Magnetoresistance of narrow GaAs-(Al,Ga)As heterostructures in the quasi-ballistic regime

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On a étudié expériméntalement la magnétorésistance en champ faible de gaz d'électrons quasi unidimensionnels dans des hétérostructures GaAs-(Al,Ga)As limitées latéralement. À basse température, les effets de taille classiques et quantiques sont importants ainsi que les effets quantiques d'interférences sur la conductivité. On a fait les expériences en régime de haute mobilité électronique, caractérisé par un libre parcours moyen élastique plus grand que la largeur de l'échantillon, mais beaucoup plus petit que sa longueur. Dans ce régime quasi balistique, le transport est balistique sur la largeur et se fait par diffusion sur la longueur. On discute les résultats expérimentaux dans le cadre des théories existantes pour ce régime.

An experimental study of the low field magnetoresistance of quasi-one dimensional electron gas channels in laterally restricted GaAs-(Al,Ga)As heterostructures is presented. At low temperatures classical and quantum mechanical size effects are important, along with quantum interference effects on the conductivity. The experiments are performed in a high mobility regime characterized by an elastic mean free path larger than the sample width, but much smaller than its length. In this quasi-ballistic regime the transport is ballistic over the width but diffusive over the length. The experimental data are discussed in relation to the available theories for this regime.

STUDIES of low temperature electronic transport in a laterally constricted two dimensional electron gas show a variety of interesting magnetoresistance effects associated with the quasi-one dimensional character of the system [1]. The effective dimensionality of a specific structure depends on the phenomenon under study, since each effect is governed by different characteristic length scales. These are the mean free path $l = v_f \tau$ (with $v_f$ the Fermi velocity and $\tau$ the mean time between (elastic) collisions), the phase coherence length $l_p = (D\tau_p)^{1/2}$ (with $D$ the diffusion constant, and $\tau_p$ the phase coherence time), the thermal diffusion length $l_T = (\pi^2 \rho)/(kT)$ and the Fermi wavelength $\lambda_F = (2\pi n_e)^{1/2}$ (with $n_e$ the sheet carrier concentration). A magnetic field introduces two additional effective length scales into the problem. Firstly, the electron trajectories become curved with the classical cyclotron orbit radius $l_{cyc} = m^* v_f/(eB)$, with $m^*$ the electron effective mass. Secondly, the effect of the field on the phase of the electron wave function is characterized by the magnetic length $l_B = [\hbar/(eB)]^{1/2}$. The magnetic field can thus serve as a probe for the length scales relevant for the effect under study.

Due to the high mobility attainable in narrow GaAs-(Al,Ga)As heterostructures the quantum interference effects such as one-dimensional weak localization and universal conductance fluctuations [2-13] are relatively large, since the characteristic diffusion lengths $l_d$ and $l_\tau$ are long (of the order of 1 μm). The same holds for the quantum corrections associated with electron-electron interactions. Traditionally, one dimensional localization and interaction have been studied in evaporated metal wires or narrow silicon MOSFETs, where the mean free path is short. The existing theoretical framework [1] is derived for this dirty metal regime, and is not directly applicable to the pure metal regime of high mobility GaAs-(Al,Ga)As heterostructures, where the mean free path can exceed the sample width.
In this paper we describe the quasi-ballistic regime defined as $W < l_c < L$ with $W$ the channel width and $L$ the channel length. In this regime the electrons move ballistically between the channel boundaries, but the transport is still diffusive on the length scale $L$. The nature of the boundary scattering will affect the diffusion constant and the various magnetoresistance effects. For simplicity we will only consider the limiting cases of diffuse and specular boundary scattering. In the quasi-ballistic regime quantum mechanical and classical size effects are both important. To study these effects we will treat the electron motion semiclassically. The validity of this approach is limited to channels wide compared to $\lambda_e$ (several one dimensional subbands occupied). A study by K.K. Choi et al. [14] on wider structures down to a width of 1.1 $\mu$m has shown the onset of the quasi-ballistic size regime, while G. Timp et al. [6] and M.L. Roukes et al. [7] in recent studies have focused on narrower samples with even higher mobility, which in some sense behave as an electron waveguide. It should be pointed out that the theoretical framework for the magnetoresistance effects in the regime under study is still incomplete, so that in some cases only a qualitative discussion of the data is possible.

