J. Phys.: Condens. Matter **8** (1996) L337–L343. Printed in the UK

LETTER TO THE EDITOR

On the acoustoelectric current in a one-dimensional channel

J M Shilton†, D R Mace†, V I Talyanskii†, Yu Galperin‡, M Y Simmons†, M Pepper† and D A Ritchie†

† Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK
‡ Department of Physics, University of Oslo, PO Box1048, Blindern, N-0316 Oslo, Norway

Received 7 March 1996

Abstract. We report the first observation of the direct current induced by a surface acoustic wave through a quantum point contact defined in a GaAs–AlGaAs two-dimensional electron gas by means of a split gate. We have observed giant oscillations in the acoustoelectric current as a function of gate voltage, with minima corresponding to the plateaux in quantum point contact conductivity. A theoretical consideration is presented which explains the observed peaks in terms of the matching of sound velocity with electron velocity in the upper one-dimensional subband of the quantum point contact.

The interaction of a surface acoustic wave (SAW) with a two-dimensional electron gas (2DEG) in a GaAs–Al$_x$Ga$_{1-x}$As heterostructure has recently attracted much attention [1–10]. Usually, two kinds of effect are studied. The first kind is the attenuation and change in velocity of the sound wave due to interaction with electrons. For small amplitudes, these effects are linear in the acoustic wave amplitude. Analysis of these effects allows us, in principle, to study the linear response of carriers to alternating strain deformation and electric fields at the SAW frequency. An important consideration is that these measurements do not require any contacts to be made to the sample. Very interesting studies of these effects in quantum Hall systems were carried out, in particular, in [1, 4].

The second class of studies deal with the so-called acoustoelectric effects in 2DEGs. These are due to a drag of the 2D electrons by the SAW [5–10], and for small signals are quadratic in the SAW amplitude. As described, an acoustic wave, while travelling across the sample is attenuated due to interaction with the electrons, and transfers some of its momentum to them. As a result a d.c. current in a closed circuit appears (the acoustoelectric current). In an open circuit, a d.c. voltage is generated. Thus in principle these acoustoelectric effects can be used to study both the d.c. and a.c. response of the carriers.

Drag of the electrons in a quantum point contact by non-equilibrium phonons has been considered in [11]. This paper discussed a current flowing through a channel due to a 'phonon wind' in the leads, and predicted its quantization, similar to the conductance quantization. We believe that such a mechanism is not important in our case, because of the strong screening of the interaction outside the QPC.

In this letter we present the first experimental and theoretical study of the acoustoelectric current in a quasi-one-dimensional ballistic channel defined in a 2DEG by split-gate-induced depletion. We observed a very specific behaviour of the acoustoelectric current, qualitatively different from the behaviour of the conductance. In particular no quantization of the

0953-8984/96/240337+07$19.50

acoustoelectric current was observed. On the contrary, a plot of current versus gate voltage shows giant oscillations having minima at those gate voltages which show plateaux in the conductance. It is useful to compare the acoustoelectric effect with the rectification of far-infrared radiation in a ballistic quantum point contact (QPC) [12, 13]. Here the rectification is due to a non-linearity of a QPC's *I*–*V* characteristic and for a symmetrical QPC should appear at non-zero source–drain bias. The acoustoelectric effect, however, may cause a current to appear even in an unbiased symmetrical QPC if the SAW wavelength is comparable to the QPC length. This results in a spatially varying SAW electric field inside the channel. The SAW wavevector (q) breaks the symmetry of the problem and thus makes rectification (the acoustoelectric current) possible. In the limit $qL \ll 1$ (L is the QPC length) one would expect the acoustoelectric current to be proportional to qL.

