Temperature as a Limitation to the Accuracy of SETSAW Devices as Quantum Standards of Current

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1. Abstract

We have made measurements of the slopes $(\Delta I/\Delta V_g)_n$ of the acousto-electric current plateaux $I_n = nef$ for n=1 and 2, as a function of the bath temperature T in the range 0.3 to 4.2 K. Electrons, constrained in 1-dimensional channels, `surf' a surface acoustic wave of frequency $f \approx 2.8$ GHz, generated by transducers deposited on a GaAs heterostructure. The channel width is controlled by the application of voltages V_g to Schottky gates also deposited on the heterostructure. The normalised slopes $S = (\Delta I/\Delta V_g)_n / (\Delta I/\Delta V_g)_{n-1\rightarrow n}$ are compared with those calculated using a model describing the device behaviour proposed by Flensburg *et al* [11]. In this model S is related to an effective temperature T_{eff}, which can be greater than T. The measurements indicate that for n=1, T_{eff} has a minimum value of 1.65±0.1 K corresponding to a minimum value of $S \approx 10^{-3}$.

2. Introduction

There is presently considerable research work in national metrology institutes with the aim of developing quantum standards of current based on single electron transport. NPL is involved in two such projects, one using a single electron R-pump (detailed elsewhere in this digest [1]), and the second, based on the SETSAW (Single Electron Transport by Surface Acoustic Waves) technique which is the subject of this paper.

Figure 1 shows a schematic of a SETSAW device. The device is fabricated on a semiconductor substrate ($GaAs/Al_xGa_{1-x}As$ heterostructure) containing a quasi two-dimensional electron gas (2DEG) near the surface. An interdigitated transducer (IDT) at one end of the device produces a surface acoustic wave (SAW) which propagates past a central region where a constriction in the 2DEG has been formed. This traveling mechanical wave produces a corresponding electrical potential in the piezo-electric GaAs material, which interacts with the 2DEG. In the region of the constriction (usually formed by a metallic split-gate deposited on the surface and held at a negative potential with respect to the 2DEG) the minima of the SAW potential can be regarded as moving quantum wells, which transport electrons through the constricted channel. If the channel is sufficiently closed i.e. 'pinched-off' such that normal conduction is prohibited and the potential of the SAW can be arranged such that each potential minimum transports the same (small) number of electrons, then the device functions as a current source, generating a current $I=nef$, where n is an integer, e is the electron charge and f is the frequency of the SAW.

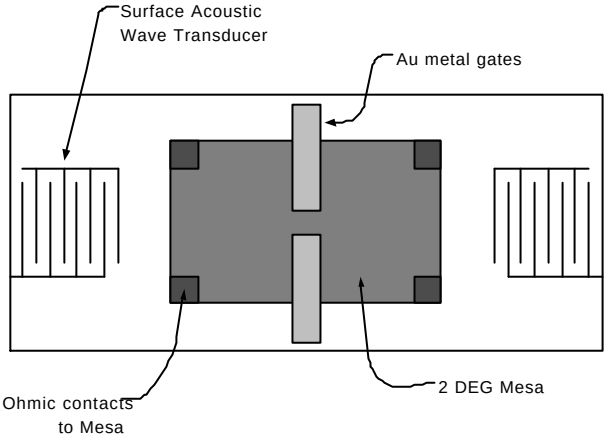

Figure 1 – SETSAW device layout

The first realisation of a quantized current as described above was reported in 1996 [2]. The advantage of this technique over that using electron pumping through metal-insulator-metal tunnel junctions, is the higher frequency of operation – up to 5 GHz [3] generating nearly 1 nA compared with about 10 MHz generating a few pA. However, despite continued research and development over the last 5 years [e.g. 4,5,6], the accuracy of quantization of SETSAW devices remains inferior to that of electron pumps [7]. This paper presents results of an experiment to measure the temperature dependence of SETSAW device characteristics with a view to better understanding (and hopefully controlling) the error mechanisms.

3. Motivation for Research

Two macroscopic quantum effects have already been adopted by the metrological community for the practical realisation of electrical quantities – the quantum Hall effect and the Josephson effect for resistance and voltage standards respectively. If an ideal quantum current standard producing a known current nef existed, the obvious experiment would be to measure this current in terms of the existing voltage and resistance standards. This linking of the Josephson constant ($K_J=2e/h$ where e and h are the electron charge and the Planck constant respectively) and the von Klitzing constant ($R_K=h/e^2$) via a quantum current has been described as 'closing the metrological triangle' between voltage, resistance and frequency. Information about the consistency of the quantized electrical quantities derived by very different techniques would be obtained if closure with sufficient accuracy (at least 1 part in 10^7 – see [9] for a full account) could be achieved.