Two classes of magnetoresistance effects can be distinguished. Classically a magnetic field deflects the electron trajectories between impurity collisions (over an angle $\omega_c \tau_c$ with $\omega_c = eB/m^*$ the cyclotron frequency). In a homogeneous degenerate electron gas characterized by a single mobility $\mu$ this does not cause any magnetoresistance, since the Hall field ensures that there is no lateral drift of the electrons. In the quasi-ballistic regime this situation is modified by boundary scattering. In the specular case a negative magnetoresistance is observed, presumably due to the occurrence of skipping orbits [14].

Quantum Mechanically, a weak magnetic field introduces a phase shift in the electron wavefunction, depending on the electron path. A phase shift of order unity occurs for a trajectory if it encloses an area $l_b$, with $l_b$ the magnetic length. This affects the quantum interference corrections to the conductivity in the following way. A first quantum effect is weak localization, which is caused by constructive interference of electrons which are back-scattered after multiple elastic scattering from randomly distributed impurities. The resistivity is enhanced because of this effect. In a magnetic field trajectories enclosing a large area acquire a large phase shift. Such trajectories will, on the average, no longer contribute to the weak localization. Upon increasing the magnetic field the number of contributing trajectories will thus decrease monotonically, leading to a negative magnetoresistance. In the quasi-ballistic regime boundary scattering induces flux cancellation [13, 15], and therefore a larger field is needed to suppress weak localization. This effect is illustrated in figure 1. Also, if the mean free path is not negligibly small compared to the phase coherence length, the non-diffusive motion of the electrons on length scales short compared to the elastic length becomes important.

A second quantum interference effect is the occurrence of reproducible but aperiodic fluctuations in the magnetoresistance, so called universal conductance fluctuations [16-18]. These fluctuations are seen in samples which are so small that their conductance is not simply determined by the average impurity concentration. Instead the specific distribution of the impurities over the sample is important. The fluctuations are associated with interference of the electrons moving in the random impurity potential. Even though the pattern of magnetoresistance fluctuations is sample specific, a correlation function can be extracted from the data, and this function can be compared with theoretical calculations for the ensemble average. The magnitude of the fluctuations is characterized by a variance, and the typical field scale on which they occur by a correlation field. The variance of these fluctuations has a universal value at absolute zero (at least if $L > l_c$), while at finite temperature the magnitude is reduced due to averaging and thermal smearing effects. The correlation field of the fluctuations is modified by boundary scattering in a similar way as in weak localization. Again the non-diffusive motion of the electrons on short length scales may become of importance.

A third quantum effect is the correction to the conductivity associated with electron-electron interactions. As shown by A. Houghton et al. [19] the electron-electron interaction effects on the conductivity lead to a parabolic magnetoresistance at higher fields due to the curvature of the electron trajectories. As noted by K.K. Choi et al. [14] as a consequence of boundary scattering the curvature effects will be partially suppressed in narrow channels. At present no theory for this regime is available.

At fields high enough that $\omega_c \tau > 1$ and $\hbar \omega_c > kT$ the electrons condense into Landau levels, and Shubnikov-de Haas oscillations appear in the magnetoresis-
tance. For narrow channels \((W<2L_{\text{cycl}})\) hybrid magneto-electric subbands develop due to the lateral confinement of the electrons. The oscillations in this case show deviations from a \(1/B\) periodicity. As described in detail by K.F. Berggren et al. [12, 20, 21] an analysis of this effect yields information about effective channel width and sheet carrier concentration.

We have performed an experimental study of the weak field magnetoresistance at low temperatures in GaAs-(Al,Ga)As heterostructures with effective channel widths \(W\) down to 100 nm. In earlier work [2, 9, 10, 13] we have focused on several aspects of the various magnetoresistance effects in a sample with \(W\sim 110\) nm. It is the purpose of this paper to contrast the quite different behavior of the magnetoresistance of two samples with \(W\sim 0.1\) and 1.1 \(\mu\)m, and to give an overview of the great variety of magnetoresistance effects in narrow structures.

The outline of this paper is as follows. Firstly the theoretical background is outlined and the different experimental regimes are defined. Then the samples are described and the experimental results are presented. Finally a discussion of the results and concluding remarks are given.

