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MICROWAVE EMISSION FROM *n*-TYPE InSb ASSOCIATED WITH HELICAL INSTABILITY

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The microwave emission from *n*-type InSb in crossed magnetic and low electric fields at nitrogen temperature was investigated experimentally. It was found that the emission was caused by a helical instability of a high-current filament formed at an electrode contact.

Microwave emission from *n*-type InSb which is subjected to magnetic fields and relatively low electric fields has been observed by several authors.[1-6] Helicon waves interacting with drifting carriers[2] and acoustic phonons interacting with drifting electrons via deformation-potential coupling[6,7] have been proposed as origins of the microwave emission but these explanations have not been successful. We further investigated this type of microwave emission with *n*-type InSb and *n*-type Ge crystals and have come to the conclusion that the microwave emission is closely related to a helical instability on a high-current filament formed in the vicinity of the electrode contact.

Experimental setup. —About 120 pieces of *n*-type InSb single crystal of impurity concentration 1×10^{14} cm^{-3} were investigated. All the specimens had a cross section 1×1 mm^2 but their lengths ranged from 0.2 to 10 mm. The specimen was mounted as part of the inner conductor of a coaxial line and immersed in liquid nitrogen. A dc magnetic field was applied at an angle to the length of the specimen. One end of the coaxial line was connected with heterodyne receivers which covered from 25 kHz to 1.4 GHz and from 1.8 to 7.6 GHz. An electric field was applied across the length of the specimen.

Effects of electrode contact. —Musha, Lindvall, and Hägglund[3] and Eidson and Kino[4] reported that the microwave emission was affected by the polarity of the applied electric field. The observations suggest to us that current oscillations are generated in the vicinity of electrode contacts and give rise to the microwave emission. Three types of electrodes were used in our experiment; (1) a silver wire of diameter 100 μm which was indium soldered, (2) a silver wire of diameter 100 μm which was spot-welded, and (3) a tungsten wire of diameter 120 μm with a very sharp end which made a point contact to the specimen.

In order to see whether the current oscillation is generated near the electrode or deep in the body of semiconductor, a specimen (10 mm long) was made which had a indium-soldered contact at one end and a spot-welded contact at the other. In addition, contact was made to a ring electrode painted with silver paste, 1 mm from the spot-welded end. It was found that the microwave emission was observed when the electric field was applied between the spot-welded electrode and the third electrode which was positively biased, and that the strength and polarity of the electric field applied between the indium-soldered electrode and the third electrode had little effect on the microwave emission.

This observation shows that the semiconductor bulk plays no crucial role in the generation of the current oscillation. Strong microwave emission was detected when the electric field was applied such that electrons were injected into the specimen from a spot-welded contact or from a point-probe contact. As reported by others,[2-4] we also observed both noiselike and coherent emissions. The threshold electric and magnetic fields for onset of the noiselike emission were in approximate agreement with those of Musha, Lindvall, and Hägglund[3] and Eidson and Kino.[4] The orientation of the crystal axis did not affect the emission.

Voltage-current characteristics.—Specimens with spot-welded or point-probe electrodes gave nonlinear voltage-current (V-I) characteristics. When the electric field was applied such that electrons flowed into the specimen from a spot-welded contact one was able to see a current-controlled negative resistance which looked like a step on the oscilloscope trace of the V-I curve, as shown by the lower trace of Fig. 1. As the magnetic field was rotated, steps (sometimes two or three steps appeared) on the V-I curve changed their locations, and sometimes the V-I curve itself snaked. When the current was swept in time the microwave emission was always detected after a step in voltage, as shown by the upper trace of Fig. 1. Furthermore, a slope of the V-I curve changed abruptly at the current where a strong emission was observed. With specimens which had indium-soldered electrodes at both ends we also observed very weak microwave emission as already reported.[1-6] At the same time very small steps in the V-I curves were found if they were magnified on an oscilloscope after the Ohmic currents were subtracted.

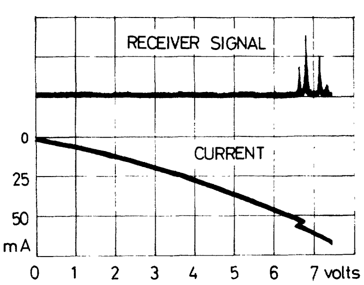

FIG. 1. The upper trace shows the output of a receiver tuned at 1185 MHz. The magnetic field of 7 kG is applied almost parallel to the current. The dimension of the specimen is $1\times1\times2$ mm^3. The lower trace shows the voltage-current characteristic. The horizontal axis is the voltage and the vertical axis is the current. The direction of the electron current from a spot-welded electrode to the specimen is taken downward. A current-controlled negative resistance appears at 6.6 V.

