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The Shubnikov–de Haas effect in InP close to the metal–insulator transition

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Abstract. The usual criterion for the observation of the Shubnikov–de Haas effect is that $\omega_c\tau \gg 1$ where ω_c is the cyclotron frequency. The mean free time between collisions, τ, is normally obtained from the conductivity $\sigma = ne^2\tau/m^*$. We have observed Shubnikov–de Haas peaks in InP close to the metal–insulator transition for which $\omega_c\tau = 0.1$. It is clear therefore that the mean free time derived from conductivity measurements is not the same as the time the electron spends in a cyclotron orbit before scattering occurs.

From measurements of the diffusion constant D and the inelastic scattering time τ_i we deduce an inelastic length $L_i = (D\tau_i)^{1/2}$. We show that, in the relevant region, the magnetic length $L_H = (h/Be)^{1/2}$ becomes smaller than L_i and also smaller than d, the average distance between impurities. When this occurs the mean free time τ becomes field dependent and an increased proportion of electrons n_f are then able to perform complete cyclotron orbits without collisions, thus contributing to the Shubnikov–de Haas effect. While performing a cylotron orbit these electrons are not contributing to the current. The measured conductivity may then be considered to be due to a smaller number of electrons $n - n_f$. Hence the value of τ derived from the simple relation $\sigma = ne^2\tau/m^*$ is no longer appropriate for the Shubnikov–de Haas criterion.

1. Shubnikov–de Haas criteria

Standard textbook discussions of Shubnikov–de Haas oscillations emphasize that, for the effect to be observed, the condition $\omega_c\tau \gg 1$ must be satisfied ($\omega_c = Be/m^*$ is the cyclotron frequency; τ, the mean free time between collisions, can be obtained from the measured conductivity $\sigma = ne^2\tau/m^*$, n being the electron density). However, a number of publications reporting the conductivity just on the metallic side of the transition report a Shubnikov–de Haas oscillation where this criterion is far from being satisfied.

We report, below, a Shubnikov–de Haas peak where $\omega_c\tau$ is as low as 0.1. We discuss possible reasons for which, for a combination of high magnetic field and low temperature, such observations are possible.

2. Experimental measurements

Two samples were measured with electron concentrations derived from low-temperature Hall measurements: (1) $5.3 \times 10^{22}\,m^{-3}$ and (2) $3.3 \times 10^{22}\,m^{-3}$. The critical concentration n_c derived from $n_c^{1/3}a_H = 0.26$ is $3.4 \times 10^{22}\,m^{-3}$. Sample 2 was thus just on the insulating side of the transition in zero magnetic field. The samples were epitaxial layers of clover-leaf shape and were measured in a van der Pauw configuration using an AC potentiometric conductance bridge operating at 27.5 Hz.

The conductivity of sample 1 was measured at a number of temperatures down to 45 mK, each point being measured at steady temperature and field. A fairly sharp minimum in conductivity was obtained at about 3.16 T. If we assume that this minimum in conductivity occurs at a field where the $n = 1$ Landau level coincides with the Fermi surface, we obtain $n = 5.8 \times 10^{22}\,\mathrm{m}^{-3}$.

A further oscillation corresponding to the next Landau level can be observed but is not well resolved. To improve the resolution the magnetic field was swept at a suitable rate and the signal double differentiated. Two clearly defined peaks were now obtained. This procedure was repeated at six different temperatures between 4 K and 60 mK and the results averaged. A scatter of less than 3% was obtained with no apparent temperature dependence in peak position as is to be expected for Shubnikov–de Haas oscillations. The standard formula $K_F^2 = 2e/\hbar\Delta(1/B)$ gave an electron density of $5.6 \times 10^{22}\,\mathrm{m}^{-3}$. This compares with $5.8 \times 10^{22}\,\mathrm{m}^{-3}$ derived from equating the point-by-point extremum to $\frac{3}{2}\hbar\omega_c$ and with $5.3 \times 10^{22}\,\mathrm{m}^{-3}$ from low-temperature Hall measurements. Calculating τ from the conductivity at 1.9 T appropriate for the $n = 2$ Landau level, we find $\omega_c\tau = 0.24$ which is of course far below the requirement $\omega_c\tau \gg 1$.