THEORETICAL BACKGROUND

Classical effects

The classical Drude conductivity of a degenerate 2-dimensional electron gas is given by

\[
\sigma_0 = n_e e^2 \tau_e / m^* = n_e e \mu,
\]

with \(n_e\) the sheet carrier concentration, \(\mu = e \tau_e / m^*\) the mobility and \(m^* = 0.067 m_c\) the electron effective mass. Using the Einstein relation between mobility and diffusion constant this can be written as

\[
\sigma_0 = N(E_F) e^2 D, \quad N(E_F) = m^* / (\pi^2 k_F^2)
\]

the density of states at the Fermi energy (for spin degeneracy 2, and no valley degeneracy). The diffusion constant in the absence of boundary scattering effects is

\[
D = \nu_0 \tau_e / \tau_c / 2.
\]

Specular boundary scattering does not change \(D\) from this bulk value since the electron momentum along the channel is conserved. Diffuse boundary scattering randomizes the electron momentum along the channel, leading to a reduced diffusion constant given by [13]:

\[
D = \frac{1}{2} \nu_0 \tau_e \left[ 1 - \frac{4L}{\pi W} \int_0^1 s(1-s)^{\nu_0} \left( 1 - \exp \left( \frac{W}{s\tau_c} \right) \right) ds \right].
\]

Quantum mechanical effects

At low temperatures the classical conductivity is dominated by elastic scattering on stationary impurities. The phase coherence of the electron waves is not disturbed by such scattering events, although the phase is shifted. Inelastic scattering, on the other hand, is an example of a phase coherence limiting mechanism, setting the length scale \(l_p\). Weak localization is a consequence of constructive interference between time reversed pairs of coherently backscattered electron waves. The total backscattering probability is thereby enhanced and the conductivity is accordingly reduced. If \(L > l_p > W\) this effect has a 1-dimen-
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1. Introduction

Quantum interference also gives rise to aperiodic magnetoresistance fluctuations in small samples. At $T=0$ the amplitude of these fluctuations is independent of channel length or degree of disorder, as shown by B.L. Al'tshuler, P.A. Lee and A.D. Stone [16-18].

The electron-electron interactions $\mathcal{g}^e = (\hbar D/(kT))^2$ are a factor $\pi$ larger than in the classical Drude theory of this effect has recently been reviewed [1]. A third quantum correction to the classical Drude result for the conductivity at low temperatures is due to the effect of electron-electron interactions.

The theory of this effect has recently been reviewed [1]. A discussion in relation to experiments on narrow GaAs-(Al,Ga)As heterostructures has been given by K.K. Choi et al. [14]. Under conditions also valid in our experiment the electron-electron interactions give rise to a magnetic field independent conductivity correction.* In the 1-dimensional regime $L > h > W$ this correction is given by:

$$\delta G_{ee} = -g_{10} e^2 h/(2^{1/2} \pi \hbar L).$$

Here $g_{10}$ is an effective interaction parameter theoretically predicted to be about 1.3 [14] for 1D-channels. The contribution of the electron-electron interactions to the conductance has a $T^{-1/2}$ dependence since $h \equiv (\hbar D/(kT))^{1/2}$. The electron-electron interactions

* In the low field range where we study weak localization the magnetoresistance is an orbital effect and quantum corrections from electron-electron interactions contribute only via the so-called Cooper channel [1]. Relative to the weak localization contribution this is of the order $[1+(\Delta B)^2/2]^{-1/2} \sim \rho/(\hbar T_\Phi)^{1/2}$, where $T_\Phi$ is the Fermi temperature and the coupling constant $\Delta$ is of order unity for GaAs [14]. For sample B ($f = 105 K, T = 4 K$) $\rho/(\hbar T_\Phi) = 1.5 K$ this would be a 10% correction, which is ignored. At much higher fields where spin splitting plays a role other field dependencies related to electron-electron interactions are introduced. However at these high fields the weak localization is already completely suppressed.

** Note that in [14] $h$ has been defined a factor $\pi$ larger than in this paper.

2. Theory

The conductance fluctuations are characterized by the correlation function:

$$F(\Delta B) = \langle G(B)G(B+\Delta B) \rangle - \langle G(B) \rangle \langle G(B+\Delta B) \rangle,$$

where the brackets denote an ensemble average over different impurity configurations. Two characteristic quantities are the variance of the fluctuations $F(0)$ and the correlation field $\Delta B_c$ defined by $F(\Delta B) = F(0)/2$. At finite temperatures the magnitude of the fluctuations is reduced as a consequence of averaging (if $L < L_c$) and thermal smearing (if $h < h_c$). In the regime $\tau_e < \tau_\Phi$ and $W < L_c < L$ the variance is given by [26]:

