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# MAGNETO-TUNNELING IN InSb

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We have studied the phenomenon of tunneling in InSb at 77°K in magnetic fields up to 88 000 gauss. Current-voltage characteristics with the magnetic field parallel and perpendicular to the current flow across the $p$-$n$ junction are shown in Figs. 1 and 2. As can be seen from the figures, the effects are comparable for the magnetic field in the two directions. A marked decrease in the tunneling current with increased magnetic field was observed both in forward and reverse bias. The peak voltage is increased by the parallel magnetic field but is not affected to the same extent by the perpendicular magnetic field. A large magnetic effect was also observed in forward bias for the minority carrier injected current.

Several diodes were fabricated by alloying spheres of 99.9% indium and 0.1% cadmium into $n$-type InSb containing $1.5\times10^{17}$ - $6\times10^{17}$ net impurities per cm$^3$. Peak to valley current ratios at zero field varied from 1.4 to 1, to 7 to 1 and the diodes showed magneto-tunneling characteristics similar to those shown in Figs. 1 and 2. Measurements have been made with resistors in the magnetic field contiguous to and shunting the diodes so the characteristics in the negative resistance region could be determined as shown. No sensible change in the values of the shunting resistors used was found either with temperature to 77°K or with magnetic field to 88 000 gauss. While the diode of Figs. 1 and 2 was mounted on a Kovar tab, similar results have been obtained for InSb tunnel diodes on nonmagnetic mounts.

The effects of the magnetic field on the tunneling current can be attributed to the creation of magnetic sub-bands and their shift in energy with increasing magnetic field. The rate of Zener tunneling per cm$^3$ in the absence of a magnetic

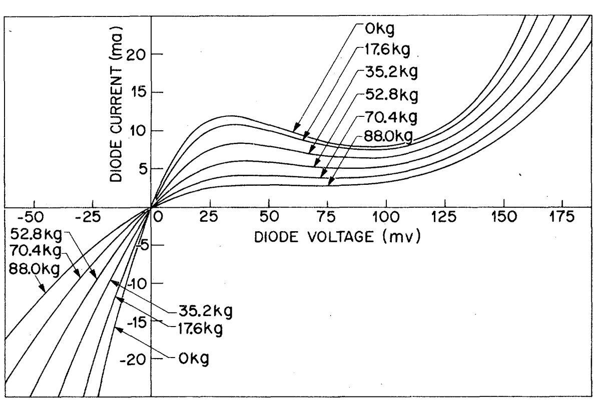


FIG. 1. Current-voltage characteristics at 77°K of an InSb tunnel diode in different magnetic fields parallel to the current flow across the $p$-$n$ junction. This diode was fabricated using $n$-type InSb with impurity density $\sim10^{17}$ cm$^{-3}$.

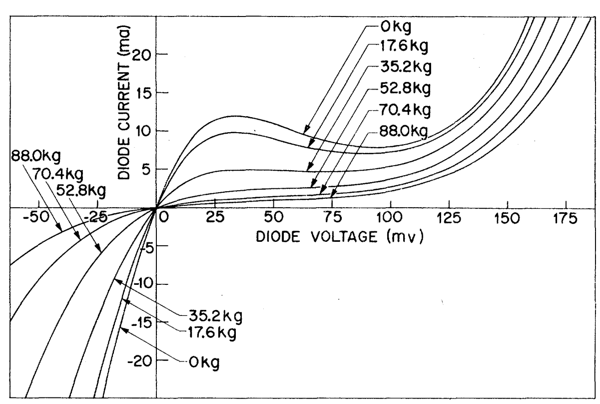


FIG. 2. Current-voltage characteristics at 77°K for the InSb tunnel diode of Fig. 1 in different magnetic fields perpendicular to the current flow across the $p$-$n$ junction.

