

Surface-acoustic-wave-defined dynamic quantum dots

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Declaration

The work presented in this thesis was carried out at the Semiconductor Physics Group in the Cavendish Laboratory, University of Cambridge between October 2004 and January 2008.

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where otherwise acknowledged. It has not been submitted in whole or in part for any degree at this or any other university, and is less than sixty thousand words long.

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January 31, 2008.

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Summary

The strain associated with a surface acoustic wave (SAW) propagating across a piezoelectric medium creates a travelling electric potential. Gallium Arsenide is such a piezoelectric material, and so SAWs can be used with existing semiconductor technologies for creating complex low-dimensional nanostructures. A SAW travelling along an empty quasi-one-dimensional channel creates a series of dynamic quantum dots which can transport electrons at the SAW velocity ($\sim 2800 \text{ ms}^{-1}$), allowing high-frequency operations to be carried out on the electron without the need for fast pulsed-gate techniques. Such dynamic quantum dot devices can provide valuable insights into fundamental physical phenomena and could have technological applications in quantum information processing.

This thesis details investigations into SAW-defined dynamic quantum dot devices. Chapter 1 introduces the scientific background to the experiments described in this thesis; Chapter 2 provides details of the processing and measurement techniques used to perform these experiments.

Chapter 3 consists of a study into the effect that reflections have on the acousto-electric current generated in a SAW channel. Reflections create a modulation to the channel entrance potential which is critical in determining the magnitude of the acousto-electric current. As the frequency of the SAW is varied, a particular reflection creates a periodic interference with the main SAW driving the current which can be observed in the Fourier transform of the acousto-electric current's frequency dependence. The period of these oscillations is directly related to the distance which the reflection has travelled relative to the main SAW, which allows the principle reflection mechanisms to be characterised. Reflections persisted on a SAW device for large amounts of time, giving rise to much of the “noise” seen in the frequency dependence, and the pattern of reflections was found to be chaotic.

Chapters 4-8 show the results obtained with a device where two SAW channels were linked by a tunnel barrier. This device allowed quantum mechanical tunnelling of electrons from the dynamic quantum dots to be observed over a subnanosecond timescale. Chapter 5 describes how the escape

rates of the electrons from dynamic quantum dots can be measured using a rate equation analysis, and these rates are fit to a simple tunnelling model to derive the addition energies of the dynamic quantum dots. In Chapter 6 the tunnelling current was found to contain low-visibility oscillations, which cannot be explained by simple models. It is thought that these oscillations are caused by the non-adiabatic time-evolution of the electron wave function when the tunnel barrier is lowered suddenly. Chapter 7 shows how a crosstalk current through a short constriction is sensitive to local potential changes in an analogous manner to a quantum point contact, and how this effect can be used to detect the occupation of dynamic quantum dots in a nearby SAW channel. Chapter 8 collects some minor observations which have been made whilst studying the tunnel barrier device. In Chapter 9 I present the conclusions of the experiments presented in this thesis, and provide some ideas for future directions this work may take.

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Chapter 1

Background

1.1 Low dimensional semiconductors

In a suitably engineered semiconductor system, an electron may be confined in a certain direction to a distance comparable to or smaller than the electron's Fermi wavelength. When confinement reaches this length scale, the electronic wavefunction in this direction becomes restricted to the lowest energy eigenfunctions of the confining potential, and motion in this direction is restricted; the electron effectively behaves like a particle in a low-dimensional system. The confinement of electrons to quasi-low-dimensional systems has provided a rich area of research, both from the point of view of observing fundamental phenomena which test the validity of quantum mechanics and in producing new technologies.

1.1.1 The two-dimensional electron gas

Two-dimensional electron gases (2DEGs) may be formed in a number of systems where free electrons are confined to a plane, such as in a silicon metal-oxide-semiconductor field-effect transistor (MOSFET). However, MOSFETs are unsuitable for observing complex quantum-mechanical behaviour because of the roughness of the semiconductor-oxide interface where the 2DEG is formed, and because of the presence of donors throughout the semiconductor, which scatter the free electrons in the 2DEG. The GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructure avoids these problems by having an atomically precise, lattice-matched interface between the GaAs and the $\text{Al}_x\text{Ga}_{1-x}\text{As}$, and by separating the donor layer from the interface where the 2DEG forms by several tens of nanometers, so that the 2DEG exists in a high purity material.

The simplest GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructure is the high-electron-mobility transistor (HEMT) [Fig. 1.1(a)]. High quality heterostructures are grown

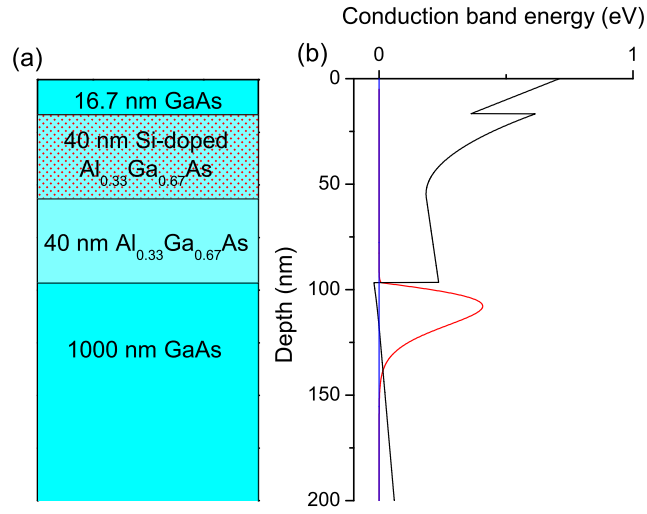


Figure 1.1: (a) Standard layer structure for a 40 nm HEMT design of a GaAs/ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ heterostructure. (b) Resulting conduction band edge (black line), calculated by solving the one-dimensional Poisson and Schrödinger equations for the layer structure shown in (a) in a self-consistent manner. The conduction band edge dips below the Fermi energy (E_F , shown as blue line) at the lower GaAs/ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ interface, creating a 2DEG. Solution to the one-dimensional Schrödinger equation (red line) shows the vertical position of the 2DEG; only the lowest-energy subband is populated (one-dimensional Poisson and Schrödinger equations solved using the computer programme *1D Poisson/Schrodinger: A Band Diagram Calculator*, G. L. Snider).

using epitaxial techniques such as molecular beam epitaxy, which allow the creation of atomically precise layers. Using $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ ensures the lattice spacings of the GaAs and $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ are matched, but the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ has a bandgap of $\sim 1.8\text{ eV}$ compared to $\sim 1.4\text{ eV}$ in GaAs. As a result of the silicon dopant, the conduction band edge dips below the Fermi energy at the GaAs/ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ interface, as shown in Fig. 1.1(b). At the interface the electron wave functions are quantised across the quantum well, and can be separated into sub-bands which share the same wave function in the vertical (z) direction. The Schrödinger equation has the form

$$-\frac{\hbar^2}{2m^*}\nabla^2|\psi\rangle + V_{\text{CB}}|\psi\rangle = E|\psi\rangle \quad (1.1)$$

which leads to solutions with the energy

$$E_{i,\mathbf{k}} = \frac{\hbar^2 k^2}{2m^*} + \varepsilon_i \quad (1.2)$$

where V_{CB} is the conduction band potential, ε_i is the sub-band energy, m^* is the effective mass of an electron, and $\mathbf{k}$ is the two-dimensional electron wave vector (k_x, k_y). The HEMT can be grown so that the electrons are sufficiently confined in the z direction that only the lowest energy transverse sub-band is below the Fermi energy, and the electrons will then behave as a 2DEG [1].

Metallic gates on the surface of the heterostructure form Schottky barriers, so that when large negative voltages are applied to the gates no current flows to the 2DEG and the conduction band edge is pulled above the Fermi energy. This technique allows complicated nanostructures to be defined in the 2DEG by appropriate gate geometries.

1.1.2 Quantum dots

A quantum dot is a mesoscopic semiconductor structure in which the free electrons are confined in all three dimensions. The effect of this confinement is to make the electrons behave like zero-dimensional particles, in a similar way to electrons bound in atomic shells of atoms; because of this quantum dots are sometimes referred to as *artificial atoms*. Experimentally there are a number of ways of generating quantum dots (Fig. 1.2):

lateral quantum dots are defined in a 2DEG by isolating a small region of the 2DEG by applying negative voltages to surface gates to deplete the electron gas underneath them, by etching away the semiconductor, or some combination of both these techniques. The remaining 2DEG is usually used to provide source and drain reservoirs.

