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QUANTUM GALVANOMAGNETIC EFFECTS IN n-InAs

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The Hall effect and the electrical resistance of n-InAs were investigated in strong pulsed magnetic fields at 20—360°K. Quantization of the carrier motion in the magnetic fields produced an infinite rise in the resistance. At liquid hydrogen temperatures a carrier-density effect was observed.

THERE are several theories of galvanomagnetic effects in semiconductors in very strong magnetic fields.[1-5] However, these theories lead to contradictory results.[2,3] The available experimental data are insufficient to check the theories; furthermore, disagreement between one of the theories[3] and experiment has been reported.[6,7] New data are obviously needed in the region of strong fields. The present paper describes investigations of the Hall effect and magnetoresistance of n-InAs at 20—360°K in pulsed magnetic fields. To the authors' knowledge this is the first such study on n-InAs.

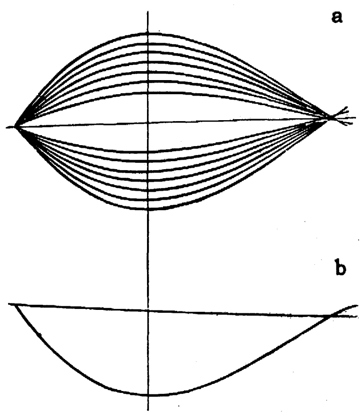

FIG. 1. a) Oscillograms of magnetoresistance; b) oscillogram of magnetic field.

EXPERIMENTAL METHOD

Pulsed magnetic fields were produced by discharging a capacitor bank through a solenoid made of beryllium bronze. The bank had a capacitance of 1200 μf and was charged to 3 kv. The apparatus produced fields of 450 kgauss in a working volume of 0.4 cm^3. In this volume the field was uniform to within 3%. The field intensity was measured with an integrating circuit.[8] The field-intensity oscillogram is given in Fig. 1. The samples were rectangular parallelepipeds of dimensions from $5 \times 0.5 \times 0.5$ mm to $8.0 \times 0.5 \times 0.5$ mm, and were cut from a homogeneous ingot. The homogeneity was verified by measuring the electrical resistance and the Hall effect. Current leads and potential probes were soldered to the samples using pure tin. The potential probe contacts were ohmic and their areas did not exceed 0.12 mm^2. To avoid surface effects the samples were etched.[9]

A check of the influence of the sample shape showed that the magnetoresistance in a quantizing magnetic field is independent of the length-to-width ratio provided that this ratio is greater than 10 (Fig. 2). The Hall potential difference was measured across transverse potential probes placed symmetrically in the middle of the sample. The magnetoresistance was measured using the potential probes as well as the sample ends. No edge effects were observed in the quantizing field. Experiments using steady magnetic fields showed that edge effects were strong in weak fields, but

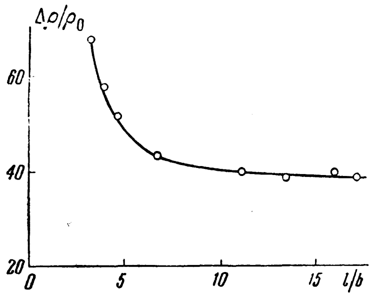

FIG. 2. The dependence of magnetoresistance on the parameter l/b for sample G1; l is the length of the sample and b is its width. H = 350 kgauss, T = 77°K.

in fields capable of quantization (H ≥ 25 kgauss at 77°K) the magnetoresistance measured using the potential probes was indistinguishable from that across the ends of the sample.

The results obtained in weak pulsed magnetic fields were checked by measurements in steady fields of 26 kgauss. The measured potential differences were recorded with an OK-17M oscillograph. Induction effects were cancelled out with a coil placed in the field with the sample.

The dependence of each effect (the Hall effect or magnetoresistance) on the field was determined using the two outer oscillograms (Fig. 1) obtained for two opposite directions of current. Records of the effect at five selected values of the field, taken in steps of 50—80 kgauss, were made on the same oscillogram frame. The peak oscillogram values were then used to plot the field dependence of the effect. Both methods of obtaining the field dependence gave the same results, with all experimental points lying on the same curve. The absence of hysteresis in curves obtained with increasing and decreasing field corroborated the results.

