Single-electron transport in a one-dimensional channel by high-frequency surface acoustic waves

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We report a detailed experimental study of the quantized acoustoelectric current induced by a surface acoustic wave in a one-dimensional channel defined in a GaAs-$Al_xGa_{1-x}As$ heterostructure by a split gate. The current measured as a function of the gate voltage demonstrates quantized plateaus in units of $I=ef$ where e is the electron charge and f is the surface acoustic wave frequency, the effect first observed by Shilton *et al.* The quantization is due to trapping of electrons in the moving potential wells induced by the surface acoustic wave, with the number of electrons in each well controlled by electron-electron repulsion. The experimental results demonstrate that acoustic charge transport in a one-dimensional channel may be a viable means of producing a standard of electrical current. [S0163-1829(97)01248-4]

INTRODUCTION

Electron-electron interactions in submicrometer devices have made it possible to control electric current at the single-electron level. Devices based on Coulomb blockade of the tunneling have been proposed that are controlled by an external radio frequency (RF) signal and deliver quantized current, in units of $I=ef$ where e is the electron charge and f is the RF signal frequency.[1–6] Many-junction electron pumps exist that are now capable of transferring up to 10^8 electrons without an error.[6] This field has attracted great interest because of possible applications to an accurate current standard and other devices. Unfortunately the existing devices employing Coulomb blockade of the tunneling operate at low frequencies (a few megahertz) and therefore deliver low quantized current, which limits their applications.

In this paper we describe an approach to the problem of single-electron transport that results in quantized currents in the nanoamp range, nearly three orders of magnitude larger than the ''conventional'' [1–6] devices produce. We employ a surface acoustic wave (SAW) to drag current through a one-dimensional channel formed in a GaAs-$Al_xGa_{1-x}As$ heterostructure. A SAW propagating on a piezoelectric substrate, such as GaAs, is accompanied by a wave of electrostatic potential, which acts on electrons in the channel [a discussion of SAW-2DEG (two-dimensional electron gas) interaction can be found in Ref. 7]. SAW's of sufficient amplitude will transport the charge in the form of electron packets residing in the potential minima that can be considered, for a small ($\lambda<1\ \mu$m) SAW wavelength, as moving quantum dots. The Coulomb interaction between electrons in one packet will result in the appearance of band gaps in the energy spectrum of the dots. In our experiments the one-dimensional channel is defined by a split gate[8] so that the SAW transfers electrons between two 2DEG areas, source and drain, separated by the channel. When the channel is pinched off, electrons are brought up the potential hill in the SAW potential well, the number of electrons in each well being determined by the SAW electric potential strength and the shape of the potential hill. If the local potential minimum moving up the potential hill at the ''entrance'' to the channel is not sufficiently deep (on the scale of the Coulomb charging energy) to hold more than one electron, then the system will demonstrate single-electron transport per SAW cycle and deliver quantized current $I=ef$ within some interval of the relevant parameters. As the gate voltage is made less negative the SAW will be able to bring two electrons up the potential hill in each potential well, and so on.

Experimentally, the acoustoelectric current in a one-dimensional channel was studied in Refs. 9 and 10. In Ref. 9 the length of the channel was smaller than the SAW wavelength ($\lambda\approx3\ \mu$m), and for this reason single-electron effects did not appear in those experiments. The extension of this work to higher SAW frequencies ($f\approx3$ GHz, $\lambda\approx1\ \mu$m) in Ref. 10 did reveal single-electron effects in the acoustic charge transport. At high SAW power levels, an acoustoelectric current was observed at gate voltages beyond pinch-off, and the current displayed a steplike behavior as a function of the gate voltage with the current value on the plateau corresponding to the transfer of one electron per SAW cycle.

In this work, we present a number of further observations concerning this acoustically driven single-electron transport. In particular, we have been able to observe clearly up to four plateaus in the current corresponding to the transfer of one to four electrons in each SAW potential well. By studying the acoustoelectric current for different SAW frequencies we detected the expected frequency dependence of the quantized current. Accuracy of the measurement of the current has also been improved. Probably the most surprising fact is that the accuracy of the quantized current that the conceptually simple arrangement produces is very high, and is limited at present by the error (0.3%) of our measuring instrument.

