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Single-electron acoustic charge transport on shallow-etched channels in a perpendicular magnetic field

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The effect of a perpendicular magnetic field on the quantized current induced by a surface acoustic wave in a quasi-one-dimensional channel is studied. The channel was defined in a GaAs heterostructure by a shallow-etching technique. The quantized current in this constriction displayed superior precision (± 60 ppm) and robustness to dc bias relative to that observed previously in Schottky-gate-defined channels. In a perpendicular magnetic field commensurability oscillations were observed in the interval of current between quantized plateaus. The phase of the oscillations changes when a plateau is approached, which leads to an oscillatory change in the slope of the plateaus.

Since 1990 there has been considerable interest in the metrological community in the development of a quantum standard of current to compare with existing quantum standards of voltage and resistance. To be useful in metrological applications, a future current standard is required to deliver current in the nanoampere range with a relative uncertainty smaller than one part in ten million. Devices based on Coulomb blockade of tunneling have been developed[1–3] that are controlled by an external radio frequency signal and deliver quantized current in units $I=ef$ where e is the electron charge and f is the signal frequency. These devices are bound, for intrinsic reasons, to operate at low frequencies (≈ 10 MHz), therefore delivering low current (≈ 1 pA). A different approach toward a current standard was described in Refs. 4–6. A powerful surface acoustic wave (SAW) transported charge along a quasi-one-dimensional (quasi-1D) channel defined in a GaAs-AlGaAs heterostructure by a split gate. The SAW transports electrons in packets confined to the minima of the wave's electrostatic potential. The interaction between electrons can suppress fluctuations in the number of electrons in each packet, resulting in a current that is proportional to the SAW frequency. The SAW approach is not reliant on the slow process of tunneling and therefore can produce large currents without compromising accuracy. The experiments in Refs. 4–6 demonstrated a quantized acoustoelectric current in the nanoampere range with a relative accuracy of approximately 3×10^{-3} or 3000 ppm (parts per million).

In the present work we have investigated the quantized acoustoelectric current in a perpendicular magnetic field for both Schottky-gate-defined channels and channels formed using a shallow-etching technique.[7] The behavior was found to be qualitatively the same for both types of contact. At the same time we have found that etched channels produce a more precise quantized current, which is also more robust to source-drain bias. For this reason we shall discuss below magnetic field data obtained in an etched constriction. Conductance quantization in shallow-etched quasi-1D channels has previously been studied in Ref. 8. The shallow-etching technique allows a precise control over the shape of the constriction, and can produce quasi-1D channels with a large subband separation.

The experimental arrangement used in this work is similar to that described in Refs. 4–6 with the exception of the quasi-1D channel design. The design is illustrated in Fig. 1. The constriction is contained between two shallow-etched trenches and consists of a straight segment 1 μm long and 0.2 μm wide connected to quadrants of radius 5 μm. Areas of 2D electron gas (2DEG) adjacent to the constriction serve as gates. The wafer used had a low-temperature mobility of $1.0\times 10^{6}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ and a carrier concentration of $1.9\times 10^{11}\,\mathrm{cm}^{-2}$. The acoustoelectric current through the channel induced by the SAW was measured by a low-noise cur-

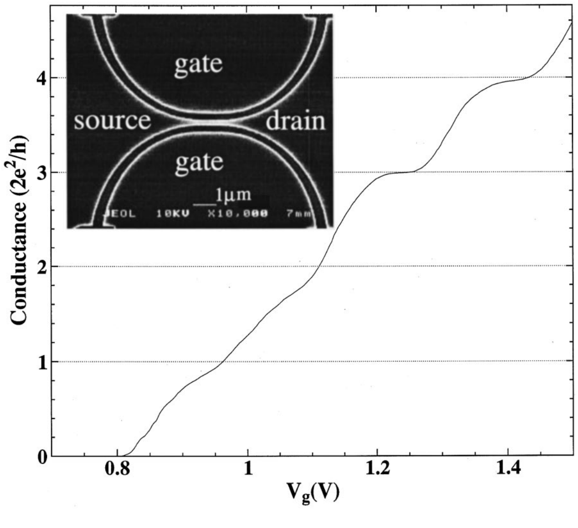

FIG. 1. Main figure: Conductance of the quantum point contact (QPC) as a function of gate voltage. $T=1.2$ K. Data were taken using a 10 μV excitation voltage in a standard lock-in technique. The data are corrected for a series resistance of 1.2 kΩ, comprised of the Ohmic contact and 2D lead resistances, chosen to align the conductance plateaus to $2e^2/h$. Inset: micrograph of the shallow-etched constriction. 2DEG areas marked ''gate'' are isolated from source and drain regions by etched trenches.