We turn now to sample 2 whose behaviour has been proposed (Finlayson *et al* 1987) as an example of the Shapiro (1984) phase diagram in that, starting as an Anderson insulator in zero field, it becomes metallic in low magnetic fields and a magnetic insulator in high fields. In the following section we report measurements that help to confirm the Shapiro double transition.

3. Conductivity versus $T^{1/3}$

Altshuler and Aronov (1983) have shown that, at fields greater than that required for the spin-splitting condition $g\mu_B B = \pi kT$ and close to the transition, the conductivity will be given by $\sigma = a + bT^{1/3}$. Maliepaard *et al* (1988) further showed that the dominant length scale did not change on going through the transition, so $\sigma = a + bT^{1/3}$ still applied but a became a negative quantity.

With this in mind we have measured the conductivity of sample 2 as a function of magnetic field and temperature in the neighbourhood of the transition. The results are shown in figure 1 where the conductivity is plotted against $T^{1/3}$. Reasonably good straight-line plots are obtained in the region where $g\mu_B B > \pi kT$. A computer fit to $\sigma = a + bT^{1/3}$ gave negative values for a, so for fields greater than that required to satisfy the spin-splitting condition, the material is insulating. In other words, by the time the field is high enough to satisfy $g\mu_B B > \pi kT$ the sample has reverted to the insulating state and so no $T^{1/3}$ region exists for this sample in the conducting state. We may note that the zero-field conductivity has a lower value at all temperatures than the extrapolated $T^{1/3}$ plot at 2.8 T which yields a negative value for a at zero T, thus confirming the insulating character at zero field.

Turning now to the intermediate conducting state, the magnetoresistance versus field at 0.58 K is shown in figure 2. A clear Shubnikov–de Haas peak is observed at 2.3 T. Taking $E_F = 1.5\,\hbar\omega_c$ yields $n = 3.6 \times 10^{22}\,\mathrm{m}^{-3}$, to be compared with $3.3 \times 10^{22}\,\mathrm{m}^{-3}$ from low-temperature Hall measurements. The peak can therefore be identified with the

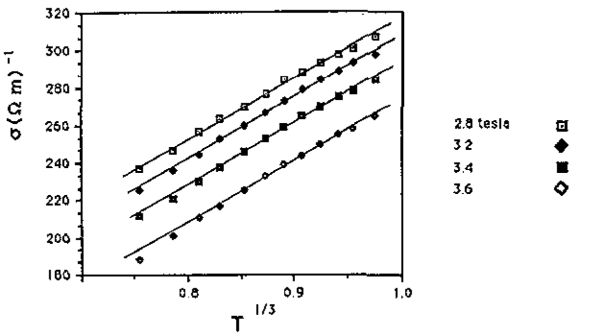

Figure 1. Conductivity versus $T^{1/3}$ at fields of 2.8, 3.2, 3.4 and 3.6 T.

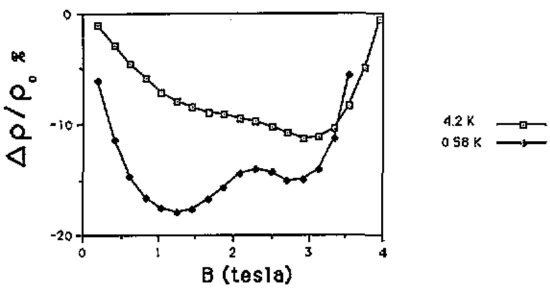

Figure 2. Negative magnetoresistance ratio versus magnetic field at temperatures of 4.2 and 0.58 K showing Shubnikov–de Haas oscillations.