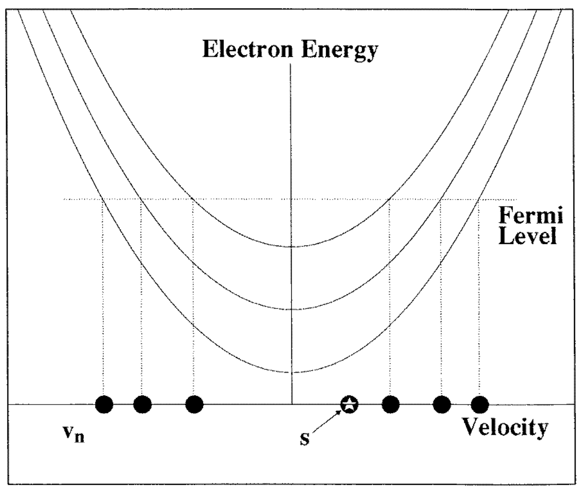

Figure 1. A schematic diagram of electron energy versus velocity for a ballistic quasi-one-dimensional channel.

The theoretical explanation presented below attributes the observed acoustoelectric current peaks to the electrons in the upper one-dimensional (1D) subband of the QPC. We notice that only electrons with energies close to the Fermi energy can contribute to the drag current. When the conductance of the QPC shows a step the minimum of the upper subband dispersion curve is close to the Fermi level (figure 1). This means that the Fermi velocity of the electrons in the upper subband is very low and may be close to the SAW velocity. Such electrons interact strongly with the SAW and dominate the acoustoelectric current. The theoretical consideration has been carried out for a long QPC such that $qL \gg 1$, while in the present experiment the estimated product $qL \approx 1$. However, we believe that the main physical features remain the same in the general case (the results for which will be published elsewhere).

A schematic diagram of the sample is shown in figure 2. A QPC was defined in the 2DEG by means of a split gate situated in between two interdigitated transducers. The QPC and transducers were made by electron beam lithography and subsequent metallization. The transducers' operating frequency is 923 MHz (at 4 K), which corresponds to a SAW wavelength (λ) of approximately 3 μm. The transducers consist of forty 250 μm long finger pairs. The transmittance characteristic of the SAW delay line comprised of the two transducers is shown in the inset in figure 2. We used a heterostructure with carrier density

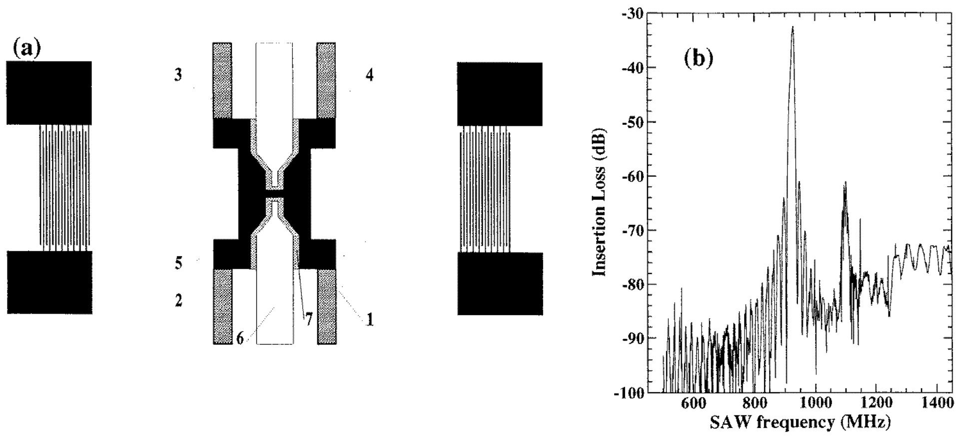

Figure 2. (a) A schematic diagram of the sample showing the SAW transducers. 1–4— ohmic contacts, 5—2DEG mesa, 6—split gate, 7—gate-induced depletion region. (b) The frequency response of the SAW filter comprised of the transducers on either side of the Hall bar. The curve was taken by a network analyser at room temperature.