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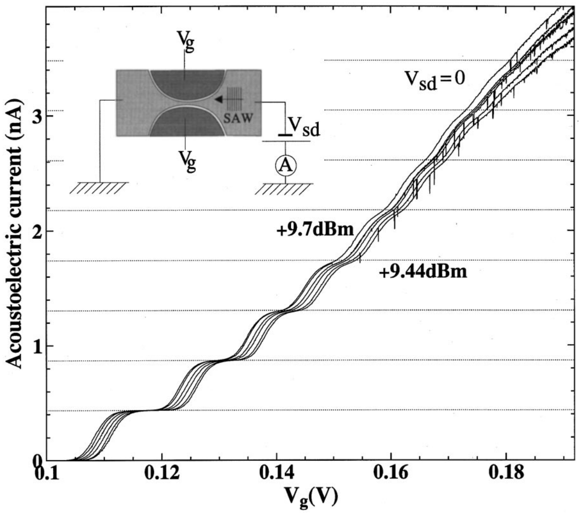

FIG. 2. The acoustoelectric current as a function of gate voltage for different SAW power levels. Figures in dBm refer to the power level of the microwave source connected to the transducer. The dashed lines represent the expected value of the quantized current at this frequency.

rent preamplifier with accuracy ±0.7%. The SAW, at a frequency of 2.716 25 GHz, was launched by an interdigital transducer situated 3 mm away from the channel. In Fig. 1 the conductance of the constriction with no SAW applied is shown. The shape of the first two plateaus in conductance is distorted by an impurity potential. The pinch-off voltage is positive since the channel is depleted at zero gate voltage by surface states in the etched trenches. At gate voltages below approximately 0.8 V the channel contains no electrons and the potential profile along the channel resembles a potential hill.

When a powerful SAW is present it transfers electrons through the channel even in the gate-voltage domain below pinch-off voltage for conductance. Electrons are transported along the channel in SAW potential minima. The electrostatic interaction between electrons in a SAW potential minimum results in a quantized acoustoelectric current[4,5] as demonstrated in Fig. 2.

We iteratively adjust the frequency (within the transducer passband) and power of the surface wave in order to obtain the flattest achievable plateau. A closer look at the first plateau in acoustoelectric current under optimum conditions is presented in Fig. 3. The data in Fig. 3 are the result of averaging over four consecutive traces. The first plateau is sufficiently flat to enable determination of the quantized current with a precision of ±60 ppm. This result represents an improvement of nearly two orders of magnitude compared to our previous work using one SAW.[5] We have recently observed a quantized acoustoelectric current in a Schottky-gated contact with precision ±50 ppm using a different experimental technique employing two counterpropagating SAW's.[9]

Another distinctive feature of the etched constriction is its robustness against source-drain bias. This is an important property because it determines the internal impedance of the SAW device as a current source. The bias is applied using the internal voltage source of our preamplifier in such a way that it affects the potential profile at the entrance to the channel, as shown schematically in the inset to Fig. 2. In Fig. 4 we show the acoustoelectric current traces for different source-drain biases. The device withstands a bias at least ten times larger than that discussed in Ref. 5. The inset to Fig. 4 shows a close-up of the plateau under the action of a bias. A 3 mV change in bias with gate voltage kept constant results in an approximately 0.01 nA change in the current. The corresponding impedance is $3\times10^8\ \Omega$.