The implementation of this experiment is limited by the accuracy of devices presently available and the resolution of the small currents they produce. A measurement system based on a cryogenic current comparator (CCC) has been designed at NPL. Although this CCC has a resolution and accuracy presently limited to about 1 ppm for a measurement of 1 nA [10], even a 1 nA current standard with an accuracy of 1 ppm related to R_K and K_J would still be a useful device. There is presently an increasing interest in the measurement of small currents and high value resistors (which require small currents), motivated by the need for improved measurement of ionisation currents and currents generated in the ever-decreasing size of electronic devices. A SETSAW current source could find an application for calibration services in this area.

4. Theoretical Models

A recent paper by Robinson and Barnes [10] describes a classical model of the dynamics of electron transport in a SETSAW device. In this model the potential minimum created by the surface acoustic wave initially captures a large number of electrons from the 2DEG into a quantum dot. As each dot approaches the potential barrier formed by the gated constriction, its size and the number of electrons it can hold are reduced. The mutual coulomb repulsion of the electrons means that they are ejected from the shrinking dot, and returned to the 2DEG over the barrier. For a SETSAW device operating on the $n=1$ plateau, by the time the dot has passed the peak of the barrier, it ideally contains only one electron.

The removal of electrons as the dot shrinks leaves those remaining in an excited state. The rate at which electrons are ejected from the dot is too high for thermal equilibrium with the 2DEG to be maintained. A large number of computer simulations of this mechanism have been carried out in [10] and, for the $n=1$ current plateau, they predict an effective temperature of about 1.7 K for the remaining electron. This temperature, elevated above that of the surrounding 2DEG, leads to an increased probability of empty dots being transported, resulting in sloping plateaux whose value falls mainly below the true quantized value, ef.

Flensberg *et al* [11] have used a quantum mechanical approach to model the same process. The principle of this mechanism is that electrons in the moving quantum dot can return to the 2DEG by tunnelling through the potential barrier as the dot approaches the channel entrance. Since the confining potentials are changing rapidly in this region non-adiabatic effects become significant, causing electrons remaining in the dot to have an effective temperature T_{eff} above that of the surrounding 2DEG.

The plateau slope predicted by this model is

$$S = \frac{1}{nef}\left(\frac{dI}{dN_g}\right)_{N_g \to n} \approx \left(2E_c / kT_{eff}\right)\exp -\left(E_c / kT_{eff}\right)$$

where N_g is the variation of dot occupation with gate voltage and n is the integer occupation on a plateau. T_{eff} is an effective temperature given by $T_{eff} = \sqrt{T^2 + T'^2}$ where T is the 2DEG temperature and $T' = c/\tau \approx$ 1K, where $c \approx 1$ and τ is a time constant describing the switching off of the tunnelling coupling between the 2DEG and the moving quantum dot. E_c is the charging energy of the dot and k is the Boltzmann constant.

This model can be related to the experimental curves of current vs. gate voltage by measuring the minimum gradient $D_{\min}=\left(\Delta I/\Delta V_g\right)_n$ in the centre of a plateau, and the maximum gradient $D_{\max}=\left(\Delta I/\Delta V_g\right)_{n-1\to n}$ between plateaux. A reasonable approximation to $(1/nef)\ (\mathrm{d}I/\mathrm{d}N_g)_{Ng\to n}$ is $2D_{min}/D_{max}$ so D_{max} is used to normalise the slope on the plateau. The expression to be compared with experiment now becomes:

$$D_{\min}/D_{\max} \approx (E_c/kT_{eff}) \exp -(E_c/kT_{eff})$$

5. Experimental Set-up and Results

Devices for measurement are mounted in a commercial sorbtion pumped ^{3}He variable temperature cryostat. The device holder is contained in a vacuum space and mounted in good thermal contact with the ^{3}He pot of the refrigeration system. This arrangement allows the device temperature to be varied over a wide range (300mK to 20 K) with little variation in the environment, which could affect the IDT optimization parameters.

Most devices investigated show optimum plateaux for microwave powers in the region +5 to +10 dBm, as measured at the output of the RF source. The losses in the cryogenic coaxial lines have been measured at about 3 dB, but coupling into the IDT is poorly defined and unknown. A power of +5 dBm at the source output (about 2 mW dissipated in the ^{3}He system) makes temperature control below 4K very difficult. The device on which the results presented below were obtained was unique in that the optimum operating power was as low as 0 dBm. This enabled reasonable periods of stable control for temperatures as low as 300 mK, and permitted investigation of physical effects which had previously been masked by heating of the sample by the applied RF power [6].