4.1×10^{11} cm^{-2} and mobility 240 000 cm^2 V^{-1} s^{-1} at 1.7 K. The 2DEG mesa near the QPC had the form of a narrow strip, so the width of the gate-uncovered 2DEG regions alongside the split gate was approximately 10 μm (see figure 2). The gates defining the QPC were 1000 Å wide and the distance between them was 5000 Å. Such a geometry of the QPC results in definition of a long ($L \approx 5000$ Å) quasi-one-dimensional channel in the 2DEG as shown schematically in figure 2. We have chosen a long split gate and narrow 2DEG regions outside it to make the signal from the QPC detectable and to increase its contribution to the acoustoelectric current, compared to that from the plain 2DEG regions. To detect the acoustoelectric current we applied an amplitude-modulated (30 Hz, 90%) r.f. signal at 923 MHz to one of the transducers and measured the current between contacts 1 and 2 (figure 2) using standard lock-in techniques. The experimental technique used and precautions taken to eliminate parasitic crosstalk signals are described in more detail in [7, 8]. We have found the problems associated with the crosstalk signal more difficult to solve for gated devices than for a plain 2DEG mesa [7, 8]. The signal that we will be discussing below appears at an r.f. generator frequency which coincides with the transducers' operating frequency and therefore is acoustoelectric in origin. However, at present we cannot rule out any mechanism of a SAW-induced current which is due to the simultaneous action of the SAW's and the crosstalk's electric fields.

In figure 3 we show the experimental gate voltage dependencies of the acoustoelectric current and two-terminal conductivity of the QPC. The first plateau in the conductivity curve is strongly distorted but plateaux from 2 to 6 are clearly seen. This distortion is presumably due to an impurity which is likely to appear in the relatively long QPC. It is well known that impurity-induced potential is the main problem restricting the length of ballistic quasi-one-dimensional channels [14]. Nevertheless there are at least two important reasons to study such long QPCs. The first one is that a long QPC results in a measurable acoustoelectric current. Even in large plain 2DEGs acoustoelectric effects are rather difficult to observe at zero magnetic field and this was reported only recently [7, 8]. The physical reason for the importance of the QPC in comparison with the much larger region of 2DEG

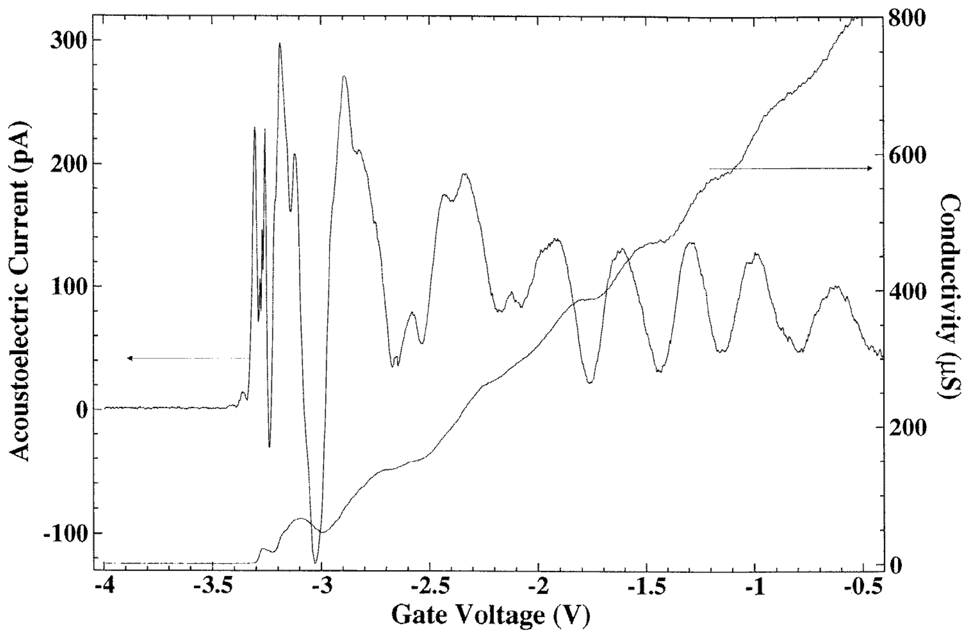

Figure 3. Experimental dependencies of the QPC conductivity and the acoustoelectric current. The conductivity values at the plateaux are disturbed by ≈1 kΩ in-series resistance, comprised of the 2DEG and contact resistance. The r.f. generator power was –2 dBm.

outside the gates is the absence of effective screening of the SAW electrostatic field inside the quasi-1D channel. The second advantage of a long QPC, as far as acoustoelectric effects are concerned, is that one can study the interaction of ballistic electrons with a sliding SAW electrostatic potential under conditions where the de Broglie and SAW wavelengths are comparable. We will discuss this point in more detail below.

