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The Effects of Hydrostatic Pressure on Hot-electron Phenomena in n-InSb

Abstract: The effect of hydrostatic pressure on the Gunn effect (high pressures) and bulk avalanche breakdown (low pressures) in n-InSb is studied. The measured generation rates of electron-hole pairs at 77°K and 195°K at several pressures are compared with the theory of Dumke.

Introduction

InSb is a direct band-gap semiconductor with both the lowest conduction band minimum and the valence band maximum at the Brillouin zone center and separated by an energy gap E_g of approximately 0.2 eV. In addition there are higher lying conduction band minima at the L point,[1,2] separated from the lowest minimum by an energy $\Delta > E_g$. Application of hydrostatic pressure causes E_g to increase at a rate 15×10^{-6} eV/bar while Δ is expected to decrease at a rate of approximately 10×10^{-6} eV/bar.[3]

If a uniform electric field F of a few hundred volts per centimeter is applied to a homogeneous bulk sample of n-type InSb at atmospheric pressure and at 77°K, a substantial fraction of the electrons acquire sufficient energy to create electron-hole pairs by impact ionization of electrons from the valence band.[4] With a pressure of approximately 10 kilobars applied to the sample, however, Δ has decreased and E_g has increased sufficiently so that electrons may transfer to L minima, where they have a low mobility, before thay have enough energy to impact ionize. This transfer results in a bulk negative differential conductivity (BNDC) and the Gunn effect is observed.[5] The implications for the energy band structure of InSb of these and related resistivity-pressure dependence results are the subject of a separate publication.[5] In this paper we report further studies of the Gunn effect and impact ionization. In particular we report measurements of the Gunn threshold, and experimental determination of the generation rate $g(E)$ for electron-hole pairs due to impact ionization,[6] as a function of pressure and temperature. The results for $g(E)$ are compared with Dumke's[7] theory for impact ionization in polar semiconductors.

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Experimental details

Current-voltage characteristics of samples typically 1 mm long were measured with short ($\leq$50 nsec) pulses. $g(E)$ was measured as previously described.[6] The ohmic contacts were formed by alloying an evaporated layer of Sn (2% Te) into both polished surfaces of a wafer of InSb before dicing the wafers to produce samples of the desired size. This ensures that the contacts are planar.

Capacitive probe measurements of the electric field in the samples were performed at 77°K and atmospheric pressure, for low applied voltages as well as under conditions of avalanche breakdown. The samples used were electrically uniform at low fields. No large inhomogeneities in the field during the avalanche process were observed within the temporal (1 nsec) and spatial (20 μm) resolution of the probe. Any small disturbances in the field distribution disappear rapidly with increasing electron concentration.

Gunn effect threshold and carrier freezeout

Figure 1 shows the threshold field F_T for the Gunn effect as a function of pressure for two types of samples. In type A samples, which exhibit a minimum in the F_T vs p curve, the Gunn effect disappears above p = 13 kilobars. These samples show a large decrease in free carrier concentration beginning at about 8 kilobars. This decrease is probably caused by de-ionization of the electrons into impurity states associated with higher lying minima.[5] In samples of type B, which have a monotonically decreasing dependence of F_T on p, the Gunn effect persists up to the maximum attainable pressure, about 14 kilobars, and there is no de-ionization. Repeated cycling of the samples to high pressure and fields above F_T results in lower values of F_T at a given pressure, as well as in the observation of the Gunn effect at lower pressures than for a virgin sample. This effect is believed to be caused by irreversible changes produced near the sample contacts when a large domain goes across the sample at high pressure. The data in Fig. 1 are undoubtedly affected by these changes. In these experiments the threshold was first measured at about 6 kilobars, then the sample was taken to the maximum pressure, and finally the low pressure data were taken. The threshold was observed in this low pressure region at fields at which oscillations had not been seen in a virgin sample. The differences between type A and B samples in Fig. 1 in the region where they are both decreasing with pressure are of the same order as the differences between identical samples.

Generation rate versus pressure

The rate of generation of electron-hole pairs, $g(E)$, was studied as a function of pressure in the pressure and field range where appreciable rates could be obtained below F_T. In view of the irreversible effects mentioned above, these measurements were made on virgin samples which had never experienced the Gunn effect.