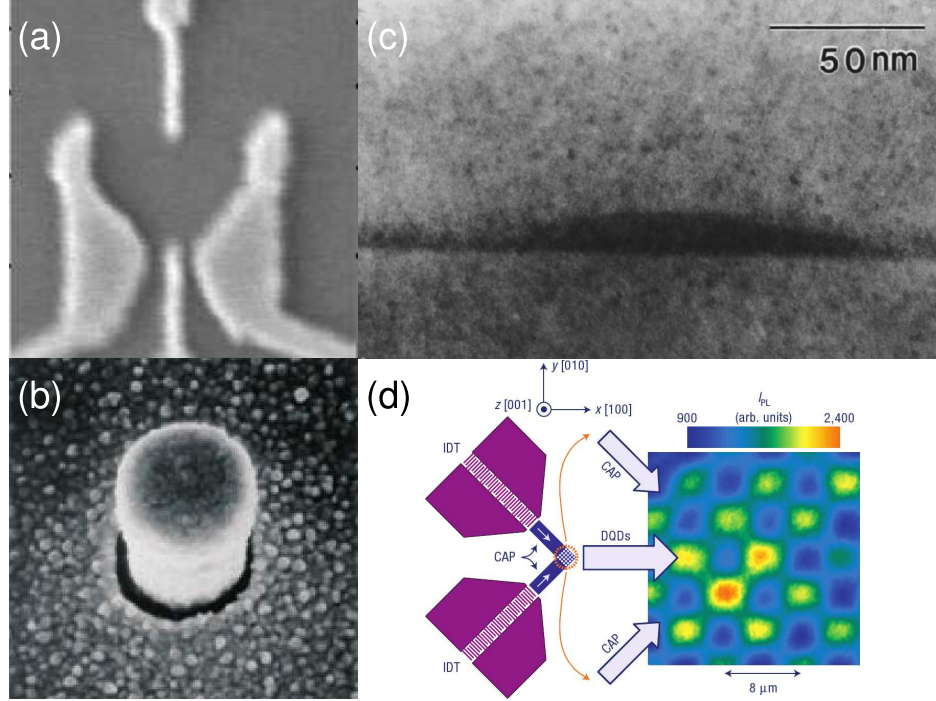


Figure 1.2: Images of various types of quantum dots. (a) Scanning electron microscope (SEM) image of a gate-defined lateral quantum dot (taken from Ciorga *et al.* [2]). (b) SEM image of a vertical quantum dot (taken from Kouwenhoven *et al.* [3]). (c) Transmission electron microscope image of a self-assembled InGaAs quantum dot grown in GaAs using the Stranski-Krastanov method (taken from Nishi *et al.* [4]). (d) Array of dynamic quantum dots created by SAWs propagating in perpendicular directions. The image on the right of the diagram shows a stroboscopic photoluminescence image of the dynamic quantum dot array at a particular phase of the dynamic quantum dot motion (taken from Stotz *et al.* [5]).

vertical quantum dots are defined by etching a pillar of semiconductor which contains a 2DEG in a layer in the middle of the pillar. Heavily doped layers above and below the 2DEG are used as the source and drain contacts to the dot.

self-assembled quantum dots are grown using the Stranski-Krastanov technique: they occur when a thin layer of atoms is grown which has a lattice mismatch to the base material. The mismatch leads to strain in the semiconductor crystal which may be relieved during growth by the atoms migrating to form islands. The islands are then embedded in further layers of material to create quantum dots. These quantum dots are difficult to individually address using electrical methods and are usually used in optical experiments.

dynamic quantum dots are defined by providing confinement using the modulation in the piezoelectric potential of a semiconductor that occurs when a surface acoustic wave (SAW) travels across a semiconductor that contains a 2DEG (see Section 1.2). Additional confinement can be provided either by using gates or etching to create a channel in the 2DEG, or by using two SAWs travelling perpendicular to each other.

Coulomb blockade

Because of their small size, the most important factor governing electrical transport through a quantum dot is the classical effect that the discrete charge of the electron passing through the quantum dot has on the dot's energy. When transport through a quantum dot happens relatively slowly (i.e. the quantum dot is strongly decoupled from the surrounding environment by large tunnel barriers), the number of electrons N in the dot must always be an integer. Current may flow by electrons sequentially tunnelling into and out of the quantum dot, but Coulomb interactions between the electrons in the dot and those in the reservoirs, gates, etc. result in a large energy cost in adding an extra electron. For current to flow, this addition energy must be overcome by incoming electrons. This phenomenon, shown in Fig. 1.3, is known as *Coulomb blockade*.

The simplest model which describes the energetics of Coulomb blockade is the *constant interaction model*. This model is based on two assumptions: that the Coulomb interactions of an electron within the quantum dot with all other electrons (both inside and outside the quantum dot) can be described by a constant capacitance C ; and that the single-particle energy ε_N of the N^{th} electron is unaffected by electron-electron interactions. The total energy

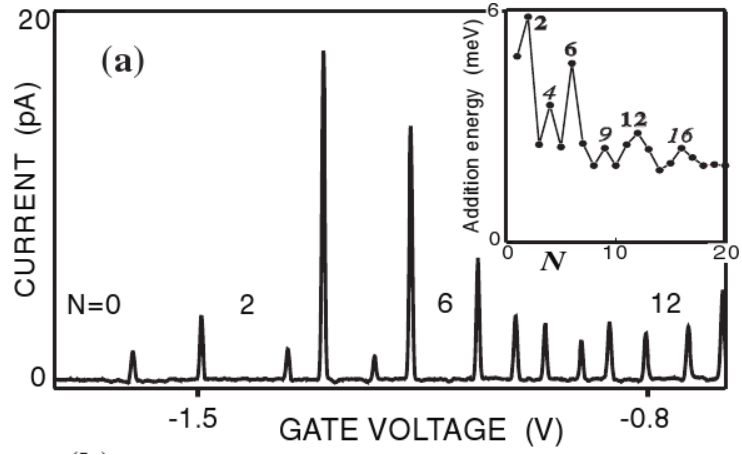


Figure 1.3: Coulomb blockade in the current through a two-dimensional circular quantum dot where the source and drain voltages are approximately equal. The leftmost peak marks the voltage where the energy cost of having $N = 1$ electrons is the same as having $N = 0$ so current can flow through the dot. To the right of this peak the dot is blockaded with one electron in it. N increases by one as each subsequent peak is passed. The distance between adjacent peaks is proportional to the addition energies $\Delta E_{N \rightarrow N+1}$, shown in the inset (taken from Kouwenhoven *et al.* [3]).

$U(N)$ of an N -electron quantum dot is then given by

$$U(N) = \frac{[-e(N - N_0) + C_g V_g]^2}{2C} + \sum_N \varepsilon_N \quad (1.3)$$

where $N = N_0$ at a gate voltage $V_g=0$ and $C_g V_g$ is the effective background charge induced by the gate voltage, including contributions from positive background ionised donors. The electrochemical potential of the quantum dot $\mu_{\text{dot}}(N)$ is defined as the change in the total energy of a system caused by removing an electron, i.e. $\mu_{\text{dot}}(N) = U(N) - U(N - 1)$. A current can only flow through the quantum dot if the electrochemical potential of the quantum dot lies between the electrochemical potentials of the source and drain i.e. $\mu_{\text{source}} > \mu_{\text{dot}}(N) > \mu_{\text{drain}}$. From Equation 1.3 the chemical potential is

$$\mu_{\text{dot}}(N) = \left(N - N_0 - \frac{1}{2}\right) \frac{e^2}{C} - \frac{C_g}{C} e V_g + \varepsilon_N \quad (1.4)$$

The addition energy ($\Delta E_{N \rightarrow N+1}$) of the quantum dot is the amount that the electrochemical potential is increased by adding another electron

$$\begin{aligned} \Delta E_{N \rightarrow N+1} &= \mu_{\text{dot}}(N + 1) - \mu_{\text{dot}}(N) \\ &= \frac{e^2}{C} + \varepsilon_{N+1} - \varepsilon_N \\ &= \frac{e^2}{C} + \Delta \varepsilon_{N \rightarrow N+1} \end{aligned} \quad (1.5)$$

1.2 Surface acoustic waves

Lord Rayleigh first described surface acoustic waves (SAWs) in 1885 [6]. SAWs travel across the free surface of an elastic material, causing any single point in the material to undergo displacement in a retrograde ellipse (see Fig. 1.4). The amplitude of the wave decays exponentially into the bulk of the material over a distance of approximately one wavelength. In a piezoelectric material, there is a coupling between the strain and electric potential, and SAWs can be produced by applying an alternating voltage to a suitably designed transducer. The simplest design of transducer is a series of interdigitated fingers with a periodic spacing, as shown in Fig. 1.5. Because such a transducer will also produce an electrical signal if a SAW passes across it, different designs and arrangements of transducers can be used in high frequency signal filter, delay line, and sensor applications [7].