EXPERIMENTAL RESULTS

The device comprises two SAW interdigital transducers separated by 4 mm, with a split gate on a 2DEG mesa in between. The 2DEG was a GaAs-$Al_xGa_{1-x}As$ heterojunction with electron density 2.7×10^{11} cm^{-2} and mobility 7×10^5 cm^2/V s. The transducers operate at frequency 2886 MHz corresponding to a SAW wavelength $\lambda\approx1\ \mu$m. The split gate was 0.7 μm long, with a 0.7-μm gap, dimensions chosen to give an electrostatically defined channel the same

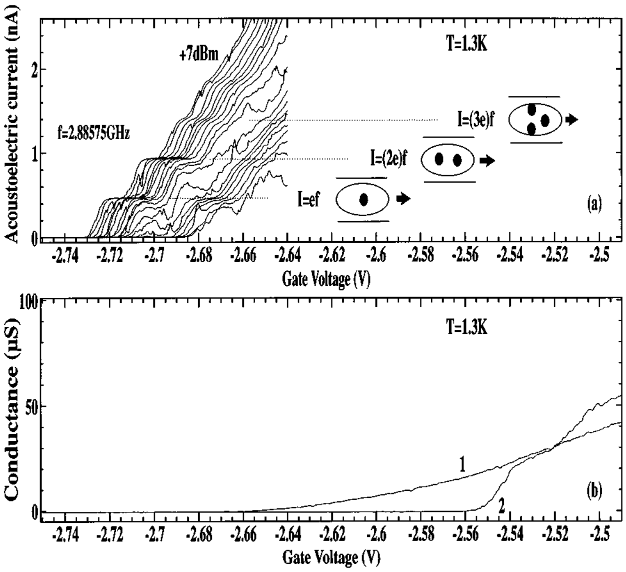

FIG. 1. (a) The acoustoelectric current as a function of split gate voltage. The different curves correspond to different RF power levels from +3 up to +7 dBm in steps of 0.2 dBm. The diagrams illustrate our explanation of the plateaus in the acoustoelectric current (see text). (b) The conductance of the channel as a function of the gate voltage on the same voltage scale. Curve 1 is taken with +7 dBm unmodulated SAW on.

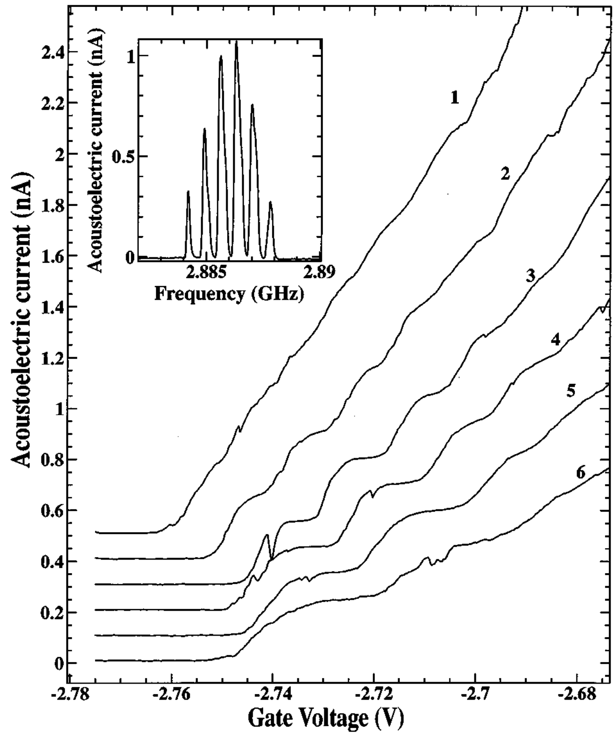

FIG. 2. The acoustoelectric current vs gate voltage for slightly different SAW frequencies. Curves from 1 to 6 correspond to frequencies from 2.885 600 to 2.885 850 GHz incrementing in 50-kHz steps. RF power level +6 dBm, temperature 1.3 K. Inset: variation of the acoustoelectric current with frequency for constant gate voltage $V_g = -2.77$ V. RF power +5 dBm, temperature 1.3 K.

length as the SAW wavelength. SAW-induced current was measured by connecting an ammeter to two Ohmic contacts on the 2DEG mesa on either side of the split gate. Both ac and dc techniques were used with the accuracy of the current measurements ±1% and ±0.3% for ac and dc methods, respectively. For ac measurements the RF source feeding the SAW transducer was pulse modulated with duty cycle 0.5 and frequency around 200 Hz and a standard lock-in technique was used. The experimental technique is described in more detail in Ref. 10.

The experimental data for the acoustoelectric current in an open channel are presented in Refs. 9 and 10 and will not be discussed in this paper. We would like only to mention here that the physics behind the acoustoelectric current in an open channel[9,11] is quite different from that discussed in the Introduction. The picture of the transport in the form of electron packets is not applicable in this regime (at least at the SAW power levels attainable in our experiments) because of the screening of the SAW electric field by 1D electrons.

