High-frequency breakdown in *p*-type InSb

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High-frequency breakdown in *p*-type indium antimonide was investigated experimentally at 77 °K in a magnetic field. The use of circularly polarized waves has revealed that near the ionization threshold the breakdown in the volume of the semiconductor is initiated by the minority carriers, the electrons, and if the threshold is greatly exceeded the breakdown can also be produced by heavy holes. In crossed microwave electric and stationary magnetic fields, the appearance of a constant emf was observed under the breakdown conditions.

Interband breakdown in p-InSb in a constant electric field was investigated in[1-6]. The main question, however, namely which type of carrier acquires an energy exceeding the width ϵ_g of the forbidden band initiates the cascade-like ionization process, has not been answered to this day. It is assumed in[2] that breakdown in p-InSb, depending on the experimental conditions, say the type of contacts, can be due either to heavy holes or to injected electrons. A hypothesis is advanced in[3] that the cascade is due to light holes, owing to their high mobility. It is stated in[4-6] that the necessary condition for the onset of breakdown is the presence of contacts that inject the electrons. Heavy holes and intrinsic electrons, in the opinion of the authors of[4-6], are incapable of causing breakdown, since the former have too high a mass and the latter have too low a mass to cause the observed degree of ionization.

We have investigated experimentally high-frequency breakdown (HFB) in p-InSb at 77°K. The proposed investigation method has that advantage that in this case the electric field in the semiconductor can be excited by a contactless method, so that the influence of the electrons injected from the contact can be excluded. We have investigated a p-InSb sample with hole density $\sim 5 \times 10^{13}$ cm^{-3} and Hall mobility $\mu \sim 7.4 \times 10^3$ cm^2/V-sec. The experiment was carried out in the 4-mm band in a single-mode waveguide, the cross section of which was completely covered by the semiconductor plate. The measurements were carried out in the regime of short ($\sim 10^{-7}$ sec) pulses with large off-duty cycle ($\sim 5 \times 10^3$), to prevent heating of the lattice. The HFB were registered with the aid of oscillograms of the envelope of the microwave pulse, in analogy with the procedure used in[7]. Figure 1 shows typical oscillograms of a radiation pulse passing through the sample at low power P of the incident wave (a) and at a power exceeding a sudden threshold value $P_0 \sim 65$ W, at which breakdown takes place (b). Figure 2 shows plots of the reflection and transmission coefficients R and T (in terms of power) against P, measured at the instant when the indicated coefficients reach their stationary values during the pulse. In the weak field, the contribution of the free carriers to the high-frequency dielectric constant ϵ of the semiconductor is negligibly small, and R and T are independent of P. If $P \gg P_0$, then the concentrations of the nonequilibrium carriers greatly exceed the corresponding equilibrium values. The main contribution to ϵ at the radiation frequency ω is then made by the conduction electrons, and the sharp decrease of T and increase of R are due to the fact that ω becomes smaller than the plasma frequency of the non-equilibrium electrons, and the real part of ϵ becomes negative.

The breakdown was investigated first, in the case when the sample made contact with the waveguide walls, and second, when it was completely insulated from the waveguide by thin ($\sim 5 \times 10^{-3}$ mm) teflon liners. In both cases, the breakdown developed in the same manner. It was therefore concluded that the onset of HFB in p-InSb is not connected with the presence of contacts, and consequently with electron injection. Estimates of the threshold value of the field E_{thr} according to data of an experiment with linear polarization, yielded a value $E_{thr} \sim 900$ V/cm.

To identify the carriers that initiate the breakdown at a slight excess at P over P_0, a p-InSb sample in the form of a flat disk of thickness 0.15 mm was placed in a round waveguide and was irradiated with a circularly-polarized wave in the presence of a magnetic field H.

In this case, the expression for the carrier energy can be written in the form

$$\mathscr{E}=e^2E_\sim^2/2m^*[(\omega\pm\omega_H)^2+\nu^2]. \tag{1}$$

Here e and m* are the charge and effective mass of the carrier, ω_H is the cyclotron frequency, ν is the collision frequency, $E_\sim$ is the amplitude of the high frequency field, and the sign plus or minus is chosen in

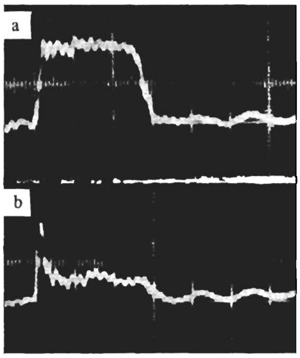

FIG. 1. Oscillograms of high-frequency radiation pulse passing through a semiconductor sample; a) $P < P_0$; b) $P > P_0$.