Within a piezoelectric material, the SAW potential will interact with the material's free electrons [8]. In GaAs/AlGaAs heterostructures, where free

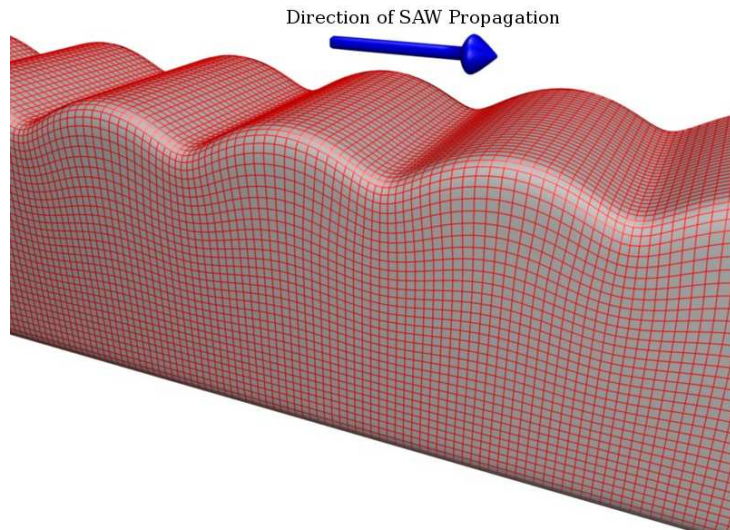


Figure 1.4: Representation of the displacement of the material as a SAW passes across the surface (vertical displacement is exaggerated).

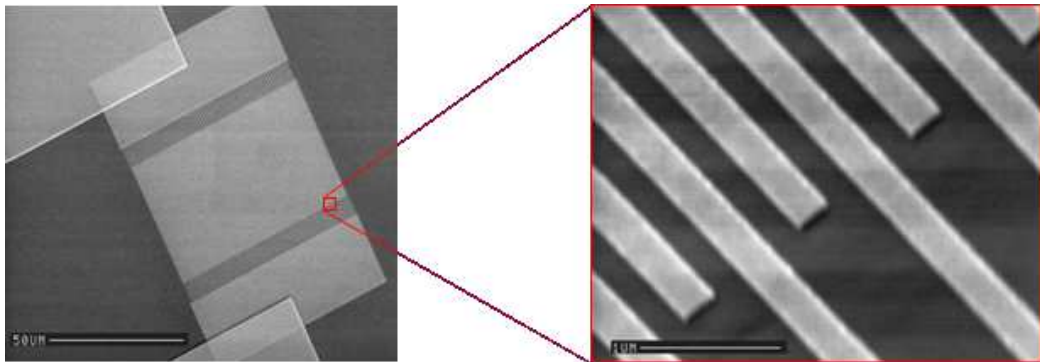


Figure 1.5: Single-finger interdigitated transducer used to generate and detect SAWs, made of 70 pairs of fingers spaced with a one micron period.

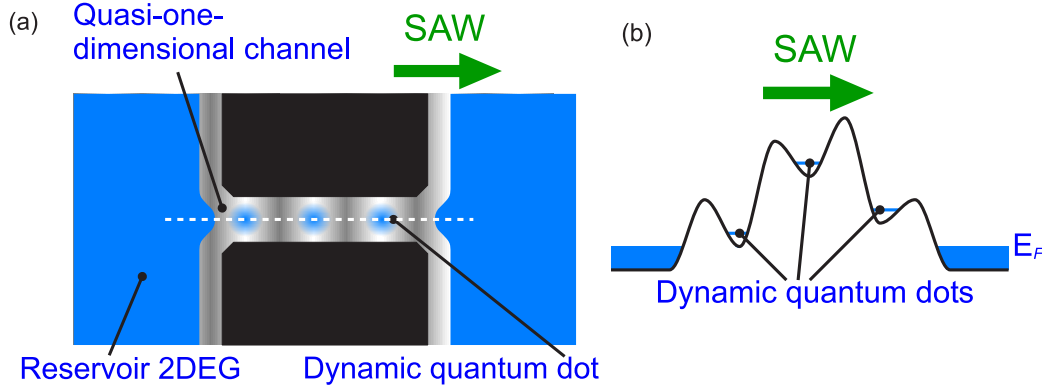


Figure 1.6: (a) Simplified experimental circuit of an acousto-electric current through a Q1DC. (b) Potential along white dotted line in (a). The SAW potential carries electrons from the left reservoir 2DEG to the right one at the SAW frequency f , in dynamic quantum dots. If each dynamic quantum dot contains an integer n electrons, then the acousto-electric current is quantised to $I = nef$, where e is the charge of an electron.

electrons are confined to a two-dimensional electron gas (2DEG) at an interface, SAWs have been instrumental in probing the electronic states at the Fermi surface of the system [9], proving particularly useful in providing experimental evidence for the theory of composite fermions [10]. More recently, SAWs have been used to trap and transport electrons through quasi-one-dimensional-channels (Q1DCs) defined by gating or etching the 2DEG [11, 12] (Fig. 1.6). This acousto-electric current may have applications as a new current standard in metrology [13], and by creating more complex nanostructures in the 2DEG [14, 15] acousto-electric generation of individual electrons could be used to study the quantum behavior of single electrons [16] and lead to new methods of quantum information processing (see section 1.3)[17, 18]. Integration of SAW devices with optical systems is also leading to devices for spin measurement [5] and single photon generation [19, 20].

1.3 Quantum computation

Conventional computation uses bits as a basic unit of information to represent any data. A bit can be in either the “0” or “1” state at any time. In 1982 Feynman proposed that if a quantum system was used to carry out the calculation, the quantum bit (qubit) could be in a superposition of the “0”

and “1” states [21]. This effectively allows a quantum computer to perform a calculation on many different numbers at the same time, and for certain algorithms such as Shor’s factorisation algorithm [22], a quantum computer may be exponentially faster than a conventional computer.

Because quantum mechanics describes all physical systems, a large number of possible candidates for qubits exists. In order to create a working quantum computer a qubit system must obey five criteria originally proposed by DiVincenzo [23]:

- Be a scalable physical system with well-defined qubits.
- Be initialisable to a simple fiducial state such as $|000\dots\rangle$.
- Have long relevant decoherence times (much longer than the time taken to perform many gate operations).
- Have a universal set of quantum gates.
- Permit qubit-specific measurements with high quantum efficiency.

Recently, considerable interest has been shown in experimental systems which could perform quantum computation. For example, simple quantum operations have been demonstrated using nuclear magnetic resonance [24], linear optics [25], trapped ions [26] and superconducting loops [27]. Electron spins in semiconductor nanostructures provide an attractive set of qubits because of the relatively long spin-coherence time and the highly-developed level of semiconductor processing technology [28, 29, 30], and a quantum computer based on static quantum dots has been proposed (see Fig. 1.7) [31]. Rather than using static quantum dots, electrons confined to dynamic quantum dots by a surface acoustic wave could be used as the qubits [17]. The spins of individual electrons in parallel SAW channels would form a two-level qubit system, using either electron spin resonance pulses or magnetic surface gates to perform single spin rotations, and tunnelling barriers to entangle spins in neighbouring channels (Fig. 1.8). An alternative proposal which might be experimentally easier to make would use collections of three electrons as pseudospin qubits [18]. SAW computation would have the inherent advantage that each row of SAW minima performs one calculation as it passes through the system: the device thus performs billions of repeated calculations per second allowing averaging to generate reliable results. Additionally, using SAWs in an integrated system would enable the transfer of quantum information between different types of static and flying qubits (eg. static quantum dots [32] or polarised photons [19]).