When the split gate is pinched off, the acoustoelectric current can be observed only for sufficiently high RF power levels, consistent with electrons being forced through the channel by the SAW. This is shown in Fig. 1 along with the channel conductance data. As the gate voltage is made less negative the current shows quantized plateaus with up to four plateaus clearly seen [Fig. 1(a)] with the width and the flatness of the plateaus consistently deteriorating. The experimental value of the quantized current agrees with calculated value $I = efn$ which implies that plateaus correspond to the transfer of the same number of electrons in each SAW potential well, as illustrated by diagrams in Fig. 1. A small change of the SAW power shifts the threshold value of the gate voltage where the current appears but leaves the quantized current value on a plateau unchanged. Figure 1(b) demonstrates the conductance behavior close to pinch-off, the conductance being measured by the usual ac lock-in technique. Trace 2 was taken with +7 dBm unmodulated applied SAW. We can see that the SAW alters the conductance curve, washing out the steplike increase of the conductance at the pinch-off voltage. The data in Fig. 1(a) display an interesting feature: the existence of domains of RF power level where the plateaus are clearly seen. The plateaus are seen to exist in intervals of the RF power levels from 7 to 5.2 dBm and from 4.0 to 3.2 dBm and to disappear in between. This fact is unexpected and at present we have no explanation. Another rather unexpected observation concerns the influence of a slight change in SAW frequency (within the transducer's passband) on the acoustoelectric current in the gate voltage region close to pinch-off. This is illustrated in Fig. 2. The threshold gate voltage is seen to alter with the change of the SAW frequency in a nonmonotonic way. If the gate voltage is set to a constant value below the pinch-off voltage then this mechanism can result in giant 0.7 MHz oscillations of the acoustoelectric current as a function of the SAW frequency, as shown in the inset in Fig. 2. This is explained as being due to partial reflection of the SAW from the second (unconnected) transducer, which causes a slight spatial modulation of the SAW amplitude due to the interference between the forward and the backward beams. A slight shift in the SAW frequency (well within the transducer's passband) will change the position of the SAW amplitude's minima and maxima along the channel. This spatial

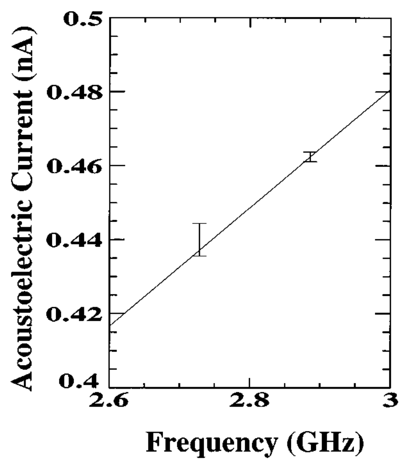

FIG. 3. Comparison of the value of the acoustoelectric current on the first plateau for two samples. The straight line corresponds to $I=ef$ dependence where e is the electron charge.

distribution of the SAW amplitude repeats itself periodically as the SAW frequency varies and the period can be calculated from the distance between the transducers and the SAW velocity giving a value of 0.7 MHz. When the split gate is open then the movement of the spatial distribution of the SAW amplitude gives rise to a weak modulation of the acoustoelectric current.[10] Below or close to the pinch-off voltage the small change in RF frequency has a more pronounced effect as shown in Fig. 2. This is because the threshold voltage for the acoustoelectric current is very sensitive to the SAW magnitude (see Fig. 1). Different RF frequencies correspond to different SAW amplitudes at the entrance to the channel and therefore to different threshold voltages for the acoustoelectric current. This proposed explanation of the 0.7-MHz modulation is supported by the observation that a sample with only one SAW transducer did not show the modulation.

In Fig. 3 we compare the quantized current values on the first plateau obtained in the present and previous work.[10] The frequencies of SAW in these two experiments differ by 5% and the experiments have confirmed the expected frequency dependence of the quantized current (see Fig. 3). The present data shown in Fig. 3 were taken by a dc technique, which resulted in a smaller error.

Application of a rather large (± 5 mV) dc source-drain bias does not change the quantized acoustoelectric current for the first plateau, as shown in Fig. 4. These data allow us to estimate the internal impedance of the device as a current source to be well above 10 MΩ.