The experimental dependence of the acoustoelectric current shown in figure 3 reveals very complicated peak-like structure at gate voltages close to pinch-off. The structure of the acoustoelectric current resembles (but does not coincide with) the derivative of the conductivity with respect to the gate voltage. We found that the behaviour of the acoustoelectric current close to the pinch-off voltage can change from sample to sample and even with time for the same sample. The charge transport through a QPC influenced by an impurity could be rather complicated and dominated by Coulomb-blockade-type effects [15], and in what follows we will not discuss the behaviour of the acoustoelectric current in the region close to pinch-off.

In the region where the gate voltage $V_g > -2.5$ V the conductivity curve in figure 3 shows regular behaviour with clearly seen plateaux. We attribute this to more effective screening of the impurity potential inside the QPC. The direction of the acoustoelectric current corresponds to negatively charged carriers being dragged by the SAW. The acoustoelectric current in this region shows giant oscillations with minima corresponding to plateaux in the conductivity. In what follows we will discuss a possible explanation for this behaviour.

The electron wavefunction in a QPC with uniform width can be expressed as a superposition of transverse modes $|n, k\rangle = \chi_n(z, x) \exp(\mathrm{i}kx)$ where $\chi(z, x)$ is the wavefunction corresponding to the nth mode of transverse motion and the z- and x-axes are directed perpendicular to and along the channel respectively. In the presence of a SAW at frequency ω and wavevector q the electrons acquire a perturbation

$$\hat{H}_{int} = U \sum [C_{n,k,k'}(q) a^{+}_{nk} a_{nk'} + \mathrm{HC}]$$

where

$$C_{n,kk'}(q) = |\langle n, k| \exp(\mathrm{i}qx) |n, k'\rangle|^2$$

and U is the SAW electrostatic potential amplitude. For a uniform channel $C = \beta_n \delta(k - k' - q)$ and we can consider the electrons of the nth mode as moving in the effective field $V_n(x) = U\beta_n \cos(qx - \omega t)$.

The kinetic equation for the electron occupation number $f_{np}(x)$ in the nth mode has the form

$$\left(\frac{\partial}{\partial t} + \upsilon_n \frac{\partial}{\partial x} - \frac{1}{m}\frac{\partial V_n}{\partial x}\frac{\partial}{\partial \upsilon} + \hat{I}_n\right) f_{np}(x) = 0$$

where υ_n is the electron velocity, and $\hat{I}_n$ is the collision operator describing relaxation of the non-equilibrium distribution. Assuming

$$\begin{aligned} &f_{np}(x) = f_0[\varepsilon_{np} + V_n(x)] + f_1 + f_2 \\ &f_1 \propto U\beta_n \exp(-\mathrm{i}\omega t) \\ &f_2 \propto |U\beta_n|^2 \end{aligned} \tag{1}$$

we obtain

$$\begin{aligned} &\hat{B}_n f_1 = -\mathrm{i}\omega U \beta_n \left(-\frac{\partial f_0(\varepsilon_{np})}{\partial \varepsilon_{np}}\right) \\ &\hat{I} f_2 = \left\langle \frac{\partial V_n(x)}{\partial x}\frac{\partial f_1}{\partial p}\right\rangle_t . \end{aligned} \tag{2}$$

Here we have introduced the operator

$$\hat{B}_n(q, \omega) = \hat{I}_n - \mathrm{i}\omega + \upsilon_n \frac{\partial}{\partial x} = \hat{I}_n + \mathrm{i}(q\upsilon_n - \omega)$$

having the meaning of the operator of the linearized kinetic equation. Angular brackets mean averaging over time t:

$$\langle \ldots \rangle_t = (\omega/2\pi) \int_0^{2\pi/\omega} \cdots \,\mathrm{d}t.$$