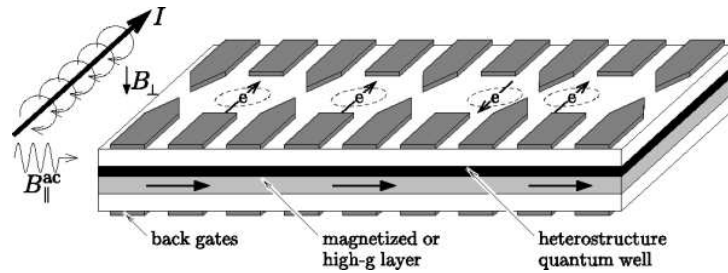


Figure 1.7: Quantum computer based on an array of static quantum dots. Electron spins split by an external perpendicular magnetic field provide a two-level qubit system. Single qubit operations are carried out by using an electron-spin-resonance microwave pulse, and qubit entanglement can be achieved through the exchange interaction by lowering the tunnel barriers between neighbouring quantum dots (taken from Loss and DiVincenzo [31]).

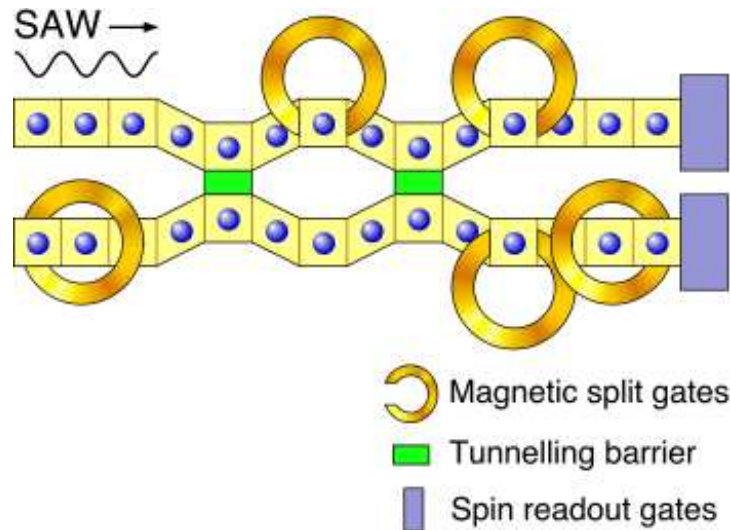


Figure 1.8: Control-NOT gate from a proposed quantum computer based on SAW-defined dynamic quantum dots. The qubits are the spins of electrons (blue circles), which are carried through the device from left to right by the SAW. Single-qubit operations are performed as the electrons move past nano-magnetic gates, while two-qubit operations occur at tunnel barrier regions. The electron spin could be read out at the end of the channel by spin-charge conversion and detecting the current, or by combining the electron with a hole to form a polarised photon which could be detected through standard optical measurements (taken from Barnes *et al.* [17].)

Chapter 2

Processing and measurement techniques

2.1 Processing

The wafers used for this work are standard 40 nm HEMTs (see Section 1.1.1) grown in the [001] crystallographic direction, which results in the wafer having a 2DEG approximately 90 nm below the surface of the wafer. The SAW devices are 8 mm $\times$ 2 mm and, as it is easier to process a number of devices on the same piece of wafer, it is necessary to cleave the wafer into rectangles of $\sim$ 14 mm $\times$ 10 mm before starting processing. Due to its crystal structure, GaAs cleaves along the [110] direction so using a diamond tipped scribe to introduce weaknesses to the wafer in the desired place makes it easy to accurately cleave. The typical steps involved in device fabrication of the devices are described in the following sections.

2.1.1 Cleaning

It is necessary to keep the surface of the chip totally free from dust, debris and scratches, or these could interfere the passage of the SAW during measurement. All processing was carried out in a class 1000 cleanroom, and the lithography was done in a class 100 area. Also, before each processing step the device was cleaned by covering with acetone and placing in an ultrasonic bath for one minute, followed by a rinse in isopropyl alcohol (IPA) and drying with N₂.

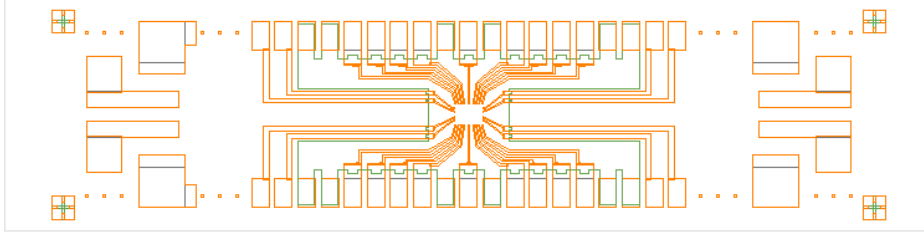


Figure 2.1: Mask pattern for the optical lithography stages of the device.

2.1.2 Optical lithography

Optical lithography is used to define the mesa, ohmic contacts and optically-defined gates, as shown in Figs. 2.1, 2.2(a-d).

Mesa etch

To isolate the 2DEG region, the upper layers of GaAs were etched away where they are not necessary, leaving a mesa. This allows electrical contacts to gates and ohmic contacts to be easily isolated from each other. The etch also removes the 2DEG from beneath most of the path of the SAW, as otherwise the SAW will be attenuated. The pattern of the mesa was transferred from a mask by optical lithography. Shipley S-1813 positive photoresist was applied to the chip's surface, and the chip was spun at 5500 rpm for 30 seconds to create a uniform thin layer of resist. This was then baked on a hot-plate at 115°C for one minute to drive out solvent.

To transfer the mesa pattern from the mask to the resist, the mask and chip were placed in a contact aligner. Once the pattern had been aligned the mask and chip were brought into contact and then illuminated by ultraviolet light for 6.5 seconds. The pattern was then developed by placing the chip in MF319 developer for 40 seconds, rinsed in deionised (DI) water, and dried with N₂. To ensure that the pattern had been successfully transferred, the chip was checked under an optical microscope before continuing with the process.

The height of the photoresist was measured with the Dektak depth profiler before starting the etch, so that the equivalent height could be measured after etching to calculate the etch depth. The etchant used consisted of H₂SO₄:H₂O₂:H₂O in the ratio 1:8:111, which should etch GaAs at a rate of $\sim 10 \text{ nm s}^{-1}$. The chip was placed in the etchant for seven seconds, then rinsed thoroughly in DI water and dried with N₂. The depth of the etch was measured with the Dektak and this was used to calculate the exact etch

