Quantum interference in two independently tunable parallel point contacts

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We have fabricated two independently tunable quantum point contacts in a parallel configuration, by wet etching a 2000-Å-diameter hole in the center of the constriction of a split-gate device in an $Al_xGa_{1-x}As/GaAs$ heterojunction. The number of occupied subbands in the point contact on either side of the etched hole can be tuned independently by biasing the gate, with each channel exhibiting conductance steps in units of $2e^2/h$, independent of the other. In the quantum Hall regime, nearly periodic resistance fluctuations are observed when both gate biases are fixed and the magnetic field B is swept. Further, periodic resistance fluctuations are observed when B and the bias on one gate is fixed, while the bias on the second gate is swept. In both cases, fluctuations are due to tunneling between the opposite edge channels via magnetically bound states encircling the etched hole, whose energies are quantized such that each encloses an integral number of flux quanta. Tunneling occurs when an allowed bound-state energy coincides with the chemical potential, and when the edge channel occupations of the two quantum point contacts are nearly equal, as discussed in a simple model.

I. INTRODUCTION

In recent years much effort has been directed towards the investigation of quantum confined structures, including quantum wires containing a one-dimensional electron gas (1D EG). Rapid advances have occurred, due in large part to concurrent developments in materials growth and ultrafine lithographic technologies.[1] A common method of forming a 1D EG is through the electrostatic confinement of a two-dimensional electron gas (2D EG) into a narrow channel, utilizing either etching[2] or depletion by a pair of closely spaced gates on the surface.[3]

One of the remarkable manifestations of quantum confinement is the quantized conductance exhibited in quantum point contacts[4] (QPC's), narrow gate-defined constrictions, whose width W is of the order of the Fermi wavelength λ_F, and whose length $L \ll l_e$, where l_e is the mean free path. The small W causes one-dimensional electric subbands to be formed within the constriction region, while the short L ensures that electrons traverse the constriction without scattering, i.e., transport through the constriction is ballistic. Because, for each subband, the product of the one-dimensional density of states and the group velocity does not depend on the dispersion relation $E(k)$, each subbands has a conductance of $2e^2/h$. As the negative gate voltage on the device is varied, the number of occupied subbands changes, producing steps in the conductance at integer multiples of $2e^2/h$.

Shortly after the first observation of QPC's, Wharam *et al.*[5] examined the behavior of two QPC's in series, placed within l_e of one another. When the width of each QPC was varied independently, the total resistance of the device was approximately equal to the resistance of the single QPC with the lowest number of occupied subbands. Beenakker and van Houten[6] demonstrated the same behavior in a classical calculation. Recently, Smith *et al.*[7] have studied two QPC's in parallel, also placed within l_e of one another. The device was made with a single gate over a patterned layer of polymethylmethacrylate (PMMA) resist, and the width of each QPC could not be varied independently. They observed steps in the conductance at integer multiples of $4e^2/h$, and argued that not only did the conductances of each QPC combine additively,[8] but that they changed their occupancies cooperatively in lock step in order to minimize the total energy of the device. They also observed oscillations in the resistance both as a function of magnetic field B and as a function of gate voltage, but the B was too low to clearly identify Landau-level filling factors ν.

At high B such that $\omega_c\tau \gg 1$ (where ω_c is the cyclotron frequency and τ is the scattering time), the nature of transport in small structures changes dramatically. Electrons travel in current carrying edge channels[9] which follow equipotentials along the physical edges of the device, and the total resistance of the device is given by Landauer-type formulas[10] in terms of the probabilities of scattering from incoming to outgoing edge channels. Washburn *et al.*[11] and Haug *et al.*[12] have observed quantization of the diagonal resistance R_{xx} due to the controlled reflection of selected edge channels utilizing a top gate across a small Hall bar. Jain and Kivelson[13] predicted that the random potential fluctuations in a narrow Hall bar would give rise to magnetically bound states near the center of the channel, whose allowed energies are quantized by the Bohr-Sommerfeld quantization condition that each encloses an integral number of flux quanta $\Phi_0 = h/e$. When the chemical potential μ coincides with allowed bound-state energies, resonant tunneling between incoming and outgoing edge channels occurs via the bound states, giving rise to sharp resistance spikes periodic in μ or B. Subsequently, Simmons *et al.*[14] observed resistance fluctuations quasiperiodic in B near the R_{xx} minima in narrow Hall bars, whose period and temperature dependence were consistent with the model of Jain and Kivelson. Recently, van Wees *et al.*[15] have observed nearly periodic oscillations in a geometry consisting of two point contacts in series, separated by a ~ 1.5-μm-diameter circular region. Their case differs from that considered by Jain and Kivelson, in that the circular region represents a potential well.

