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Nonlinear conductance of quantum point contacts in a magnetic field

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Abstract. The conductance of geometrically asymmetric quantum point contacts formed in 2DEGs in GaAs/(AlGa)As heterojunctions has been studied as a function of the applied bias and magnetic field. The nonlinear conductance is found to be independent of bias direction in zero magnetic field in agreement with other workers but at higher magnetic fields the $I(V)$ curves are highly asymmetric in terms of both the onset and the type of nonlinearity observed. The curves are described using simple theory. The same experimental arrangement is also used to study nonlinearity in the quantum Hall régime when the device acts as an adjustable, narrow channel. The nonlinearity is qualitatively different to the first case and there are discontinuous changes in the dissipation which we identify with scattering between magneto-electric subbands.

When the electrons in a high mobility two-dimensional electron gas (2DEG) are confined to a short, narrow channel, the conductance of the resulting ballistic resistor, or quantum point contact (QPC), exhibits quantum behaviour depending on the number of 1D subbands occupied in the channel [1, 2]. However, the situation is modified in the nonlinear régime when the voltage applied across the QPC is comparable to the spacing of the 1D subbands [3]. In this case, the conductance depends on the detailed distribution of the voltage drop within the device although the differential conductance may still be quantized in some circumstances [4]. In this paper we study the behaviour of a geometrically asymmetric QPC in the nonlinear régime in zero magnetic field and in magnetic fields (B) strong enough for Landau quantization. We find that the magnetic field has a strong effect on the reversibility of the device with respect to current direction, and hence on the way the voltage is dropped across the QPC. Also we investigate the breakdown of the quantum Hall effect (QHE) in the high magnetic field régime where the QPC is used as a narrow, adjustable conductor. We find that in this case the breakdown is accompanied by a series of current plateaux when a gate voltage is applied.

Figure 1(a) shows a schematic diagram of the device. The hatched regions represent metallic gates on the surface of the high-mobility 2DEG ($n=1.8\times10^{15}\,\mathrm{m^{-2}}$; $\mu=52\,\mathrm{m^2\,V^{-1}\,s^{-1}}$ at 100 mK) formed in a GaAs/(AlGa)As heterostructure. The gates are fabricated from Ti/Au using electron-beam lithography and lift-off techniques and are 200 nm wide. A negative voltage, V_g, can be applied separately to either or both gates and the QPC is formed between adjacent nearest corners. The letters A, B, C, D refer to four ohmic contacts. To avoid problems with contact resistances, which might be dependent on magnetic field, measurements were performed using a four-wire technique with A and D as the current contacts and B and C used to measure the voltage. When the device is operated in the QPC regime the voltage difference between B and C can be converted to the equivalent two-terminal voltage between A and D simply by the addition of the Hall voltage [5]. Note that this correction is the same for both current directions and does not affect the reversibility of the device.

In zero magnetic field the mechanism for the onset of nonlinearity is well understood [3, 4]. Figure 1(b) shows the energy of electrons in 1D subbands of the QPC as a function of the 1D k vector. The broken line represents the equilibrium Fermi energy, ε_F. When a small voltage is applied across the QPC the $+k$ and $-k$ states are occupied unequally. The states with $+k$ are occupied to μ^+, the electron-source chemical potential, and the $-k$ states are occupied to μ^- which is the chemical potential of the electron drain. In a magnetic field the relevant chemical potentials are those of the reservoirs which feed the edge states (for a detailed discussion of edge states see [6]) entering the QPC. For the magnetic field direction consistent with the current direction along edge states shown in figure 1(a) these would be μ_A and μ_D. There are two possibilities for the onset of nonlinearity. First, μ^+

