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**LETTER TO THE EDITOR**

# High-frequency single-electron transport in a quasi-one-dimensional GaAs channel induced by surface acoustic waves

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**Abstract.** We report on an experimental investigation of the direct current induced by transmitting a surface acoustic wave (SAW) with frequency 2.7 GHz through a quasi-one-dimensional (1D) channel defined in a GaAs–AlGaAs heterostructure by a split gate, when the SAW wavelength was approximately equal to the channel length. At low SAW power levels the current reveals oscillatory behaviour as a function of the gate voltage with maxima between the plateaux of quantized 1D conductance. At high SAW power levels, an acoustoelectric current was observed at gate voltages beyond pinch-off. In this region the current displays a step-like behaviour as a function of the gate voltage (or of the SAW power) with the magnitude corresponding to the transfer of one electron per SAW cycle. We interpret this as due to trapping of electrons in the moving SAW-induced potential minima with the number of electrons in each minimum being controlled by the electron–electron interactions. As the number of electrons is reduced, the classical Coulomb charging energy becomes the Mott–Hubbard gap between two electrons and finally the system becomes a sliding Mott insulator with one electron in each well.

The application of a surface acoustic wave (SAW) to a two-dimensional electron gas (2DEG) is of considerable interest [1–8]. A SAW propagating on a piezoelectric substrate is accompanied by a wave of electrostatic potential, thus permitting the investigation of the interaction of 2D electrons with a travelling electric field wave. Two types of effect due to the interaction between a SAW and a 2DEG have been investigated. The first corresponds to the change in both SAW damping and velocity and has been studied by several groups [1–3]. Using this technique Willett *et al* [2] discovered geometric resonances of the cyclotron orbits of composite fermions with the SAW wavelength. Paalanen *et al* [3] observed a broad conductivity resonance at about $\omega = 2\pi \times 10^9$ s$^{-1}$, in the small-filling-factor limit, interpreted as the pinning mode of a disordered Wigner crystal. The second type of interaction between a SAW and a 2DEG is the acoustoelectric effect, i.e. the inducement of a direct current or voltage in the 2DEG due to momentum transfer from the SAW to the 2DEG [4–8].

In this letter we report on the acoustoelectric drag current induced by a SAW in a quasi-one-dimensional channel defined in a GaAs–AlGaAs heterostructure by a split gate technique [9]. The SAW wavelength ($\lambda = 1$ $\mu$m) was approximately equal to the channel length. This experimental system allows one to study the interaction of one-dimensional ballistic electrons with the sliding electrostatic wave induced by the SAW.

Our principal motivation for this, and earlier work [6–8] is that the SAW technique provides a new approach to the development of a solid state current standard, in which the

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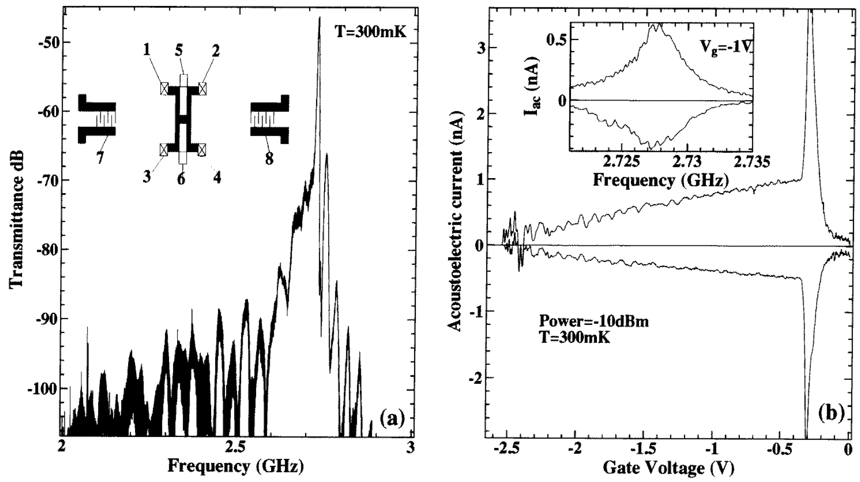