The experimental data described above (except for the one point in Fig. 3) were taken by ac lock-in technique. For a metrological application dc measurements of the current, providing higher accuracy, are preferred. For these measurements a Keithley 236SMU operating in the ''current measure'' mode was directly connected to the Ohmic contacts to the 2DEG mesa and unmodulated RF power was applied to the SAW transducer. The 236SMU instrument was set to have an averaging time of about 0.7 s. In Fig. 5 we show the current curves for different RF generator power levels. The data display the presence of noise that is most intense in the regions between the plateaus. The behavior of the noise is

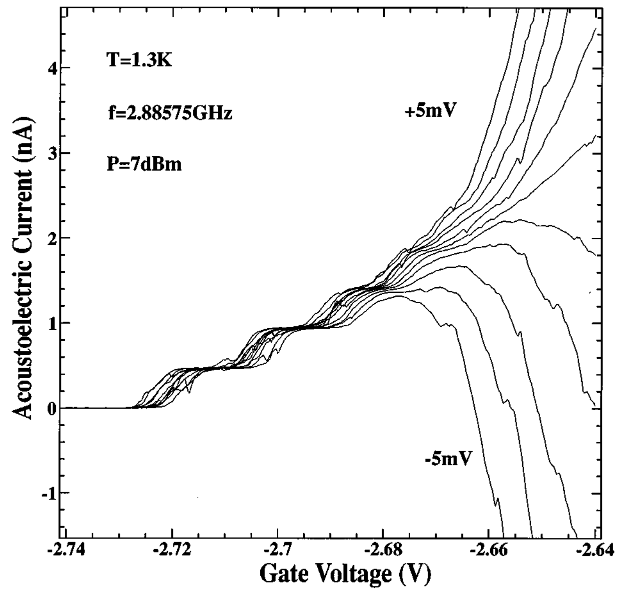

FIG. 4. The acoustoelectric current vs split gate voltage at different source-drain bias. The value of source-drain bias increments in 1-mV steps.

demonstrated more clearly in Fig. 6 for RF power level 6 dBm. The data in this figure were obtained by taking several (nine for this figure) readings of the current at fixed values of gate voltage separated by 0.25 mV. The noise is seen to behave differently on each side of the plateau. When the gate voltage is more negative, ''spikes'' point downwards and on the right-hand side of the plateaus where the acoustoelectric current exceeds the quantized value ''spikes'' are directed upwards. It is natural to choose the point on a plateau where the ''spikes'' change direction to determine the experimental value of the quantized current. In this way we determined the experimental quantized currents for seven sweeps similar to

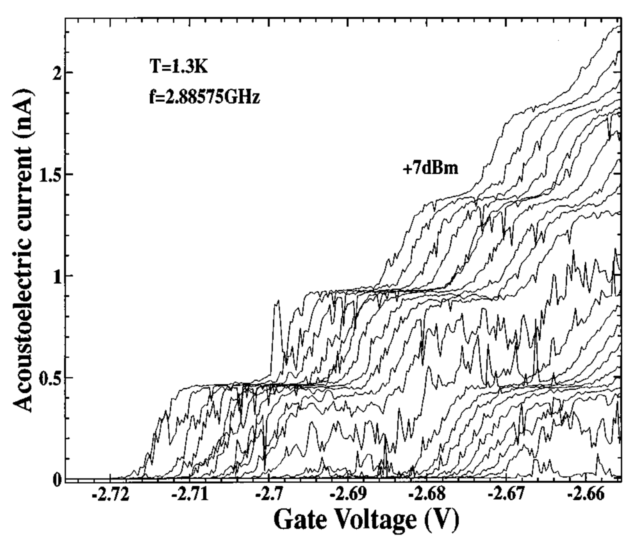

FIG. 5. The acoustoelectric current vs gate voltage for different values of SAW power level. The leftmost trace corresponds to +7 dBm SAW power level and the power level decreases by 0.2 dBm from trace to trace. Data taken by dc technique.