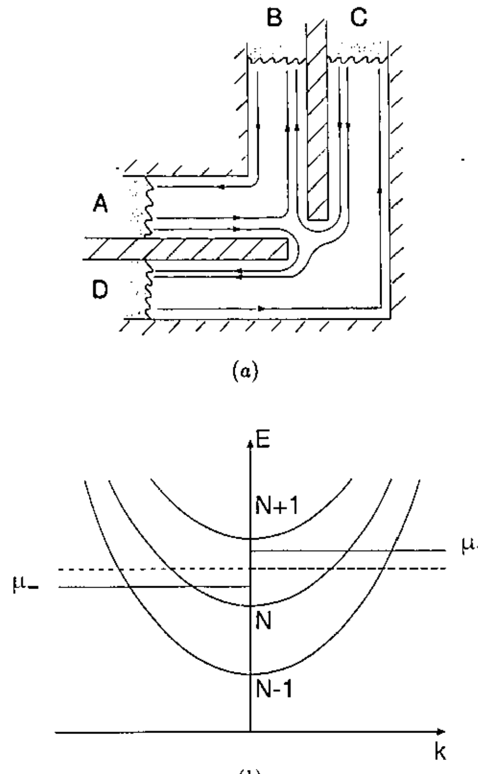

Figure 1. (*a*) Schematic diagram of the asymmetric QPC. The letters A, B, C, D refer to ohmic contacts and the lines are edge states with the arrows representing the current direction. (*b*) Energy against wavevector of electrons in 1D subbands of a QPC. The broken line is the equilibrium Fermi energy and μ^+ and μ^- are the chemical potentials of the electron source and drain reservoirs respectively.

might rise sufficiently to populate the next 1D subband. In this case the current is given by [3]

$$I_1 = \frac{2e}{h}[(\varepsilon_F - \varepsilon_{N+1}) + eV(N+f)] \tag{1}$$

where ε_{N+1} is the energy barrier at the QPC to the $(N+1)$th subband, $\mu^+ - \mu^- = eV$ and $\mu^+ = \varepsilon_F + feV$. The second possibility is that μ^- becomes too low to populate the Nth subband in which case the current is [3]

$$I_2 = \frac{2e}{h}[(\varepsilon_f - \varepsilon_N) + eV(N+f-1)] \tag{2}$$

where ε_N is the barrier for the Nth subband. In general, reversing V will only give the same current if $f = \frac{1}{2}$ and the voltage is dropped symmetrically across the device.

There are two experimental parameters that determine the onset of nonlinearity, the magnitude of the voltage V and the fraction, f, which describes how it is dropped across the QPC. For the first case, (leading to I_1) nonlinearity will occur when $feV \geqslant \Delta_1$, where Δ_1 is the energy difference between ε_F and the bottom of the $(N+1)$th subband. Similarly, the second case will occur if and when $(1-f)eV > \Delta_2$ where Δ_2 is the energy difference between ε_F and the bottom of the Nth subband.

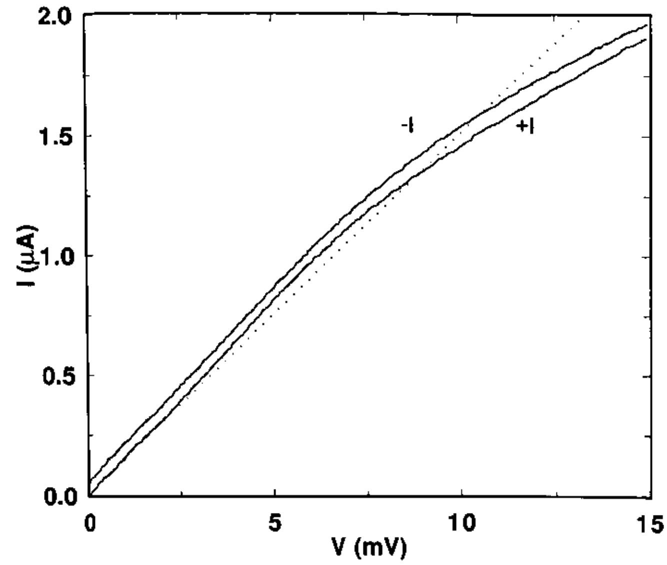

Figure 2. Current against voltage for a QPC for positive and negative bias in zero magnetic field at T=100 mK. The dotted line is the linear resistance (~6.4 kΩ) and the $-I$ curve is offset by 50 nA for clarity.

