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LETTER TO THE EDITOR

Negative magnetoresistance in a parallel-conducting InGaAs structure

D R Mace†, M Pepper† and R Grey‡

† Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

‡ Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 4DU, UK

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Abstract. The magnetoresistance of a device fabricated from a bulk InGaAs layer on an InP substrate has been studied. The device exhibited both 2D conduction at the InP–InGaAs interface and 3D conduction in a doped InGaAs layer at the surface. We have observed negative magnetoresistance arising from the quenching of weak localization in the device. The effect is observed in both transverse and parallel fields, although that in the parallel field is of smaller magnitude than that in the transverse field. It is proposed that the structure contains a two-dimensional electron gas (2DEG) in parallel with a bulk conducting region. The temperature dependence of the negative magnetoresistance has been investigated and phase breaking times have been calculated by fitting the experimental data to the formula given by Hikami *et al* in 1980 for the 2D effect. A comparison is made with theoretical electron inelastic scattering times, and conclusions as to the nature of scattering in InGaAs structures are drawn.

The decrease in resistance of a 2DEG at a semiconductor heterojunction at low temperatures under the influence of a magnetic field has been studied in a number of systems (see for example Uren *et al* (1981) and Pepper (1985) (silicon inversion layers); Newson and Pepper (1986) GaAs MESFET; Poole *et al* (1981) and Taboryski and Lindelof (1990) (GaAs–AlGaAs heterostructures); and Alferov *et al* (1984) (InGaAs–InP heterostructures)). The reduction in resistance is usually explained by the magnetic quenching of the weak localization. Electrons in a disordered sample may be scattered in either direction around a self-intersecting loop; the wavefunctions corresponding to such complementary paths are coherent. This phase coherence enhances the probability for electron backscattering and so leads to an increase in the resistance of the sample above the expected classical resistance. This mechanism is known as weak localization or quantum interference, and is reviewed by Bergmann (1984). The presence of a magnetic field will introduce a phase shift in the wavefunctions of the complementary pair that depends upon the direction of traversal of the loop. Only at zero field will all such complementary pairs in the sample be in phase at the origin and thus a magnetic field suppresses the enhanced backscattering and so causes a decrease in resistance.

Altshuler *et al* (1980), Maekawa and Fukuyama (1981), and Hikami *et al* (1980) derived an expression for the variation of the conductivity as a function of magnetic field in the absence of spin–orbit and magnetic interactions:

$$\Delta\sigma(B,T) = \frac{\alpha e^2}{2\pi^2\hbar}\left[\Psi\left(\frac{1}{2}+\frac{1}{a\tau_\phi}\right) - \Psi\left(\frac{1}{2}+\frac{1}{a\tau}\right) + \ln\left(\frac{\tau_\phi}{\tau}\right)\right] \quad (1)$$

where $a = 4eDB/\hbar$; Ψ is the digamma function; τ_ϕ is the phase breaking time; τ is the elastic scattering time; and α is a constant. Hence by fitting the magnetoconductance to this formula, it is possible to deduce the phase breaking time.

The phase breaking time measured in weak-localization experiments is the lifetime of the complementary pair in the weak-localization interaction. There have been numerous attempts to calculate this time, although it is now generally accepted that the expression derived by Altshuler *et al* (1982) and Fukuyama (1984) is applicable to conductivity experiments. Fukuyama (1984) finds

$$1/\tau_\phi = (kT/2E_F\tau)\ln(4E_F\tau/\hbar) \quad (2)$$

for 2D systems in which $E_F\tau/\hbar \gg 1$. Equation (2) differs from that of Altshuler *et al* (1982) by a factor of 4 in the logarithm, although this factor is not considered significant and depends upon the method of calculation employed (Fukuyama 1984).