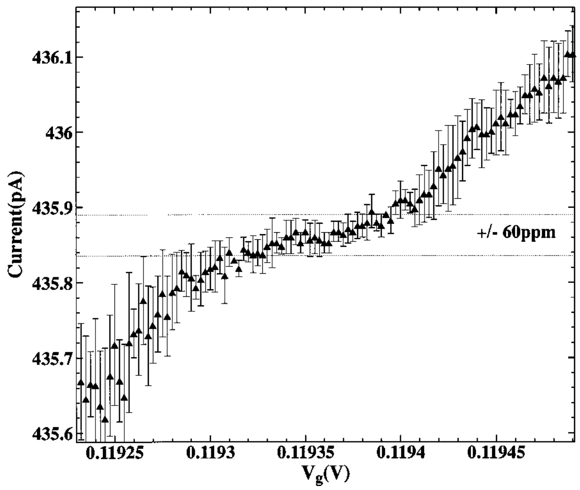

FIG. 3. Detail of the first acoustoelectric current plateau under optimum conditions (see text) of SAW, frequency ($f = 2.716\,25$ GHz) and rf power (9.7 dBm). Temperature is 1.2 K. Error bars represent one standard deviation from the mean current recorded at each value of gate voltage. The horizontal lines represent the error in determining the experimental value of current from the noise on the data, equivalent to approximately ±60 ppm. The experimental value of current calculated from the mean of the data within this limit is 435.86 pA. The expected quantized value ($ef = 435.19$ pA) is well within the stated accuracy of the preamplifier used in the measurement (±0.7%).

The longer length of the channel is likely to be the reason for the reduced susceptibility to dc bias. We note that the

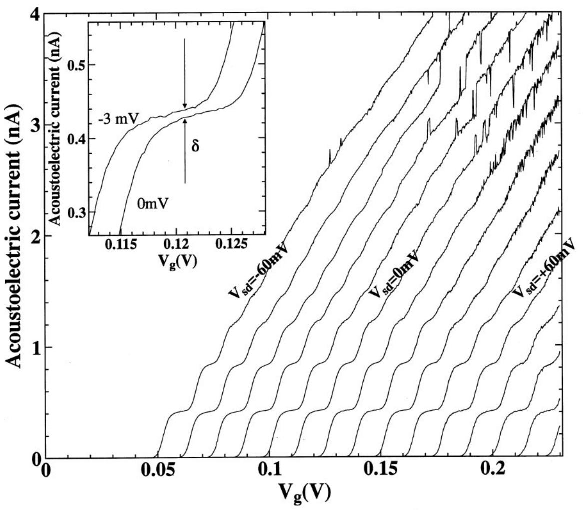

FIG. 4. Traces of acoustoelectric current for different values of the source-drain bias V_{sd}. Current was measured from an Ohmic contact nearest the entrance of the channel and bias was applied as shown in the inset to Fig. 2. Inset: Close-ups of the first plateau at 0 and −3 mV.

