Magnetic surface quantization in indium antimonide

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The first observation of oscillations in the magnetoresistance in weak magnetic fields is reported. The oscillations are interpreted as a manifestation of a magnetic quantization of the energy spectrum of the free electrons near the surface of the sample.

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We have studied the magnetoresistance of indium antimonide samples with various degrees of electron degeneracy in weak magnetic fields.

Figure 1 is a typical plot of the second derivative of the resistance, $\partial^2\rho/\partial B^2$, vs the magnetic field. These measurements were carried out by modulating the magnetic field and extracting the signal at the harmonic of interest with a synchronous detector.[1] In addition to the usual Shubnikov–de Haas peaks, which have been observed many times previously under similar conditions,[2] a sharply defined oscillatory structure appears at fields below 200 Oe at low temperatures.

Figure 2 shows the part of the magnetoresistance curve for a degenerate sample which is typical of weak magnetic fields at $T = 2.8$ K. The series of peaks in $\partial^2\rho/\partial B^2$ corresponds to a series of steps on the $\rho(B)$ curve (Fig. 2), found through a numerical integration of the experimental curve of $\partial^2\rho/\partial B^2$.

Let us examine the most interesting results.

1) The series of $\partial^2\rho/\partial B^2$ peaks is seen in weak magnetic fields, under the condition $\omega_c\tau_p < 1$, and with a temperature-induced blurring of the Landau levels, i.e., with

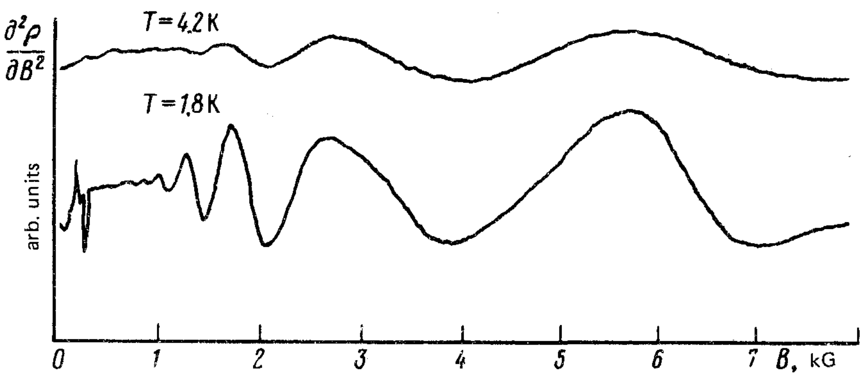

FIG. 1. Second derivative of the magnetoresistance of n-InSb vs the magnetic field. Along with the ordinary Shubnikov–de Haas oscillations, there are structural features at weak magnetic fields at $T \lesssim 3$ K (lower curve).

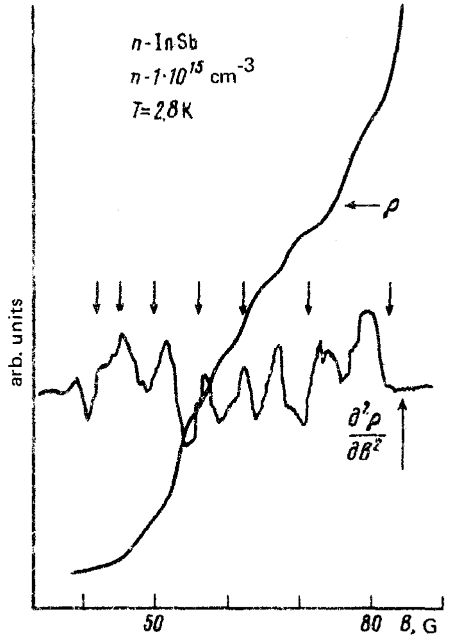

FIG. 2. Typical curve of the magnetoresistance in the region of weak magnetic fields. The arrows are the theoretical field values calculated from Eq. (3).

$\hbar\omega_c < k_0 T$, where $\omega_c = eB/m^*c$ is the cyclotron frequency, τ_p is the momentum relaxation time, and m^* is the effective electron mass.