**Figure 1.** (*a*) Transmittance of the SAW delay line. Inset: a schematic of the device. 1–4, ohmic contacts; 5, 6, split gate; 7, 8, the SAW transducers. (*b*) The acoustoelectric current as a function of split gate voltage for each transducer. Inset: variation of the acoustoelectric current with frequency for each transducer at gate voltage $V_g = -1$ V.

dc current $I$ is given by $I = nef$ where $e$ is the electron charge and $f$ is the frequency of excitation imposed on the electron gas and '$n$' is an integer. The SAW propagating along a quasi-one-dimensional channel creates local potential minima which move with sound velocity ($\approx 2.7 \times 10^5$ cm s$^{-1}$). In the case of sufficiently powerful SAWs the charge is transported along the channel in the form of electron packets residing in SAW minima. For small wavelength ($\leqslant 1$ $\mu$m) these minima can be considered as moving quantum dots in which the Coulomb charging energy may be quite large. The charging energy will result in the appearance of a band gap in the energy spectrum of the dots. If the system of quantum dots is brought into contact with a reservoir whose Fermi energy lies inside the Coulomb band gap then each dot will carry an integer number of electrons, thus delivering a current $I = nef$, where $n$ is a number of electrons in each dot. A small ($\leqslant 1$ $\mu$m) SAW wavelength means that the SAW frequency is in the range of 3 GHz and higher. Therefore a SAW-based current standard is expected to produce current in the nanoamps range. This arrangement is closely related to the general issue of quantized adiabatic charge transport [10–13]. It has been shown that if an electron system is subjected to the action of an external potential with spatial and temporal periodicities, so that the Fermi gap between the filled and empty bands of the instantaneous Hamiltonian remains open at all times, then this system acts as a quantum pump, transferring an integer number of electrons through an external circuit during one period. The cause of the Fermi gap is not necessarily the electron–electron interaction: it could be minigap formation due to the diffraction of the electrons on the external spatially periodic potential [12]. To access this minigap regime the SAW wavelength must be of the order of 0.1 $\mu$m. In the regime when both the electron–electron interaction and the electron diffraction are essential it is convenient to discuss the system in terms of the Mott–Hubbard model with the state corresponding to one electron in a well being a sliding Mott insulator.

The design of the sample and typical experimental traces are shown in figure 1. The sample is a GaAs–AlGaAs heterojunction with electron concentration $2.7 \times 10^{11}$ cm$^{-2}$ and mobility $7 \times 10^5$ cm$^2$ V$^{-1}$ s$^{-1}$. Two SAW interdigital transducers, separated by 4 mm, with 70 pairs of 80 $\mu$m long fingers, operate at a resonant frequency $f_0 = 2728.6$ MHz, and combine to form a delay line, with transmittance characteristic shown in figure 1(*a*). Between them the 2DEG mesa with a split gate which defines the quasi-one-dimensional channel completes the device (see inset in figure 1(*a*)). The split gate geometry (0.7 $\mu$m long gates with a 0.7 $\mu$m gap) was chosen to produce an electrostatically defined channel slightly longer than the SAW wavelength ($\lambda = 1$ $\mu$m). For measuring the acoustoelectric current one of the transducers was linked with an RF generator by cryogenic coaxial cables. The RF generator is pulse modulated at frequency 225 Hz and duty cycle 0.5. The acoustoelectric current flowing between contacts 1 and 2 in figure 1(*a*) was measured by standard lock-in techniques. Great care had to be taken to suppress a parasitic dc current due to rectification of airborne RF field by the sample [6]. To this end a 2000 Å dielectric layer and 1000 Å thick metal layer (electrically connected to the metal sample holder) was put on top of the mesa and the split gate (not shown in figure 1(*a*)). This results in a capacitive coupling between the split gate (and the mesa) and the electrical ground. Further suppression of the cross-talk signal has been achieved by careful design of the sample holder. Figure 1(*b*) shows typical traces of the acoustoelectric current versus gate voltage taken for both transducers. The dependence of the acoustoelectric current on RF frequency is shown in the inset in figure 1(*b*). One can see on top of these traces weak oscillations with period 0.7 MHz. These could be explained by a reflection of a small part of the SAW beam by the second (unfed) transducer. The interference between the forward and the backward beams results in slight spatial modulation of the SAW amplitude. By slightly changing the RF generator frequency (~0.1 MHz; well within the transducer's passband) one can move the positions of the SAW amplitude's minima and maxima along the channel. For an open channel this movement results in a weak modulation of the acoustoelectric current seen in the inset in figure 1(*b*). At high SAW power levels when the acoustoelectric current exists below the pinchoff voltage the change (~0.1 MHz) in RF generator frequency was found to change the current threshold value (leaving the quantized current value on the plateau unchanged).