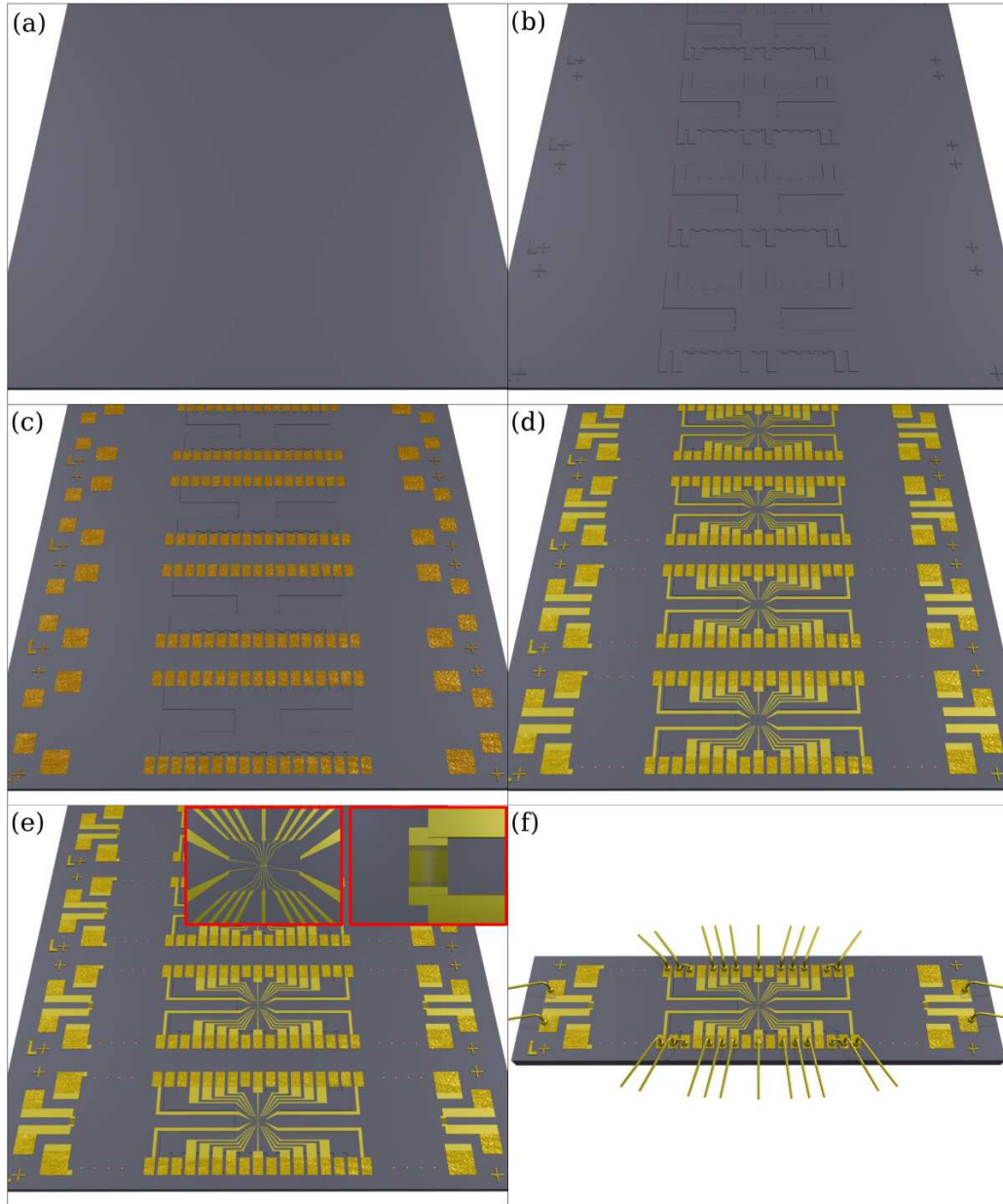


Figure 2.2: Representation of a chip at various processing stages. (a) Initial piece of wafer. (b) After mesa etch. (c) After Ohmic contact deposition and annealing. (d) After optical gate deposition. (e) After ebeam gate deposition (insets show details of device gates and transducer). (f) after final cleaving and bonding.

rate, so the process could be repeated for the correct length of time to etch to at least 100 nm (below the depth of the 2DEG). The depth of the etch must ensure that all the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ is removed (otherwise the aluminium can oxidise and leave a rough surface, which interferes with the passage of the SAW) but the etch should be no deeper than necessary (too high a mesa edge step may reflect the SAW).

Ohmic contacts

Ohmic contacts must be made to the 2DEG to perform electrical transport measurements. This was done by creating a region of GaAs that was highly doped with an n-type dopant (in this case germanium) to give approximately linear current-voltage characteristics.

The chip was coated with S-1813 resist as before, and baked for one minute at 90°C. The ohmic contact pattern was transferred from the mask to the chip using the aligner as before, taking care to align the pattern to the mesa present on the chip.

For the evaporation and lift-off technique that is used to deposit the ohmic contact metal, it is necessary to create an undercut lift-off profile in the resist or the excess metal will not easily separate away. This meant the resist had to be soaked in chlorobenzene for five minutes and dried before developing, to harden the resist surface [Fig. 2.3(a)]. Development then proceeded as before, but with a longer time in MF319 developer (~90 seconds) because of the hardened resist.

Immediately before evaporating the metal onto the chip, it was dipped into 10% HCl solution for ten seconds to remove a layer of surface oxide, followed by a rinse in DI water and N_2 dry; the surface oxide removal should also remove any small areas of undeveloped resist or dirt from the exposed areas, leaving a clean surface for the evaporated metal. AuGeNi from a slug with the correct metal proportions was evaporated onto the chip under a high vacuum (because SAW devices typically have high impedance, it is not necessary to achieve the lowest ohmic contact resistances by using layered ohmic contacts). The chip was soaked in acetone for 15 minutes to remove the resist from beneath the metal, and then the excess metal was removed from the chip by pipette and by ultrasonic agitation. The chip was checked under a microscope while immersed in IPA to ensure that all the unwanted metal was removed, and when the lift-off was satisfactory the chip was rinsed in IPA and dried in N_2 .

For ohmic contacts to work the germanium must alloy with the GaAs in the 2DEG 90 nm below the surface of the chip. To make this happen, the chip was annealed for 80 seconds at 430°C using a Leisk rapid thermal

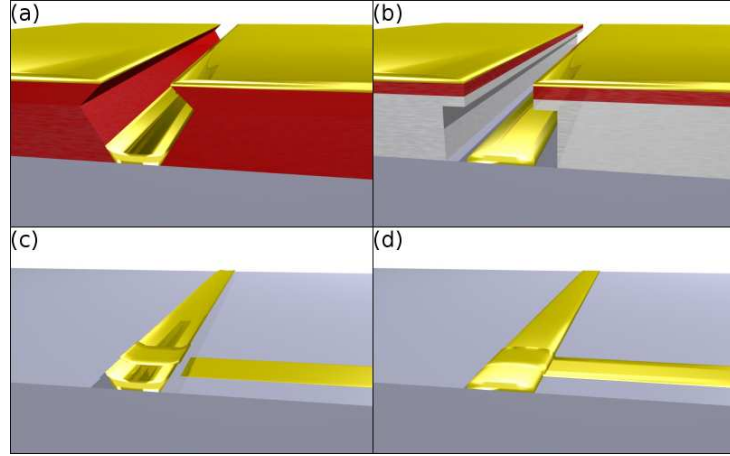


Figure 2.3: Lift-off profiles for optical resists. (a) Using Shipley S-1813 resist with Chlorobenzene soak. (b) Using double layer PMMA and Shipley S-1805 resist. (c) Result of using Shipley resist with Chlorobenzene soak process, after lift-off and subsequent electron-beam-defined gate evaporation. Note that the electron-beam-defined gate makes poor electrical contact with the optically-defined gate, due to the presence of “lily pads”. (d) Result of using double layer PMMA and Shipley resist process, after lift-off and subsequent electron-beam-defined gate evaporation. Note that there is good electrical contact between electron-beam-defined gate and optically-defined gate.

annealer. The ohmic contacts could then be checked at room temperature for an ohmic I-V characteristic using a probe station.

Optical gates

Optically defined gate contacts allow the sub-micron sized device (which is patterned using electron beam lithography) to be connected to gold wires. The gates are made of a 20 nm thick layer of NiCr, which sticks strongly to the GaAs and creates a Schottky diode insulating the gate from the 2DEG, and a 60 nm thick layer of Au to give good electrical conductivity.

A double layer polymethyl methacrylate (PMMA) and optical resist process was used for optical gates to prevent “lily-padding” of the metal, which can cause poor electrical contact between the optical and ebeam gates (see Fig. 2.3). Two layers of 495K PMMA (spun on at 3000 rpm for 50 seconds, and baked for one hour at 150°C) and a layer of S-1805 photoresist were applied to the surface of the chip. After alignment and development of the photoresist the chip was put in a UV Ozone cleaner for 20 minutes,

which creates a hard cross-linked layer where the PMMA and photoresist are present and exposes the PMMA where the photoresist has been removed. The PMMA was developed in 1:3 Methyl isobutyl ketone (MIBK):IPA for 30 seconds, rinsed in IPA and dried in N₂ to leave a good liftoff profile.

Evaporation of NiCr and Au and lift-off were then carried out as described previously.