$$F(0) = 6 \left(2/\pi \hbar \right)^2 \left(\frac{9}{2} \right)^{1/2} \left[1 + \frac{9}{2} \pi \frac{L_c}{\ell_1} \right]^{-1}.$$
do not have any effect on $\sigma_\lambda$. Admixture of classical curvature of the electron trajectories and the field independent conductivity correction $\delta G_{\text{ee}}$ leads upon matrix inversion to a parabolic negative magnetoresistance [19]:

$$R(B) = G_0^{-1} + [(\alpha_{\text{c}} E)^2 - 1] \delta G_{\text{ee}}/(G_0).$$  (9)

Equation (9) assumes that the electron-electron interaction correction to the conductivity is small, which is not necessarily the case for narrow channels at low temperatures. A further complication arises when boundary scattering is present, because equation (9) is based on the curvature of the electron trajectories in the bulk of the electron gas. This effect is therefore expected to be suppressed for narrow channels until the magnetic field is high enough for the electrons to be able to complete a cyclotron orbit ($2l_{\text{cyl}} < W$).

### EXPERIMENTAL RESULTS

#### Samples

The samples have been fabricated on moderately high mobility (10 m$^2$·V$^{-1}$·s$^{-1}$) at low temperatures) GaAs-(Al,Ga)As heterostructure material, grown by metal-organic chemical vapor deposition ($x = 0.35$). The sheet carrier concentration in this material (when cooled in the dark) was $5 \times 10^{15}$ m$^{-2}$. The fabrication technology is illustrated in figure 2. Long, narrow channels connecting broad 2-dimensional electron

![Fig. 2. Main fabrication steps for the shallow mesa etch definition of the narrow electron gas channel in a GaAs-(Al,Ga)As heterostructure.](image-url)

The Al$_2$O$_3$ pattern, which serves as etch mask during subsequent anisotropic etching (Reactive Ion Etching, RIE), is defined by electron beam lithography.
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Fig. 3. Schematic cross section of the shallow mesa etched GaAs-(Al,Ga)As heterostructure (a) and layout of the devices (b).

A series of samples with lithographic width between 8 μm and 0.5 μm have been studied. In this paper we will focus on two samples: samples A with lithographic width 1.5 μm and sample B with lithographic width 0.5 μm. Both channels are 10 μm long. The elastic mean free path in the wide regions is \( l > 1 \mu m \).

As we will show below, sample A is slightly wider than \( l \), while sample B is fully in the quasi-ballistic regime. The magnetoresistance of both samples is qualitatively quite different. We will first give an overview of the results, and subsequently we will give a detailed discussion.

In order to get some feeling for the influence of the channel width on the transport properties we have plotted in figure 4 the channel resistance, multiplied by \( W^{\text{inh}}/L \). For comparison the resistivity of a wide channel is also plotted. It is clear from figure 4 that the \( \text{real} \) channel width in the case of narrow channels is smaller than the lithographic width. This is confirmed by the fact that channels with \( W^{\text{inh}} \) smaller than about 400 nm turned out to be insulating. The lateral depletion width for our fabrication process is thus about 200 nm on each side of the channel. (According to M.L. Roukes et al. [7] it is possible to reduce this effect by optimizing the etch depth). It should be noted that even in the simple case of specular scattering (which will be shown to apply to our samples) the mobility of the narrow electron gas channels depends on the channel width in an indirect way: the sheet carrier concentration diminishes on reducing the width. The mobility in heterostructures at low temperatures is dominated by ionized impurity scattering. In these systems the mobility is known to be proportional to \( n^{3/2} \). In table I it is shown for the channels studied that the ratio of \( \mu \) and \( n^{3/2} \) is indeed nearly constant. It can thus be concluded that the mobility in our samples is not significantly degraded in the course of the microfabrication process [1]. We will return to the problem of determining the real channel width later. The large resistance rise at low temperatures for sample B is related to quasi-one dimensional weak localization and electron-electron interaction effects. Part of the resistance increase on lowering the channel width is related to the lower value for \( n \) and thus for \( \mu \). We note that the sheet carrier concentration varies.

\* The same conclusion was reached by H Z Zheng et al [4] in their study of narrow channels defined by a split-gate technique.