In this paper we report on our measurements of an island-in-the-strait geometry device, designed to further test the Jain-Kivelson model. The device is basically a single point contact with an artificial impurity in the center of the constriction. When $B=0$, the device behaves as two independently tunable QPC's in parallel. At high B, the sample exhibits resistance fluctuations nearly periodic in B in the vicinity of the Landau-level filling factor $\nu=1$ minimum of R_{xx}, with a period consistent with the diameter of the artificial impurity. Highly periodic resistance fluctuations are also observed when the voltage on one gate is swept, while B and the voltage on the other gate are held fixed. In both cases the oscillations are consistent with the Jain-Kivelson model of interedge channel tunneling via magnetically bound states which encircle the etched hole.

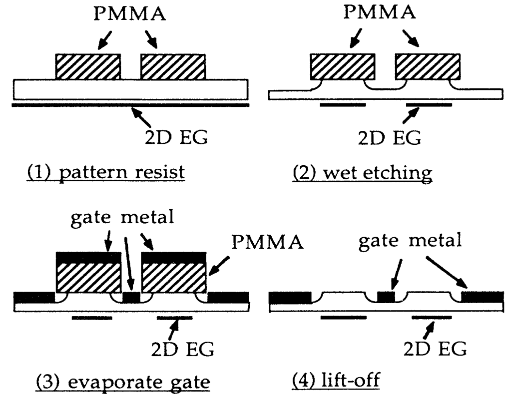

FIG. 2. The four basic processing steps of the self-alignment technique are illustrated. The central gate is a remnant of fabrication and not contacted.

II. FABRICATION OF THE DEVICE

The device was designed to realize a magnetically bound state in the center of a narrow constriction at high B. The material from which it was fabricated was a high mobility $Al_xGa_{1-x}As$/GaAs heterojunction of density $n_{2D}=1.1\times10^{11}$ cm^{-2}, and mobility $\mu=1.6\times10^{6}$ cm^2/V sec at 4.2 K. The device consists of an etched and gated point contact region of width 14 000 Å, with an etched hole of diameter ~ 2000 Å in the center of the constriction (see Fig. 1). It was fabricated by a self-aligned gate technique whereby the structure is both etched and gated on a single lithography step. Figure 2 shows the processing steps. The PMMA resist was patterned in an electron beam writing system, defining both the outer regions of the constriction and the central 2000-Å impurity. The sample was then wet etched 500 Å, and *without* removing the PMMA, 100 Å of Cr and 500 Å of Au were evaporated. (The etching is deep enough to completely deplete the electrons beneath it due to band bending.) A lift-off is then performed. In the resulting final device, the two outer gates have no electrons beneath them, but are close enough to the 2D EG to cause lateral depletion when biased. The gate over the central hole is a remnant of the fabrication process and is not contacted.

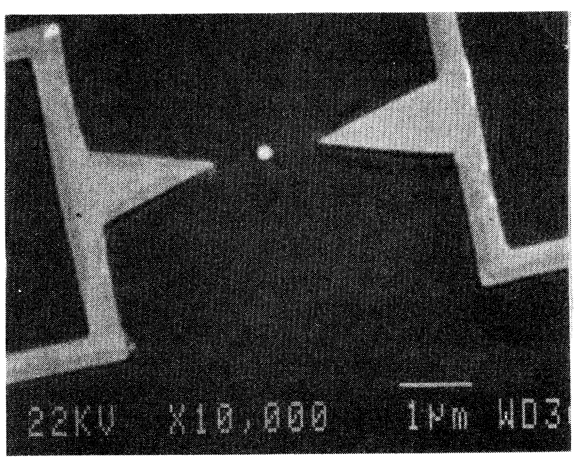

FIG. 1. An electron micrograph of the sample. Gate A is at left, gate B is at right, and the 2000-Å etched hole is in the center.