The authors have encountered a number of unpublished examples (including InGaAs–InP heterostructures and delta-doped GaAs–AlGaAs heterostructures—see Newson *et al* (1985) for a 3D example) in which there is no agreement between the experimentally determined phase breaking time and the theoretical time of equation (2). In a number of these systems this disagreement arises from a failure to take into account the parallel conduction within the samples. The device discussed below has two conducting regions: the dopant spike at the InP–InGaAs interface which gives rise to a low-mobility 2DEG; and the doped InGaAs layer which is a bulk conducting region. The system illustrates graphically the effect on the magnetoresistance of the 2DEG caused by the bulk layer.

The wafer was grown by molecular beam epitaxy at the University of Sheffield. The device structure is very simple. Approximately 1 μm of nominally undoped $In_{0.53}Ga_{0.47}As$ was grown on a semi-insulating InP substrate. This was capped with a 0.4 μm layer of $In_{0.53}Ga_{0.47}As$ doped n-type with a donor density of 3×10^{21} m^{-3} silicon. The doping level was calculated to take into account the loss of electrons in the $In_{0.53}Ga_{0.47}As$ surface states such that the doped layer would be just conducting at helium temperatures. Hall bars were wet-etched in the wafer using standard optical lithography techniques. Electrical contact was made to the doped layer and 2DEG by thermally annealed AuGeNi contacts.

The electrical characteristics of several Hall bars were measured using a constant current of 100 nA. No experimentally significant difference was found between the Hall bars. All measurements took place in a 1.5 K pumped ^{4}He cryostat with the capability of applying fields between -0.5 T and $+8$ T. None of the samples measured conducted when initially cooled to 1.5 K, suggesting that all the electrons occupied bound states. However, persistent conduction could be induced by illuminating the Hall bar briefly with a LED. Once illuminated, the device showed little variation in conductance over time.

The longitudinal and transverse magnetoresistances were measured at various temperatures in magnetic fields oriented both parallel and perpendicular to the direction of current flow in the Hall bar, as shown in figure 1. In a transverse field, Shubnikov–de Haas oscillations were observed at magnetic fields in excess of 1 T. No similar oscillations were observed when the field was rotated through 90°. This confirms the presence of a 2DEG. At high parallel magnetic fields the resistance of the sample increased. This is due to magnetic depopulation; the carrier densities in both layers are close to the critical densities for metallic conduction. Negative magnetoresistance effects were observed in both transverse and parallel fields. These results show that on illuminating the device, electrons were not only excited into the bulk region but also formed a 2D electron gas at the $InP–In_{0.53}Ga_{0.47}As$ interface and hence there were 2D and 3D contributions to the conductivity of the device.

An electron density of 1.4×10^{15} m^{-2} was calculated for the electrons in the 2D region from the Shubnikov–de Haas oscillations. The carrier density in the 3D region was then calculated from the Hall resistance by subtracting the contribution of the electrons in the 2D region. For this it was assumed that the bulk conducting region was 0.4 μm thick, i.e. that of the doped region. The electron density in the bulk region was 2.9×10^{21} m^{-3}. The Hall voltage remained approximately linear up to fields of 8 T suggesting that the electron mobilities in the 2D and bulk regions were similar. See Kane *et al* (1985) for a discussion on Shubnikov–de Haas oscillations and Hall effect in parallel-conducting systems.

The longitudinal resistance of the device was measured as a function of magnetic field at temperatures between 1.5 K and 6 K in both transverse and parallel fields, as shown in figure 2. The magnetic field was swept exceedingly slowly between ± 0.15 T. The magnitude of the negative magnetoresistance in parallel fields was smaller than that in transverse fields.

Initially, the raw transverse magnetoresistance data were fitted to equation (1) but the phase breaking times yielded from such a fit are an order of magnitude smaller than those predicted by equation (2). This misleading result can be explained if the magnetoresistance effect of the bulk electrons is taken into account. In the transverse field, the negative magnetoresistance is due to quenching of the weak localization in both the 2D and bulk layers.