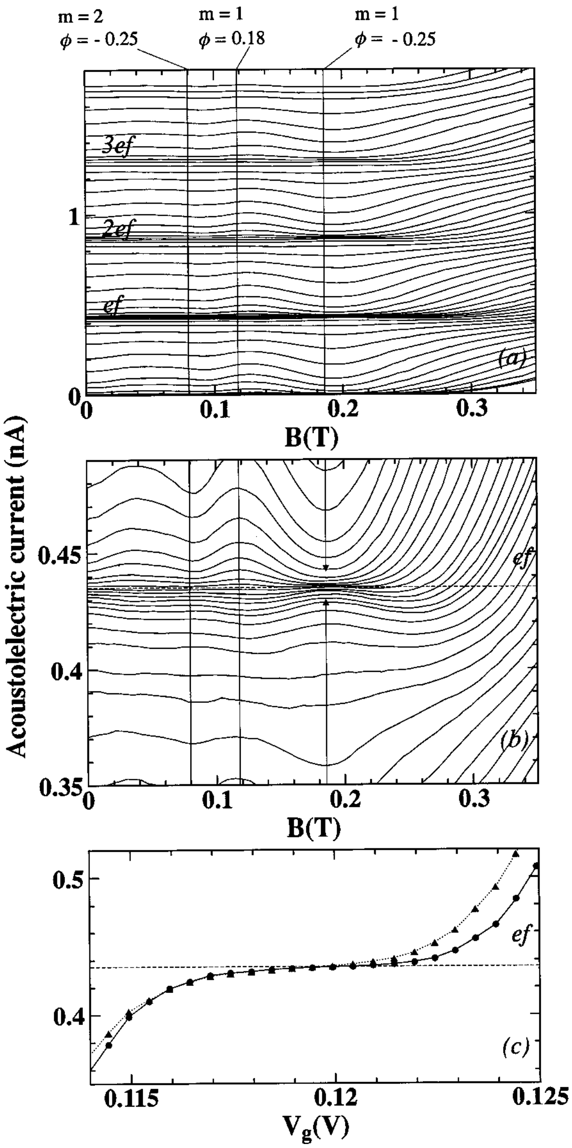

FIG. 5. (a) Dependence of the acoustoelectric current on magnetic field applied perpendicular to the plane of the 2DEG for a range of gate voltages covering the first three plateaus. The gate voltage is incremented in steps of 1 mV, between sweeps of magnetic field. The vertical lines represent the expected field positions of 2D commensurability maxima and minima for the SAW wavelength used, with carrier concentration N assessed from the longitudinal 2D SdH period. (b) Detail of the first plateau in acoustoelectric current taken in the same manner as (a), but with finer gate-voltage increments between subsequent sweeps (0.5 mV). (c) Acoustoelectric current as a function of gate voltage. Dashed line is at $B=0$ T and solid line is at 0.18 T.

quantized current plateaus observed here occur in a region of gate voltage up to 600 mV beyond conductance pinch-off. In comparison, the corresponding values for Schottky gates were under 100 mV.

We now discuss the influence of a perpendicular magnetic field on the acoustoelectric current. The dependence of the acoustoelectric current on a small magnetic field at different values of gate voltage is shown in Fig. 5. The plateaus in acoustoelectric current manifest themselves in Fig. 5(a) as extended black areas made up of several condensing curves. The graph displays oscillations of the current in the region below 0.2 T. These can be identified as commensurability oscillations on the basis of the results contained in Ref. 10, where similar oscillations were observed. In that work the acoustoelectric current induced in a plain 2DEG mesa by a SAW was studied for different SAW wavelengths. The oscillations of the current as a function of magnetic field were observed with the oscillatory structure shifting to higher magnetic fields for shorter SAW wavelengths. This behavior[10] demonstrated unambiguously that the oscillations are due to the geometric resonances between the SAW wavelength and the cyclotron diameter. The positions of the maxima and minima are found to be reasonably well described by a theory[11] developed to explain commensurability oscillations in dc magnetoresistance.[12] These positions [calculated using Eq. (1) of Ref. 11] are shown by vertical lines in Figs. 5(a) and 5(b). Calculated positions are seen to be in good agreement with the experimental ones except for the first maxima at 0.04 T. The oscillations are due to the SAW-electron interaction in the 2DEG areas [the cyclotron diameter exceeds the channel width ($\leqslant$200 nm) for $B\leqslant 0.6$ T], and it is not clear at present how they affect the acoustic transport through the 1D channel. One simple mechanism could be that the SAW creates a potential buildup in the adjacent 2DEG's, which is equivalent to a source-drain bias across the channel. The potential drop is likely to oscillate as a function of B due to the geometric resonances between the cyclotron diameter and the SAW wavelength. The oscillating bias results in the oscillations of the acoustoelectric current through the channel. This model explains why the oscillations grow weaker as the gate voltage approaches the value corresponding to the plateau in current (as the plateau current is insensitive to the bias); however, it fails to explain the change in phase of the oscillations as the gate voltage crosses the ''plateau value'' [Figs. 5(a) and 5(b)]. An interesting result of this change of phase is that the curves converge at some particular field value (corresponding to $2R_C = 1.18\lambda_{\mathrm{SAW}}$) as shown by the arrows in Fig. 5. This means that the first plateau in the acoustoelectric current becomes flatter at this value of the magnetic field [Fig. 5(c)]. Another possible mechanism for the oscillations in Figs. 5(a) and 5(b) could be that B modulates the density of states in the 2DEG adjacent to the 1D channel entrance and thus affects the probability of backward tunneling of the electron trapped in the moving SAW dot. This mechanism was suggested and is currently being considered by Gumbs and Aizin.[13] If proven, the mechanism will indicate that the backward tunneling constitutes a noticeable source of error in the SAW pump. From an experimental point of view it seems possible to suppress the backward tunneling by making a more elaborate SAW pump. An interesting possibility is to replace the 2DEG-type entrance to the depleted 1D channel by a 1D channel with controllable electron density. This can be done with the help of an additional split gate in close proximity to the main gates defining the depleted 1D channel. The additional split gate allows control of the density of states in the electron reservoir and the entrance to the main channel and therefore control of the backward tunneling.

