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LETTER TO THE EDITOR

Quantum interference and Landau level broadening in narrow GaAs–AlGaAs channels

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Abstract. High 2D electron mobility narrow Hall bars, 0.8 μm wide by 30 μm long, were fabricated in which, after photoexcitation, the scattering mean free path was up to 4.5 μm long at 1.3 K. The low field negative magnetoresistance arises from quantum interference (weak localization) with the flux cancellation mechanism [1] absent, even though the mean free path is much greater than the width. The Landau levels are significantly broadened, implying that a flat-bottomed model potential is inappropriate in this particular case. It is suggested that the potential fluctuations giving rise to the broadening are responsible for the absence of the flux cancellation, and when small angle scattering contributes to the elastic mean free path. The value of this length compared with the width is no longer a sufficient criterion for the determination of the nature of the magnetoresistance.

In this letter we discuss the electronic properties of GaAs–AlGaAs heterojunction samples in which the mean free path is larger than the width of the channel, but shorter than the length. This quasi-ballistic regime has previously been studied experimentally and theoretically by several authors, for example [2–5].

The initial processing of the heterojunction layers was performed using standard optical lithography. Small Hall bars 30 μm long by 0.8 μm wide were then defined by electron beam lithography in PMMA resist. The pattern was developed, and a shallow mesa etch [6] used to define the structures. The sample was reactively ion etched [7] in a plasma technology RIE80 machine using methane and hydrogen ions for two minutes with a $CH_4:H_2$ precursor ratio of 1:3. This just etched off the GaAs capping layer and 15–20 nm of the AlGaAs layer.

After processing, the channels did not conduct electrically in the dark, probably because the silicon donors were passivated with hydrogen, but illumination with a LED could excite carriers by the persistent photoconductivity effect. The resistance and carrier concentrations remained very stable for long periods; at 1.2 K the change was less than 0.5% over a 24 h period.

A number of samples were fabricated from two different wafers, C147 and C187 which, before processing, possessed mobility values of up to 170 $m^2\ V^{-1}\ s^{-1}$. Each sample was tested at around 20 different carrier densities, varied either by consecutive

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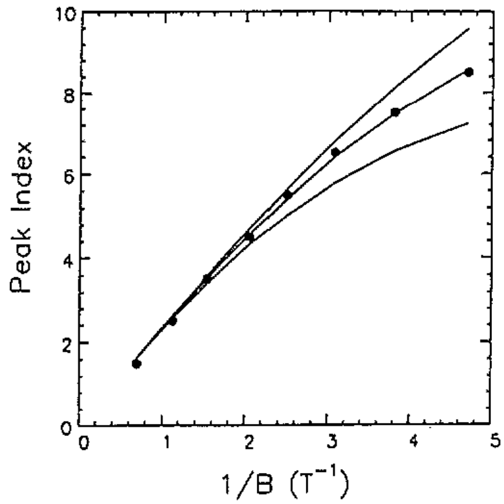

Figure 1. A graph of the peak index against $1/B$ (in reciprocal tesla) for a sample from wafer C187. The curvature of the graph gives the width. The central curve is a least squares fit, and the outer curves are for widths of 70% and 140% of the best fit width of 0.43 μm.

Table 1. Properties of some of the narrow structures tested.

Sample	Resistance (Ω) ±0.5%	Carrier density (10^{15} m^{-2}) ±2%	Width (μm) ±20%	Mobility (m^2 V^{-1} s^{-1}) ±20%
C147 #2	2700	5.6	0.75	14.4
C187 #1	771	2.23	0.8	136
C187 #1 (after cycling)	1175	2.8	0.8	71
C187 #2	12440	1.23	0.55	34
C187 #2 (after cycling)	2001	2.56	0.92	45
C187 #3	1540	2.72	0.7	63
C187 #4 (gate voltage = 0 V)	3750	2.4	0.65	30
C187 #4 (gate voltage = −0.35 V)	38400	1.4	0.28	5.0

illumination, or by the use of a gate. It was found that processing tended to reduce the mobility to between 25% and 70% of its original value indicating that, perhaps, an element of diffuse scattering emanates from the walls of the sample.