III. EXPERIMENTAL SETUP

Temperatures on the order of 1 K are often required to observe clear quantized steps in a QPC, while lower T on the order of 100 mK are needed for the observation of resistance fluctuations at high B. The sample was measured in a pumped He^3 system and also a top-loading He^3-He^4 dilution refrigerator. Four terminal resistance measurements were made using a standard low-frequency ac lock-in technique with 1-nA excitation current.

IV. $B=0$ TRANSPORT RESULTS: TWO QPC's IN PARALLEL

That the device behaves as two independently tunable QPC's can be seen by the fact that each of the two gaps in the device produces, independently of the other, conductance steps characteristic of QPC's. In Fig. 3(a) are shown two curves taken at a temperature of 350 mK at $B=0$: one is the four terminal resistance of the device when gate A is grounded ($V_A=0$) and the voltage on gate B (V_B) is swept; the other is when $V_B=0$ and V_A is swept. If the device is truly two point contacts in parallel, whose conductances combine additively, the total resistance R of the device should be given by

$$R=R_{bg}+\left[\frac{1}{R_A(V_A)}+\frac{1}{R_B(V_B)}\right]^{-1}, \tag{1}$$

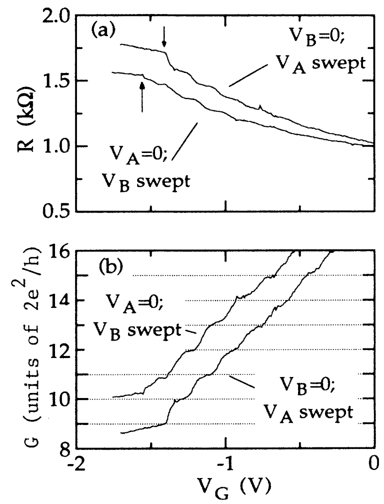

FIG. 3. (a) Resistance data taken when $V_B=0$ and $V_A=V_G$ (upper curve) and $V_A=0$ and $V_B=V_G$ (lower curve), at $T=350$ mK and $B=0$. (b) The conductance converted from (a) after subtracting the background resistance R_{bg} (the upper curve is for $V_A=0$ and $V_B=V_G$, and the lower curve is for $V_B=0$ and $V_A=V_G$). Vertical arrows indicate pinch-offs of the biased channel.

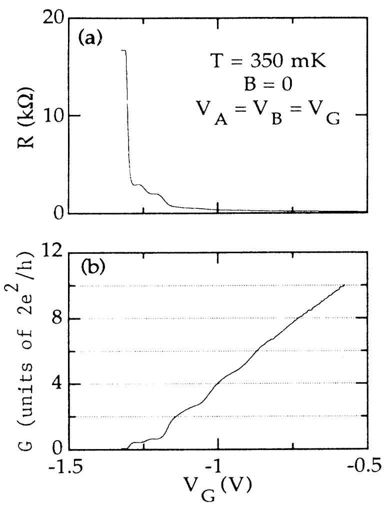

FIG. 4. (a) Resistance data taken when $V_A=V_B=V_G$. (b) The conductance converted from (a).

where R_A is the resistance of QPC A alone and is assumed to depend on V_A only, R_B is the resistance of QPC B alone and is assumed to depend on V_B only, and R_{bg} is the background resistance of the 2D EG lead regions. For our device, when $V_B=0$ and V_A is swept, $R_A(V_A)$ exhibits resistance steps at values $h/2Ne^2$, which are reflected as smaller steps in R as described by Eq. (1), and as seen in Fig. 3(a). As $-V_A$ is increased, QPC A eventually pinches off at $V_A=-1.45$ V and $R_A(V_A)\rightarrow\infty$, at which point R exhibits a plateau at $R=R_{bg}+R_B(V_B=0)=1.75$ kΩ. Similar behavior occurs when $V_A=0$ and V_B is swept, with R_B pinching off at $V_B=-1.55$ V, at which point a plateau appears at $R=R_{bg}+R_A(V_A=0)=1.55$ kΩ. (The fact that after pinch-off occurs, the resistances are not strictly constant, is due to a slight dependence of R_A on V_B and R_B on V_A.)

In Fig. 3(b), we plot the same data as in Fig. 3(a), only converted to conductance, after subtraction of the background resistance of 280 Ω. Here, it is clear that the steps in the conductance occur at integer multiples of $2e^2/h$, demonstrating that each channel in the device acts as an independently tunable QPC. The total conductance changes from $\sim 38e^2/h$ at $V_A=V_B=0$, to $G_B(V_B=0)\sim 18e^2/h$ or $G_A(V_A=0)\sim 20e^2/h$ when one of the two QPC's is pinched off.

