Single Electron Transport in a One-Dimensional Channel

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Abstract

The acoustoelectric current generated by the transport of single electrons in a one-dimensional channel offers the possibility to realize a quantum standard of current. At NPL we have developed a measurement system using a cryogenic current comparator for determining the accuracy of this current and in this paper we present the experimental set-up and preliminary measurements of the quantized current.

Introduction

Recently workers at Cambridge University [1, 2] have observed a quantized acoustoelectric current induced by a surface acoustic wave (SAW) in a one-dimensional (1D) channel defined in a GaAs-$Al_xGa_{1-x}As$ heterostructure. The current measured as a function of channel width was observed to be quantized in units of $I = ef$ where e is the electron charge and f is the SAW frequency. In order to confirm this relationship it is necessary to measure I with very high precision in terms of the existing electrical units of resistance and voltage which are universally represented by the von Klitzing constant R_K, and the Josephson constant K_J, respectively. This would effectively complete the so-called "metrological triangle". However, for this measurement to have a significant impact either as a determination of R_K in terms of h/e^2, or as a quantum standard of current, it will be necessary to measure I with a relative uncertainty smaller then 1 part in 10^7. The single electron current generated in these new devices is typically in the range of 1 nA, i.e. an accurate resolution of current smaller then 10^{-16} A will be necessary. At NPL we are adopting a cryogenic current comparator which should enable us to resolve the metrological triangle with an accuracy of 1 part in 10^6.

CCC Design and Measurement Circuit

At NPL we are adopting a cryogenic current comparator (CCC) bridge technique [3, 4] which should enable us to resolve the metrological triangle with an accuracy of 1 part in 10^6. In a CCC the windings are surrounded by a superconducting shield constructed by overlapping thin lead sheets separated by an insulated layer to form a torus. This results in near perfect ratios between the windings calculated from the number of turns forming the windings. The torus is closely linked to a pick-up coil which forms a flux transformer when connected to the input coil of a SQUID, as shown in the bottom half of Figure 1. For a current change ΔI in a CCC winding of N turns, the resulting change in current, $\Delta I_{cc} = N \times \Delta I$, in the superconducting shield gives rise to a change, $\Delta\phi_s$, in the magnetic flux sensed by the SQUID. We use a commercial dc SQUID (Quantum Design) which has white noise of 3.2 $\mu\phi_0/\sqrt{\text{Hz}}$. The current sensitivity of the CCC was measured to be 10.7 μA.turns/ϕ_0 and thus an equivalent current noise of ≈ 0.5 fA/$\sqrt{\text{Hz}}$ can be expected in the large (40960 turn) winding. A preliminary measurement of the sensitivity and accuracy of the CCC have been made by driving a 1 nA current through the large winding. For a measurement time of $\approx$10 minutes the uncertainty for a reversible 1 nA current was 5 parts in 10^6, which is a factor of 10 larger than that estimated above. Consequently, it may be necessary to control the temperature of the helium bath more carefully, to prevent temperature fluctuations causing induced currents generated from trapped flux in the pick-up coil and/or improve the magnetic shielding around the cryostat.

The top half of Figure 1 completes the measurement circuit. In this scheme the CCC compares the SAW current through a device $I_Q = ef_1$, where f_1 is the rf frequency, with a larger current NI_Q flowing through a quantized Hall resistance R_K/i. The Hall voltage Nef_1R_K/i is compared with a

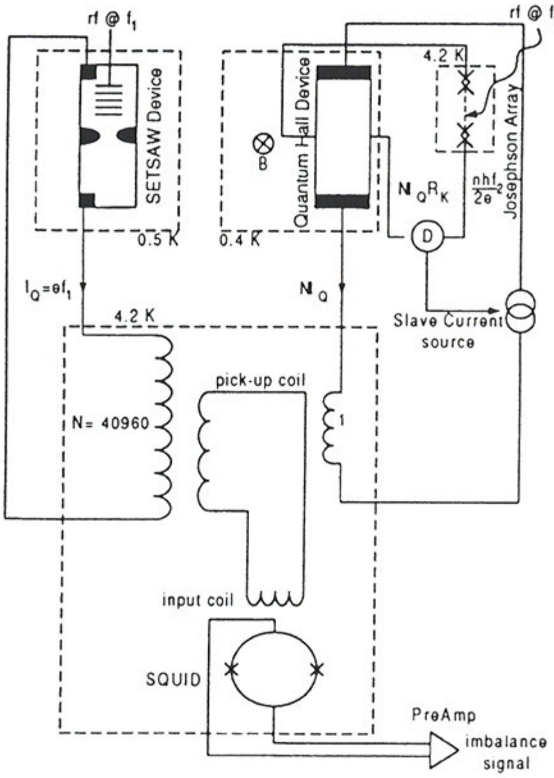

Figure 1: Principle of the application of a CCC for the comparison of the quantized acoustoelectric current with the quantum Hall resistance and Josephson voltage.

similar voltage $nf_2(h/2e)$, developed across an array of Josephson junctions coupled to microwave radiation at frequency f_2, where n is an integer. The relationship

$$R_K = (h/e^2) \times (f_2/f_1) \times (n/2iN) \tag{1}$$

is an alternative measurement of R_K in units of (h/e^2) and any differences between R_K and h/e^2 should be revealed by this experiment.