To obtain the magnetoresistance of the 2D layer alone, the parallel magnetoresistance data were subtracted from those in transverse fields. It is assumed that there is no dependence of the 2DEG conductivity on a parallel magnetic field. It is also assumed that the magnetoresistance of the bulk layer is independent of the magnetic field orientation. The latter assumption is only valid for systems with a completely isotropic band structure. Figure 3 shows these data in terms of conductance; a negative magnetoresistance is shown as a positive magnetoconductance. It was observed that the magnetoresistance in parallel fields was of equal magnitude to that in transverse fields when the magnetic field exceeded 0.1 T. This suggests that the magnetic length at 0.1 T is equal to the elastic length, and so the 2D weak-localization effect is quenched. This agrees with the elastic length calculated from the Hall and Shubnikov–de Haas data.

It should be noted that, for the 2DEG in this sample, the value of $E_F\tau/\hbar$ varies from 1.4 to 1.1 over the temperature range investigated. Hence, the criterion that $E_F\tau/\hbar \gg 1$ is not strictly satisfied, and so the comparisons between the measured phase breaking time and the theoretical result discussed below should be treated with some caution, particularly at the lowest temperatures where the $E_F\tau/\hbar$ approaches 1.

The subtracted data were fitted to equation (1) and the phase breaking time extracted. In figure 4, the inverse measured phase breaking time is plotted against temperature. The points lie approximately on a straight line that passes through the