A typical nonlinear $I(V)$ characteristic is shown for both current directions in $B = 0$ at 100 mK in figure 2. At this gate voltage, $V_g = 1.893$ V, the linear resistance is 6.5 kΩ, consistent with the initial slope of the characteristic. The two curves are virtually identical, indicating that $f = \frac{1}{2}$ and the voltage drop is the same on each side of the device despite the geometrical asymmetry (compare with [3]).

The nonlinearity begins at $V_1 \sim 3$ mV and is of the first type, where the conductance increases due to population of the third subband. At a slightly higher voltage ($V_2 \sim 5$ mV) the differential conductance falls due to μ^- becoming lower than the bottom of the second subband. It is very easy to show that if $f = \frac{1}{2}$ then $eV_1/2 + eV_2/2 = \Delta$ the subband spacing, which in this case would be 4 meV. The symmetry of the $B = 0$ characteristic is unchanged if the QPC is formed using difference biases on each gate.

In a magnetic field the symmetry is no longer apparent. Figure 3(*a*) shows the $I(V)$ curves for two-current directions at $B = 2.19$ T and $V_g = 1.849$ V, corresponding to two Landau levels occupied in bulk and $N = 1$ for the linear QPC. There is clear asymmetry in two ways. First, the voltages for the breakdown of linearity are different for the two current directions and, secondly, the currents are different in the nonlinear region. The dotted line is the linear resistance which is ~13 kΩ consistent with $N = 1$. The asymmetry is seen even more clearly in figure 3(*b*) which is the smoothed differential conductance for the data shown in figure 3(*a*). The upper curve corresponds to the current flow from A to D in figure 1(*a*) and the lower curve from D to A. Defining the breakdown voltage, V_B, as when the differential conductance departs more than 1% from its linear value, we find $V_{B1} = 2.2$ mV for the upper curve and $V_{B1} = 3.3$ mV for the lower curve. Furthermore the nature of the nonlinarity is different in

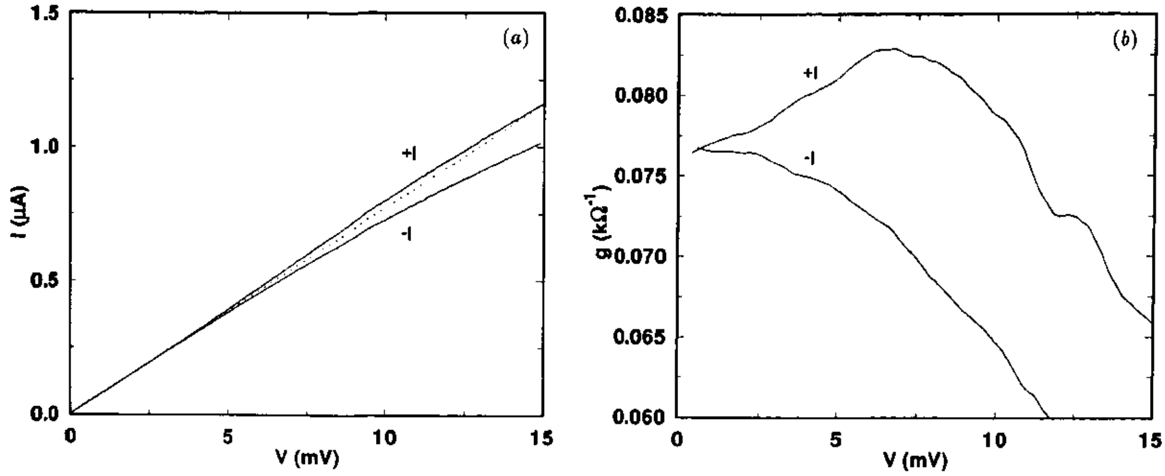

Figure 3. (*a*) Current against voltage for a QPC for positive and negative bias for $B=2.19$T. $V_g=1.894$ V and the dotted line is the linear resistance (~ 13 kΩ). (*b*) Differential conductance for the data of (*a*).