Formation of current filament.—At a non-Ohmic contact high electric fields will be developed, and above a certain critical voltage electrons will be injected into the body of the semiconductor after being accelerated to high enough energy for electron-hole pair creation across the band gap (0.23 eV at room temperature) for indium antimonide; hence a current-controlled negative resistance appears because of the space-charge accumulation, as is the case in gas discharges. The electron density in this filament is estimated to be an order of magnitude larger than the impurity concentration judging from a current increase at the step, and from the filament radius, which will be estimated later. With a specimen 2 mm long and 10^{14} impurities per cm^3, the minimum voltage required to see the microwave emission was observed to be 0.7 V. As a check on this assumption we took Sb-doped germanium (4.3 Ω cm) of the same geometry. The band gap of germanium is about 0.67 eV at room temperature. By applying pulsed electric fields on the specimen with a point-probe electrode we observed the microwave emission at 700 MHz and about 10 kG. The minimum voltage necessary to cause the emission was 22 V, much larger than that for InSb, as was expected.

Helical instability.—When a current filament, which is an electron-hole plasma column, is immersed in a magnetic field a helical instability can set on. A theoretical analysis for a helical instability in a solid-state plasma column was first given by Glicksman.[8] With the magnetic field kept constant the applied voltage was swept from 0 up to 10 V repetitively, and the tuned frequency of the receiver was increased until a signal was detected. These observed frequencies are plotted as a function of the magnetic field in Fig. 2. A curve calculated by Glicksman was superimposed and we can see a fairly good agreement between them. Here we have assumed the following: The electron mobility in the column is 1.43×10^4 cm^2/V sec (the measured Hall mobility at room temperature is 6.8×10^4 cm^2/V sec); the ratio of the electron mobility to the hole mobility is 50; and the electron density is zero at the column boundary. From the theory a radius r of the column was estimated to be

$$r = 3.9\ (T_e/1000)^{1/2}\ \mu\mathrm{m}, \tag{1}$$

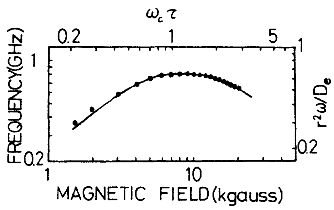

FIG. 2. Dots are the measured threshold frequencies for the same specimen as in Fig. 1. The solid line is Glicksman's calculation (Ref. 8). ω is the frequency multiplied by 2π and D_e is the diffusion coefficient of the electrons.

where T_e is the electron temperature in the Kelvin scale. According to the theory the electron velocity at threshold should be approximately proportional to $(\omega_c\tau)^{-1}T_e^{1/2}$, where ω_c is the electron cyclotron frequency and τ is the mean collision time of the electrons in the plasma column. From the comparison of the observation with the theory the electron velocity at threshold becomes 6×10^7 cm/sec for $T_e = 1000$°K and $\omega_c\tau = 1$ (7 kG). From the electron mobility we have already obtained, the electric field which gives this velocity is about 4×10^3 V/cm and the thickness of the high-field region or the filament length is estimated to be some tens of microns. As the relation between the threshold electric field and the threshold magnetic field for onset of the noiselike emission agrees with Glicksman's calculation, it seems that the noiselike emission is of the same origin as the coherent one. Since the wavelength of the helical instability in the present experimental conditions is almost equal to the filament diameter (~10 μm) (see Fig. 2 of Ref. 8), the noiselike emission was probably caused by a current filament whose length was less than its diameter.

The greater part of the specimen plays the role of a series resistance connected with an active element (the current filament). A specimen of smaller cross section has a larger series resistance and, consequently, has a larger threshold voltage for onset of the current oscillation. The dependence of the threshold voltage V_{th} on the cross section s of the specimen is given by

$$V_{th} = V_{th}^0 + (l/\sigma s)\, I_{th}^0, \qquad (2)$$

where V_{th}^0 is the threshold voltage across the current filament, I_{th}^0 is the current at threshold, l is the length of the specimen minus the filament length, and σ is the electric conductivity of the specimen. If I_{th}^0 is independent of s because the current is concentrated in the filament near the electrode, Eq. (2) can explain the result shown in Fig. 2 of Ref. 2.

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THE DISTRIBUTION OF MAGNETIC MOMENT IN THE Ni-Cu ALLOY SYSTEM*

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We report neutron measurements of the magnetic disorder scattering cross section for $Ni_{0.8}Cu_{0.2}$. These indicate that the magnetic moment disturbance produced by Cu in Ni is essentially limited to first-neighbor effects.

The Ni-Cu alloy system has been considered the classic example of rigid-band behavior in that the average magnetic moment decreases by about $1\mu_B$ per added Cu atom. This rate of decrease is larger than for simple dilution and indicates that the average moment per Ni atom also decreases with increasing Cu content. For a better understanding of the electronic structure and magnetic behavior of this alloy system it is important to know if this Ni moment reduction is