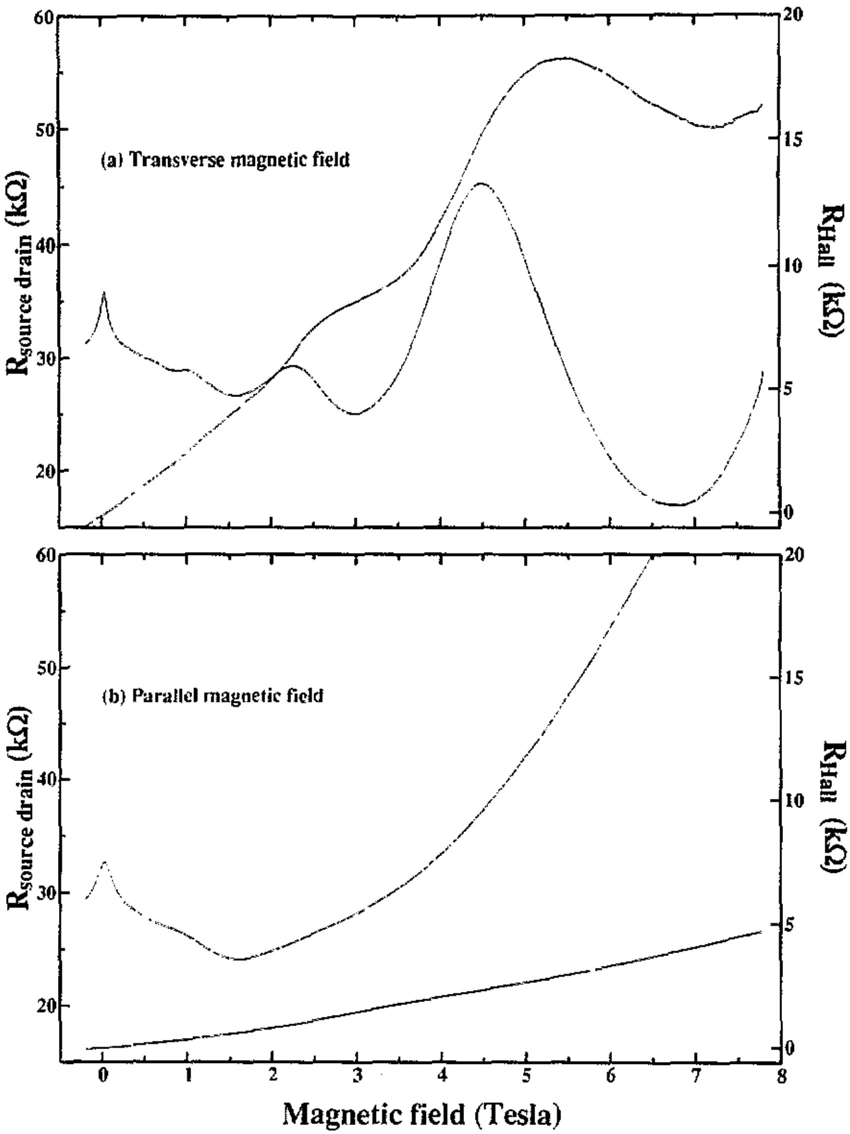

Figure 1. The longitudinal and Hall resistance measured in (*a*) a transverse magnetic field, and (*b*) a parallel magnetic field. The Shubnikov–de Haas oscillations are only present in the transverse field. The rise in resistance in the parallel field is due to magnetic depopulation.

origin. This is as predicted for a disordered 2DEG; fitting the raw transverse field data directly led to scattering times that showed a saturation of the phase breaking time as the temperature approached zero.

The measured phase breaking times were compared with the characteristic time given in equation (2), as shown in figure 5. There is good agreement between experiment and theory, particularly at higher temperatures. The energy relaxation times, calculated using the formula of Abrahams *et al* (1981), are a factor of 5 smaller than the measured phase breaking times. This suggests that the energy relaxation time