The major problem in the characterization of these samples is to obtain the width, which is required in order to calculate the aspect ratio. In turn this allows the calculation of the scattering times and mobility of the sample. The method used was to plot a graph of Shubnikov–de Haas peaks and trough indices against $1/B$ [8]. This gives a straight line in the 2D limit, but bends over for 1D samples at those low fields where the cyclotron radius becomes comparable to the width of the channel. In order to obtain an analytic form for the peak positions, a parabolic potential was assumed, which has been shown not to introduce significant inaccuracies [9]. An example fit is shown in figure 1.

The width obtained with the above procedure is stated in table 1 and is to be compared with the etched width of 0.8 ± 0.1 μm obtained using an electron microscope. At low carrier densities, the electrical width was roughly half the etched width, and increased with carrier concentration until the two widths were about the same. The results were also consistent with a width obtained from associating the minimum in the magnetoresistance curves at around 0.2 T with a cyclotron radius fitting in the channel.

For a narrow (quasi 1D) system with a 2D density of states, where the mean free path is much less than the width, Al'tshuler and Aronov [10] obtain for the total weak localization correction to the conductance g

$$\Delta g = -(e^2\sqrt{D}/\pi\hbar L)(1/\tau_\varphi + 1/\tau_B)^{-1/2} \tag{1}$$

with

$$\tau_B = 3L_B^4/DW^2 \tag{2}$$

where W is the width, D the diffusion constant, L the length, τ_φ the phase breaking time, τ the scattering time and the 2D magnetic length is given by $L_B = \sqrt{\hbar/eB}$.

The diffusion picture breaks down when the mean free path is longer than the width of the channel. The regime of specular scattering from the channel walls has only recently become experimentally accessible. Dugaev and Khmel'nitskii [11] first investigated theoretically the weak localization in a film, when the mean free path was longer than the thickness. Beenakker and van Houten [1] subsequently adapted the approach of [11] to the narrow channel case, and also computed the results for the intermediate case in which the width is of the same order of magnitude as the mean free path.

As pointed out by Dugaev and Khmel'nitskii [11], the main feature occurring, when the mean free path is much longer than the width, is a flux cancellation. The areas where the flux makes a positive contribution to the loop are cancelled out by areas which make a negative contribution. It is only the existence of impurity scattering that disturbs this exact cancellation. In the case of the narrow channel, when the mean free path $l \gg W$ Beenakker and van Houten [1] give as a replacement to τ_B in equation (2),

$$\tau_B = CL_B^4/W^3 v_F \tag{3}$$

where C is a constant roughly between 10 and 3, the exact value of which depends on the scattering mechanism and weakly on the field regime and v_F is the Fermi velocity.

In such channels, the phase breaking length can often be comparable to the mean free path, making it important that the cut-off for small loops is calculated correctly. Beenakker and van Houten include a factor in the calculation to ensure that the electron has to scatter at least once before its contribution to weak localization can begin. This gives

$$\Delta g = -(e^2\sqrt{D}/\pi\hbar L)[(1/\tau_\varphi + 1/\tau_B)^{-1/2} - (1/\tau_\varphi + 1/\tau_B + 1/\tau)^{-1/2}]. \tag{4}$$

Van Houten *et al* [3] demonstrated that both the original Al'tshuler and Aronov theory and the modified theory fitted acceptably to their data. However, the original theory required a value of the mean free path greater than the width to fit their data, which is out of the range of the validity of that theory. This contradiction was regarded as proof of the validity of the flux cancellation theory. Hiramoto *et al* [4] performed similar experiments on wires fabricated by ion beam implantation; they obtained similar fits for the Al'tshuler and Aronov and Beenakker and van Houten theories, but reject the former for the same reason as [3], i.e. that the fitted value of the mean free path exceeds the width.

