Single-electron acoustic charge transport by two counterpropagating surface acoustic wave beams

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A powerful surface acoustic wave can transport charge along a quasi-one-dimensional channel defined in a piezoelectric semiconductor in packets confined to the minima of the wave's electrostatic potential. The interaction between electrons can suppress fluctuation in the number of electrons in a packet, resulting in a current that is proportional to the surface acoustic wave (SAW) frequency. This effect has been observed experimentally and is presently being considered as a possible route towards a standard of electric current. Here we present further study of this acoustic charge transport. The main finding is that a weak counterpropagating SAW beam can be used to improve the precision of the current delivered by the device. [S0163-1829(99)02431-5]

INTRODUCTION

The ability to manipulate charge on the level of single electrons has led to devices that are controlled by external ac signals and produce current that is proportional to the frequency of the signal.[1–6] One of the goals behind the development of such devices is an electric current standard. At present the many-junction electron pumps[6] can transfer electrons with an error approximately one part per 10^8. The low delivered current of around 1 pA is the main drawback of this type of device.

A different approach towards a current standard was employed in our previous work[7–9] that has resulted in quantized currents in the nanoamp range. We investigated the acoustoelectric current in a one-dimensional channel defined in a GaAs-$Al_xGa_{1-x}As$ heterojunction induced by a high-frequency surface acoustic wave (SAW). The acoustic charge transport takes place in the form of moving quantum dots with a fixed number of electrons in each dot, the channel being formed by the split-gate technique.[10] The acoustoelectric current vs gate voltage trace was observed[7–9] to display a plateaulike structure. The value of the current on the plateau is $I=efn$, where e is the electron charge, f is the SAW's frequency, and n is the number of electrons transferred through the channel per SAW cycle.

In the present study we attempted to address an intrinsic source of error in the SAW pump, namely, the slope of the acoustoelectric current plateau. This problem had not been investigated in detail in Refs. 7–9 mainly because of random telegraph signal (RTS) like noise that affected the observations. We have now found that the noise can be eliminated or greatly reduced by a proper choice of high-quality heterojunction. We also noticed during the previous studies[7–9] that the slope may be influenced by a small change of the SAW frequency within the transducer passband. This was suggested as being due to a partial reflection of the SAW from the second (unconnected) transducer. To clarify a possible role of the reflected SAW beam we have employed an experimental arrangement that allowed us to launch two counterpropagating SAW beams and to vary the relative magnitude and phase of the main and counterpropagating SAW beams. The corresponding experiments, described below, not only confirmed the role of the reflected beam, but have also shown that the arrangement with two counterpropagating SAW beams can be used in order to substantially improve the flatness of the quantized acoustoelectric current plateau.

EXPERIMENTAL TECHNIQUE AND RESULTS

A schematic of the experimental arrangement is shown in Fig. 1(a). This differs from that used in the previous studies[7–9] by the provision to feed both transducers simultaneously with two coherent microwave signals. The relative magnitude and phase of the microwave signals can be changed with the help of a phase shifter and an attenuator. This setup also allows experiments in the ''one-beam geometry'' with only one SAW transducer connected.

The sample geometry [Fig. 1(b)] was the same as discussed in Refs. 7–9 with the SAW transducers operating at a frequency around 3 GHz, corresponding to a SAW wavelength around 1 μm. The wafers used in this work are GaAs-$Al_xGa_{1-x}As$ heterojunctions with mobilities around $10^6\ cm^2/V\,s$ and carrier densities around $2\times10^{11}\ cm^{-2}$. The