SETSAW Devices

SETSAW (an acronym for Single Electron Transport using Surface Acoustic Waves)devices are made by further squeezing a 2D electron gas in a high mobility heterostructure, into a 1D channel. Two different types of devices have been used in our investigation. The first type (sample 1) consists of a metal split gate, 1.1 μm wide and 0.6 μm long, evaporated on top of a high mobility heterostructure. A 1D channel is formed by applying a negative voltage to the gate which depletes the electron gas underneath. For the second type (sample 2) a 1D channel was produced by shallow etching [5]. The constriction consists of a straight segment 1 μm long and 0.2 μm wide that smoothly widens into the 2DEG. Figure 2(left side) shows an SEM picture of the constriction. The cut-out areas of 2DEG, on opposite sides of the constriction, serve as gates. At zero gate voltage the constriction is pinched-off by the surface states in the trenches so that in this case a positive gate voltage is required to open the channel. Conduction in the channel which is quantized in units of $2e^2/h$ is controlled by varying the gate voltage thus adjusting the effective channel width. Conduction through the channel can be totally inhibited (pinched-off) if the gate voltage is made sufficiently negative, and electrons approaching the channel are met by an impenetrable potential

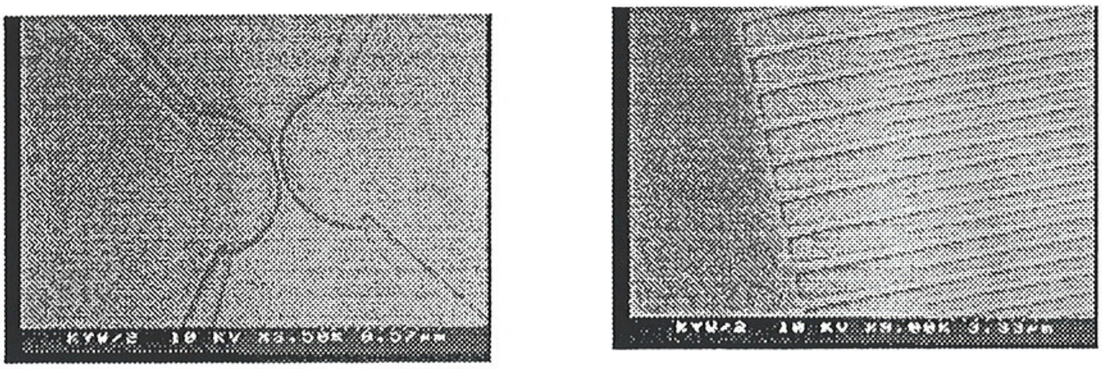

Figure 2: Left side: SEM picture of shallow etched 1D channel. Right side: Close up of fingers of rf transducer.

barrier. In a SETSAW device a transducer of surface acoustic waves is deposited by electron beam lithography in front of the 1D channel. When this is excited by electromagnetic radiation of frequency f a potential wave (SAW) is generated which propagates in the direction of the channel. This has the effect of partially reopening the channel and electrons trapped in each potential well per SAW wavelength are driven through the channel. Both types of devices have similar rf transducers on either side of the 1D channel which operate at around 2.7 GHz corresponding to a SAW wavelength $\lambda \approx 1$ μm. Figure 2(right side)shows a close up of the fingers of the transducers.

For our preliminary investigations of the SAW current we use a commercial electrometer (Keithley 6514) with a quoted accuracy of 0.2% of the reading which corresponds to $\approx$1 pA uncertainty in a 0.5 nA SAW current. However, by making a calibration directly before and after a measurement to NPL standards it is possible to reduce this uncertainty to $\leq$15 fA.

Results

Figure 3(a) shows a typical measurement of the quantized SAW current as a function of gate voltage for sample 2. The horizontal lines indicate the values of $I_n = nef$, and at least 5 current plateaux can be distinguished. The right hand axis shows the standard error of the measurement. A regularly appearing feature in SAW devices is the presence of random telegraph signals (RTS) [2], as demonstrated more clearly in Figure 3(c) for sample 2. The RTS noise is most dominant between current plateaux and reduces strongly towards the centre of a plateau. A second feature of the RTS noise is the different behaviour on each side of the plateau. On the low current side the "spikes" point predominantly downwards and on the high current side predominantly upwards as is shown explicitly for several traces in the inset of Figure 3(c). At present we need to make more measurements to ascertain the exact relationship between this minimum in RTS noise and the corresponding value of SAW current.