Figure 2 shows g vs F at 77°K at four values of pressure. Within the experimental error, the curves at each pressure are parallel over the range of generation rate studied. The field for a given generation rate at atmospheric pressure reported here is 15% higher than the values reported by McGroddy and Nathan.[6] The planar nature of the contacts used in this work allows a much more accurate determination of the sample length than was possible for the samples used in the earlier measurements, which probably accounts for the discrepancy.

In Fig. 3 the field necessary for a generation rate of 4×10^7 sec^{-1} is plotted as a function of pressure. Figure 4 shows similar data at 195°K for a generation rate of 4×10^6 sec^{-1}. Comparison of the value of F at $p = 0$ in Fig. 4 with the corrected values from McGroddy and Nathan at 77°K and 145°K shows that F has decreased by about 15% in going from 145°K to 195°K.

The experimental generation rate was compared with the theory of Dumke,[7] which yields the generation rate in a semiconductor with a hyperbolic conduction band and dominant polar optical mode scattering. It is assumed in these calculations that both the energy gap and the

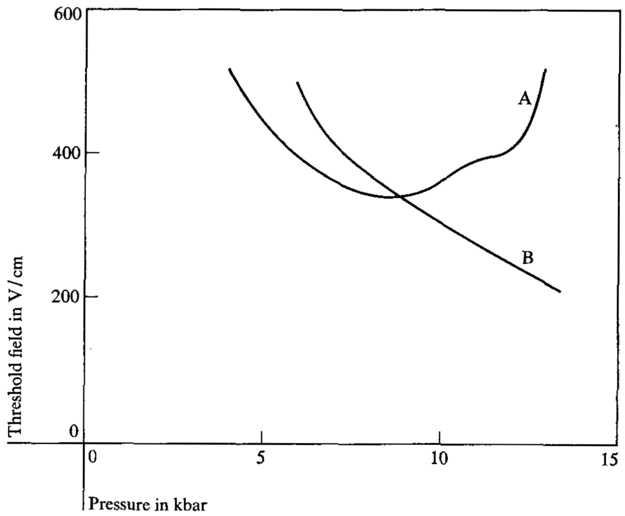

Figure 1 Behavior of Gunn threshold field as a function of pressure for two classes of samples. Samples of Type A show carrier de-ionization at pressures above the minimum in the curve, while samples of type B show no carrier de-ionization.

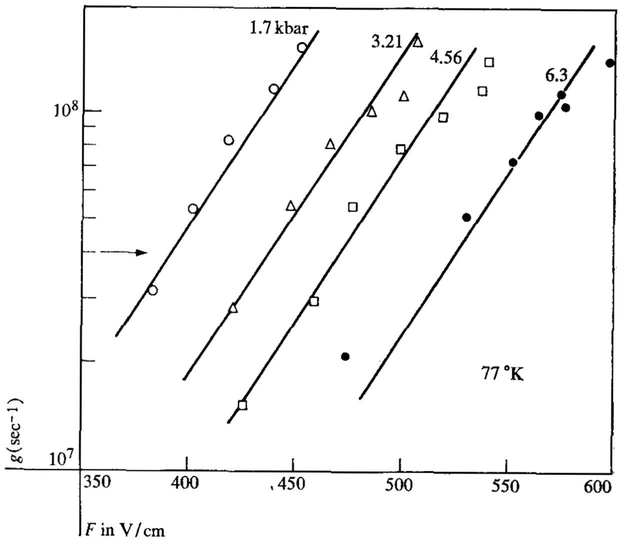

Figure 2 Pair generation rate as a function of electric field at 77°K for four values of applied hydrostatic pressure.

effective mass at the bottom of the conduction band increase linearly with pressure. The effective mass was taken to be proportional to the energy gap.

Atmospheric pressure values of 0.014 for the effective mass ratio and 0.225 and 0.21 eV for the energy gap at 77°K and 195°K were used.

Other quantities given in Ref. 7, such as the ionicity and the optical mode frequency, were assumed not to vary significantly with pressure.