2.1.3 Electron beam lithography

Device lithography

The actual device must be made by electron beam lithography due to its small size. To generate a good lift-off profile a double layer of PMMA was used. 1:1 100K PMMA:Anisole was spun on at 3000 rpm (creating a layer of thickness ≈ 70 nm) and baked for 5 mins at 150°C, and then 1:1 950K PMMA:MIBK was spun on at 8000 rpm (thickness ≈ 40 nm) and baked for one hour. The lower molecular weight (100K) PMMA is developed more quickly, resulting in the desired overhang profile.

The device patterns were generated in Autocad and transferred into the PMMA by David Anderson using a Leica VB6-UHR electron beam writer. The chip could then be developed in 5:15:1 MIBK:IPA:methyl ethyl ketone for five seconds, rinsed in IPA and dried in N₂. 10 nm NiCr and 20 nm Au were evaporated onto the chip, and lift-off was carried out as described previously.

Transducer lithography

Transducers were made in a similar way as for the device lithography, using 7 nm NiCr and 10 nm Au. Because the transducers consist of a large area of fine features to be lifted off, and the very highest resolutions are not necessary, neat 495K PMMA was spun on at 8000 rpm (thickness ≈ 150 nm) for the first layer. This thicker resist profile aided lift-off.

2.1.4 Packaging and bonding

The chip was covered in a protective layer of PMMA before cleaving into individual devices. After cleaving an ultrasonic bath and IPA was used to clean any dust from the PMMA surface, then the PMMA was removed with acetone and ultrasound, finally rinsing in clean IPA.

The chip was glued to the sample holder using GE-varnish, and a gold-ball thermosonic bonder was used to attach gold wires from the sample holder to the chip. To ensure there was no build up of static charges which could

damage the gates, the sample holder was grounded at all times, the charge on the wire was allowed to dissipate for 90 seconds between flaming the gold wire and bonding to the chip, and a constant stream of ionised air was blown across the chip. The tip of the ball bonder is ceramic, and so there is a slim possibility that static charge may remain on the tip after flaming the wire. Because of this, a wedge bonder was used instead of a ball bonder for very static-sensitive devices—the wedge bonder does not need to flame the wire and the tip of the wedge bonder is metallic and grounded so there is no possibility of static charge remaining on the tip.

The sample holder is designed to fit into sample discs, which are attached to the cryostat so that the chip can either be parallel or perpendicular to the cryostat's magnetic field. The sample discs incorporate copper shielding to reduce the amount of the radio-frequency (rf.) signal fed to the transducer which is picked up by the device gates.

2.2 Measurement

2.2.1 Testing transducers

The transducers were tested at room temperature using a network analyser by attaching a port of the network analyser to each transducer. If the transducers are working S_{11} and S_{22} (the reflected signal from each transducer) will show a dip of typically 1-3 dB at the transducer resonance because of the energy lost to create the SAW, and S_{12} will show a peak of ~ -80 dB caused by the SAW carrying energy from one transducer to the other (usually the S_{12} signal will have to be averaged a few hundred times to make it stand out from background noise). The background of S_{12} should be less than -90 dBm after signal averaging; if this is not the case then there is a problem with the shielding, leading to strong electromagnetic pick-up between the transducers. When the transducer is cooled to 4 K and lower, the transmission peak will increase to ~ -50 dB as the SAW is transmitted more efficiently at low temperatures (there is less thermal scattering from the lattice).

2.2.2 Transport measurements

Conductance tests

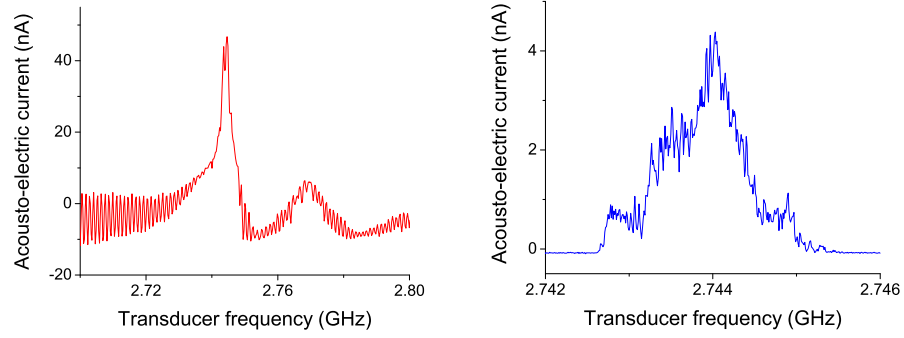
Before commencing any SAW measurements, the conductance of the device must have been fully checked to ensure that it is usable. These checks would normally be carried out at 4 K on any new device, and also after loading the device into any new system in case the device became damaged during

transfer. The conductance between pairs of ohmic contacts was measured with a lock-in amplifier to make sure that none of the ohmic contacts had frozen out, that the 2DEG was continuous across the device, and to establish which had the lower contact resistances for use later on. Then the conductance through a split gate could be checked using the lock-in amplifier. The gates should show the typical definition and pinch-off characteristics of long one-dimensional channels; if this was not the case then possibly the gates had blown and destroyed the 2DEG region between them, there were problems with the bond wires or gate contacts, or there was a leakage current flowing from the gates into the 2DEG. The leakage of the gates could also be checked using a Keithley Source-Measure Unit (SMU) with a compliance of ~ 20 nA: the gates should show negligible leakage if up to a 2 V negative voltage is applied to them, whereas they would normally leak to compliance with 0.3–0.8 V positive voltage applied. If the sample passed all these checks it could be used for SAW measurements.

Generic surface acoustic wave measurements

For each device, it was necessary to begin by looking for the parameters that give a quantised current through a split gate. The gates were swept to the pinch off voltage and an rf. signal was applied to the transducer to generate an acousto-electric current, which was detected using a current pre-amp. By sweeping the frequency of the rf. signal the optimum value for generating SAWs could be determined from the maximum current (in reality the best frequencies are usually slightly to the side of the maximum, as a maximum value will also be the point of maximum cross-talk and reflections so would generate a noisy signal). As the channel is pinched off further the cross-talk (caused by the interference between the SAW and the free-space electromagnetic wave which is picked up by the gates) has less effect, so it was necessary to repeatedly pinch off the channel further and sweep the frequency to find the ideal operating conditions (see Fig. 2.4). After the operating frequency was selected, a number of sweeps of the gate voltage were made whilst varying the power going into the transducer (see Fig. 2.5). This is for a number of reasons:

- There will be an optimum SAW power where an integer number of electrons is collected over the widest range of gate voltages, giving the largest and flattest plateaux.
- Certain gate voltages are particularly noisy (probably because they excite a random telegraph signal (RTS) noise centre) and changing the SAW power allows the plateaux to avoid these regions.



(a) Channel is slightly pinched off, showing a large amount of crosstalk. (b) Channel is further pinched off to reduce crosstalk.

Figure 2.4: Frequency dependence of the acousto-electric current.

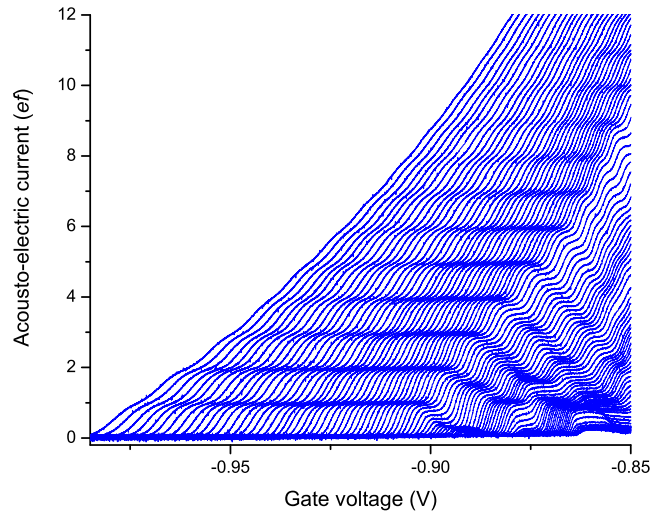


Figure 2.5: Acousto-electric current plateaux varying the power applied to the transducer from 13 dBm (left) to -5 dBm (right) step 0.2 dBm.

- The acousto-electric current curve can contain kinks due to noise that could be mistaken for a plateau if they are in the wrong place—if the feature moves from $I = Ne\hbar$ when the power shifts then it is clearly not a plateau.