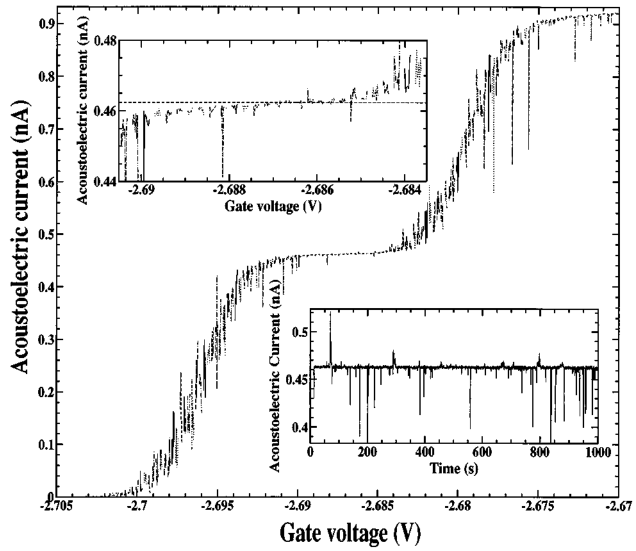

FIG. 6. The acoustoelectric current vs gate voltage taken by dc technique. Temperature 1.3 K, SAW frequency 2.885 75 GHz, RF power +6 dBm. The trace consists of many sets of data each set corresponding to nine readings of the current taken at fixed value of gate voltage within 10 s time interval. To enable these readings to be seen separately the corresponding points were shifted horizontally and connected by straight lines. After one set had been completed the gate voltage was incremented by 0.25 mV and the next set of nine readings was taken. Upper inset: blowup of the first plateau of the current. The neighboring sets of data are seen separately. The dashed line represents the acoustoelectric current value ($I=ef$) for true single-electron transport. Lower inset: variation of the acoustoelectric current with time at a single fixed-gate voltage in the middle of the first plateau. The SAW frequency 2.885 75 GHz, RF power +7 dBm.

that shown in Fig. 6 and taken for the RF power levels from 5.8 to 7 dBm (in steps 0.2 dBm). The value averaged over these sweeps was found to be 462.8 pA. If values of the current are taken at the middle of the plateaus, determined by eye, then the corresponding averaged result is 462.1 pA. The experimental value is remarkably close to the expected $ef=462.348$ pA, but caution is advised, as the quoted accuracy of the ammeter (a Keithley 236SMU) would correspond to an error of 1.3 pA. Nonetheless, the agreement is encouraging for such early experiments.

Observations of similar noise have been reported in conductance measurements on 1D channels.[12] The authors explained their results as being due to a nearby impurity switching between two states, and altering the effective width of the channel (random telegraph signal). There are effectively two curves, offset in gate voltage, and the constant switching between them has the effect of smoothing out the plateau in an experiment if the time constant of data acquisition is longer than the switching time of the noise. If this is the case with our devices, then it should be possible to fabricate samples that do not show this behavior by varying the growth conditions. The experimental data presented demonstrate single-electron transport with promising accuracy for such a conceptually simple experimental arrangement and raise the question of what the ultimate accuracy of a SAW-based current standard could be. A quantitative theory tailored to the experimental conditions is needed to answer this question. According to the qualitative picture given in the Introduction there are two sources of error in the quantized current. Firstly, not all ''extra'' electrons may have enough time to escape the SAW potential well. This error depends on how quickly the electron system adjusts to the changing potential shape of the well and can in some extent be controlled by varying the shape of the entrance potential. Secondly, some electrons that are supposed to be transferred through the channel can leave the well by tunneling under the potential barrier. To estimate these errors one needs to know the SAW potential within and near the channel. Unfortunately, this is rather difficult to calculate because of the screening action of the gates and adjacent 2DEG's.

One important aspect to be addressed by any future theory is how the accuracy of the quantized current delivered by SAW-based devices depends on the operation frequency. In the regime when the acoustoelectric current is quantized such that only one electron is allowed in a potential minima the SAW potential amplitude can be estimated to be $A_{SAW}\approx e/\kappa\lambda$ where κ is an effective dielectric constant and λ is the SAW wavelength. The effective SAW electrostatic field that acts on electrons is $E=A_{SAW}/\lambda\approx e/\kappa\lambda^2\sim ef^2/\kappa$ and increases with the increase of the SAW frequency. The impurity potential, which is always present to some extent and brings an element of unpredictability in any single-electron SAW device, does not of course depend on the SAW frequency. So we may conclude that the higher the SAW frequency the more robust the device will be against an impurity potential. Another advantage of increasing the operation frequency is the larger quantized current delivered. In the spirit of Refs. 13–15 one may expect that it is the nonadiabaticity that will determine the ultimate accuracy of the SAW-based current standard. If we assume that the ratio of sound to electron velocities is a parameter to describe the nonadiabaticity then the fractional error will not increase with the frequency. So at present increasing the SAW frequency appears to be a promising way of developing a current standard.

In conclusion, we have presented experimental data that unequivocally demonstrate acoustically driven single-electron transport. The accuracy of the current quantization observed in our experiments suggests that SAW-based devices may open a route towards the creation of a current standard. An advantage of the acoustic charge transport devices is that they deliver current in the nanoamp range, nearly three orders of magnitude larger than their ''conventional'' counterparts based on Coulomb blockade phenomena.[1–6]

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