Substituting f_1 in and using the relationship $\langle C(t)D(t)\rangle_t = \frac{1}{2}\mathrm{Re}(C_\omega D^*_\omega)$ (where C_ω is the Fourier component of $C(t)$) we get

$$f_{n2} = -|U\beta_n|^2 q\omega \hat{I}_n^{-1} \,\mathrm{Re}\left\{\frac{\partial}{\partial p}\left[\hat{B}_n^{-1}\left(-\frac{\partial f_0(\varepsilon_{np})}{\partial \varepsilon_{np}}\right)\right]\right\}. \tag{3}$$

Integrating by parts, we arrive at the following expression for the current:

$$j = -eU^2 q\omega \sum_n |\beta_n|^2 \int \frac{\mathrm{d}p}{\pi\hbar} \hat{I}_n^{-1} \,\mathrm{Re}\left[B_n^{-1}\left(-\frac{\partial f_0(\varepsilon_{np})}{\partial \varepsilon_{np}}\right)\right]. \tag{4}$$

Equation (4) is the formal expression for the acoustoelectric current. To evaluate it one needs to specify the kinetic operator $\hat{B}_n$, i.e. to discuss sources of relaxation. For our purpose it is sufficient to take the 'τ-approximation' of the collision operator $\hat{I}_n = \tau_n^{-1}$, where τ_n depends in general on the gate voltage. Then we can obtain from equation (4)

$$j = \frac{eU^2\omega}{m} \sum_n |\beta_n|^2 \int \frac{\mathrm{d}p}{2\hbar} \tau_n \left(1 + \frac{\partial \ln \tau_n}{\partial \ln \upsilon_n}\right) \left(-\frac{\partial f_0(\varepsilon_{np})}{\partial \varepsilon_{np}}\right) \Delta_n(\upsilon_n - s) \tag{5}$$

where $s = \omega/q$ is the SAW velocity while

$$\Delta_n(\upsilon - s) \equiv \frac{1}{\pi} \frac{1/q\tau_n}{(\upsilon - s)^2 + (1/q\tau_n)^2} \tag{6}$$

is a sharp function of the velocity difference $\upsilon - s$ with the width $1/q\tau_n$.

In general, the integrand in (5) contains the product of two sharply peaked functions of υ_n.

The derivative of the Fermi function shows that electronic states can contribute to the acoustoelectric current only if their energies are in the vicinity of the Fermi level.

The sharp function $\Delta(\upsilon - s)$ means that only electrons with velocities close to the sound velocity can take part in the drag. The physical reason for this is that the 'effective interaction time' during which an electron with velocity υ moves in an almost constant SAW electric field is $(q\upsilon - \omega)^{-1}$. Indeed, all other electrons feel the rapidly oscillating field of the SAW, and therefore are unaffected. Thus equation (5) predicts a set of peaks in the acoustoelectric current versus gate voltage dependence. The peaks occur at gate voltages corresponding to the steps in QPC conductivity, because at these voltages the Fermi velocity of the electrons in the upper 1D channel is very low (see figure 1). At small υ, or near the resonance ($\upsilon = \omega/q = s$), the interaction time diverges, and relaxation becomes important. As seen from equations (5) and (6) the magnitude of the acoustoelectric current is proportional to $(q\tau)^{-1}/[(\upsilon - s)^2 + (q\tau)^{-2}]$, where we can think of υ and τ as being the velocity and the relaxation time for the upper subband. The relaxation time in the upper channel of the QPC is determined by two mechanisms. An electron can pass through a QPC without scattering and then lose the momentum taken from the SAW outside the QPC in the 2DEG. The corresponding relaxation time for this process can be estimated as $\tau_1 \approx L/\upsilon$. The other mechanism is the scattering inside the QPC which is important for the upper 1D channel and manifests itself in non-quantized QPC conductivity. The corresponding time (τ_2) depends on the density of states in the QPC, which diverges at the thresholds corresponding to the filling of new levels. The total relaxation time ($\tau^{-1} = \tau_1^{-1} + \tau_2^{-1}$) should be sufficiently large to provide effective coupling of electrons in the upper subband with the SAW and therefore large peak values of the acoustoelectric current.

In conclusion, we have presented the first observation of the acoustoelectric current in a QPC. The current demonstrates strong oscillatory behaviour as a function of the gate voltage, with peaks corresponding to the steps in the QPC conductivity. We have explained this as being a result of an effective interaction between the SAW and slow electrons in the upper one-dimensional channel of the QPC.