field, as given by Kane,[1] is

$$n_0 = C_0 \exp(-\alpha E_g^{3/2}), \quad (1)$$

where $C_0 = F^2 m_r^{1/2}/18\pi\hbar^2 E_g^{1/2}$, $\alpha = \pi m_r^{1/2}/2\hbar F$, $F$ is the force on the electron, $m_r$ is the reduced mass, and $E_g$ is the band gap. In the presence of a magnetic field parallel to the current, Eq. (1) is modified to take into account the tunneling between the magnetic sub-bands of the valence and conduction bands as follows:

$$n_H = C_H \sum_n \exp\{-\alpha[E_g^2 + 4E_g((n+\tfrac{1}{2})\hbar\omega_c \pm \tfrac{1}{2}\mu_B g_0 H)]^{3/4}\}, \quad (2)$$

where $C_H = C_0 \frac{3}{2}\alpha E_g^{1/2}$, $\omega_c = eH/m^* c$ is the cyclotron frequency of the electron, $\mu_B$ is the Bohr magneton, and $g_0$ is the $g$ factor. In the derivation of Eq. (2) the nonparabolic nature of the bands in InSb has been taken into account and the equation has been derived on the basis of electron-light hole tunneling[2] where the selection rule $\Delta n = 0$ applies. The $g$ factor, as well as the effective mass, have been taken to be the same for the electron and the light hole ($m^* = 0.013 m_0$, $g = 56$). Assuming that the distance of the Fermi level into both the conduction and valence bands is large compared to the average energy of the tunneling carriers perpendicular to the junction field,[3] Eq. (2) can be approximated to give the result for the normalized current,[4] $I(H)/I(0)$,

$$\frac{I(H)}{HI(0)} \approx A \frac{m}{m^*} \sum_n \exp\left\{-2AH\left[(n+\tfrac{1}{2})\frac{m}{m^*} \pm \frac{g}{4}\right]\right\}, \quad (3a)$$

where

$$A = \frac{3\pi\mu_B m_r^{1/2} E_g^{1/2}}{2\hbar F}; \quad \mu_B \equiv \frac{e\hbar}{2mc} = \frac{1}{2}\frac{\hbar\omega_c}{H}\frac{m}{m^*}.$$

Equation (3a) can be written

$$\frac{I(H)}{HI(0)} = A \frac{m}{m^*} \operatorname{csch}\left(A \frac{m}{m^*} H\right) \cosh\left(\frac{AgH}{2}\right). \quad (3b)$$

The experimental values of $I(H)/HI(0)$ as a function of $H$ for an InSb tunnel diode for four different voltages, two in forward and two in reverse bias in the tunneling region, are plotted in Fig. 3. At sufficiently high magnetic fields only the $n = 0$ sub-bands and negative spin term contribute appreciably to the tunnel current, which allows the one unknown parameter $A$ in Eqs. (3) to be simply determined. The value of $A$ obtained in this way was used to plot the theoretical curve in Fig. 3. Considering the fact that $A$ determines both the slope and the absolute value of the curve, the fit is very good. This agreement indicates that the other effects induced by the magnetic field, such as the change in $F$ and the change in the relative position of the Fermi level with respect to the band edges, are of secondary consideration. From the value of $A = 7.1 \times 10^{-7}$ gauss$^{-1}$ one can obtain a value for the field in the junction of $5.4 \times 10^4$ volts cm$^{-1}$ for light hole-electron tunneling. Heavy hole-electron tunneling gives a value approximately a factor of $\sqrt{2}$ smaller.