In this letter, we present a direct test of the two theories in GaAs–AlGaAs heterojunctions. The mobility is sufficiently high that the flux cancellation should change the magnetic field required to quench weak localization by a factor of five. However,

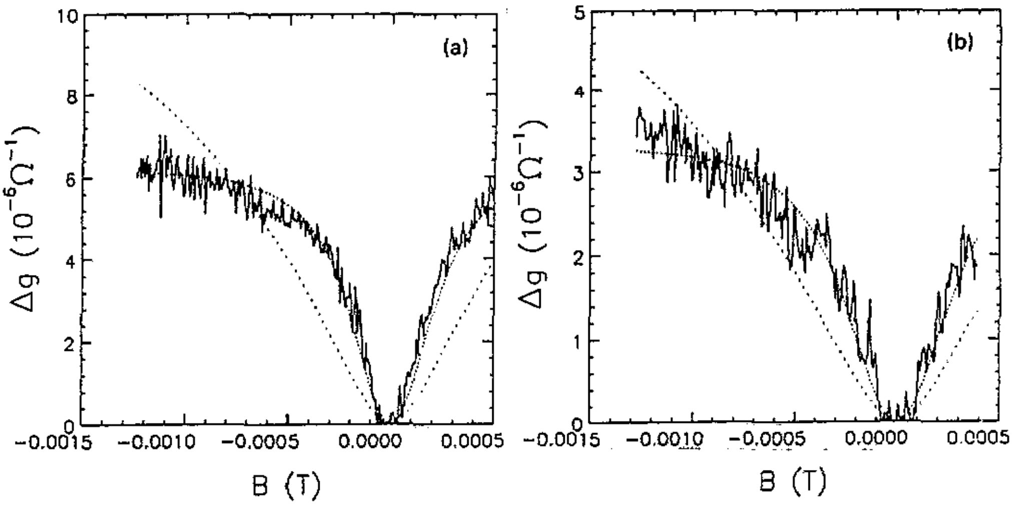

Figure 2. Low field magnetoresistance of sample C187 #1 (after cycling) at (a) 100 mK and (b) 800 mK. The fits are as follows: the dense dotted curve represents equation (1) and the spaced dotted curve representing equation (4).

Table 2. Dingle times.

Sample	Run	τ_D $(10^{-12}$ s) ±10%	τ $(10^{-12}$ s) ±20%
C187	2D control	0.32	46
C187 #2 (after cycling)		0.045	9.4
		0.064	12.3
		0.038	14.4
		0.042	14.4
		0.064	15.3
C187 #4 (application of gate voltage)	0 V	0.068	11.4
	−0.15 V	0.034	6.1
	−0.35 V	0.081	1.9

the results show that the field scale remains unchanged from the Al'tshuler and Aronov approach.

Figure 2 shows the low field magnetoresitance obtained in sample C187 No 1 (after cycling) at both 100 mK and 800 mK and the predictions of the two theories. The value of the mean free path was (4.5 ± 0.5) μm with a width of (0.8 ± 0.2) μm. The negative magnetoresistance shown is temperature dependent and saturates at about 5×10^{-4} T, characteristic of quantum interference. The agreement between experiment and equation (4) has τ_φ as the only variable parameter. The difference between the two theoretical predictions is the use of different formulae ((2) and (3)) for τ_B in terms of the magnetic field.

As can be seen, agreement is much better using the original formula, equation (1). Here it is possible to match with only one parameter both the curvature near the conductance minimum and the field at which the weak localization is roughly quenched, $\approx 5 \times 10^{-4}$ T. The flux cancellation formula (4) fails to do this. In this sample the flux cancellation mechanism does not occur, even though the mean free path, as obtained from the mobility, is much greater than the width.

In the samples with lower mobilities the distinction was less clear cut, figure 3. Both formulae gave acceptable agreement with the data. This is compatible with the results for samples of similar mobilities studied by the previously quoted authors. However, in view of the results reported in the previous paragraph it does not seem reasonable to exclude the original formula merely because the mean free path remains twice as long as the width.