In Fig. 3 the electric field necessary to produce a calculated generation rate of 4.10^7 sec^{-1} at 77°K is plotted on the solid curve as a function of pressure. The slope

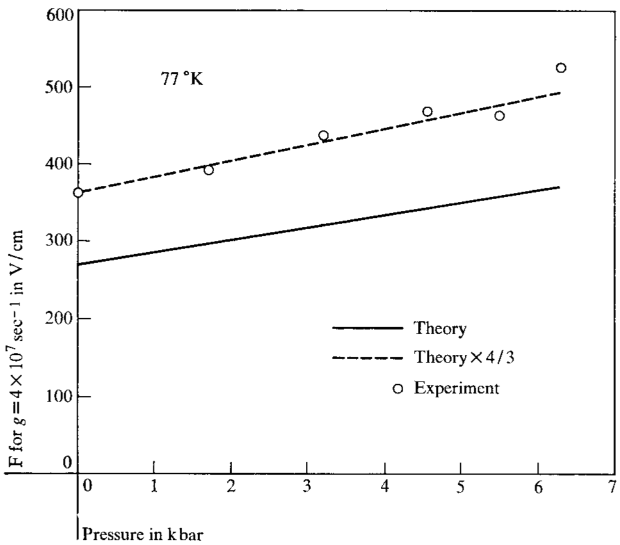

Figure 3 Electric field required for a generation rate of 4×10^7 sec^{-1} at 77°K as a function of pressure. Solid curve—Dumke's theory. Dotted curve—Dumke's theory $\times 1.33$. Points, experimental. (See text.)

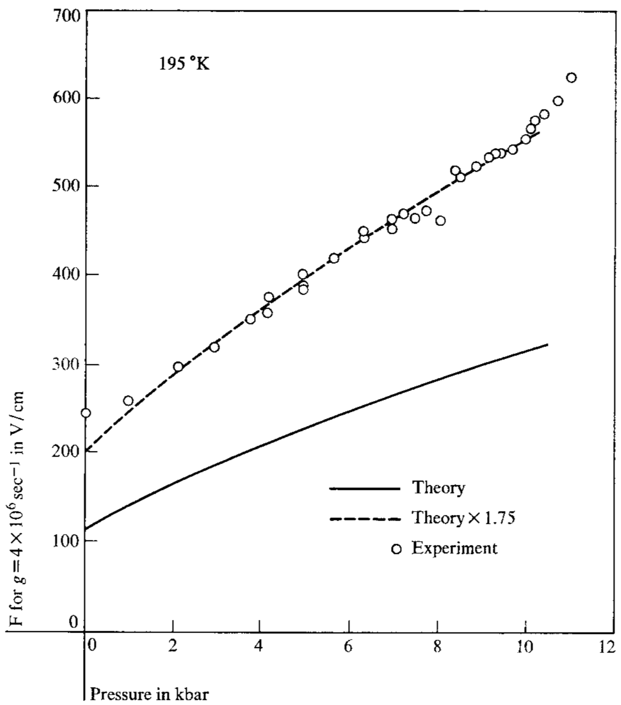

Figure 4 Electric field required for a generation rate of 4×10^6 sec^{-1} at 195°K as a function of pressure. Solid curve—Dumke's theory. Dotted curve—Dumke's theory $\times$ 1.75. Points, experimental. (See text.)

of field vs pressure is similar to the experimental results although the calculated fields are smaller than the experimental values by a ratio of approximately 3 to 4. In view of the 5 to 10% uncertainties in values used in the theory, this agreement is not unreasonable. The difference in the fields may, however, indicate the electron distribution in InSb is not nearly so anisotropic as the maximum degree assumed in Ref. 7. It also may indicate that ionization does not occur as abruptly with increasing energy as has been assumed in theory and that electrons may have to get up to somewhat higher energies to produce pairs.

In Fig. 4 the field necessary to produce a somewhat smaller g of 4.10^6 sec^{-1} at 195°K is plotted along with the experimental points. Here the agreement is worse than at 77°K. This poorer agreement is probably due in large measure to the decrease in the anisotropy of the electron distribution function with increasing temperature and also results from calculating a lower g than at 77°K. For a higher g the field would be higher and the distribution more anisotropic.

By multiplying the theoretical values of the electric field by factors of 1.33 at 77°K and 1.75 at 195°K, as shown by the dotted lines in Figs. 3 and 4, one is able to obtain very close agreement with the experimental points. It seems plausible that the multiplicative factors are related to the anisotropy in the following way: The rate of gain of energy from the field F by an electron with velocity v is given by $eFv \cos \theta$, where θ is the angle between F and v. For the completely anisotropic distribution assumed by Dumke, $\cos \theta = 1$. In order to obtain the same average energy input for a distribution of electrons for which $\langle \cos \theta \rangle$ is less than 1, we must have a higher field given approximately by $F' = F / \langle \cos \theta \rangle$. The fact that a single multiplicative factor for a given temperature and value of g yields close agreement with experiment is perhaps somewhat fortuitous.

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