For measurements at liquid-nitrogen temperature, the magnet and the sample were placed inside a nitrogen bath. Liquid hydrogen was poured into a special Dewar which contained a holder and the sample. This Dewar was placed in the working volume of the magnet. The sample temperature was measured with a copper-constantan thermocouple. The sample temperature was unaffected by passage of currents of density up to 120 amp/cm². The current density actually used in the measurements did not exceed 15 amp/cm². In a field of 450 kgauss at 20°K the electric field intensity in pure samples reached 8 v/cm but there were no departures from Ohm's law.

RESULTS

Eight samples were cut from an ingot with an impurity carrier density $n \approx 3 \times 10^{16}$ cm^{-3}. Four

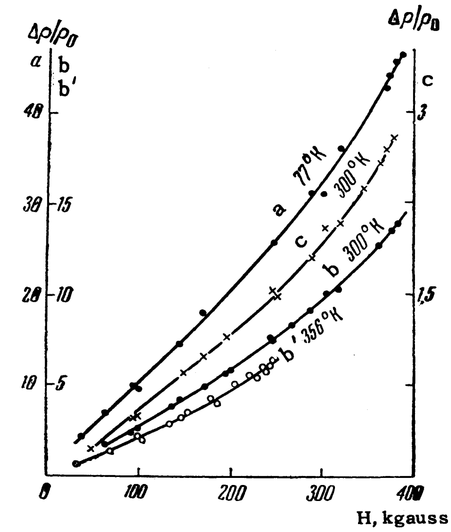

FIG. 3. The dependence of magnetoresistance on the magnetic field intensity for two samples of InAs: G1 (curves a, b, and b′) and M-13 (curve c).

more samples were obtained from a less pure ingot with $n \approx 2 \times 10^{18}$ cm^{-3}. Figures 3 and 4 give the Hall coefficient R and the magnetoresistance $\Delta\rho/\rho_0$ in a transverse magnetic field, for two typical samples: G1 with a conductivity of 175 ohm^{-1} cm^{-1}, R = 200 cm³/coul at 77°K, and M-13 with a conductivity of 2870 ohm^{-1} cm^{-1}, R = 3 cm³/coul at 77°K.

If the effective carrier mass in n-InAs is taken to be $m^* = 0.03m_0$, where m_0 is the free-electron mass, then at $H > 10^5$ gauss the cyclotron resonance frequency is $\hbar\omega_0 > 5.8$ kT at 77°K and $\hbar\omega_0 > 22$ kT at 20°K.

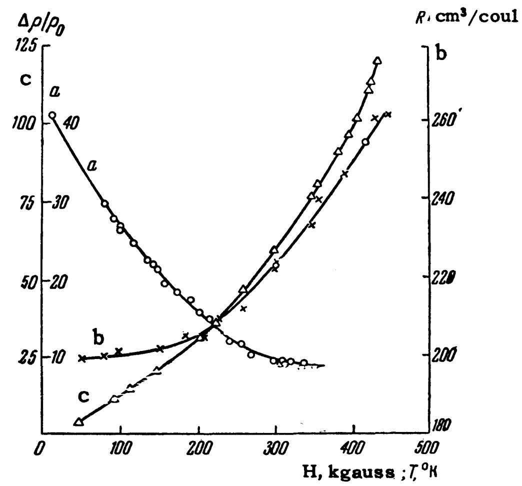

FIG. 4. Sample G1: a) the dependence of magnetoresistance on temperature (H = 252 kgauss); b) the dependence of the Hall coefficient on the magnetic field intensity (T = 20°K); c) the dependence of magnetoresistance on the magnetic field intensity (T = 20°K).

The Hall coefficient of sample G1 was independent of the magnetic field intensity up to 400 kgauss both at 300 and at 77°K. At 20°K the value of R was also practically constant in fields of up to 160 kgauss. Above 160 kgauss, R began to rise and increased by a factor of 1.4 when 450 kgauss was applied. An increase of the Hall coefficient with the magnetic field intensity was reported earlier for n-InSb[10,11] and for p-Ge.[12] An interesting feature in the case of InAs is that sample G1 was degenerate at 20°K and its reduced chemical potential in the absence of a magnetic field was $\mu^* = \mu_0/kT = 8.1$, taking the effective electron mass as $0.03m_0$.[13] The conduction band and impurity levels overlapped in the absence of a magnetic field. With increase of the magnetic field intensity the overlap was removed and above 160 kgauss the activation energy of impurities became positive and greater than the mean energy of conduction electrons. Consequently the equilibrium carrier density decreased above 160 kgauss.