The most likely reason for the failure of flux cancellation is small angle scattering, which destroys flux cancellation without affecting the measured mean free path. The mechanism of the cancellation arises because a closed path results in the equal areas producing equal but opposite phase changes. The presence of small angle scattering will remove this effect, particularly as the principal contribution to the magnetoresistance comes from electron trajectories which are at grazing incidence to the channel edge. Essentially, the effect arises because the sharp difference in approach between [10] and [1] and [11] is not found in practice. Small angle scattering reduces the diffuse scattering mean free path by a small amount as measured by the mobility, but by a much larger amount as measured by the Shubnikov–de Haas effect and the negative magnetoresistance. The exact small angle scattering time is difficult to measure, because the envelope of the Shubnikov–de Haas oscillations does not give this time in narrow samples, as discussed below. However, the small angle scattering time in the original wafer can be measured from a fit to the envelope of Shubnikov–de Haas oscillations and gives a characteristic time $\tau_{sa} = 3.3 \times 10^{-13}$ s. This corresponds to a mean free path of 4.6×10^{-8} m, ten times less than the width of the device. Therefore, the amount of small angle scattering is large.

It is now necessary to consider the modifications required to theory in this new regime. The scattering time introduced remains the momentum scattering time, τ, because it represents the typical time of the first back-scattering event, which is necessary for quantum interference. Similarly the value of D is that calculated from the conductivity, again because it is the back-scattering events that cause the loops needed for quantum interference. Therefore, if τ and D are interpreted in the original fashion, the Al'tshuler and Aronov formula remains unchanged, even when the mean free path is much greater than the width. When the momentum scattering time is less, then the number of diffusion loops decrease, and the flux cancellation formula will give a better agreement with experiment as we (figure 2), and others, have found, [3, 4].

The magnitude of Shubnikov de Haas oscillations depends on the broadening of the Landau levels [12, 13]. This broadening may be described by a Dingle scattering time τ_D which is not the same as the momentum scattering time in modulation doped heterostructures. The size of this broadening can be found by a fit to the envelope of the Shubnikov–de Haas oscillations, using a 2D formula because the cyclotron radius is much smaller than the width. This formula gives [12]

$$\rho_{xx} \propto \exp(-\pi/\omega_c \tau_D) \tag{5}$$

An example fit of the Shubnikov–de Haas oscillations to equation (5) is shown in figure 4, the oscillation amplitude does fit this simple formula, implying that the broadening of the Landau levels can be described by a single parameter, which is not dependent on the field. Results from two samples are shown in table 2, the measured Dingle time was

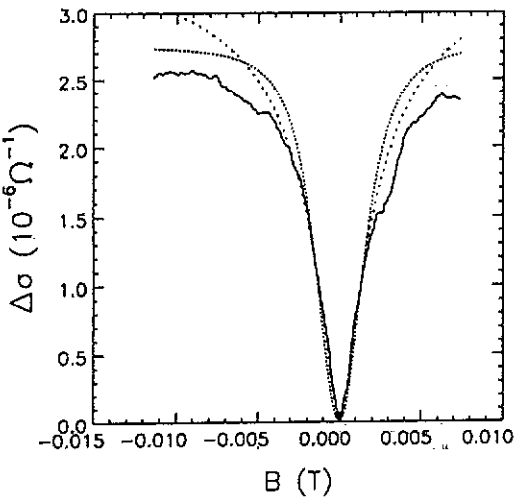

Figure 3. The low field magnetoresistance exhibited by a sample from C187 with mean free path of ~1 μm which is comparable with the width. The close spaced dotted curve is the fit with equation (1) and the spaced dotted curve is with equation (4).

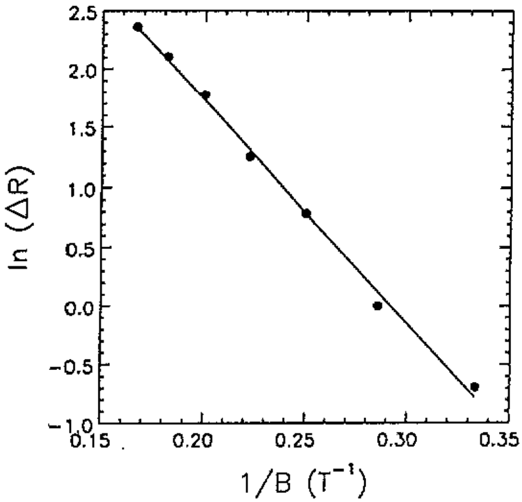

Figure 4. Dingle plot and fit to equation (5) for sample C187 #2 at 1.4 K.

always between five and ten times lower than in the original wafer. This means that Landau level broadening has been significantly increased by the fabrication of the narrow channel.