2) The oscillations occur in only a bounded interval of weak magnetic fields; they are not observed as $B \to 0$ or above a certain critical field, up to fields at which the Shubnikov–de Haas oscillations become noticeable.

3) Degenerate and nondegenerate samples exhibit different $\partial^2\rho/\partial B^2$ features. In samples with a low concentration, $\rho(B)$ has only a single step, which is smeared over the entire typical range of magnetic fields. With increasing degeneracy, a complex structure of the type in Fig. 2 appears. A further increase in the concentration narrows the peaks and also the field range in which the peaks are found.

4) In degenerate samples, as the temperature is lowered from 4.2 to 1.8 K we first find a single large step in the magnetoresistance; this single step then breaks up into a finer structure, which is also visible in Fig. 2. At a low carrier concentration this structure does not appear.

These facts suggest that we are seeing here a phenomenon which is related to the quantum oscillations of the surface impedance which were first observed by Khaĭkin in metals.[3] A theory for this effect was derived by Prange and Nee.[4] Khaĭkin[5] has analyzed in detail the mechanism for the formation of magnetic surface states, which are responsible for the observed oscillations in the coefficient for microwave absorption by the surface of a pure metal. Khaĭkin[5] predicted a possible manifestation of magnetic surface states in the magnetoresistance of metals, also, through a mechanism analogous to the Shubnikov–de Haas effect.

The magnetoresistance in semiconductors under conditions of magnetic surface quantization has been studied only theoretically.[6,7] Only Boltzmann statistics have been considered, and in this case the oscillations should not occur.

We can thus find numerical estimates only from a theory that is correct, strictly speaking, only for metals.

According to Ref. 4, the magnetic-quantization energy levels are

$$E_N = \left(\frac{3he}{4\sqrt{2}c}\right)^{2/3} \frac{v_F}{p_F^{1/3}} (B N)^{2/3}. \qquad (1)$$

We assume that the structural features (steps) on the magnetoresistance curve $\rho(B)$ should appear under the condition

$$E_N = E_F . \qquad (2)$$

Here E_F, v_F, and p_F are the Fermi energy, velocity, and momentum, respectively, and N is the index of the magnetic surface state. From (1) and (2) we find the magnetic fields at resonance to be

$$B_N = \frac{1}{N} \frac{4m^* c}{3he} E_F , \qquad (3)$$

where m^* is the effective electron mass.

For an InSb sample with $n = 10^{15}$ cm^{-3} the Fermi energy is $E_F = 2.7$ meV (which corresponds to 30 K), and we have $B_N = 500/N$. The peaks should therefore be cut off at $B = 500$ G, but we observe a last peak corresponding to $N = 6$ at $B \approx 80$ G. It can be seen from Fig. 2 that the oscillation period is given well in order of magnitude by (3).

The energy spacing of the levels is $\Delta E = E_6 - E_7 \approx 2.3 \times 10^{-2}$ meV (≈ 2.7 K), in agreement with the fact that we observe the system of peaks only at temperatures below 3 K.

Why is it that, in a sample with macroscopic dimensions ($1.5 \times 1.5 \times 10$ mm), we were able to detect a contribution to the magnetoresistance from a thin layer of magnetic surface quantization. The answer evidently lies in the particular nature of the weak magnetic fields. By virtue of the degenerate statistics, the ordinary magnetoresistance, involving exchange mechanisms, is weak in these fields, and our method easily detects the relatively sharp changes in the resistance when the magnetic field reaches its resonant values, (3).

In summary, all these features of the oscillations which we observe in weak magnetic fields are described satisfactorily at a qualitative level by the simple theory of Ref. 4. On the other hand, we lack an explanation of the observed shift of the oscillation region toward stronger fields as the temperature is lowered. We believe that this effect is somehow related to the specific properties of the surface of the semiconductor, which are generally not as simple as for a metal.

We note in conclusion that these oscillations in the magnetoresistance in weak magnetic fields apparently constitute the first observation of magnetic surface channeling in semiconductors.

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