It was usually necessary to repeat this process for a number of iterations, varying the operating conditions, to find the best plateaus.

2.2.3 Cryogenic systems

Initial tests are carried out in a liquid helium (LHe) dipping dewar, which is at 4 K. LHe will damp the SAW, so the sample is lowered until it is slightly above the LHe level—this can be done accurately by monitoring S_{12} on a network analyser, as the transmission peak will significantly drop once the sample is submerged in LHe.

A ^3He cryostat is used to make lower temperature measurements. A small amount of LHe in the 1 K pot is pumped on by a rotary pump, which lowers the temperature of the LHe to ~ 1.3 K. ^3He is released by a sorption pump when it is heated to 45 K, and this condenses by the 1 K pot to produce liquid ^3He . When the sorption pump heater is switched off it cools to 4 K and reabsorbs any ^3He gas; this pumps on the liquid ^3He which reduces its temperature to 270 mK. The sample is thermally connected to the liquid ^3He by copper.

The ^3He cryostat was also used for measurements at ~ 1.3 K by leaving the sorption pump heated and so the ^3He gas acts as an exchange gas between the 1 K pot and the sample.

2.2.4 The effect of biased cooldowns

Pirola-Ladière *et al.* reported that by applying a positive bias to the gates as the sample is cooled down from room temperature, RTS noise is greatly reduced [33]. In my measurements, biased cooldowns were attempted in a number of ways.

Originally +0.3 V was applied by using an IOtech high-resolution digital-analogue converter, connected to the gates through a gate filter. The gate filter is a low-pass filter containing two 1 M Ω resistors in series with the signal line. The gates leak to the GaAs at high temperatures, and so because of the gate filters a leakage current of only the order of ~ 100 nA would result in the voltage applied to the gates being much less than the desired +0.3 V. When the biased cooldown was tried with this set-up, RTS noise was reduced, but the shifting of the gate definition and pinch-off voltages which had been seen

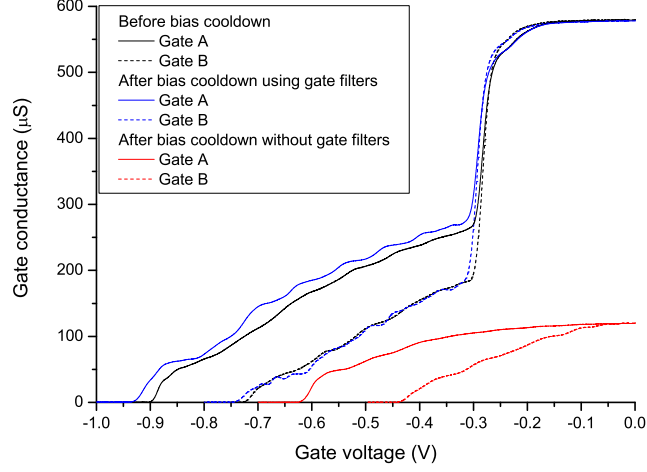


Figure 2.6: The effect of biased cooldowns on two gates. The decrease in RTS noise can be seen from the increased visibility of one-dimensional conductance plateaus and oscillations caused by impurity structures, which are washed out on the original data due to RTS noise with a higher frequency than the measurement bandwidth.

by Pioro-Ladière did not occur (see Fig. 2.6, blue traces). Note that this fact throws doubt upon the explanation of reduced RTS noise given in reference [33], which explained the effect in terms of the shifted gate voltages.

Because applying the bias through gate filters appeared to be only partially successful, the biased cooldown was repeated using $+0.3$ V applied through a Keithly SMU with compliance set to $200 \mu\text{A}$. Using this method, the gate definition and pinch-off voltages shifted by approximately 0.3 V, as had been seen elsewhere. The RTS noise was also reduced even more than it had been using the previous method (Fig. 2.6, red traces).

As well as in the conductance characteristics, the reduction of RTS noise after biased cooldown can also be seen in the SAW quantisation (Fig. 2.7). The quality of plateaux is greatly increased after biased cooldown, suggesting that high-frequency RTS noise is at least partially responsible for the poor quality plateaux seen in some devices.

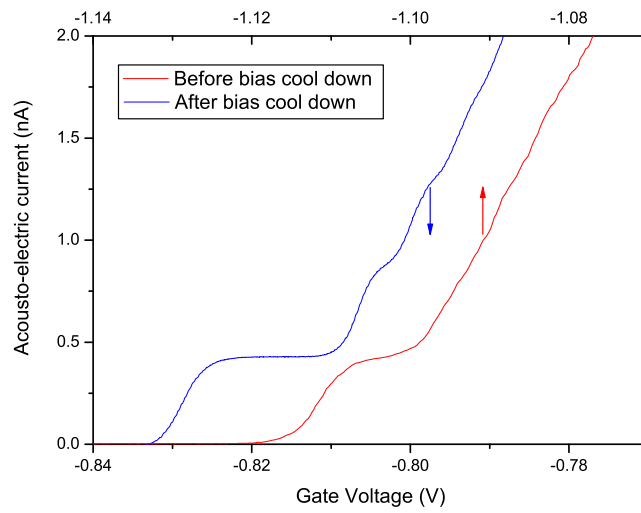


Figure 2.7: The effect of biased cooldowns on the acousto-electric current produced by a SAW. The $N = 1$ plateau becomes much wider and flatter after the biased cooldown, and $N > 1$ plateau become visible.

Chapter 3

The effect of SAW reflections

It is possible for a SAW to be reflected from various structures on the device. Certain features of the frequency response of the acousto-electric current have been ascribed to the effect of reflections and cross-talk (the signal due to interference between the SAW and the free-space electromagnetic wave) [11], but previously there has been no systematic study of how reflections affect the acousto-electric current, and which parts of the device cause them. By using pulse-modulation techniques the individual reflection paths can be isolated and understood. Ideally for sensitive SAW measurements one would use pulse conditions that meant no reflections or cross-talk were present as the principal SAW passed through the device. However, the quality of the SAW current plateaux becomes seriously degraded at very short pulse lengths as the pulse is broadened by the finite bandwidth of the transducer [34] (Fig. 3.1). Thus a good understanding of when reflections are present in the device is required for optimizing SAW devices.

A reflected SAW will interfere with the principal SAW modifying the SAW potential and changing its ability to confine electrons, and will thus change the magnitude of the acousto-electric current generated. This can happen in two ways:

- If the principal and reflected SAW are travelling in the same direction, they will interfere constructively or destructively depending on the phase difference between the two SAWs. The resulting SAW will have a larger or smaller amplitude depending on this phase difference, and hence the mean number of electrons confined to each minimum will be increased or decreased.
- If the principal and reflected SAW travel in opposite directions they will combine to create a standing wave in addition to the principal travelling wave. The acousto-electric current carried through a split gate

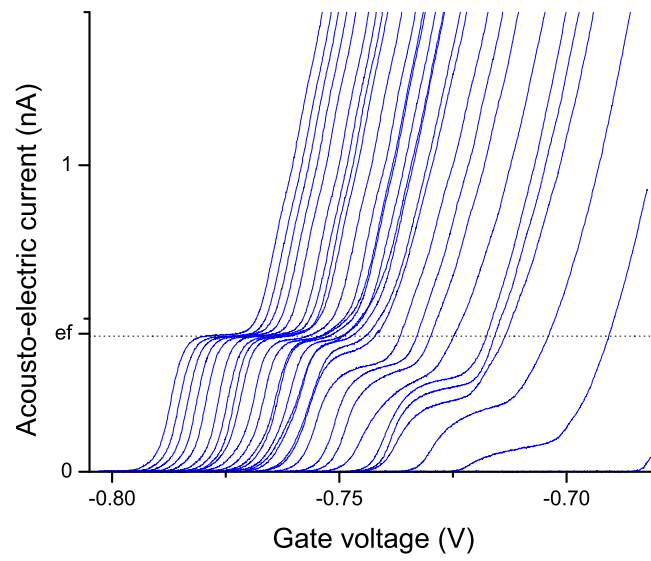


Figure 3.1: Acousto-electric current plateaux using a pulsed SAW. Pulse width w varies (left to right) from $100\ \mu\text{s}$ to $10\ \mu\text{s}$ ($10\ \mu\text{s}$ step), $10\ \mu\text{s}$ to $1\ \mu\text{s}$ ($1\ \mu\text{s}$ step) and $1\ \mu\text{s}$ to $0.1\ \mu\text{s}$ ($0.1\ \mu\text{s}$ step), pulse period $\tau = 3w$ —traces offset horizontally for clarity, data has been rescaled by $\frac{\tau}{w}$.

is strongly dependent on the relative position of a node of the standing wave and the crucial region of the split gate (where the strongest confinement occurs [35]), as demonstrated in experiments with counter-propagating SAWs [36, 37].