Thus the traces in figure 1(*b*) allow one to conclude that the measured signal is purely due to the SAW. The low value of $I_{ac}$ at $V_g = 0$ is due to the shorting out of the acoustoelectric current by the 2DEG area under the gates unaffected by the SAW beam. In a narrow interval of the gate voltage, corresponding to the depletion of the 2DEG under the gates, $I_{ac}$ shows a strong peak (figure 1(*b*)). This observation is in agreement with [14] where the acoustoelectric current in a 2DEG with an unpatterned front gate has been studied. The likely reason for the peak in $I_{ac}$ is the high value of the derivative of the 2DEG conductivity with respect to the carrier density ($\partial\sigma/\partial n$) at the definition voltage, since according to the theory in [4] and [5] $I_{ac} \sim \partial\sigma/\partial n$. In the following we concentrate on the gate voltage region below the definition voltage where $I_{ac}$ can flow only through the channel.

Figure 2(*a*) shows the channel dc conductivity with the SAW on and off. The presence of the SAW (at +4 dBm output power from the RF generator) is seen to wash out the conductance plateau and moves the pinchoff voltage. Figure 2(*b*) shows that the $I_{ac}(V_g)$ dependence oscillates with minima corresponding to the plateaux in the channel conductivity. This is in agreement with theory [15] which explains the observed peaks in terms of the matching of sound velocity with electron velocity in the upper 1D subband of the channel. When the 1D conductance shows a quantized step the minimum of the upper subband dispersion curve is close to the Fermi level. Therefore there is always a gate voltage when the Fermi velocity of the electrons in the upper subband is very low and close to the SAW velocity. Such electrons interact strongly with the SAW and dominate the acoustoelectric current. The oscillations of the acoustoelectric current through a 1D ballistic channel have been seen in [8] in the regime where the SAW wavelength is much larger than the 1D

