PRESSURE DEPENDENCE OF THE CURRENT-VOLTAGE CHARACTERISTICS OF ESAKI DIODES*†

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Esaki[1] has discovered a new tunneling phenomenon in narrow p-n junctions which yields a negative resistance characteristic in the forward direction. Measurements are reported here on the variation of this phenomenon with hydrostatic pressure in germanium. These data make it possible to obtain the dependence of tunneling current on the energy gap E_g. Measurements of the "ordinary diode current" in the forward direction indicate that the pressure variation of E_g is approximately the same for degenerate material and pure germanium.

Pressure experiments at room temperature were carried out in an apparatus of the type described by Bridgman[2] using pentane as a pressure transmitting fluid.

The variation of the peak current with pressure divides all of the diodes studied into three distinct groups. Representative curves for these groups are shown in Fig. 1 in which $\ln J_p$ is plotted against pressure. It is found that almost the same curves result from a plot of $(dJ/dV)_{V=0}$ vs pressure. Those diodes whose J vs V curve at 4°K exhibits structure caused by phonon participation in tunneling[3] give curves like (a). These are very close to straight lines. Curves similar to (b) and (c) are obtained for units in which there is no evidence for phonon-assisted tunneling at 4°K. Curves of type (c) are typical of units made by alloying n-type material (SnAs) on a p-type substrate while the units giving curves (a) and (b) were made by alloying p material (either SnGa or InGa) on an n-type substrate. The total relative change of peak current with pressure increases with decreasing current density from diode to diode. It varies from a factor of 5 to about 65 in 30 000 kg/cm^2. The break in curves of type (b) occurs at 8000 kg/cm^2 regardless of the magnitude of J_p (over at least a factor of seven), the kind of impurity in the substrate, or the nature of the alloying dot. The pressure effects are independent of the crystallographic orientation of the substrate. The insensitivity to orientation and the results of a resistivity measurement on a sample of the same geometry lead to the belief that the pressure is essentially hydrostatic.

The valley current, J_v (Fig. 1), is larger than is predicted on the basis of a simple tunneling picture and ordinary diode theory.[4] J_v also shows a decrease with pressure, although the over-all change is smaller than the change in J_p for the same unit. There is frequently a plot like curve (b) with a break at 8000 kg/cm^2. This is, however, not correlated with the detection of phonon-assisted tunneling current. It may be an indication that the valley current is related in physical mechanism to the nonphonon tunneling

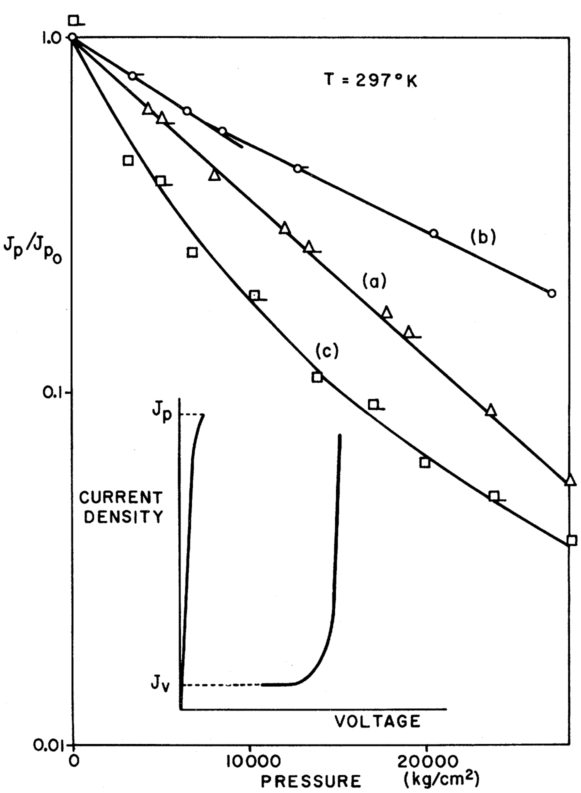

FIG. 1. Peak current density divided by its value at atmospheric pressure vs pressure. The circles, triangles, and squares designate points taken on the return to atmospheric pressure. Inset shows typical J-V characteristic of these diodes.

current.