Another finding illustrated in Figs. 5 and 6 is that a perpendicular magnetic field negatively shifts the pinch-off voltage for acoustoelectric current. If the gate voltage is set such

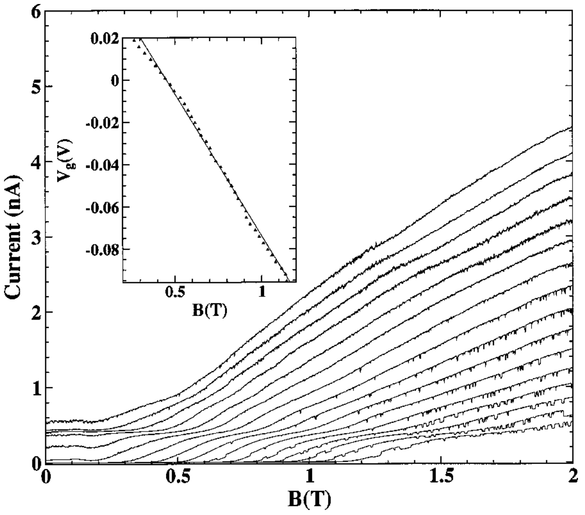

FIG. 6. Dependence of the acoustoelectric current on magnetic field for a larger interval of field and gate-voltage values. Inset: Pinch-off voltage of the acoustoelectric current as a function of magnetic field. We define pinch-off as the point at which the acoustoelectric current falls below 5 pA. Pinch-off is seen to move to more negative gate voltage with increasing perpendicular magnetic field linearly. The solid line is a least-squares fit to the data.

that the channel is closed for acoustoelectric current at $B=0$, a sufficiently large magnetic field can open the channel at this fixed gate voltage. The inset of Fig. 6 shows how pinch-off voltage for acoustoelectric current depends on magnetic field strength. This is a rather surprising effect because it is known that the pinch-off voltage of a quasi-1D channel is independent of magnetic field.[14] We have performed conductance measurements on our channel and observed that the pinch-off voltage for conductance is unaffected by the magnetic field in the regimes shown in Figs. 5 and 6.

There is presently no theoretical description of either of these effects. When discussing the magnetic field data in Figs. 5 and 6 one should consider any possible influence of the field on the SAW amplitude. The one-dimensional channel is adjoined by 2DEG's (Fig. 1), and the SAW field within the channel may depend on how it is screened by their proximity. The screening of the SAW field by a 2DEG is determined by the 2DEG conductivity and is therefore a strongly nonmonotonic function of magnetic field strength.[15] Nevertheless, we have not observed any features in the curves in Figs. 5 and 6 that could be associated with Shubnikov–de Haas (SdH) oscillations (the onset of which is at 0.25 T for the wafer used) in the 2DEG conductivity. For this reason it is likely that the effect of the magnetic field on pinch-off voltage for acoustoelectric current is not caused by the field-dependent screening of the SAW in the adjacent 2DEG areas.

In conclusion, we have observed the effect of perpendicular magnetic field on the quantized acoustoelectric current in a one-dimensional channel. We used a shallow-etched channel SAW device, which displayed a more precise and robust quantized acoustoelectric current than has been previously reported. Experimental results have been presented that show oscillatory structure at low magnetic field between current plateaus with a periodicity identical to the 2D commensurability period. A change in phase of the oscillations occurs as a current plateau is approached from below. In larger magnetic fields the pinch-off voltage for acoustoelectric current moves to more negative values of gate voltage. We hope that this work will stimulate further theoretical investigation of acoustoelectric current quantization in quasi-1D systems.

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