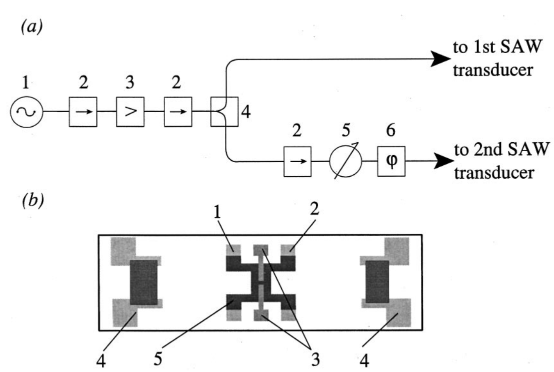

FIG. 1. (a) Schematic of the experimental setup. 1, the HP83620A microwave source; 2, an isolator; 3, minicircuits microwave amplifier ZHL with a 27 dB gain; 4, a 3 dB m hybrid-coupler that serves as a splitter; 5, a HP attenuator; 6, MA/Com phase shifters (two shifters in series were used). (b) Schematic of sample geometry. 1 and 2 Ohmic contacts between which acoustoelectric current was monitored; 3, split gate 4, interdigital SAW transducers; 5, mesa containing 2 DEG.

depth of the two-dimensional electron gas (2DEG) from the wafer surface was 100 nm in all cases. Samples were measured in a ^{3}He system fitted with coaxial lines to connect the transducers to a microwave source. The SAW-induced current was measured between contacts 1 and 2 [see Fig. 1(b)] as a function of gate voltage by a Stanford Research Systems SR 570 low noise current preamplifier with quoted accuracy $\pm 0.7\%$. Some samples were positioned in the cryostat in such a way that an in-plane magnetic field could be applied along the one-dimensional channel.

We used the following procedure for the measurements. Initially, optimal conditions of the two main parameters, SAW frequency and microwave power, were found. We monitored the acoustoelectric current as a function of gate voltage and incremented these two parameters iteratively to obtain the flattest achievable plateau. For a more accurate assessment of acoustoelectric current plateaus we used (in addition to continuous sweeps of gate voltage) a so-called ''stop and wait'' technique of taking data. In this technique the gate voltage was kept constant for 10 sec and during this time 100 readings of the acoustoelectric current were taken. Then the gate voltage was incremented by 100 μV and another set of data was taken and so on. This allowed us to average values of current over time.

The quantized steps in the acoustoelectric current have been observed only in a gate voltage interval below the pinch-off voltage of the channel (a possible reason is discussed in Ref. 8). All data discussed below were taken at 1.2 K. Cooling the samples down to 300 mK has not shown an improvement in plateau flatness. Only samples showing no RTS-like noise will be discussed below.

We have investigated many samples in the same way as described previously,[7–9] with only one transducer connected, when there is no control over the reflected SAW beam. This experimental geometry will be referred to as the ''one-beam geometry'' (despite the possibility that a second beam is reflected from the other, unconnected, transducer).

We have found that the plateau shape is such that there is an inflection point. Part of the plateau around the inflection point within a several millivolts interval of gate voltage can be approximated rather well by a straight section. Thus the flatness of a plateau can be quantified by a fractional slope $\Delta I/I\Delta V$, the latter being expressed as percent per mV or ppm (parts per million) per mV. The length of this segment determines the imprecision of the current that can be associated with the plateau. As the length of the segment is typically 1–2 mV in gate voltage then a value of the slope expressed in %/mV or ppm/mV gives at the same time the imprecision of the current in % or in ppm, respectively. In some cases, also discussed below, the first quantized current plateau displays a distinctive flat straight section and the imprecision of the current can be estimated in a straightforward way. We use in these cases the stop and wait technique described above to determine the mean and standard deviation of the current for a series of consecutive gate voltage increments on the plateau. We then define the imprecision of the plateau as an interval of current which includes all the means with standard deviations taken at each gate voltage on the flat section (Fig. 2).