In the region of the characteristic where the "ordinary diode forward current" predominates, it is found that $J \propto \exp(eV/kT)$ at room temperature. If the usual diode equation is assumed, the change in V at constant current will equal the change in E_g with pressure provided that variations in effective mass, lifetime, and mobility are neglected.[5] The variation in E_g with pressure up to 30 000 kg/cm² obtained by this method is the same to within 15% for these heavily doped materials as that observed in intrinsic Ge by measurement of bulk conductivity.[6] These data are plotted in Fig. 2 for two diodes. Since the effective energy gap for this phenomenon is determined by the energies and effective masses of the (111) and (100) conduction band minima, this is an indication that the band structure is not seriously perturbed.

Some features of the data in Fig. 1 are consistent with the tunneling theory given by Keldysh[7] and Price and Radcliffe.[8] Their results for phonon-assisted tunneling can be put in the form:

$$J_p = K\exp(-\alpha E_g W_0). \qquad (1)$$

W_0 = junction width at atmospheric pressure and zero applied bias. α is a parameter which depends on the effective mass and the dielectric constant. In what follows, the pressure variations of α and K are neglected despite the fact that these may occur. From Eq. (1) it can be shown that

$$\ln J_p = \ln K + E_g(d\ln J_p/dP)/(dE_g/dP), \qquad (2)$$

where the derivatives are with respect to pressure.

Fig. 3 shows a plot of $\ln J_p$ vs $(d\ln J_p/dP)$ for all of the units measured in the pressure experiments except those made by alloying n on p material. A line drawn through the points for the units showing phonon-assisted tunneling has a slope of 12.4×10^4 kg/cm². This number agrees with the value obtained by taking

$$E_g/(dE_g/dP) = 0.65\,\text{ev}/(0.05\times10^{-4}\,\text{ev cm}^2/\text{kg}) = 13\times10^4\ \text{kg/cm}^2.$$

A determination of W_0 for several selected units by measurement of capacitance leads to a value for the parameter α in Eq. (1) of 2×10^7 (ev - cm)$^{-1}$ for phonon-assisted current. This corresponds to a reduced effective mass of 1/20 of the free electron mass, if Keldysh's[7] form for α is used,

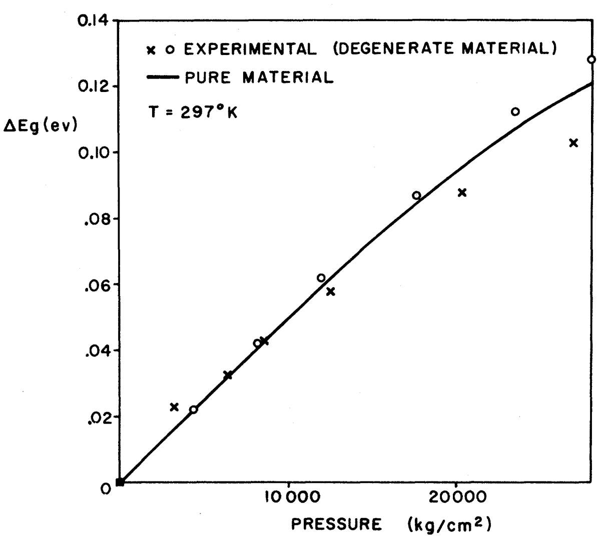

FIG. 2. The change in voltage with pressure at constant current compared with the known change in energy gap with pressure for intrinsic germanium.