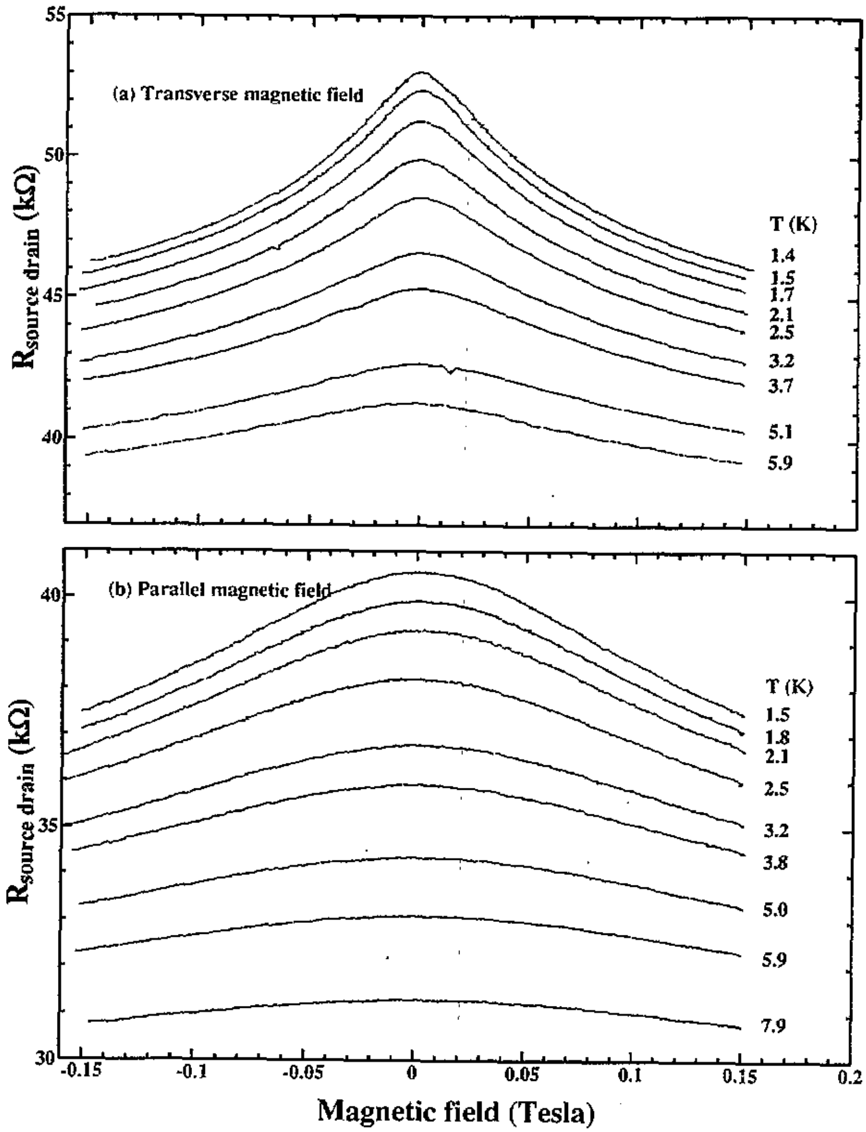

Figure 2. Negative magnetoresistance in (*a*) a transverse magnetic field, and (*b*) a parallel magnetic field. The transverse field data show quenching of the weak localization in both the bulk and 2D layers, whereas the parallel-field data show the effect of the field on the bulk region only.

is not relevant to weak localization and is in agreement with other work (see, for example, Lee and Ramakrishnan 1985). If the mobility (and hence elastic scattering time) is assumed to be slightly higher in the 2DEG than in the bulk layer, then the agreement between experiment and theory is further improved. However, there is little point in extending the analysis in this particular system to extract information on the relative mobilities of the bulk and 2D layers as the conditions required for equation (2) are not well satisfied.

From these results we conclude that it is possible to measure phase breaking times

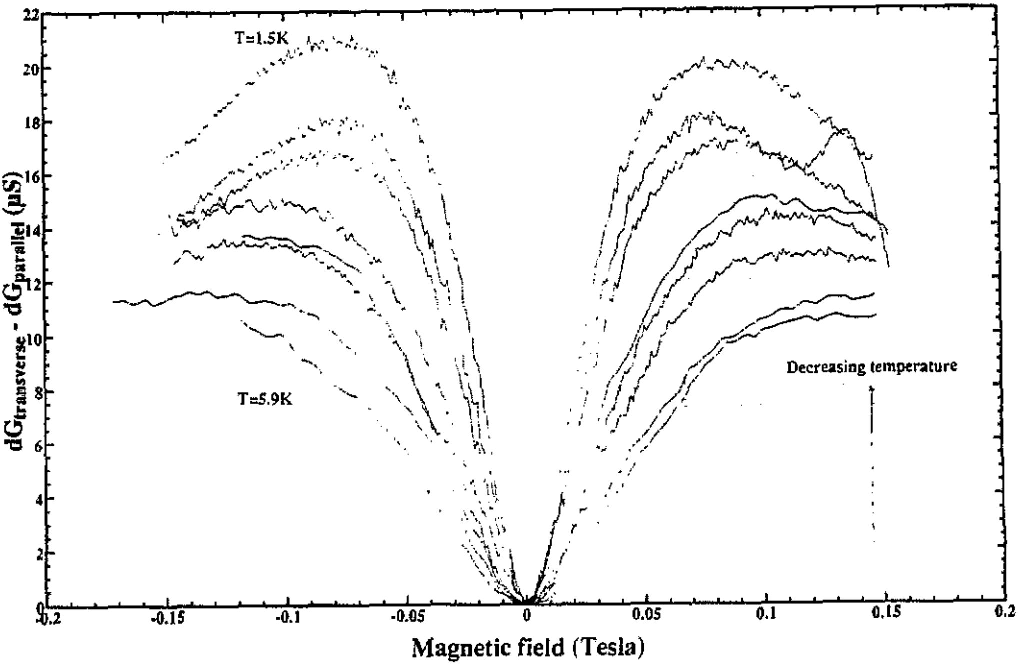

Figure 3. The magnetoconductance in the transverse field with the magnetoconductance in the parallel field subtracted. The negative magnetoresistance is solely due to the 2DEG.