In Fig. 4(a), we show the resistance of the entire device as a function of gate voltage when both gates are biased together so that $V_A=V_B$. Figure 4(b) shows the same data converted to conductance, after subtraction of the background resistance. In contrast to the situation when a single QPC is biased, here 2 or 3 steps separated by $4e^2/h$ are clearly visible before both channels pinch-off at $V_A=V_B=-1.35$ V. (The fact that the pinch-off voltage when both gates are biased together, -1.35 V, is a smaller negative value than the pinch-off voltage of either QPC biased independently, is because QPC A is slightly influenced by V_B, and vice versa.)

V. $B\neq 0$ TRANSPORT: RESISTANCE FLUCTUATIONS IN B

After warming the sample to 300 K, the sample was loaded in a He^3-He^4 dilution refrigerator, cooled to 30 mK, and illuminated with a red light-emitting diode (LED). On this second cooldown, the $B=0$ behavior of the device is for the most part qualitatively similar to that observed on the first cooldown, described above, except that the pinch-off voltage for QPC B becomes significantly larger than for QPC A, due to a change in its conducting width from the temperature cycling.

The island-in-the-strait geometry of our device was chosen in order to observe the interedge channel tunneling phenomenon discussed by Jain and Kivelson.[13] When B is in the quantum Hall regime,[16] the magnetically bound "edge" states will form along the equipotentials encircling the etched hole. When μ coincides with the allowed bound-state energies, scattering from an edge channel on one side of the sample to an edge channel on the opposite side can take place via tunneling through the intermediate bound states. Thus as either μ or B is swept, periodic peaks in the resistance occur, corresponding to the quantized bound-state energies. Previously observed resistance fluctuation in sweeping B is due to the bound states produced by the sample's disorder potential[14] rather than an intentionally made potential hill.

Figure 5 shows the R_{xx} of the device as a function of B on the second cooldown, at a temperature of 30 mK. In contrast to a wide Hall bar made from the same material

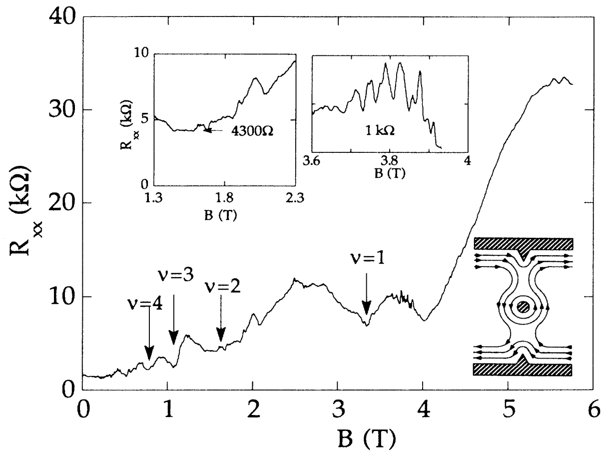

FIG. 5. B scan of R_{xx} when $V_A = V_B = 0$ at $T = 30$ mK. The upper right inset shows an enlarged view of the resistance fluctuations near $\nu = 1$ with periodicity of 0.043 T. The upper left inset shows the quantized plateau of 4300 Ω at $B = 1.5$ T. The lower inset shows that the number of populated edge channels is different in the two QPC's and, as a result, the $\nu = 2$ edge channel does not completely encircle the potential hill.

and measured in series with the device, none of the quantum Hall R_{xx} minima is very deep. There is a small density difference between the constriction regions and the wide 2D EG lead regions, and so the two regions are never at the same ν. Nevertheless, we are able to assign filling factors $\nu = 1$ and 2 at $B = 3.32$ and 1.66 T, respectively, by analyzing the Shubnikov–de Haas oscillations at low B. (The assignment is further supported by data from other island-in-the-strait geometry devices of slightly larger width, which did show clear identifiable R_{xx} minima at slightly higher values of B.) The density in the device is $\sim 0.80 \times 10^{11}$, which is $\sim 30\%$ lower than in the wide Hall bar. This assignment of ν is also supported by the presence of a resistance plateau quantized to ~ 4300 Ω near $B = 1.5$–1.6 T (see the left inset of Fig. 5). Such quantized plateaus in R_{xx} occur[11,12] when edge states in a wide region of filling factor N_w are reflected by a potential barrier consisting of a region of lesser filling factor N_n. Thus 4300 $\Omega = (h/e^2)(1/N_n - 1/N_w) = (h/e^2)(\frac{1}{2} - \frac{1}{3})$, and we can assign in the narrow region of the two QPC's a filling factor of $\nu = 2$ near $B \sim 1.6$ T.