![Fig. 3. Schematic cross section of the shallow mesa etched GaAs-(Al,Ga)As heterostructure (a) and layout of the devices (b).](image)

![Fig. 4. Temperature dependence of the channel resistance \( R \) (multiplied by \( W^{\text{inh}}/L \)) for sample A (●), sample B (▲) and for a wide channel (●).](image)

From [2]
somewhat (up to 20 %) each time the sample is cooled down from room temperature. This should be kept in mind if different data-sets for the same sample are to be compared. No drift has been observed if the samples were kept at low temperatures, however.

In figure 5 and 6 the magnetoresistance for samples A and B are shown in the temperature region between 4 K and 28 K. The behavior of sample A, which has a lithographic width of 1.5 μι, is similar to the results reported by K.K. Choi et al. [14] for a sample with \( W^{\text{inh}} = 1.9 \) μι, \( L = 6.2 \) μι. A practically temperature independent negative magnetoresistance is observed around \( B = 0 \) T. We attribute this to the classical skipping orbit effect of [14]. For higher fields a parabolic temperature dependent negative magnetoresistance occurs as predicted by equation (9), and the onset of Shubnikov-de Haas oscillations is seen. On increasing the temperature this negative magnetoresistance is reduced, and eventually a positive magnetoresistance is seen at high temperatures.

The magnetoresistance of the narrower sample B (fig. 6) looks very different. This behavior arises because the quantum mechanical corrections to the conductivity are much larger in this sample, while the classical skipping orbit effect occurs at a much higher field scale, so that it can only be seen clearly at higher temperatures where the quantum mechanical effects are suppressed. A pronounced, temperature dependent, negative magnetoresistance peak is seen around \( B = 0 \) T, which we attribute to weak localization in the quasi-ballistic regime. The temperature dependent parabolic negative magnetoresistance seen at higher fields in sample A appears to be suppressed in the narrow channel B. Large aperiodic fluctuations in the magnetoresistance occur at lower temperatures, while Shubnikov-de Haas oscillations begin to appear around 1 T (see p. 36). All magnetoresistance effects in the present field range are caused by the orbital movement of the electrons in the plane of the original 2-dimensional electron gas. This is illustrated in figure 7, where the angular dependence of the magnetoresistance is shown for this sample (the conductance fluctuations follow a different pattern than in figure 5 because the sample had been cycled to 293 K). The minima of the fluctuations shift with \( \cos \theta \) (not shown), which confirms again that they are sensitive to the perpendicular component of the field only. We now turn to a more detailed discussion of the various phenomena.

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### TABLE I

Parameters for a wide channel and for samples A and B.

<table>
<thead>
<tr>
<th>sample</th>
<th>( W^{\text{inh}} ) (μι)</th>
<th>( W ) (μι)</th>
<th>( n_0 ) ( \times 10^3 ) (m(^{-2}))</th>
<th>( \mu ) (m(^2)V(^{-1})s(^{-1}))</th>
<th>( \mu/\hbar^{2} ) ( \times 10^{-23} ) m(^5)V(^{-1})s(^{-1})</th>
<th>( l_0 ) (μι)</th>
<th>( l_1 ) (1 K) (μι)</th>
<th>( h ) (1 K) (μι)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide</td>
<td>4.0</td>
<td>10</td>
<td>3.9</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1.5</td>
<td>11</td>
<td>3.6</td>
<td>7.5</td>
<td>3.5</td>
<td>0.74</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>0.12</td>
<td>2.5</td>
<td>4</td>
<td>3.2</td>
<td>0.36</td>
<td>0.87</td>
<td>0.54</td>
</tr>
</tbody>
</table>

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**Fig. 5.** Magnetoresistance for sample A. The inset shows reproducible fluctuations at 4 K.

**Fig. 6.** Magnetoresistance for sample B.

From [2]
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Fig. 7. Angular dependence of the magnetoresistance for sample B at 4 K
From [9]

Classical skipping orbit effect

The temperature independent negative magnetoresistance seen in figure 5 for sample A has a half-width at a field ~0.2 T and in figure 6 for sample B at ~1 T. This is consistent with the classical skipping orbit effect discussed p. 29. The interpretation leads to values for the respective channel widths of 1.0 μm and 0.15 μm. These values are in reasonable agreement with other estimates (see table I).