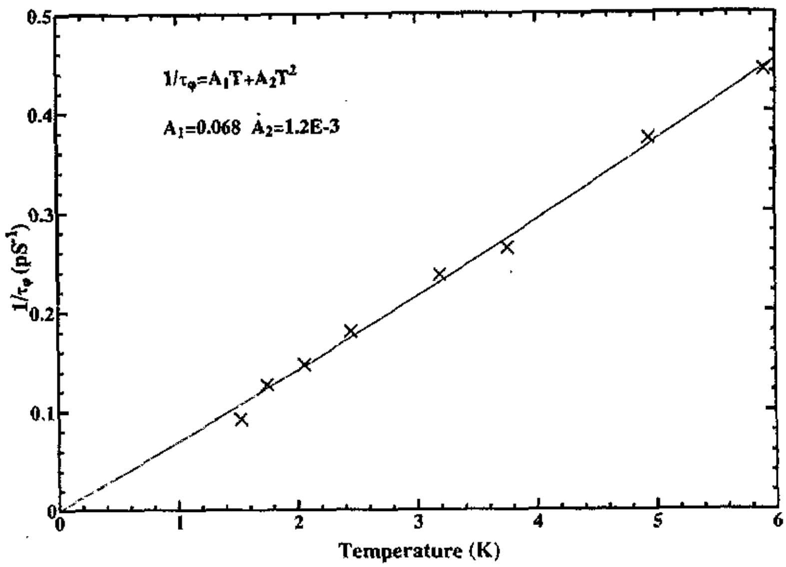

Figure 4. $1/\tau_\phi$ plotted against temperature. There is a linear relation between the two quantities, showing that the conduction is two-dimensional.

in a 2DEG by magnetic quenching of the weak localization, even when the conduction is complicated by parallel-conducting regions. There is reasonable agreement between the formula derived by Fukuyama (1984) and experiment, suggesting that the inelastic

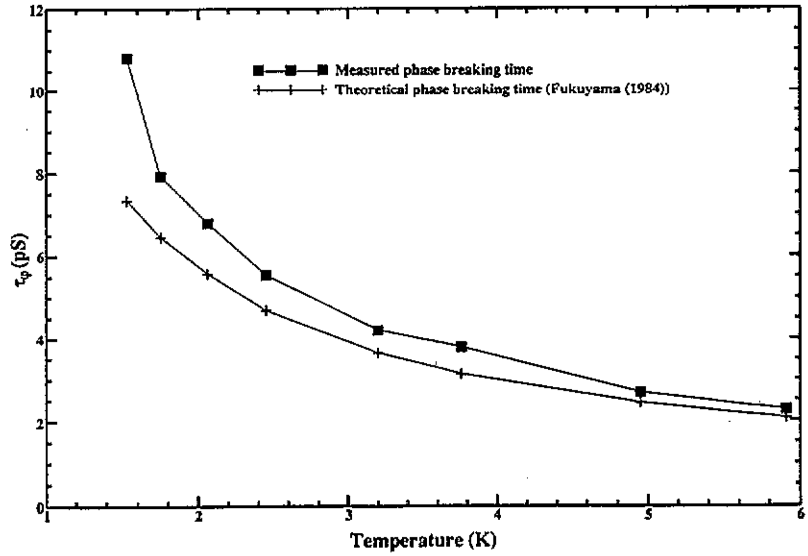

Figure 5. A comparison between the measured phase breaking times as a function of temperature and those predicted by Fukuyama (1984).

scattering mechanisms in a 2DEG in a ternary alloy such as $In_{0.53}Ga_{0.47}As$ are no different from those in other 2D systems such as GaAs/AlGaAs.

It is theoretically possible to use this technique to analyse more complicated wafers with three or more regions of parallel conduction, although other measurements such as *C–V* profiling would need to be undertaken to determine the carrier densities and thicknesses of the bulk conducting regions. Measuring the resistance of a sample in a parallel magnetic field is a useful method for determining the degree of bulk parallel conduction.

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