Near $B \sim 3.8$ T, on the high B side of $\nu = 1$, there are very strong fluctuations. In the right inset of Fig. 5, we show the fluctuations at an expanded scale. The fluctuations are ~ 1 kΩ, and are nearly periodic, with a period of ~ 0.043 T. We can estimate the radius r of the bound state from the measured period ΔB by using a simple formula,[14]

$$\Delta B = \frac{h}{e} \left[\pi r^2 + \frac{r h^2 n_{2D}}{m^* e E_r(\mu)} \right]^{-1} , \quad (2)$$

where $E_r(\mu)$ is the electric field at the bound state in the radial direction at μ. Assuming $E_r = 10^6$ V/cm, we get $r = 1700$ Å. Since the radius of the etched hole is 1000 Å, we deduce an edge depletion of 700 Å from this result.

The fact that tunneling resonances appear even though the R_{xx} minima never reach zero is due to the density difference between the constricted regions and the wide lead regions. When the constricted QPC regions are at a filling factor $\nu = 1$, the lead regions will be at a higher filling factor $\nu > 1$, and not in a dissipationless integer quantum Hall state. Thus the resistance of the total device never reaches zero. (Indeed, because the filling factor is still less than 2 in the lead regions, the $\nu = 2$ edge channel may flow in a complicated percolating path throughout the bulk of the lead regions). In the constricted regions, however, the $\nu = 1$ channels on the two edges of the sample are well separated except around the potential hill of the etched hole, where they can tunnel through the bound states, causing the nearly periodic resistance fluctuations.

That the resistance fluctuations appear only near $\nu = 1$ is due to a slight difference in density between the QPC's known from our data at $B = 0$. Such a small density difference can lead to a different number of populated edge channels in the two QPC's at higher ν. Thus at lower B, the innermost (or the highest populated) edge channel will not completely encircle the potential hill (see lower inset of Fig. 5), and the relevant bound states giving rise to the resistance fluctuations are not present. In short, the lack of resonances at higher ν is due to the fact that the two QPC's, as prepared, are not identical.

VI. RESISTANCE FLUCTUATIONS IN GATE VOLTAGE

Our device allows us to tune each QPC with respect to the other so as to acheive a resonance condition. If the gates are biased so that each QPC is traversed by the same number of edge channels, we can observe periodic resistance oscillations as a function of gate voltage. This tuning is accomplished by changing the potential hill with the biases, and thus changing the energies of the allowed bound states around it. Figure 6 shows four scans:

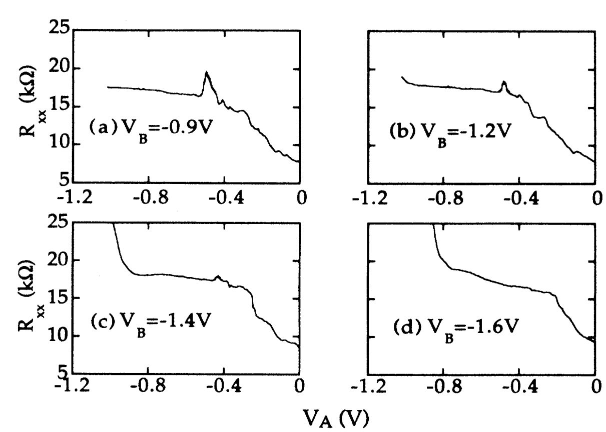

FIG. 6. (a)–(d) show the R_{xx} as a function of V_A taken at $B = 1.33$ T and $T = 30$ mK for $V_B = -0.9$, -1.2, -1.4, and -1.6 V, respectively.