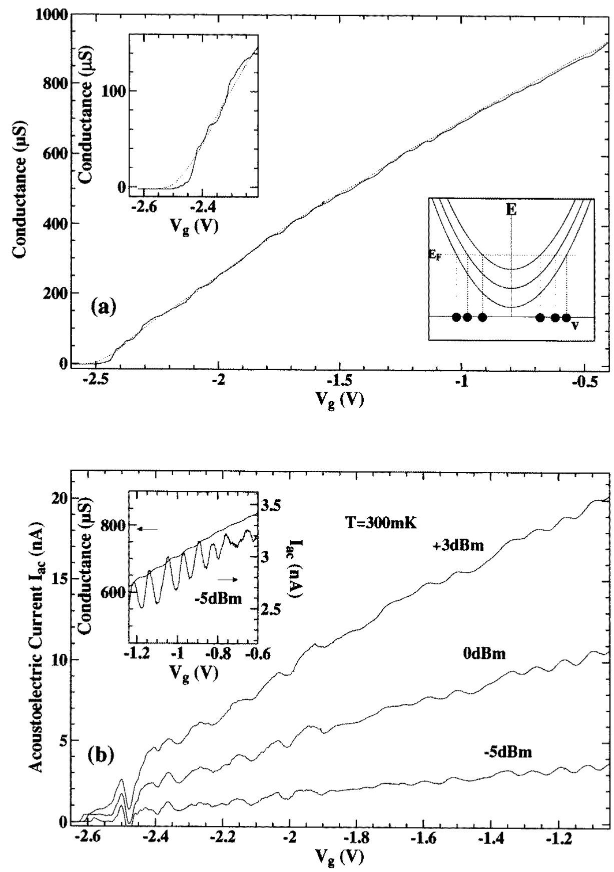



**Figure 2.** (*a*) The conductance of the device as a function of split gate voltage at 0.3 K. The shapes of several last plateaux are seen to be disturbed, presumably by an impurity potential. The dotted line shows the conductance when SAWs are applied without modulation at RF generator power +4 dBm. The upper inset is an enlargement of the region close to pinchoff. The lower inset shows a schematic diagram of electron energy *versus* velocity for a ballistic quasi-one-dimensional channel. The black dots show the Fermi velocities of electrons in different 1D subbands. (*b*) The acoustoelectric current as a function of split gate voltage for different SAW power levels. Inset: comparison of the conductance and acoustoelectric current. This shows that the minima in current coincides with plateaux in the conductance.

channel length. The data in figure 2(*b*) demonstrate that this effect continues when the SAW wavelength is comparable with the channel length, the situation considered by the theory in [15].

At sufficiently high SAW power level the acoustoelectric current is seen to be present beyond the pinchoff voltage. In figures 3–5 we present a detailed study of this new experimental finding. As $V_g$ is made less negative the acoustoelectric current appears as a step from zero current keeping constant over ≈10 mV interval of the gate voltage and corresponding to a transfer of one electron per cycle. At further decrease of the negative gate voltage the second plateau (corresponding to the attempted transfer of two electrons per SAW cycle) is seen to begin to develop (figure 3). A change in the SAW magnitude (within some interval) shifts the threshold for the $I_{ac}$ but leaves the value of the one-electron plateau current unchanged (figure 3). As we will show later the first plateau is

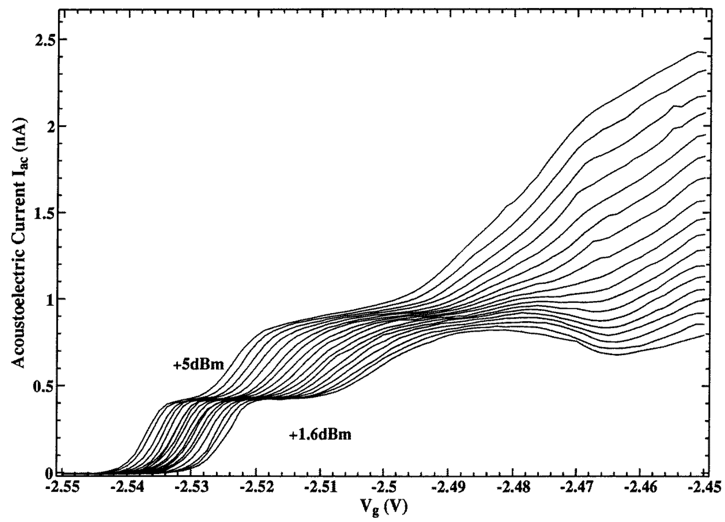



**Figure 3.** The acoustoelectric current as a function of split gate voltage beyond pinchoff voltage for different values of SAW power in the range from 1.6 to 5 dBm. The SAW frequency is 2728.4 MHz.

very robust against the change of relevant parameters of the system. The second plateau in figure 3 is much more vulnerable to a change of the system parameters. It is most clearly seen (figure 3) when the RF frequency deviates slightly (200 kHz) from the transducers' resonant frequency. This is believed to be due to the slight spatial variation of the SAW amplitude which appears (see discussion above) as a result of the superposition of the main and reflected SAW beams. By tuning the RF frequency one moves the spatial distribution of the SAW amplitude into a position favourable for the observation of the second plateau.