the two cases, which is again an indication of the asymmetry of the voltage drop. The upper curve in figure 3(*b*) has an enhanced conductance, corresponding to population of the $N = 2$ subband, whereas in the lower curve the conductance decreases indicating that μ^- has fallen below the bottom of the $N = 1$ subband. Neither curve in figure 3(*b*), however, shows fully developed constant conductance in the nonlinear regime below ~ 15 mV. At higher voltages the differential conductance is almost constant but may include a contribution from the bulk. This can be compensated by taking the difference in the currents in the two bias directions, ΔI. This gives

$$\Delta I = \frac{2e^2 V}{h}(2f - 1). \tag{3}$$

Note, of course, that for $f = \frac{1}{2}, \Delta I = 0$. A plot of ΔI against V is shown in figure 4 for the data in figure 3. For $V \geqslant 20$ mV the data lie on a straight line passing through the origin as predicted by equation (3). We can then determine $f = 0.6$ for this configuration, implying that 60% of the voltage drop occurs between the QPC and D. Similar curves at different values of gate voltage from 1.58 V to 1.85 V gives the same value of f within experimental error. We can also estimate f from figure 3(*b*) by noting that the conductance of the upper curve begins to fall again at a voltage $V_{B3} \sim 6$ mV. If this is identified with μ^- falling below the bottom of the subband then we have

$$efV_{B1} = \Delta_1 \tag{4a}$$

$$efV_{B2} = \Delta_2 \tag{4b}$$

$$e(1-f)V_{B3} = \Delta_2. \tag{4c}$$

Using the experimental values for V_{B1}, V_{B2} and V_{B3} gives $f = 0.65$ and $\Delta = \Delta_1 + \Delta_2 = 3.7$ meV. The value of f is in reasonable agreement with that found from figure 3, given the approximate determination of V_{B3}. The value of Δ corresponds to the energy spacing between the spin-split subbands within $N = 1$.

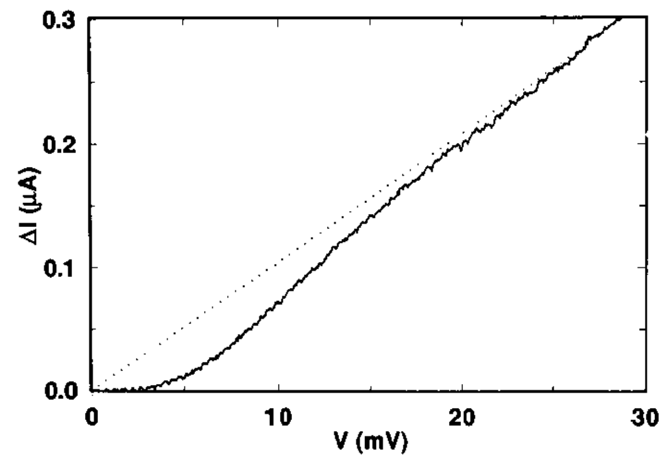

Figure 4. Current difference, ΔI, against bias for the two curves shown in figure 3(*a*). The dotted line shows the behaviour described by equation (3).

We have also studied the nonlinearity in the quantum Hall régime, defined as when R_{xx}, the four-wire longitudinal resistance, is zero when measured in our standard four-wire geometry. Typical data are shown in figure 5 for a number of gate voltages for $B=4.3$ T, which corresponds approximately to the centre of the bulk R_{xx} minimum for one spin-degenerate Landau level occupied. Two features are immediately apparent. Even a very small gate bias has a profound effect on the breakdown voltage. Also the breakdown behaviour is qualitatively different to that for the quantum point contact, with clear plateaux in the $I(V)$ curve. Since the measurement corresponds to constant current, the physical significance of the plateaux is a discontinuous increase in the dissipation at certain values of the current, or, more physically, the Hall voltage since that determines the chemical potential difference across the narrow channel. Similar features have been seen by other authors in fixed-width narrow channels [7, 8].