Weak localization

We have measured the negative weak field (B<0.2 T) magnetoresistance for sample B for temperatures between 100 mK and 14.3 K. Representative data between 4 K and 14 K are plotted in terms of conductance in figure 8. The observed effect is clearly a 1-dimensional weak localization effect, since the 2-D weak localization theory would predict a saturation of the effect if the magnetic length \( l_B = \left( \frac{\hbar}{eB} \right)^{1/2} \) becomes comparable to \( l_c \), which implies much lower saturation fields than the typically observed fields of 0.2 T. Although the AA-theory (see p. 29) for 1-D weak localization fits our data well, this analysis is inconsistent since the resulting parameter values (\( W \sim 60 \text{ nm}, l_c \sim 600 \text{ nm} \)) violate the criterion \( l_c \ll W \) for its applicability.

The data are analyzed in terms of the equations given pp. 30-31 [10]. The electron gas density in the narrow channel is estimated to be \( 2.5 \times 10^{10} \text{ m}^{-2} \) (see p. 36). Two of the three unknown parameters (\( W, \tau_0 \) and \( \tau_e \)) can be eliminated using estimated values for the classical conductance \( G_0 = \left( \frac{\pi e^2}{eB} \right) \left( \frac{W}{L} \right) D = 18 \times 10^{-6} \text{ S} \), as obtained from extrapolation of a plot of \( G(0) \) versus \( T^{-1/2} \), see figure 11) and for the saturation value of the magnetoconductance:

\[
G(\infty) - G(0) = \frac{e^2}{\pi \hbar} \frac{D^{1/2}}{L} \left( \frac{1}{\tau_p} + \frac{1}{\tau_e} \right)^{-1/2}.
\]

(12)

The third parameter is obtained by a fit, considering only data points for which \( l_0 \gg W \) (see p. 30). This procedure was followed for the 4.0 K data, for which we estimate \( G(\infty) \sim 13.9 \times 10^{-6} \text{ S} \). Despite the uncertainties in \( G(\infty) \) we did not perform a two or three parameter fit, because of the limited field range \( l_0 \) available for the fit. For fits to the data at other temperatures the values for \( W \) and \( l_c \) were kept fixed. As shown in figure 9, for specular scattering a reasonable fit is obtained with \( W = 106 \text{ nm}, l_e = 351 \text{ nm} \). (An assumption of diffuse scattering does not work since it leads to values for \( l_e \) much larger than in wide 2DEG regions, which is evidently unreasonable). We will refrain from a detailed discussion of the values for \( l_0 \) given in figure 9, since in view of the uncertainties in the modelling of the short time behavior (in equation (2)) these values may not be very accurate. Finally, we remark that at millikelvin temperatures the weak localization effect (and also corrections to the conductivity due to electron-electron interactions) are so large that they are no longer a small correction to the Drude conductivity. The
Fig. 9. Magnetoresistance data between 500 mK and 143 K for sample B
The solid curves result from the theory for weak localization in the quasiballistic regime with specular boundary scattering

From [10]

A: T=0.5 K, \( \xi = 1.038 \) nm , B: T=0.7 K, \( \xi = 970 \) nm , C: T=1 K, \( \xi = 869 \) nm , D: T=4 K, \( \xi = 450 \) nm , E: T=5.9 K, \( \xi = 375 \) nm , F: T=10 K, \( \xi = 243 \) nm , G: T=14.3 K, \( \xi = 213 \) nm

various conductivity corrections presumably are no longer additive in this case (see equation (13) and also figure 11). This may be the reason that at temperatures below 200 mK a saturation is found of the values for \( \xi \) obtained from the weak localization in the present analysis.

Universal conductance fluctuations

We now turn to the fluctuations observed in the magnetoresistance at lower fields (see figures 5 and 6). As expected from the UCF theory the oscillations in sample A are smaller than those in sample B, and they occur on a smaller typical field scale, as a consequence of the larger width. (The width ratio of about 10 roughly corresponds to the field scale ratio; cf. equation (7)). We will limit the quantitative discussion to sample B [26]. For a comparison with the theoretical predictions the correlation field and variance have to be extracted from the data. Under the usual ergodic hypothesis [18] the average over impurity configurations in equation (5) is replaced by an average over \( B \) after a correction for a constant trend which would give rise to spurious correlations. In figure 10 the resulting correlation function for a magnetoconductance trace at 2.4 K is shown. We find \( F=1.9 \times 10^{-4} \) \([\pi^2/(2\pi)^2]^-2\) and \( \Delta B_c=0.05 \) T, with an estimated error of 30%. From equation (6), with an estimated value for \( \xi \), we thus find \( \xi \sim 500 \) nm, which compares reasonably well with the weak localization result (600 nm). The predicted \( \Delta B_c \), however, is a factor of two higher than the measured quantity. This discrepancy seems rather large to attribute entirely to uncertainties in \( \xi \).