In the strongly degenerate InAs sample M-13 the Hall coefficient was not affected by magnetic fields at 20°K because the conduction-band and impurity-level overlap was considerable.

Our investigations of the Hall effect showed that InAs can be used to construct probes for measuring the intensities of strong magnetic fields.

Figures 3 and 4 show that at 77°K magnetoresistance $\Delta\rho/\rho_0$ rose in sample G1 as $H^{1.20}$; in the seven other samples similar to G1 the exponent of H ranged from 1.13 to 1.20. Sample G1 was degenerate at 77°K with $\mu_0^* = 2.1$. According to the theory of Adams and Holstein,[3] there should be a strong dependence of $\Delta\rho/\rho_0$ on H in the case of degeneracy: $\Delta\rho/\rho_0 \propto H^5T$ if carriers are scattered on acoustical vibrations of the lattice, and $\Delta\rho/\rho_0 \propto H^{3/2}T^0$ in the case of pure Rutherford scattering. Measurements of the Nernst-Ettingshausen effect and values of $R\sigma$ at 20—300°K showed that carrier scattering in sample G1 was of mixed phonon-ion type. The weak dependence of $\Delta\rho/\rho_0$ on H at 20—77°K can be accounted for in terms of the Adams-Holstein theory[3] if it is assumed that a strong magnetic field removes degeneracy.[2,5] The assumption was confirmed by the fact that the criterion of degeneracy in the presence of a magnetic field,[2] $\frac{4}{9}(\mu_0/\hbar\omega_0)^2\mu_0 \gg kT$, was not satisfied in sample G1 at 77°K in a field of 10^5 gauss: $\frac{4}{9}(\mu_0/\hbar\omega_0)^2\mu_0 \approx \frac{1}{10}kT$.

Classical statistics predicts $\Delta\rho/\rho_0 \propto H^2T^{-1/2}$ for acoustical scattering and $\Delta\rho/\rho_0 \propto H^0T^{-3/2}$ for scattering of carriers on impurity ions.[3] Combination of the two types of scattering can produce the dependence of $\Delta\rho/\rho_0$ on H which was actually observed at 77°K.

At 20°K the magnetoresistance rose almost linearly with the magnetic field intensity up to 160 kgauss: $\Delta\rho/\rho_0 \propto H^{1.1}$; above 160 kgauss it was found that $\Delta\rho/\rho_0 \propto H^{1.74}$. The more rapid rise of magnetoresistance above 160 kgauss was due to reduction of the carrier density. Klinger and Voronyuk[5] showed that reduction of the equilibrium carrier density in a magnetic field makes the dependence of $\Delta\rho/\rho_0$ on H more pronounced. Above 160 kgauss it was found that $R \propto H^{0.6}$; the exponent in the dependence of $\Delta\rho/\rho_0$ on H also increased by 0.6 on transition from below 160 kgauss to stronger fields.

With increase of temperature, carrier scattering on acoustical lattice vibrations becomes more intense and scattering on impurity ions becomes important. In accordance with this prediction it was found that in the quantum region, $\Delta\rho/\rho_0 \propto H^{1.45}$ at 300°K while $\Delta\rho/\rho_0 \propto H^{1.55}$ at 360°K; the quantum region at these two temperatures lies above 240 kgauss.

The magnetoresistance of the less pure sample M-13 was an order of magnitude smaller than that of sample G1. Consequently the quantum region in M-13 began above 300 kgauss. Degeneracy was not removed by fields of up to 400 kgauss. The observed dependence $\Delta\rho/\rho_0 \propto H^{1.50}$ at $H > 350$ kgauss was less marked than the theoretical dependence[3] predicted for the degenerate case. The magnetic field intensity may have been insufficient to produce agreement with this theory.

Figure 3 gives the temperature dependence of magnetoresistance at H = 252 kgauss. When temperature was lowered from 300 to 186°K, the magnetoresistance rose according to $\Delta\rho/\rho_0 \propto T^{-1.30}$. Further reduction of temperature to 77°K showed $\Delta\rho/\rho_0 \propto T^{-0.72}$ Between 77 and 20°K it was found that $\Delta\rho/\rho_0 \propto T^{0.50}$. Below 160 kgauss the rise of $\Delta\rho/\rho_0$ on cooling from 77 to 20°K was negligible.

The longitudinal magnetoresistance, $\Delta\rho_{\parallel}/\rho_0$ was too small to be measured: in sample G1 it could not have been greater than 0.2.

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