} \tag{5}$$

and for stress parallel $[1\bar{1}0]$

$$\frac{\mathrm{d}E_g}{\mathrm{d}\chi} = K + \tfrac{1}{2}\left\{b^2(S_{11} - S_{12})^2 + 3\left(\frac{\mathrm{d}S_{44}}{2\sqrt{3}}\right)^2\right\}^{1/2} \tag{6}$$

where

$$K = (a + c)(S_{11} + 2S_{12}).$$

The quantities $a$, $b$, $c$ and $d$ are the deformation potentials. Deformation potentials $a$, and $c$ describe rigid shifts in valence and conduction band edges respectively due to a volume change. The sum $(a + c)$ describes the change in the direct gap. Deformation potentials $b$, and $d$ describe changes and splitting of the $\Gamma_8$ valency band energies for uniaxial stress parallel to the [010] and [111] directions respectively.

The compliance coefficients for InSb have been given by Potter[20]. At 100°K we have

$$S_{11} = 2\cdot 26, \quad S_{12} = -7\cdot 60, \quad S_{44} = 3\cdot 19$$

in units of $10^{-12}$ cm$^2$/dyne.

If equations (4), (5) and (6) are used in turn in (3) for each of the principle stress directions, together with the measured values for the stress coefficients and the compliance coefficients we can deduce the deformation potentials. We find values of $(a+c)$, $b$, and $d$ of $-10$, $-1\cdot 3$ and $-7\cdot 4$ eV respectively, with a probable error of ± 10 per cent. The value of the hydrostatic deformation potential $(a+c)$ is somewhat larger than reported value of $-7\cdot 2$ from optical absorption[13], and piezoemission[14], but considerably less than $-30$ and $-40$ deduced from free carrier absorption[15], and plasma piezoreflectance[16]. Deformation potentials $b$, and $d$, are in fair agreement with the piezo-emission[14] data ($b = -2$ eV, $d = -6$ eV), piezobirefringence [17], ($b = -1\cdot 8$ eV, and $d = -6\cdot 4$ eV) and the magnetoreflection experiments[18]; ($b = -2\cdot 0$ eV, and $d = -4\cdot 9$ eV).

At higher values of stress the incremental change in current decreases with increasing stress. The explanation for this, we believe, lies in a more realistic calcuation of the change in tunnel current with stress taking into account the nonparabolicity of the bands, the stress induced change in the fermi-levels, and the deformation potential of the impurity levels.

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