Figure 4 gives a closer look at the first plateau for different SAW power levels. The right-hand inset in figure 4 shows values of the current in the middle of the plateau for different SAW power levels along with the value $I = ef$. It is seen that within the experimental accuracy (≈1%) the value of the acoustoelectric current on the plateau corresponds to the transfer of one electron through the channel per SAW cycle. We have also measured the dependence of $I_{ac}$ on $V_g$ with a potential difference (Δ) between the gates ($\Delta = V_{g1} - V_{g2}$, where $V_{g1}$ and $V_{g2}$ are the voltages on the gates forming the split gate) which was kept constant when $V_{g1}$ and $V_{g2}$ were being swept. The non-zero value of Δ causes a sideways displacement of the channel. The acoustoelectric current curves for different values of the parameter Δ are shown in figure 5(*a*). The 'threshold voltage' for the acoustoelectric current is seen to strongly depend on Δ but as expected the plateau current remains the same: $I_{ac} = ef$. This 'differential' biasing of the gates noticeably changes the channel conductance behaviour near the pinchoff voltage. In figure 5(*b*) we show acoustoelectric current and the conductance traces for Δ equal to −0.1 V. The peak structure seen on the conductance trace is presumably caused by an impurity potential. Such structure has been often observed on 1D quantized conductance curves and is believed to be due to the Coulomb blockade of an impurity-induced quantum dot inside the channel [16]. There is also some structure on the acoustoelectric current trace in figure 5(*b*) which reflects the structure in the conductance. The position and shape of the peak-like structure on the conductance curve was found to be very sensitive to the value of the parameter Δ and was always accompanied by a

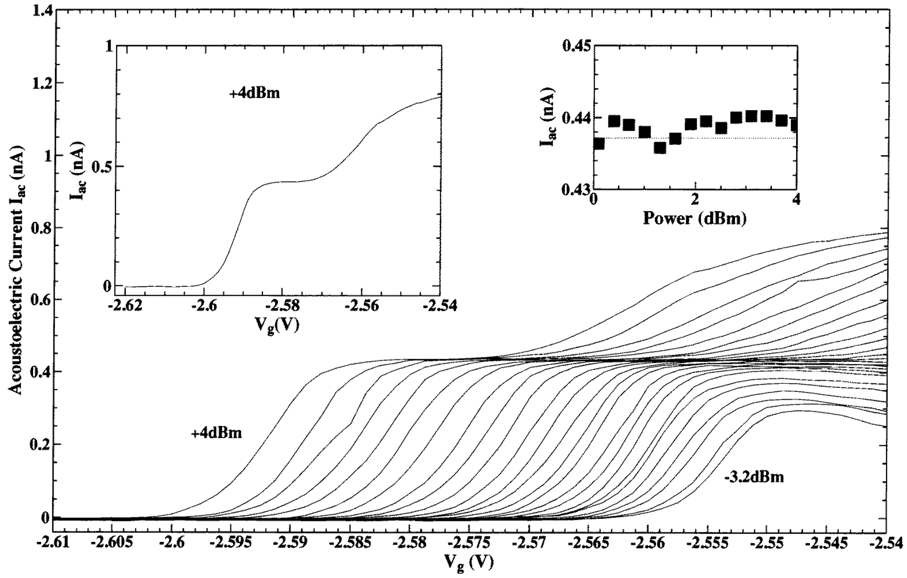



**Figure 4.** The first plateau in the acoustoelectric current for different SAW powers. The SAW frequency is 2728.6 MHz. The left inset shows the curve for the RF generator power +4 dBm. The right inset shows the height of the plateau for each of the curves shown in the main figure between RF power 0 and 4 dBm. The dotted line corresponds to current $I = ef$.