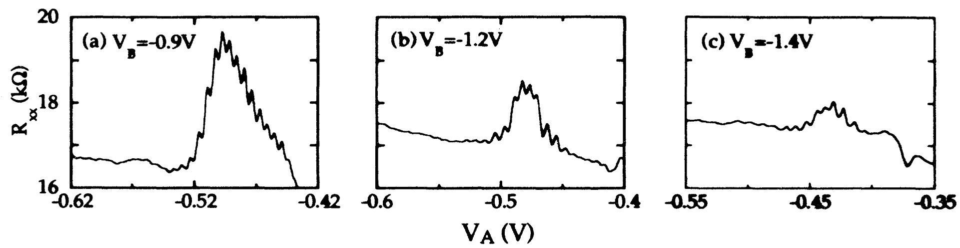

FIG. 7. (a)–(c) are the expanded plots of the resistance fluctuations for $V_B = -0.9$, -1.2, and -1.4 V, respectively.

the resistance of the device as V_A is swept while $B = 1.33$ T and V_B is held fixed at -0.9, -1.2, -1.4, and -1.6 V, respectively. Highly periodic resistance fluctuations are apparent at $V_B = -0.9$, -1.2, and -1.4 V, with the amplitude steadily decreasing from ~ 400 to ~ 100 Ω, as shown in the expanded plots in Fig. 7. At $V_B = -1.6$ V, the fluctuations are no longer observed.

Resonant reflection (or backscattering) via the magnetically bound states is not the only backscattering mechanism possible in our sample. Depending on the gate bias condition, the edge channels can also be backscattered nonresonantly. Our data can be understood in terms of a simple model based on whether the edge channels are reflected resonantly or nonresonantly as we vary V_A. In Fig. 8, we illustrate the model by showing the edge channels in the constriction region when $B = 1.33$ T and $V_B = -0.9$ V at three values of V_A. We first note that at $B = 1.33$ T, the wide lead region (not shown in Fig. 8) is in between $\nu = 3$ and 4, since the density monitored by R_{xx}, measuring only across the lead region, is $n_{2D} \sim 1.1 \times 10^{11}$ cm^{-2}. In this case, the $\nu = 1$, 2, and 3 edge channels are populated in the narrow constriction of the sample away from the QPC's. In the wide lead region, where the filling is between $\nu = 3$ and 4, electrons in the bulk Landau level can scatter and give rise to a correction to the resistance across the narrow region which we are interested in. Only the $\nu = 1$ lower edge channel traverses QPC B when $V_B = -0.9$ V, and this condition does not change until $-V_A$ is high enough to affect QPC B. At $V_A = 0$ [Fig. 8(a)], the $\nu = 2$ and 3 lower edge channels traverse QPC A and enclose the etched hole. As a result, reflection via resonant tunneling cannot take place. However, the $\nu = 3$ edge channel can tunnel across QPC A and give rise to a nonresonant reflection. Since the tunneling probability T_{A3} increases with increasing $-V_A$, we expect R to increase. After T_{A3} reached 1 (total reflection of the $\nu = 3$ edge channel at QPC A), the $\nu = 2$ edge channel can tunnel across QPC A, and consequently, R continues to increase as $-V_A$ increases without resonances. For V_A around -0.5 V [Fig. 8(b)], only the $\nu = 1$ edge channel is populated in either QPC and the bound state of the $\nu = 1$ edge channel on the etched hole allows resonant reflection of the $\nu = 1$ edge channel and gives rise to the observed periodic oscillations. As we further increase $-V_A$, QPC A is completely depleted and the $\nu = 1$ upper edge channel will enclose the etched hold and traverse QPC B [Fig. 8(c)]. Then, nonresonant reflection of the $\nu = 1$ edge channel becomes possible. Since the tunneling probability across QPC B is small and not significantly changed by V_A, R is expected to remain constant, giving rise to the wide plateau observed in the range $V_A \sim -0.5$ V to -0.9 V. The resistance should be close to the quantized value of $(h/e^2)(\frac{1}{1} - \frac{1}{3}) = 17.2$ kΩ, and the actual observed resistance is ~ 18 kΩ.

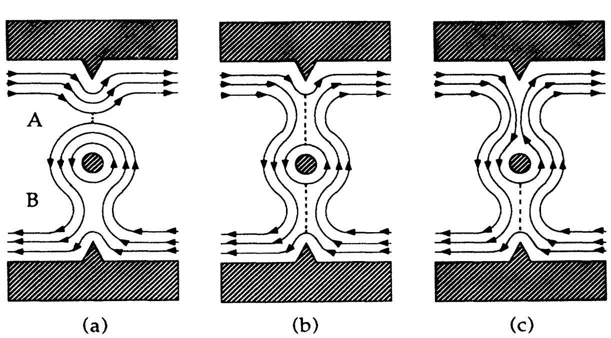

FIG. 8. (a)–(c) are schematic diagrams showing the populated edge channels in the QPC's for $V_A = 0, -0.5$ V, and $-V_A > 0.5$ V, respectively, when $V_B = -0.9$ V and $B = 1.33$ T. The dashed lines indicate finite probability of tunneling.