More likely, the reason that the correlation field turns out smaller than predicted is that, as we increase the field increment \( \Delta B \), more and more electrons lose phase coherence before entering the regime of diffusive motion. This breakdown of coherent diffusion is beyond the UCF theory, but it certainly plays a role in systems where \( \xi \) is of the order of the elastic scattering time. The effect of flux cancellation on the correlation field [25] can be studied without these complications in systems with \( \xi > W \) but \( \xi > \tau_e \).

Electron-electron interaction effects

The zero field conductance is given by:

\[
G(0) = G_0 + \delta G_{\text{loc}} + \delta G_{\text{ee}}. \tag{13}
\]

The negative localization and electron-electron interaction corrections have been given in equations (2) and (8). Once \( \delta G_{\text{loc}} \) is known, \( \delta G_{\text{ee}} \) follows from equation (13). This is illustrated for sample B in figure 11 (only low temperature data points are considered for which the short time corrections in the weak localization analysis are relatively unimportant). The resulting values for \( \delta G_{\text{ee}} \) are seen to be proportional to \( T^{-1/2} \), as predicted by equation (8), while they also extrapolate to the correct value for \( G_0 \). If we use \( D=0.039 \) m² s⁻¹ we find from the slope \( r_{10}=1.5 \), which nicely agrees with the theoretical value (1.3). The absence of the parabolic negative magnetoresistance of equation (9) is presumably caused by a quenching of the classical curvature of the electron trajectories by boundary scattering [14].

For sample A the relative effect \( \delta G_{\text{loc}}/G_0 \) is very small, and also the sample is only marginally 1-dimensional,
agrees fairly well with the estimate given above, and with the width derived from weak localization or from a simple constant depletion width argument.

DISCUSSION

In the preceding section we have tried to show that the samples under study have a rich magnetoresistance behavior at low temperatures. Not all of the effects are quantitatively understood. Still, a qualitative understanding of the various phenomena has been reached, which can serve as a guideline towards future experiments. The weak localization in the quasi-ballistic regime is relatively well understood. It would be rather premature, however, to perform a detailed analysis of the resulting 1D-coherence time in terms of the various proposed phase breaking mechanisms [28], mainly due to the uncertainties in the modelling of the short time corrections in equation (2).

A perennial problem in the study of transport in quasi-one dimensional electron gas channels in semiconductor structures is that one of the key parameters, the channel width, is not known. We have discussed the various ways in which this width can be extracted from the experimental data, and consistent results are obtained. As summarized in table I, large sidewall depletion effects are found. Similar conclusions have been reached by other authors [5, 6]. It would be interesting to compare these findings with self-consistent solutions of the electrostatic confinement, although the proper modelling of the boundary conditions on the exposed surfaces presents a problem [29].

In the quasi-ballistic regime ($k > W$) boundary scattering affects the various magnetoresistance mechanisms. We have found that in our channels the boundary scattering is predominantly specular. This can be understood as a consequence of the large Fermi-wavelength ($\lambda_F \sim 40$ nm). Specular scattering occurs for wavelengths larger than the scale of the surface irregularities.

We conclude by indicating some experimental and theoretical directions in which the present study could be extended. Further experimental work will be needed to investigate the role of the sample length $L$. A study of the transition from diffusive to ballistic electron motion could thus be envisaged. Here we would like to point out that a further increase of the mobility (e.g. by use of material grown by molecular beam epitaxy) will lead to an increase in $k$ and $h$. At the same time, however, the electron motion will increasingly become ballistic. Disorder related phenomena such as weak localization and universal conductance fluctuations may thus disappear for such extremely high mobility channels. On the other hand, 1D-subband related effects will become impor-

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**Fig. 11.** Zero field conductance ($\bullet$) and conductance corrected for the weak localization contribution ($\square$) for sample B as a function of $T^{-1/2}$.

The straight line reflects the temperature dependence for the electron electron interaction effect predicted by equation (8). The extrapolated value at high temperatures is the classical part of the conductance $G_0$.
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* Recent work [30,31] on quantum point contacts in very high mobility electron gases has demonstrated this in a striking and unexpected fashion.

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