The best result obtained so far in the ''one-beam'' geometry is presented in Fig. 2. The first plateau for this sample

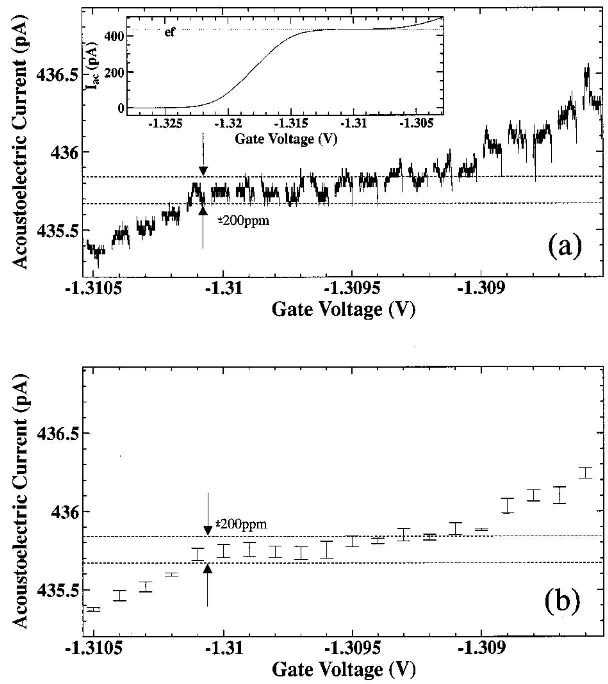

FIG. 2. (a) An enlargement of the first acoustoelectric current plateau for sample 1. Data were taken in the ''stop and wait'' fashion. Inset: the plateau with a dotted line showing the quantized value *ef*. (b) Data from (a) (main figure) averaged over time at each gate voltage. Error bars indicate the standard deviation of current at each gate voltage point.

displayed a straight flat section at the plateau center which allowed us to determine an imprecision of around ± 200 ppm using the above method. An enlargement of the first plateau for this sample (sample 1) is shown in Fig. 2(a). The noise seen in Fig. 2(a) is that produced by the 16 bit analog-to-digital converter used to measure the analogue output signal of the current preamplifier. The exact value of the quantized current for this sample $I = ef = 434.8$ pA differs by 0.23% from the experimental value 435.8 pA, the deviation being well within the quoted accuracy ($\pm 0.7\%$) of the ammeter. In Fig. 2(b) the data are presented after averaging over the readings taken at the same gate voltage. The horizontal dashed lines show the ''imprecision interval.'' Sample 1 represents the best result obtained in the one-beam geometry. The data taken for some more samples in the same geometry (samples 2 to 5) are shown in Table I. These samples showed an inclined straight segment of approximately 1 mV in length at the plateau center and we define the imprecision as an interval of current which includes all experimental points in this segment. We believe that the most likely reason for the difference in the form of the plateau for different samples is the impurity potential within the channel.

The split gates on the samples listed in Table I had slightly different widths and lengths in order to check any possible effect of the gate geometry on the quantized acoustoelectric current. To date we have not observed any definite influence of changes to the split-gate geometry on the slope of the first plateau provided that the channel is long enough for a potential well to be formed within it.

One sample (sample 6 in Table I) was prepared for measurements with the two SAW beams as shown in Fig. 1. Sample 6 had interdigital transducers with slightly different

TABLE I. This table shows the precision of quantized current for several devices (see text), along with details of gate geometry (dimensions refer to the gap between metal fingers and the length of the gate along the current path). Note that samples 1 and 6 displayed flat straight sections at the plateau center, whilst devices 2 to 5 had a finite slope as discussed in the text. All data were taken in zero magnetic field.