Figure 3(b) shows a measurement of the SAW current as a function of time for sample 1. The gate voltage was set to that corresponding to the centre of the current plateau. The line indicates the value of ef calculated using the accepted SI value of $e = 1.60217733(49) \times 10^{-19}$ C. The measured SAW current is seen to be 70±15 fA below ef. However, we must note that such a small difference in current could easily be the result of the limited flatness of the current plateau for this sample and the arbitrary choice of gate voltage.

Summary

In conclusion, a measurement set-up has been constructed and tested for the accurate determination of quantized SAW currents. However, a comparison of these currents with the quantized Hall

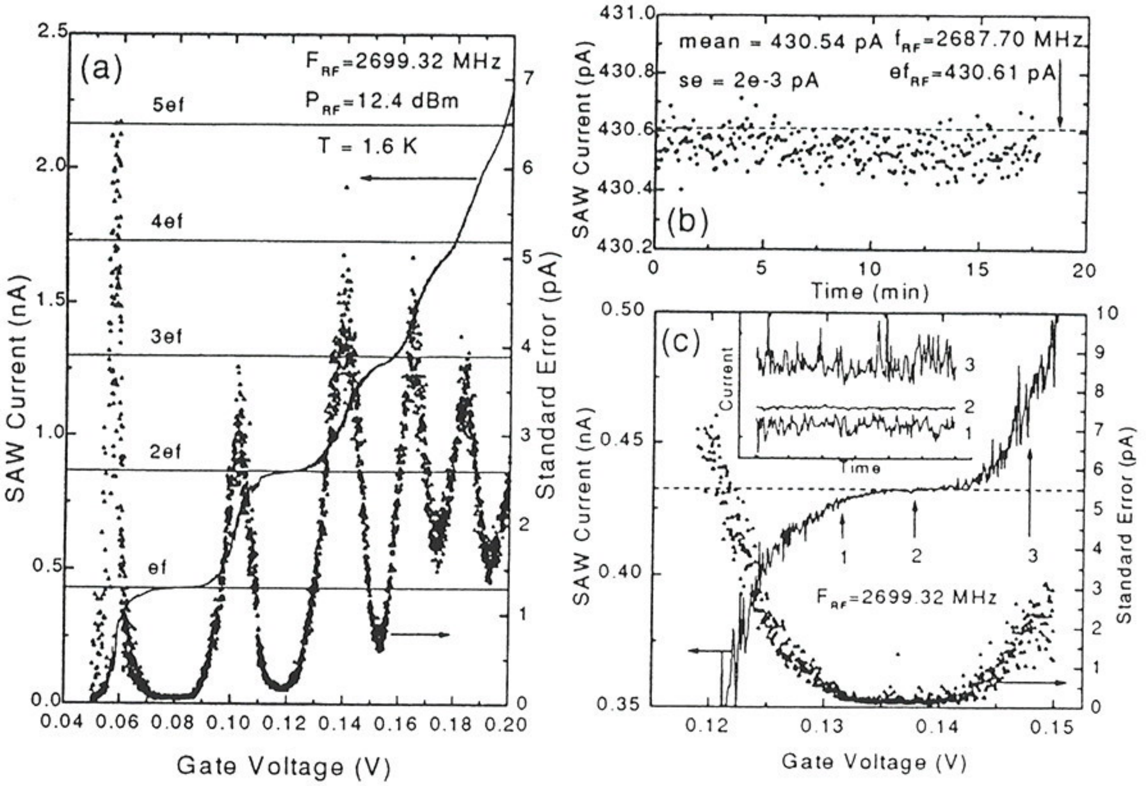

Figure 3: (a) SAW current and standard error as a function of gate voltage for sample 2. (b) SAW current as a function of time for sample 1. (c) Close up of current plateau $n = 1$ for sample 2.

resistance and Josephson voltage has yet to be performed. Such an experiment will only be meaningful if a quantized current can be generated which has comparable accuracy to measurements of the quantized Hall resistance and Josephson voltage. Presently, much of the efforts are focused on determining the parameters which affect the behaviour and flatness of the SAW current plateaux.

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References

[1] J.M. Shilton, D.R. Mace, V.I. Talyanskii, Yu Galperin, M.Y. Simmons, M. Pepper and D.A. Ritchie J. Phys.: Condens. Matter **8**, L337 (1996).

[2] 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**,15180 (1997).

[3] F. Delahaye, IEEE Trans. Intrum. Meas. **IM-27**, 426 (1978).

[4] J.M. Williams and A. Hartland, IEEE Trans. Instrum. Meas. **IM-40**, 267 (1991).

[5] A. Kristensen *et al.*, J.B. Jensen, M. Zaffalon, C.B. Sorensen, S.M. Reimann, P.E. Lindelof, M. Michel, and A. Forchel, J. Appl. Phys. **1**, 607 (1998).