The obvious explanation of this effect is that the number of scatterers has increased because of the fabrication process. However, the transport scattering time varies strongly in the same sample when the carrier density changes, and if the Landau level broadening was due to scatterers it should follow the scattering rate as the carrier density changes.

The most likely explanation for the increase in broadening is a non-constant carrier density across the channel. If the channel has a parabolic shape rather than a flat bottom the Fermi level can lie between Landau levels at the edge of the channel but pass through them in the centre of the channel, meaning that the Landau levels are broadened. Such a rounded channel interpretation is supported by the results shown in table 1. It follows that increasing the carrier density in a sample increases the measured width.

Of course, this effect can also be expressed using a more rigorous magneto-electric sub-band picture [2, 8, 14]. In this picture the effective potential depends on the centre coordinate, which in turn depends on the wavevector associated with quasi-momentum along the channel. In the high field picture where Shubnikov–de Haas oscillations occur, the effective potential is dominated by the parabolic magnetic field dependent part, added to the potential of the channel. Since the Fermi surface is constant across the channel, the varying channel potential will mean that the Fermi level will pass through the middle of some Landau-like levels, and between others, giving rise to the broadening.

We have extracted the phase coherence length from the result of figure 2 as a function of temperature. The best fit was to Nyquist behaviour in 1D previously observed in narrow Si channels [15] and theoretically predicted [16], figure 5. In the middle of the

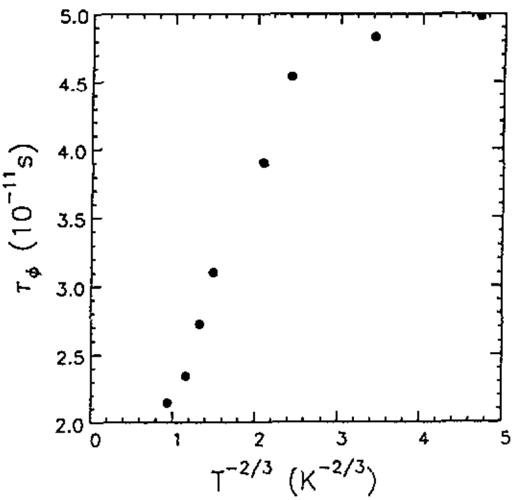

Figure 5. The phase coherence time τ_ϕ is plotted against $T^{-2/3}$, obtained from the sample used for the experiments of figure 3.

temperature range agreement with the predicted $T^{-2/3}$ behaviour of τ_φ is reasonable, as is the absolute value of τ_φ. The fit breaks down when L_φ approaches the elastic length, and for temperatures below 0.5 K the temperature dependence decreases. However, as the elastic scattering time τ is now less than $\hbar/kT$ we expect the lifetime broadening to invalidate the predicted behaviour.

To summarize, high mobility GaAs–AlGaAs heterostructures were fabricated into Hall bars of width 0.8 μm and length 30 μm by shallow mesa etching. The low field magnetoresistance was measured at 4.2 K and shown to be due to quantum interference (weak localization). The high mobility permits a direct check of the flux cancellation mechanism [1] against the standard result [10]. We find agreement only with the Al'tshuler and Aronov mechanism [10], because the large amount of small angle scattering eliminates the flux cancelling mechanism even though the mean free path for elastic scattering exceeds the sample width. This indicates that the magnitude of the elastic mean free path is not a sufficient criterion for the production of the mechanism of negative magnetoresistance. The broadening of the Landau levels was measured and shown to be consistent with a rounded channel. This suggests that screening was significantly reduced compared with that of the low magnetic field case where a flat bottomed channel is expected [4]. It is possible that the small diffuse component of surface scattering is significant [18] in this context.

Acknowledgments

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