Device	Gate geometry Gap, length (μm)	Precision (all are $\pm$)	Mobility ($\times 1E6$ cm^2 V^{-1} s^{-1})	Carrier concentration ($\times 1E11$ cm^{-2})
1	0.7, 0.95	200 ppm	0.77	1.7
2	0.7, 0.25	1.7%	0.77	1.7
3	0.7, 0.25	0.2%	0.77	1.7
4	0.7, 0.8	0.2%	0.89	1.7
5	0.8, 0.6	0.5%	0.89	1.7
6	1.1, 0.6	50 ppm	1.1	2.2

resonant frequencies so that when one transducer was disconnected from the source the reflected counterpropagating SAW beam was weak and could be neglected. This is illustrated in Fig. 3 where traces of the acoustoelectric current induced by both transducers are shown. These traces were taken at a gate voltage of -1 V corresponding to open channel conditions. Carriers in the channel are expected to screen any impurity potential so that the relative magnitude of the peaks in Fig. 3 is determined by the SAW transducers and, to a lesser extent, by any possible asymmetry of the split gate. From the data in Fig. 3 it is clear that when only one transducer is connected to the source the reflected beam is negligible. When both transducers are connected to the source one can compensate for the off-resonance excitation of one transducer by applying a sufficiently large microwave signal from the source. Thus this arrangement allowed us to explore and compare the ''one-beam'' and ''two-beam'' regimes of device operation.

In Fig. 4 we show the acoustoelectric current versus gate voltage dependence for sample 6 with only one transducer connected to the source. The SAW frequency and power were set to provide the flattest first plateau. The optimum SAW frequency (2.6822 GHz) was found to coincide with the resonant frequency of the transducer.

One of the two curves shown in the top panel in Fig. 4(a) was taken with an in-plane magnetic field of $7T$ directed parallel to the channel. The computed derivatives of these dependences are presented on the bottom panel. At least 13 quantized current plateaus are revealed in the data in Fig. 4. An enlargement of the first plateau is shown in the inset in Fig. 4(a). The data in Fig. 4 show that an in-plane magnetic

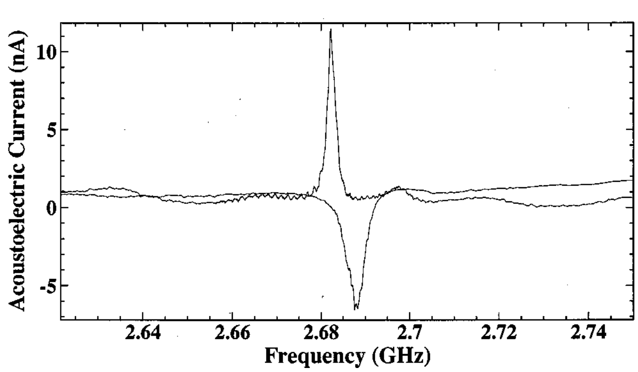

FIG. 3. Acoustoelectric current for both transducers of sample 6. The microwave power applied in both cases was +10 dB m.

field parallel to the channel noticeably improves the flatness of the plateaus. The mechanism behind the effect of a magnetic field is currently under investigation and will be discussed elsewhere. The magnetic-field data are included here only in order to demonstrate how many quantized current plateaus can be seen.

The distance between consecutive plateaus in Fig. 4 depends on plateau number (n) and can be rather well approximated by an $n^{-1/2}$ dependence as demonstrated in Fig. 5. These data contain information about the shape of the poten-