In figure 6 we have plotted the differential resistance against the Hall voltage in the narrow region (calculated from the current), V_H, in units of $\hbar\omega_c$, the Landau level

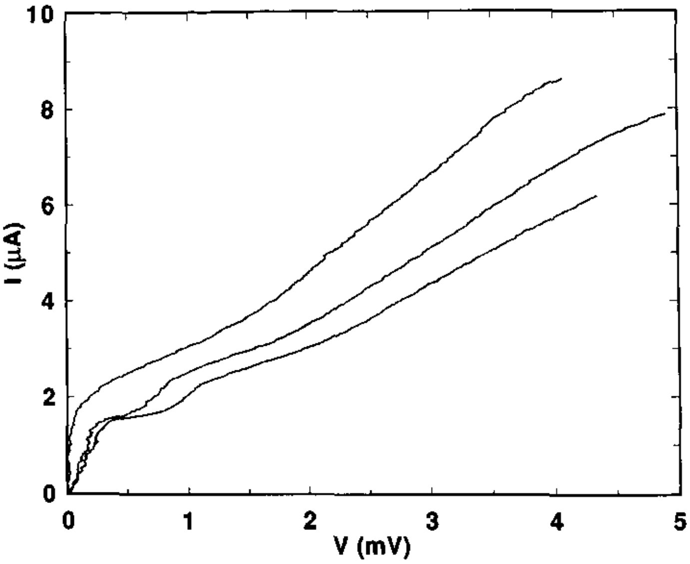

Figure 5. Current against voltage in the quantum Hall régime. $V_g = 0$ V (upper), 0.15 V (middle) and 0.2 V (lower).

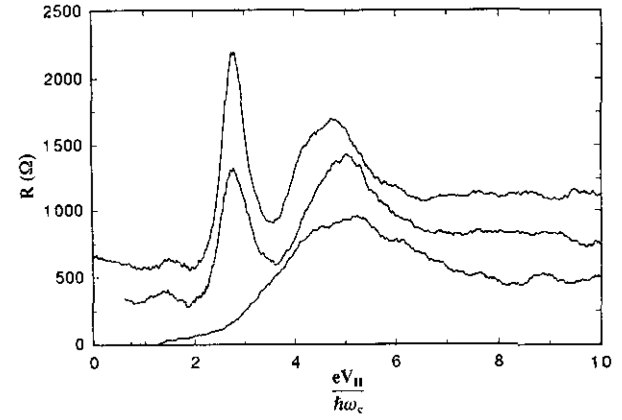

Figure 6. Differential resistance of the data shown in figure 5 plotted against $eV_H/\hbar\omega_c$. $V_g = 0.2$ V (upper), 0.15 V, (middle) and 0 V (lower). Note that the curves are in reverse order relative to figure 5 and that the upper two curves are displaced for clarity by 400 Ω and 200 Ω respectively.

spacing in the bulk material. Following [7] we identify the peaks of dissipation as being due to scattering between successive energy levels in the narrow channel. The dissipation peaks in figure 6 do not occur for eV_H at integer values of $\hbar\omega_c$, but the three peaks do occur at values of eV_H approximately in the ratio 1:2:3, indicating that in the region of the gates the energy levels are magneto-electric with electrostatic as well as magnetic confinement. This would imply that the level spacing is increased over the bulk value. However, note that the positions of the peaks are not strongly dependent on gate voltage, which is evidence against this hypothesis. Note also that the $I(V)$ curves become linear again at high currents ($I > 4\,\mu$A, $(eV_H/\hbar\omega_c) > 7$) and the differential resistance is approximately independent of gate voltage (the curves are offset for clarity). A feature not shown in figures 5 and 6 is that the structure only occurs for one current direction. In the other direction breakdown occurs at much lower current values and the curves are smooth for all gate voltages. Structure in the breakdown of the quantum Hall effect has been predicted theoretically by Jain and Kivelson [9]. The details of their predictions, however, are not consistent with our results. The detailed explanation for the asymmetry of this breakdown is not understood but it may be due to edge effects in the narrow channel. Further investigations are underway in which the gates are biased asymmetrically.

In summary, we have measured the nonlinear resistance of an asymmetric narrow channel in a 2DEG. When the channel acts as a QPC we find that a magnetic field leads to an asymmetric voltage drop across the channel, which in turn leads to a different voltage for the onset of nonlinearity in each current direction. In the quantum Hall régime the breakdown is qualitatively different and structure is observed in the $I(V)$ curves. Although this structure may be tentatively ascribed to scattering between magneto-electric subbands there are still unexplained features in the data.

Acknowledgments

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