It is beneficial at this point to discuss a possible extension of this study. The promising situation where the QPC length is nearly an order of magnitude larger than the SAW wavelength looks practically feasible. In [4] a SAW wavelength <3000 Å in a GaAs–Al$_x$Ga$_{1-x}$As heterostructure was reported, and a SAW wavelength of $\lambda \sim 2000$ Å could possibly be reached [16]. On the other hand a ballistic quasi-one-dimensional channel with a length of 1–2 μm in the best quality 2DEGs also seems realistic. One can expect that quantum mechanical effects of electron diffraction on the sliding SAW potential and therefore the appearance of minizones in an electron spectrum would be observable. There exists the interesting proposal [17, 18] that a one-dimensional electron gas subjected to the action of a potential with spatial and temporal periodicities acts as a quantum pump, transferring an integer number of electrons through an external circuit during one period, provided that the Fermi gap between the filled and empty bands of the instantaneous Hamiltonian remains open at all times. An important question which arises in this connection is whether the combination of a QPC with SAW could be a practical realization of this idea.

The authors gratefully acknowledge helpful discussions with C J B Ford and C G Smith. This work was supported by the EPSRC.

References

[1] Wixforth A, Kotthaus J P and Weimann G 1986 *Phys. Rev. Lett.* **56** 2104
[2] Wixforth A, Scriba J, Wassermeier M, Kotthaus J P, Weimann G and Schlapp W 1989 *Phys. Rev.* B **40** 7874
[3] Willett R L, Paalanen M A, Ruel R R, West K W, Pfeiffer L N and Bishop D J 1990 *Phys. Rev. Lett.* **65** 112
[4] Willett R L, Ruel R R, West K W and Pfeiffer L N 1993 *Phys. Rev. Lett.* **71** 3846
[5] Esslinger A, Wixforth A, Winkler R W, Kotthaus J P, Nickel H, Schlapp W and Losch R 1992 *Solid State Commun.* **84** 939
[6] Esslinger A, Winkler R W, Rocke C, Wixforth A, Kotthaus J P, Nickel H, Schlapp W and Losch R 1994 *Surf. Sci.* **305**
[7] Shilton J M, Mace D R, Talyanskii V I, Pepper M, Simmons M Y, Churchill A C and Ritchie D A 1995 *Phys. Rev.* B **51** 14 770
[8] Shilton J M, Mace D R, Talyanskii V I, Simmons M Y, Pepper M, Churchill A C and Ritchie D A 1995 *J. Phys.: Condens. Matter* **7** 7675
[9] Efros A L and Galperin Yu M 1990 *Phys. Rev. Lett.* **64** 1959
[10] Fal'ko V I, Meshkov S V and Iordanskii S V 1993 *Phys. Rev.* B **47** 9910
[11] Kozub V I and Rudin A M 1994 *Phys. Rev.* B **50** 2681
[12] Janssen T J B M, Maan J C, Singleton J, Patel N K, Pepper M, Frost J E F, Ritchie D A and Jones G A C 1994 *J. Phys.: Condens. Matter* **6** L163
[13] Arnone D D, Frost J E F, Smith C G, Ritchie D A, Jones G A C, Butcher R J and Pepper M 1995 *Appl. Phys. Lett.* **66** 3149
[14] Davies J H and Timp G 1994 The smallest electronic device: an electron waveguide *Heterostructures and Quantum Devices* ed N G Einspruch and W R Frensley (New York: Academic) p 385
[15] Nicholls J T, Frost J E F, Pepper M, Ritchie D A, Grimshaw M P and Jones G A C 1993 *Phys. Rev.* B **48** 8866
[16] Yamanouchi K, Meguro T, Wagatsuma Y, Odagawa H and Yamamoto K 1994 *Japan. J. Appl. Phys.* **33** 3018
[17] Niu Q 1990 *Phys. Rev. Lett.* **64** 1812
[18] Shin Wei-Kai and Niu Qian 1994 *Phys. Rev.* B **50** 11 902