corresponding change in the peak-like structure on the acoustoelectric current trace. At the same time the 'quantized' value of the current is robust against change of $\Delta$ (figure 5(*a*)). This supports the point of view that the impurity potential is not essential for appearance of the plateau in the acoustoelectric current in figures 3–5. The 'quantized' current plateau is seen to be stable over an interval of both source–drain voltage (figure 5(*c*)) and temperature (figure 5(*d*)) as well. Thus the experiment shows that the value of the acoustoelectric current $I = ef$ corresponding to the transfer of one electron per SAW cycle is insensitive to the variation of the system's parameters. The most likely reason is the strong repulsion between the electrons trapped in the SAW potential minima. The superposition of the electrostatic potential due to the gates with that of the SAW results in a washboard-type potential inside the channel (figure 6). If the local potential minima moving up the potential hill at the 'entrance' to the channel is not sufficiently deep (less than the Mott–Hubbard gap) to hold more than one electron then the system will demonstrate single-electron transport within some intervals of the relevant parameters. The data in figures 5(*c*) and 5(*d*) suggest that the gap is of the order of 1–2 meV. An accurate determination of the potential inside the channel probably requires a numerical calculation because of the screening of the SAW potential by the 2DEG and the gate metal. A further complication comes from any impurity potential which is present. If the competing SAW and the split gate potentials are large in comparison with the impurity potential then this could be unimportant. This situation is likely to happen at gate voltages well beyond pinchoff when a large SAW magnitude is required to drive the acoustoelectric current. At smaller gate voltages the acoustoelectric current is seen to display an impurity-induced peak-like structure (figure 5(*b*)). The impurity potential could be a possible reason for the suppression of the plateaux corresponding to the transfer of two, three etc electrons per SAW cycle.

Small (well within the experimental error) deviation of the 'plateau' value of the current

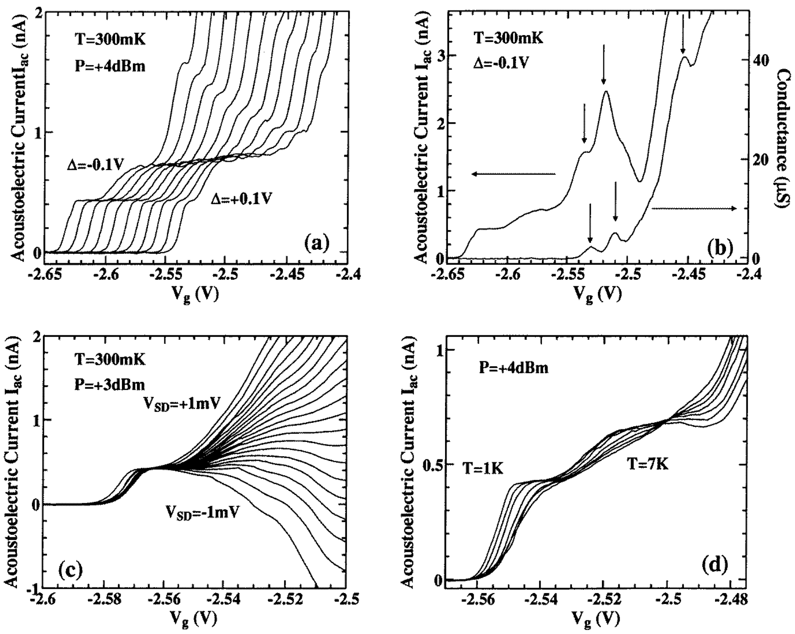
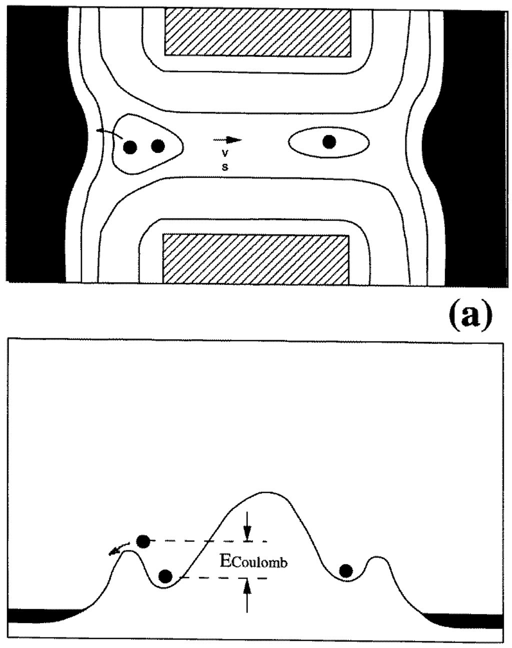