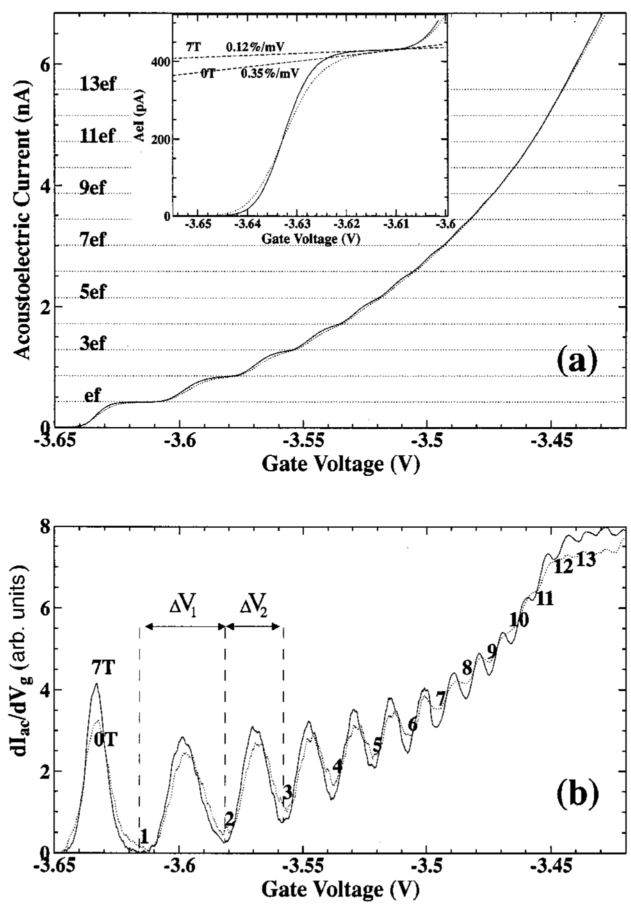

FIG. 4. (a) Traces of the acoustoelectric current for sample 6 in the one-beam geometry. The dotted and solid lines correspond to zero and 7 T magnetic field, respectively. Inset: an enlargement of the first plateau. (b) Derivative of the data from (a) (main figure) obtained numerically. The difference between consecutive plateaus ΔV_n is indicated.

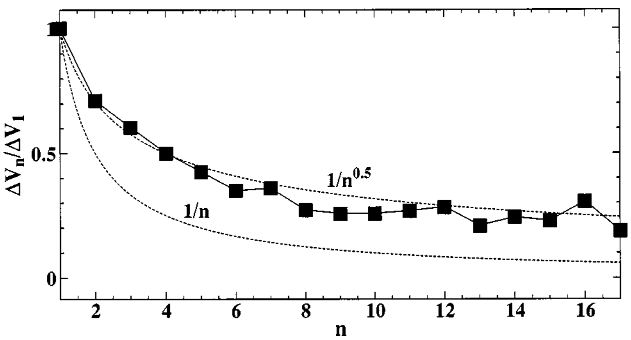

FIG. 5. The difference in gate voltage between the center of consecutive plateaus, normalized and plotted against plateau index n (squares). The data closely resembles a $n^{-1/2}$ dependence (dashed line).

tial well (which carries electrons through the channel as discussed in the next section) which will be valuable when a more quantitative theory of the device operation becomes available.

We now discuss the effect of a second SAW beam. Figure 6 shows the acoustoelectric current vs gate voltage around the first plateau at various fixed values of the phase shift between the SAW beams. The phase shift for consecutive panels differs by roughly 23°. The initial phase shift (first panel of Fig. 6) of one SAW beam relative to the other is unknown since the path from microwave source to transducers is different for the two signals (see Fig. 1). Nevertheless, we are able to control the phase shift throughout the 2π interval continuously and are therefore able to monitor the effect of any phase difference between the two beams on the current.

The attenuator (5 in Fig. 1) was set to 0 dB for all the panels. This corresponds approximately to a 10:1 power ratio of the main and counterpropagating SAW beams. The effect of the second SAW beam is dramatic and one can use it to reduce the slope of the first acoustoelectric current plateau. Data similar to those shown in Fig. 6 were taken for different settings of attenuator 5 (Fig. 1) and the source power in order