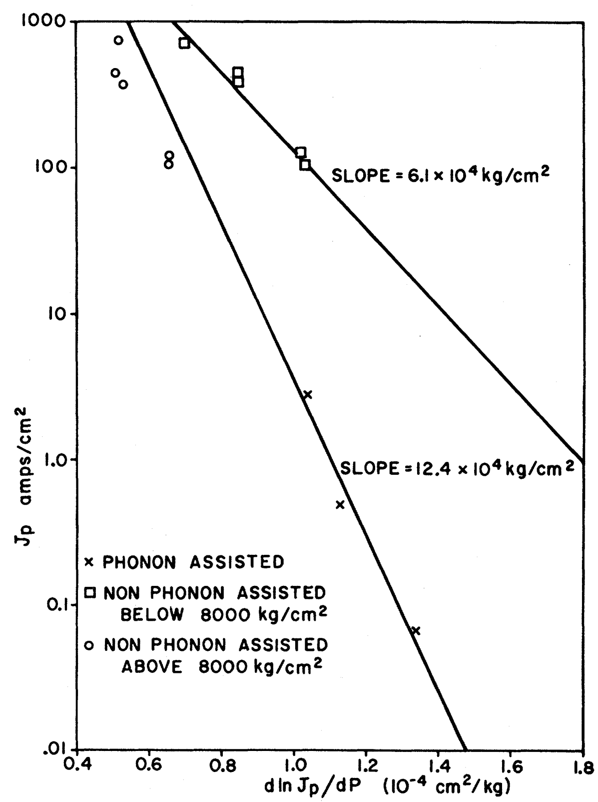

FIG. 3. Peak current density at atmospheric pressure vs $(d\ln J_p/dP)$.

and a field of E_g/W_0 is assumed.

It can easily be shown that if the phenomenological law,

$$J_p = K \exp(-\beta E_g^{\ n}), \qquad (3)$$

governs tunneling, then the slope of the plot in Fig. 3 would be divided by n. It is apparent that the data on phonon-assisted tunneling obviate values of n which depart greatly from unity. On the other hand, the plot for the low-pressure slope of units (b) seems to fit with Eq. (3) for $n=2$. This plot is also consistent with Eq. (2) if E_g is interpreted to be the gap between the (000) minima of the valence and conduction bands.[9] This suggests that the process involved may be a second order one in which there is virtual tunneling between the zone center states.[10]

Measurements on two units of type (b) at liquid N_2 temperature to a maximum pressure of 5000 kg/cm^2 indicate that the pressure dependence of $\ln J_p$ is about 25% larger at the low temperature than at room temperature. This is not easily understood on the basis of a phenomenological law like Eq. (2), since J_p is almost independent of temperature. However, these low-temperature pressure measurements are complicated by the possibility of nonhydrostatic effects. More careful measurements are necessary.

There are two general features of the data in Fig. 1 which are not understood at the present time. The first is the abrupt change in slope of units (b) at 8000 kg/cm^2. Nothing drastic is known to happen to the band structure at this pressure. The second is the difference in shape of curves (c) and (b).

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SPIN RESONANCE OF CONDUCTION ELECTRONS IN InSb

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Among the interesting properties of InSb is the very high and negative magnetic moment of its conduction electrons.[1]

We have observed directly spin resonance of conduction electrons in n-type InSb in the concentration range between 2×10^{14} electrons/cm^3 and 3×10^{15} electrons/cm^3. The $|g|$ values varied between 48.8 and 50.7 depending on the electron concentration. The experiments were performed at temperatures of 1.2°K and 4°K. By observing the resonance at two different frequencies (9000 Mc/sec and 24 000 Mc/sec) we verified that it was due to spin rather than plasma resonance. The magnetic field at which the resonance was observed was directly proportional to the microwave frequency while the plasma resonance gives rise to an inverse dependence of the magnetic field on the electronic frequency.[2] Cyclotron resonance can also be ruled out on the basis that the observed resonance occurs at approximately 2.5 times the field value of the cyclotron resonance. The widths of the observed lines (see