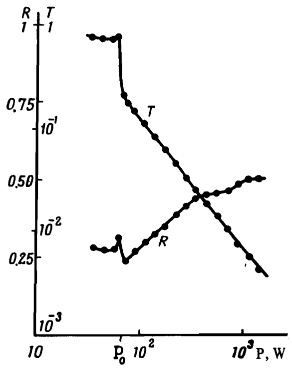

FIG. 2. Dependence of the reflection and transmission coefficients (R and T) on the power of the incident wave.

accord with the sign of the carrier charge. At a specified direction of the rotation of the polarization vector, the resonant growth of the energy at $\omega \approx \omega_H$ as a function of the direction of H will take place either for the electrons or for the holes. In the case when the electrons resonate, experiment has revealed that $P \approx 0.9P_0'$ (P_0' is the threshold power of the circularly-polarized wave at $H = 0$) the onset of breakdown at $H \approx 400$ Oe. The cascade was interrupted when H was increased to 850 Oe. At $P \approx 1.1P_0$, an increase of H from zero to 400 Oe led to an even more intense development of the breakdown, and with further increase of H the breakdown stopped at $H \approx 900$ Oe. No breakdown occurred at any H in the case of hole resonance and $P \approx 0.9P_0'$ and at $P \approx 1.1P_0'$ an increase of H from zero to 900 Oe led only to a monotonic increase of T and to an interruption of the cascade formation process. It follows from the foregoing, taking (1) into account, that at a weak excess of the power over threshold the breakdown is initiated by the electrons.

In a sufficiently strong magnetic field, the light carriers can be regarded as "magnetized" (the cyclotron frequency of the light carriers is much higher than the collision frequency or ω). The breakdown, however, can again set in when the microwave field power is increased. The case of a strong excess of the wave power over the threshold breakdown power was investigated in a rectangular waveguide with cross section 3.6 × 1.8 mm. A semiconductor plate measuring 4 × 5 mm, 0.06 mm thick, was placed in a gap in the waveguide channel and had end contacts through which a weak constant field could be applied. When the power exceeded the threshold by five times and more, the magnetic field did not stop the breakdown at a fixed value of P in the entire interval $H \lesssim 9000$ Oe. It follows therefore that at these values of the power in a strong magnetic field an important role in the breakdown development is played by heavy holes, inasmuch as even in these magnetic fields the light carriers can be regarded as "magnetized." The process of "magnetization" of the light carriers in an ionized semiconductor at $P \gtrsim 5P_0$ was itself revealed by the small increase of T at values $H \sim 1000-2000$ Oe.

Under breakdown conditions at the end of the sample, in a direction parallel to E, a constant emf E_H is observed during the time of the HF pulse, with a sign that reversed with a reversal of the direction of H. In the absence of breakdown, $E_H = 0$ at all values of H. In the presence of breakdown, the voltage E_H ranged from zero at $H = 0$ to a maximum value of $E_{H\,max}$ at the value of H that caused interruption of the breakdown, or that simply "magnetized" the light carriers. This effect is probably connected with the weak inhomogeneity of the microwave field along the waveguide axis, which leads to excitation of the carriers predominantly at one of the boundaries of the plate and to their subsequent drift along the waveguide axis. Application of a magnetic field perpendicular to the drift velocity leads to a deflection of the carriers, depending on the sign of their charge, towards opposite ends of the sample, and this is the cause of the emf.

Thus, our study has demonstrated experimentally that breakdown in p-InSb near the ionization threshold is due to the minority carriers (electrons). The fact that the light holes do not participate in the ionization process near the threshold can probably be attributed to their higher collision frequency, compared with the electrons, since the hole-collision process can be connected with their transition from one band to another (from the lighter ones to the heavier ones) as a result of the large difference between the state densities, whereas no such process takes place for electrons. When the power exceeds the threshold appreciably, the introduction of a sufficiently strong magnetic field does not stop the breakdown; the apparent reason is that the heavy holes play a decisive role in the formation of the breakdown in strong magnetic and strong microwave fields.

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