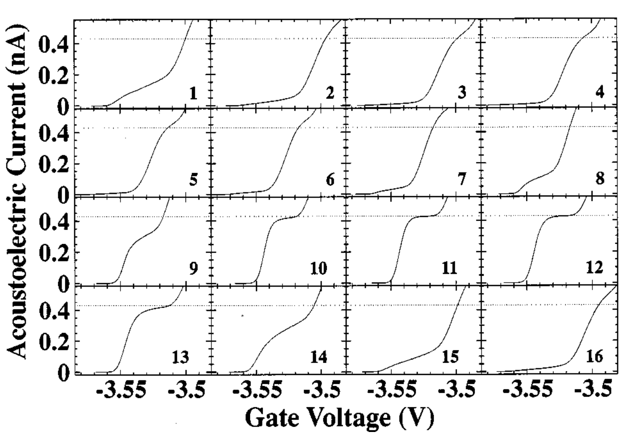

FIG. 6. Graphs of the acoustoelectric current vs gate voltage for different phase shifts between the main and counterpropagating SAW beams in zero magnetic field. Attenuator 5 [see Fig. 1(a)] was set to 0 dB, source power was +9.5 dB m after the amplifier [see Fig. 1(a)]. The phase change between consecutive panels was 23°. The change in phase moves the position of the standing wave with respect to the channel.

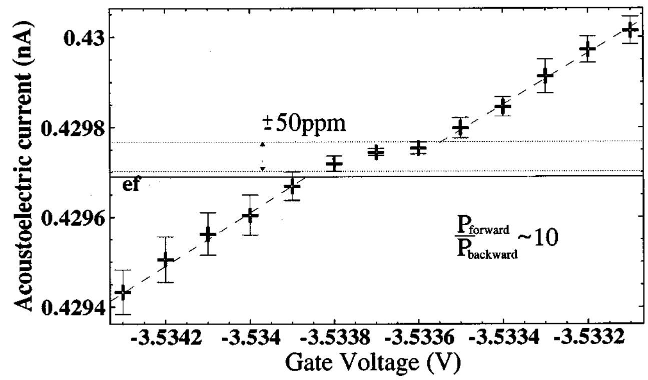

FIG. 7. Graph obtained using the stop and wait technique for the optimal phase shift between the two SAW beams in zero magnetic field. The flatter center section of the plateau allows us to choose an experimental value of current with a precision of ±50 ppm.

to find optimal values of these parameters resulting in the flattest possible plateau. The best result obtained in this way is shown in the 11th panel in Fig. 6. The slope of the plateau in this panel is 0.09% mV, nearly four times smaller than the slope obtained without the second beam (see the inset in Fig. 4). In an attempt to decrease the slope further we changed the phase shift and the source power in very small increments around the setting that corresponds to the 11th panel. We found that the shape of the plateau can be changed in such a way that the previously straight part of the plateau transformed into two straight nearly parallel sections interconnected by a segment with a very small slope. This is shown in Fig. 7 from which it is seen that an experimental value of the quantized current can be determined with an imprecision of ±50 ppm using the same method as that described above for sample 1. We would like to emphasize that the absolute value of all currents measured in this paper is subject to the ±0.7% accuracy of our preamplifier mentioned above. It is interesting to note that the optimal value of the source power that results in the flattest plateau in the two-beams geometry differs from that in the one-beam geometry (Fig. 4).

DISCUSSION

The main and rather unexpected experimental result of this study is the influence of a weak second SAW beam on the shape of the acoustoelectric current plateau. The superposition of the two traveling SAW beams can be described as a superposition of a strong traveling acoustic wave and a weak standing wave. The experimental arrangement sketched in Fig. 1(a) allows one to change the magnitude and position of the standing-wave pattern with respect to the channel. As a SAW minima moves along the channel it is affected by the oscillating standing-wave field. This changes the shape of the well (width and depth). Therefore the field associated with the standing SAW can be considered to perform a dynamic tuning of the potential wells propagating through the one-dimensional channel. The dynamic tuning is more effective than a static one because it changes the channel potential at a particular value of time that is synchronized with the SAW potential. By comparison a static tuning potential may improve the well shape during one interval of time within the SAW cycle and degrade it in another. Another advantage of the tuning by the standing SAW is that it