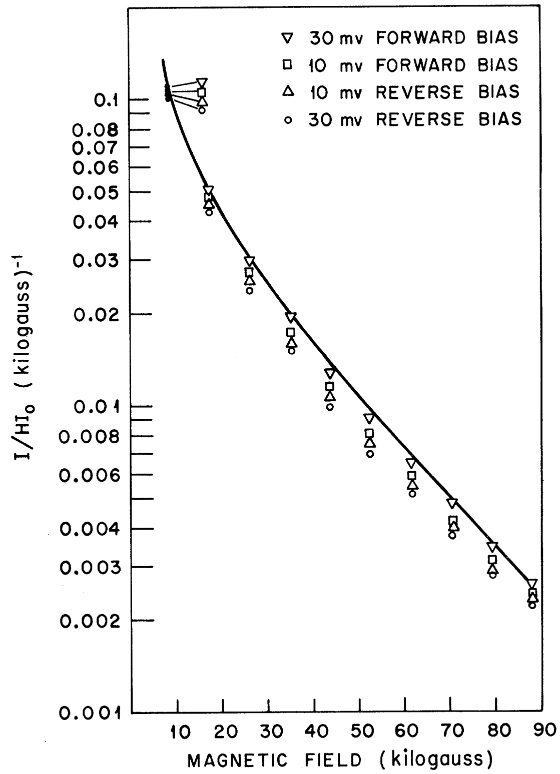


FIG. 3. Points are experimental values of $I(H)/HI(0)$ at 77°K for the diode of Fig. 1 as a function of parallel magnetic field. Values for four different diode voltages in the tunneling region are shown. Also shown is the theoretical curve determined from Eq. (3) with the constant $A = 7.1 \times 10^{-7}$ gauss$^{-1}$.

A somewhat more involved theoretical result for the perpendicular case has been obtained using the WKB method. The tunneling is summed over both sets of sub-bands since the selection rules for the magnetic quantum numbers $n_1$ and $n_2$ no longer apply.

A magnetic effect of comparable magnitude on the minority carrier current at high forward biases was also observed in a lightly doped normal diode. A preliminary analysis indicates that the effect is due to the decrease in the number of minority carriers as a result of an effective increase in the gap.

We have also seen a magneto-tunneling effect in Ge confirming the observations of Esaki,[5] but the effect is very small because of the larger masses and the larger electric fields. From the preceding theory low-gap materials would be expected to give the largest effects.

Studies of magneto-tunneling with very high magnetic fields and in crystals with anisotropic energy surfaces should provide information about the energy bands.

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[2]This assumption is made by Kane and appears to be consistent with the large magneto-tunneling effect observed. If the tunneling is electron-heavy hole, Eq. (2) must be modified but Eq. (3) is applicable except for a constant factor in $A$.

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## OBSERVATION OF STARK SPLITTING OF ENERGY BANDS BY MEANS OF TUNNELLING TRANSITIONS

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It has been shown theoretically[1,2] that the energy states available to an electron in a crystal form a series of Stark ladders if a uniform electric field $E$ is present. The separation of these energy levels is $eEd$, where $d$ is the spacing of the set of lattice planes perpendicular to the field. One can convince oneself that a structure having this periodicity is present in a given region even if the field $E$ is not homogeneous, but only slowly varying over atomic dimensions. The purpose of this Letter is to present experimental evidence for the occurrence of this predicted structure. This evidence was obtained from studies of the tunnel currents in narrow $p$-$n$ junctions of indium antimonide.

The junctions were made by alloying pellets of 0.1% Cd in In into $n$-type InSb crystals. The donor and acceptor concentrations on the $n$- and $p$-type sides were $6.7\times10^{17}$ cm$^{-3}$ and $10^{18}$ cm$^{-3}$, respectively. The field distribution in the junction was thus fairly symmetric. Using $(m^*/m_0) = 0.015$ for the electrons and 0.17 for holes, the Fermi energies on the $n$- and $p$-type sides were 0.190 ev and 0.022 ev, respectively. These junctions exhibited voltage-current characteristics in which the reverse and forward quadrants were roughly symmetric about the origin, i.e., the junctions were not narrow enough to exhibit Esaki effects.[3] Nevertheless, at all except the very highest forward biases, i.e., >200 mv, the dominant current generation mechanism was tunnelling.[4]

With the junctions immersed in liquid helium, plots of the junction conductance, $(dI/dV)$, against forward bias were obtained by means of automatic conductance plotting equipment. All junctions revealed varying amounts of structure in their conductance plots which could be interpreted in terms of phonon or multiphonon emission processes.[5,6] However, all the junctions with the above impurity concentrations showed additional fine structure at biases lying between 100 and 130 mv. This structure appeared as a small amplitude oscillation of the conductance vs bias curve. Examples of these oscillations are shown in Fig. 1. (The high sensitivity required in order to reveal these oscillations was obtained by a bucking technique. Great care was taken to rule