**Figure 5.** (*a*) The acoustoelectric current *versus* split gate voltage with voltages on the gate arms which differ by Δ (see text), which moves the channel sideways. (*b*) Comparison of the acoustoelectric current and the conductance. (*c*) The acoustoelectric current *versus* split gate voltage at different source–drain biases. (*d*) The acoustoelectric current *versus* split gate voltage at different temperatures.

from the quantized value $ef$ (see the inset in figure 4) means that the fluctuations of the number of electrons in the SAW wells are small or equivalently that the electron system has time to adjust to the varying SAW electric potential. We will refer to this property as the adiabaticity of the acoustic charge transport. The degree of the adiabaticity determines the ultimate accuracy of the device as a current standard [13]. At present there is no theory tailored to our experimental conditions so we can only make an assumption that a parameter responsible for a non-adiabatic correction (or the error of the current standard) may depend on the ratio of the sound to the electron velocities. This implies that the correction does not depend on the SAW frequency, so that the fractional error does not increase with the increase of the dc current delivered by the standard. This favourable conclusion is expected intuitively because the increase of the SAW frequency automatically scales down the size of the 'moving dots' (figure 6) and relevant electron equilibration times. In this respect the SAW approach differs from the other approaches to the current standard problem. Such devices as many-junction pumps and the 'turnstile' [17–21], which are currently being investigated as possible candidates for standards of electric current, are bound, for intrinsic reasons, to operate at low frequencies ($\leqslant$10 MHz) therefore delivering low currents ($\sim$1 pA) at very low ($\leqslant$100 mK) temperatures. In comparison our device delivers quantized current $\sim$ 500 pA at temperature $\sim$ 300 mK. Without further experimental and theoretical work it is difficult to estimate the ultimate accuracy of the experimental set-up described in this work. One can suggest different designs of the SAW based current standard. We believe that for any such design the most difficult and crucial element is the transition between moving quantum dots and the reservoir supplying electrons.




(a)

(b)

**Figure 6.** (*a*) Pictorial representation of the mechanisms believed to be responsible for the plateau in acoustoelectric current. Dark regions show 2DEG reservoirs. Shaded regions show split gate metallizations. Lines schematically show the distribution of the electrostatic potential. The electrostatic potential due to the SAW forms a succession of quantum dots in the channel, which move through with the SAW velocity $v_S$. The dots are elliptical due to the sideways electrostatic squeezing from the split gate potential. (*b*) Shows how the electrons are captured from the 2DEG by the potential minima. As the minima rise over the saddle point potential, the energy of the second bound state in the dot becomes higher than the barrier, leaving only one bound state.

In conclusion we have presented results of the first experimental study of the acoustoelectric effect in a quasi-one-dimensional channel in a strongly non-local regime when the channel length exceeds the sound wavelength. In the ballistic regime the acoustoelectric current displays oscillations which are explained as the result of the matching of the electron velocity with the SAW velocity.

The main experimental finding is that the acoustoelectric current through a depleted channel remains constant over a range of values of the relevant parameters. The current value is equal to the product of the electron charge and the SAW frequency. We explain this as being due to transfer of one electron through the channel by each SAW's potential minimum; the amount of charge is controlled at a level of one electron by the strong Mott–Hubbard electron–electron repulsion. Thus the arrangement used is a good model system for the development of a SAW based standard of electrical current and the adiabatic quantum pump in which the Fermi gap is due to the Coulomb interaction looks feasible. A further decrease of the SAW wavelength will bring the quantum interference and formation of minigaps in the channel's electron spectrum into play. The accuracy of the quantum pump as a current standard depends crucially on the degree of adiabaticity [13] of the interaction of the electrons with the external alternating field. The experimental arrangement described in this letter is convenient for the study of this problem. It is also convenient for a theoretical description since both the channel and the SAW are well defined objects.

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