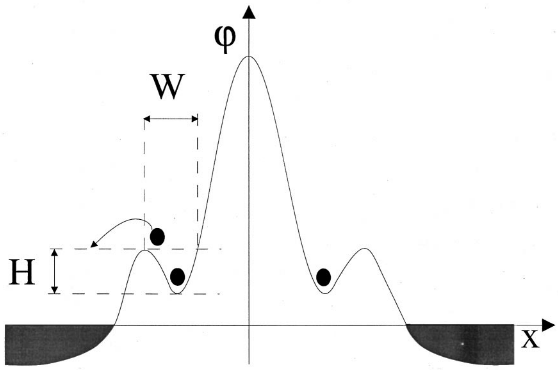

FIG. 8. Schematic of the SAW potential in the 1D channel. *W* is the well width and *H* the depth.

provides some control over the spatial position of the tuning field. Altering the phase of the counterpropagating SAW beam changes the position of the standing-wave pattern relative to the channel.

The observation that a relatively weak counterpropagating SAW beam can drastically change the shape of the plateau is in agreement with the picture we have used to explain the quantized acoustoelectric current.[7–9] According to this picture the selection of the number of electrons to be transferred takes place when the potential well moves up the potential hill at the entrance to the channel (Fig. 8). The shape of the well is determined by two factors, the static potential due to the split gate and the traveling potential of the SAW. Therefore the shape changes as the well moves into the channel because the static potential depends on position. Screening of the SAW potential by the gates and adjacent 2DEG also contributes to a spatial dependence of the well shape. By setting a gate voltage value one can control the desired number of electrons to be transferred. If the gate voltage is set to a value that only one electron per cycle can pass through, then, as the local potential minimum moves into the channel, its depth becomes insufficient to contain two electrons and only one electron is left in the well (Fig. 8). At this moment the well depth (H) is approximately related to the strength of interaction between two electrons in the well by $H = e/\varepsilon_{eff}W$, where ε_{eff} is an effective dielectric constant. ε_{eff} is approximately equal to $\varepsilon_{\mathrm{GaAs}}/2$ since the distance between electrons is much greater than the distance to the wafer surface. The width W is determined by the SAW wavelength and the spatial distribution of the potential due to the gate. For $W = 0.5\,\mu$m and $\varepsilon = 6$ one has $H = 0.5$ mV. The depth of the local minima (Fig. 8) is much smaller than an unscreened SAW magnitude (around 30 mV for the transducers used with +10 dB m power applied from the microwave source) and the height of the potential barrier due to the split gate. The latter can be estimated as the value of source-drain bias required for the current to start to flow through a pinched off channel. The corresponding measurements[11] showed that the potential barrier height for gate voltage V below pinch off can be calculated as $\alpha|V - V_g|$, where V_g is the pinch-off voltage. The coefficient α was shown[11] to be of order 0.5, resulting in typical value around 50–100 mV for the potential barrier height. As the well depth is significantly smaller than the SAW magnitude and the potential barrier height, it is not surprising that a relatively weak additional SAW beam can destroy the acoustoelectric current plateau (Fig. 6).

On the other hand, the probability of events that contribute to the error in the quantized current, such as failure of the first electron to leave the well or backward tunneling of the last electron out of the well, is very sensitive to the well shape. At this stage it is not possible to state which of these possible error mechanisms is being suppressed using the counterpropagating SAW beam, but our data demonstrate that a counterpropagating SAW beam with properly chosen amplitude and phase shift can change the well shape in such a way that the probability of unwanted events is reduced.

If the above interpretation is correct then a similar effect could be obtained by applying a microwave signal, synchronous with the SAW, to an additional gate close to the split gate. This alternating signal could be used to reduce the width of the SAW potential well and therefore enhance the electron-electron interaction at an appropriate time interval within the SAW cycle. An adjustment of the potential profile within the channel by means of an additional signal with a proper time and space dependence may significantly reduce the error of future SAW devices.

The results presented in this work show an improvement of nearly two orders of magnitude in the value of the imprecision imposed by the slope of the quantized acoustoelectric current in comparison with our first publications.[7–9] It is most likely that further improvements are possible. This expectation is supported by our recent observations[12] of a quantized current with imprecision of about ±60 ppm in an etched one-dimensional (1D) channel (prepared as described in Ref. 13) without employing the counterpropagating SAW beam technique. It is interesting to note that the observed shape of the first plateau[12] is similar to that shown in Fig. 7.