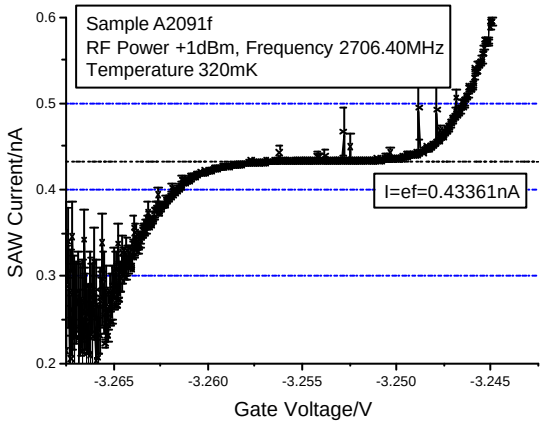

Figure 2 Plateau of SAW current against gate voltage

Figure 2 shows the best plateau for current plotted versus gate voltage (i.e. channel width) obtained from this device. The measured slope of the plateau is 300 ppm/mV of gate voltage. The measurement was made using a commercial electrometer calibrated to an accuracy of about 100 ppm using a 1 GΩ standard resistor. The dominant source of noise is due to random telegraph signals (RTS) and this limits testing the relation $I = ef$ to a few hundred ppm. More significantly, the plateau slope $D_{\min}$ makes it impossible to decide at which gate-voltage the current measurement should be made. For a true quantum standard, the plateau should have no measurable slope over a region of gate-voltage so that there is no ambiguity as to where the quantized value lies.

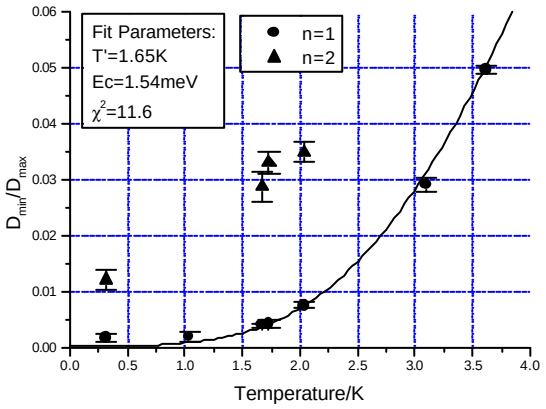

Figure 3 Temperature dependence of plateaux slopes

Figure 3 plots the results of measuring the ratio of plateaux slopes $D_{\min}/D_{\max}$ (as described in section 4) as a function of temperature for $n=1$ and 2. The temperature is that measured by a RuO_2 sensor mounted on the ^{3}He pot of the cryostat, but it is not clear how closely the measured temperature matches that of the actual device. The fit to the model is shown in figure 3, with $T'=1.65\pm0.1$ K and $E_c=1.54\pm0.02$ meV, with a χ^2 value of 11.6. Some points were measured for $n=2$, but this plateau was too noisy to give sufficient data for a meaningful fit.

Using the model, the extrapolated value of the plateau slope when $T \rightarrow 0$ K is 30 ppm/mV of gate voltage. Below 1 K the data indicate a deviation from the model. This may be due to saturation of the plateau slope caused by direct RF heating, but the inference is marginal given the error-bars.

6. Conclusions

The good fit obtained for our experimental data gives confidence in the use of the model of reference [11] to understand SETSAW device behavior. The measured value of $T' = 1.65$ K suggests that intrinsic heating in the device due to the electron transport mechanism will limit the plateau slope to 10 ppm/mV, even if RF heating can be completely controlled. This lack of quantization will limit the metrological application of these devices. However, if the model is correct any modification to the device design that reduces T' will have a large impact on the plateau slope. For example a reduction of T' to 1 K would reduce the predicted plateau slope to 0.04ppm/mV.

Such a reduction in this intrinsic heating may be achieved by controlling the shape of the potential at the entrance to the 1-D channel – for example by the use of extra gates or counter-propagating surface acoustic waves [4]. These techniques will only be useful if extrinsic heating of the device, caused directly by the applied RF power, can also be controlled. The device behaviour as a function of temperature presented in this paper was only possible because this particular device operated satisfactorily at much lower power levels than those seen previously. The reasons for this improved efficiency are not understood, and will be the subject of future work.

7. Acknowledgements

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