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Quantised Currents in One Dimensional—Channels Induced by Surface Acoustic Waves

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Abstract

Control over the transport of single electrons is of significance for a range of topics including quantum computing and memories. There is also interest in metrology in closing the triangle of the fundamental quantum constants formed by e^2/h, e/h and e, where e is the charge on the electron and h is Planck's constant. The first two are obtained by the Quantum Hall and Josephson effects, respectively, but there is no method for the direct measurement of e. Literature discussion of the requirements for the determination of e conclude that single electron transport at high frequencies offers good prospects for high accuracy measurement.

If at each cycle of an applied frequency (f) n electrons pass through the system being investigated, then a dc current flows given by $I = nef$. The condition that only n electrons are present can be achieved by utilising the mutual repulsion between the electrons in order to produce discrete energy levels, for example the Coulomb Blockade in a quantum dot. However the use of the Coulomb Blockade, or any zero dimensional device, relies on electron tunneling through the barriers to produce the current and at high frequencies an electron (for the $n=1$ case) does not tunnel during every cycle so producing an error in the quantised current.

In order to avoid this particular problem, we have investigated the high frequency transport of a controlled number of electrons by means of the acousto-electric effect. Here a current is induced by a Surface Acoustic Wave (SAW) projected through a 2D electron gas in a weakly piezoelectric Gallium Arsenide heterostructure, [1]. The SAW is essentially a sinusoidal modulation of the conduction band moving across the chip at sound velocity. The minima of the wave are potential wells in which electrons can be trapped and transported across the chip so giving rise to a current. The advantage of such a technique is that the transducers generating the SAW can be fabricated by high resolution electron beam lithography, and short wavelengths with correspondingly high frequencies up to several GHz can be obtained. As the wave moves across the GaAs surface the potential wells are initially occupied with electrons from the 2D electron gas and so tunnelling is not necessary. The electron energy levels in the moving potential wells are determined by two factors; the mutual interaction of the electrons and the geometry of the well. In order to enhance the level discreteness the wave is passed through a narrow channel so forcing the electrons closer and increasing their mutual repulsion. In our work, this reduction in size was achieved by the application of a negative voltage to two split gates on the semiconductor surface. This progressively narrows the channel, by electrostatic confinement, and reduces the number of electrons trapped in the potential minima of the SAW as the wave travels through.

The technique of split gates was first developed to produce a transition from two to one dimensional transport in semiconductor systems, [2], and has been particularly valuable in investigating quantum ballistic transport in one-dimension and one-dimensional interaction effects. For single electron transport, however, we deplete the channel much further in order to ensure that there are no free carriers in the channel. The absence of free carriers reduces the screening of potential fluctuations emanating from the surrounding semiconductor, this can have the unfortunate side-effect of increasing the noise. Initial work on this topic utilised the metal split gates used for the original 1D work, however more recently the gates have been of in-plane type etched from a highly doped n type surface layer, [3]. A particular difference of the two techniques is that in the etched samples the sideways depletion pinches off the channel at zero gate voltage, so requiring a positive voltage to open a passage and allow the acousto-electric current to flow.

As the channel becomes increasingly narrow so the acousto-electric current shows a number of plateaux as a function of gate voltage. Each plateau corresponds to an integer value of n, the number of electrons, and the existence of a plateau is due to the gap between adjacent energy levels. This requires the potential on the gate to be changed by a finite amount in order for a change in the value of n by one. Most of our experiments have been performed at a value of applied frequency of 2.716 GHz and results will be presented showing that the current corresponds to integer numbers of electrons which changes in steps of one electron as the voltage becomes more positive (negative) and the channel widens (narrows). Decreasing the SAW power reduces the depth of the potential well and so the voltage to obtain a particular number of electrons is decreased. As a result a particular plateau occurs at a less negative voltage. The one-electron current plateau is the flattest and the flatness of the central portion is within a region of 50ppm.

The factors affecting the temperature dependence will be discussed as although the plateau are observable below about 10K a temperature of 1.2K is required for optimal flatness. Further decrease in temperature does not improve the flatness and the cause of this is not fully clear but may well be related to SAW induced electron heating.

Other aspects of our work to be discussed include the dependence of the accuracy of the quantisation, on the shape of the channel entrance, {4]. The differences found between metal and etched gate devices will be reviewed as this latter technique produces a much more robust quantisation, and the prospects for increasing the accuracy to a level of metrological significance will be considered. In this latter context the role of a source-drain field will be presented as will the modification of the plateau by a non-quantising magnetic field which produces a reduction in the backscattering and hence elongation of the plateaux.

References

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