The principal source of error in the SAW single-electron devices is the nonadiabaticity (see the discussion in Refs. 8, 9, and 14) of their operation which limits their ultimate accuracy. It is presently unclear how close we are to this nonadiabaticity limit. One of the goals of future studies will be the unequivocal observation of nonadiatic effects in split gate SAW devices. This will help to establish an adequate theoretical description of single-electron acoustic charge transport.

CONCLUSIONS

We have presented data concerning the shape of the first plateau of the quantized acoustoelectric current. The central part of the plateau is usually a straight segment within an approximately 1 mV interval of gate voltage. Typical values of the imprecision associated with the plateau have been presented.

The RTS-like noise that plagued first observations[7–9] of the quantized acoustoelectric current can be eliminated by a proper choice of GaAs-$Al_xGa_{1-x}As$ heterostructure. The presence of a weak counterpropagating SAW beam was found to substantially improve the flatness of the plateau.

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[1] L. J. Geerlings, V. F. Anderegg, P. A. M. Holweg, J. E. Mooij, H. Pothier, D. Esteve, C. Urbina, and M. H. Devoret, Phys. Rev. Lett. **64**, 2691 (1990).
[2] P. Delsing, K. K. Likharev, L. S. Kuzmin, and T. Claeson, Phys. Rev. Lett. **63**, 1861 (1989).
[3] L. P. Kouwenhoven, A. T. Johnson, N. C. van der Vaarrt, C. J. P. M. Harmans, and C. T. Foxon, Phys. Rev. Lett. **67**, 1626 (1991).
[4] H. Pothier, P. Lafarge, P. E. Orfila, C. Urbina, D. Esteve, and M. H. Devoret, Physica B **169**, 573 (1991).
[5] J. M. Martinis, M. Nahum, and H. D. Jensen, Phys. Rev. Lett. **72**, 904 (1994).
[6] M. W. Keller, J. M. Martinis, N. M. Zimmermann, and A. H. Steinbach, Appl. Phys. Lett. **69**, 1804 (1996).
[7] J. M. Shilton, V. I. Talyanskii, M. Pepper, D. A. Ritchie, J. E. F. Frost, C. J. B. Ford, C. G. Smith, and G. A. C. Jones, J. Phys.: Condens. Matter **8**, L531 (1996).
[8] V. I. Talyanskii, J. M. Shilton, M. Pepper, C. G. Smith, C. J. B. Ford, E. H. Linfield, D. A. Ritchie, and G. A. C. Jones, Phys. Rev. B **56**, 15 180 (1997).
[9] V. I. Talyanskii, J. M. Shilton, J. Cunningham, M. Pepper, C. J. B. Ford, C. G. Smith, E. H. Linfield, D. A. Ritchie, and G. A. C. Jones, Physica B **249–251**, 140 (1998).
[10] T. J. Thornton, M. Pepper, H. Ahmed, D. Andrews, and G. J. Davies, Phys. Rev. Lett. **56**, 1198 (1986).
[11] A. S. Dzurak, C. J. B. Ford, M. J. Kelly, M. Pepper, J. E. F. Frost, D. A. Ritchie, G. A. C. Jones, H. Ahmed, and D. G. Hasko, Phys. Rev. B **45**, 6309 (1992).
[12] J. Cunningham, V. I. Talyanskii, J. M. Shilton, M. Pepper, A. Kristensen, and P. E. Lindelof (unpublished).
[13] A. Kristensen, J. B. Jensen, M. Zaffalon, C. B. Sorensen, S. M. Reimann, M. Michek, and A. Forchel, J. Appl. Phys. **83**, 607 (1998).
[14] Q. Niu, Phys. Rev. Lett. **64**, 1812 (1990).