$n = 1$ Landau level. Obtaining τ from the conductivity at 2.3 T we find that $\omega_c\tau = 0.12$, again far removed from $\omega_c\tau \gg 1$.

4. Discussion

The $\omega_c\tau \gg 1$ criterion for the observation of the Shubnikov–de Haas effect is an obvious physical requirement and cannot be far wrong. To explain the very low values for these two samples (and others reported in the literature, e.g. in GaAs; Maliepaard *et al* 1989) we must seek a reason for the large difference between the cyclotron and conductivity mean free times.

The magnetic length $L_H = (\hbar/Be)^{1/2}$ at 2.3 T is 1.7×10^{-8} m. Sample 2 is fairly heavily compensated with $K = N_A/N_D = 0.7$. With $N_D - N_A = 3.3 \times 10^{22}$ m^{-3}, the average distance between impurities is 1.7×10^{-8} m. The magnetic length at the Shubnikov–de Haas extremum is thus comparable to the impurity spacing, so scattering by impurities is beginning to be frozen out by the magnetic field. This represents a qualitative change in the conductivity process.

For normal scattering processes in a magnetic field some collision times will be long enough for complete orbits to occur while others will of course be much shorter. The essential feature is that the average of these, the mean free time τ, is independent of magnetic field. In his original derivation of the magnetoconductivity equations, Peierls

(1931) gave qualitative arguments to show that τ should be unaffected by the magnetic field. This was subsequently verified by Dingle (1952). What we are now suggesting is that, when the magnetic length L_H becomes comparable with impurity spacing, the mean free time τ becomes field dependent, so the situation is no longer adequately described by the magnetoconductivity equations. Indeed in the limit one has the situation that as τ tends to infinity, the conductivity σ tends to zero. (See for example, Pippard (1989): 'in the absence of collisions no steady motion of electrons can take place'). The increased number of electrons performing complete or nearly complete orbits then contribute to Shubnikov–de Haas but not to ordinary conductivity, and hence the discrepancy in the $\omega\tau > 1$ criterion.

Up to this point we have considered only elastic scattering by impurities since at low temperatures this is the main process for destroying electron momentum. However, if there are sufficient inelastic scattering events to disturb the cyclotron orbits no anomaly will be observed. Before the discrepancy in the $\omega\tau > 1$ criterion can arise, the magnetic length must be less than both the elastic and inelastic lengths.

We can calculate the inelastic length from $L_i = (D\tau_i)^{1/2}$ where $D = 2E_F\tau_0/3m^*$ is the diffusion constant, equal in this case to $2.2 \times 10^{-4}\ m^2\ s^{-1}$. τ_0 is the elastic scattering time obtained from the conductivity. The inelastic scattering time, normally inaccessible from conductivity measurements, can be obtained via Kawabata (1980) low-field magnetoresistance in the quantum interference regime. Finlayson and Mehaffey (1985) found $\tau_i = 5 \times 10^{-12}\ T^{-1}$ s. This yields $L_i = 1.6 \times 10^{-8}$ m at 4.2 K, so the magnetic length L_H is comparable to L_i even at our high-temperature limit of 4 K, giving rise to a just visible oscillation in $\Delta\rho/\rho_0$. As the temperature is lowered the peak becomes clearly defined, as shown in figure 2 for $T = 0.58$ K at which temperature the inelastic scattering length will be much greater than the magnetic length.

One might suggest that if the samples are inhomogeneous then, in some regions, $\omega\tau > 1$ can still be satisfied and a small kink appear. We may note, however, that a Shubnikov–de Haas blip has been observed, although not commented on, in several completely independent laboratories in different systems including GaAs, all using high-quality MBE material. An inhomogeneity explanation thus seems highly improbable.

Our conclusion is therefore that a scattering time τ derived from conductivity ceases to be appropriate for insertion in the relation $\omega_c\tau \gg 1$ when the magnetic length becomes comparable with the other scattering lengths.

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