The amplitude of the resistance fluctuations is maximum when the tunneling probability from one edge channel to the bound states is equal to that from bound states to the other edge channel. Even if the number of occupied channels in both QPC's is the same, the fluctuations may be very small in amplitude and not observable, as long as the two probabilities are appreciably different. Thus it is also possible to understand the data for $V_A < -0.4$ V by assuming that two QPC's are occupied with the same number of edge channels, but the fluctuations are observable in only a small range of V_A with which the tunneling probabilities from the two edges are equal.

The bias $-V_A$ corresponding to the total reflection of the $\nu = 2$ edge state becomes smaller as $-V_B$ increases, probably because the bias $-V_B$ is high enough to affect QPC A and to reduce the density of QPC A. In any case, the range of V_A in which the oscillations due to resonant tunneling are observed shifts to lower biases as we see in Fig. 6. For $-V_B \geq 1.6$ V, no resistance oscillations are observed, since QPC B is completely pinched off and resonant tunneling is not realized at any V_A.

The period of these fluctuations is ~ 7 mV. Assuming a parabolic potential profile in the constriction,[17,18] this period corresponds to an ~ 100 mK bound-state energy separation, the same order of magnitude as that from random potential fluctuations observed in Ref. 19.

It has been pointed out that the Coulomb blockade plays an important role in the charge transport through mesoscopic tunnel junctions[20] and constricted narrow channels.[21] Our device is the exact "inverse" structure of that in the recent experiment of Meirav, Kastner, and Wind[21] and Staring *et al.*,[21] demonstrating the influence of Coulomb blockade. Their devices have an isolated electron lake of a size comparable to that of our etched hole. In our device, which has an island-in-the-strait geometry, we have not observed the Coulomb blockade effect proposed by Lee.[22] The fact that we observe oscillations both as a function of B and as a function of gate voltage, together with the result from a T dependence study reported in Ref. 19, indicate that the effects, if they exist in our device, are weak. On the other hand, the edge channels and the bound states in our case belong to the same electron reservoir and, consequently, electron tunneling from an edge state to the bound state does not have to overcome any electrostatic energy.

VII. CONCLUSION

We have fabricated two independently tunable quantum point contacts in parallel by means of a self-aligned wet-etching and metallization technique. Our transport data at $B=0$ indicate that both constrictions in the device function separately as quantum point contacts. We have observed strong periodic resistance fluctuations both as a function of B and as a function of gate voltage at fixed B. The origin of these fluctuations is interedge channel electron tunneling via magnetically bound states which encircle the etched hole. The fact that when both gates are unbiased, fluctuations as a function of B appear only near $\nu=1$, is explained by a slight difference in density for the two quantum point contacts. For fluctuations as a function of gate voltage, the bias conditions, under which they appear, are explained by a simple model, in which such resonant tunneling is assumed to occur only when the edge channel occupations of the two quantum point contacts are equal.

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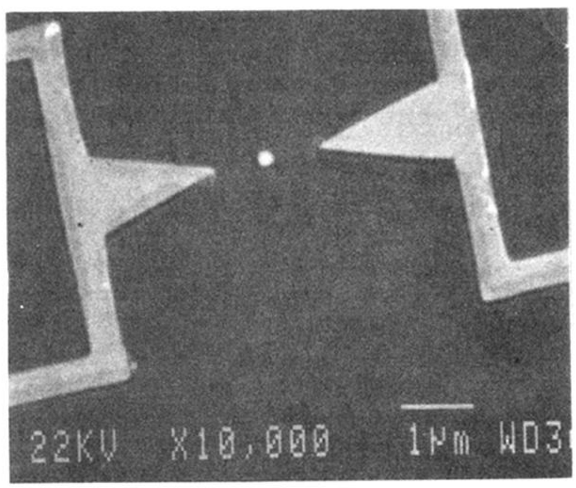

FIG. 1. An electron micrograph of the sample. Gate *A* is at left, gate *B* is at right, and the 2000-Å etched hole is in the center.