The determining factor in how the reflected and principal SAWs interact is the phase difference between the SAWs. This phase difference can be modified by varying the microwave frequency used to generate the SAW, leading to oscillations in the acousto-electric current as a function of frequency. The period of these oscillations in the frequency response (Δf) is related to the path difference x between the initial and reflected SAWs: an oscillation occurs each time the wavelength λ changes (by $\Delta\lambda$) such that the number of periods in x changes by one, i.e. $x \equiv m\lambda = (m+1)(\lambda - \Delta\lambda)$. As the resonant frequency bandwidth of the transducer is very narrow, the SAW velocity v can be considered constant and so $\Delta\lambda$ varies only with the SAW frequency ($f + \Delta f = \frac{v}{\lambda - \Delta\lambda}$). This leads to the relationship $\Delta f = \frac{v}{x}$ which can be used to determine the origin of each oscillation.

When the transducer power is pulse-modulated, SAWs are only produced when the pulsing is high (Fig. 3.2). Only the reflections that interfere with the principal SAW (i.e. that return to the device when the initial SAW is present) will contribute to the interference effects which affect the acousto-electric current, and so by modifying the pulse conditions we can change which reflections are observed.

The measurements presented here are taken from a number of devices: the measurements in Section 3.1 were carried out on device A3160-RJSES (processed by Jeff Schneble) which had a two-dimensional electron gas (2DEG) 90 nm below the surface, a mobility of 110 m²/V s and a carrier density of $1.7 \times 10^{15} \text{ m}^{-2}$, measured at 1.5 K in the dark; those in Section 3.2 were carried out on A3160-TB2 which came from the same wafer as A3160-RJSES, and T636-QC10 (processed by Masaya Kataoka) which had a 2DEG 97 nm below the surface, a mobility of 180 m²/V s and a carrier density of $1.7 \times 10^{15} \text{ m}^{-2}$. The ends of T636-QC10 had also been intentionally roughened with a diamond pen to increase SAW dissipation. The devices were set up so that the acousto-electric current was measured through a single pair of gates, as shown in Fig. 3.3. Both transducers were measured on each device, and the results were broadly the same across all samples and transducers.

3.1 Initial reflections

A typical frequency dependence of the acousto-electric current is shown in Fig. 3.4. Reflections that occur within the first microseconds give rise to

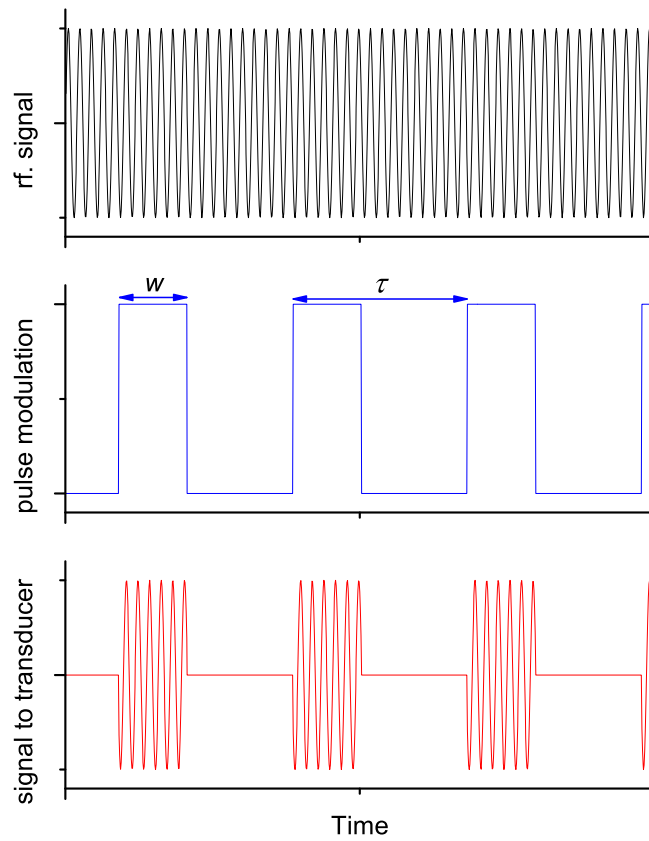


Figure 3.2: Schematic of pulse-modulation of the rf. signal. The SAW is only produced when the pulse generator produces a high output.

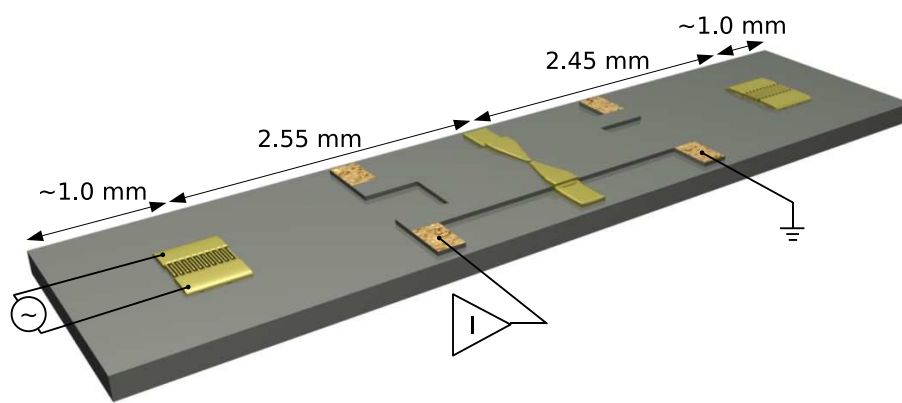


Figure 3.3: Schematic of the device set-up. The distances labeled are for device A3160-RJSES.

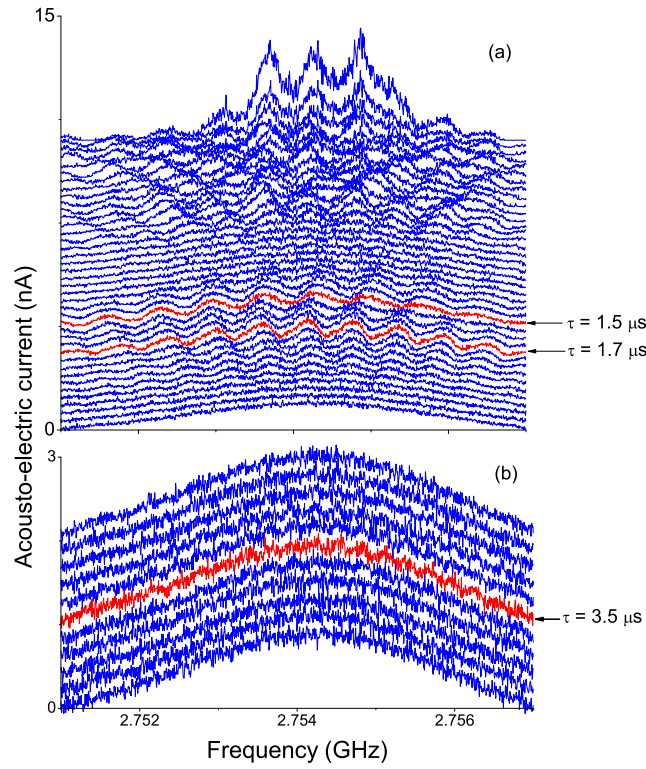


Figure 3.4: Acousto-electric current frequency dependence for pulse width of $0.2 \mu\text{s}$ and pulse period from (a) $0.25 \mu\text{s}$ to $2.2 \mu\text{s}$ and (b) $3.2 \mu\text{s}$ to $3.7 \mu\text{s}$, at $0.05 \mu\text{s}$ intervals—traces offset vertically for clarity, acousto-electric current has been rescaled by $\frac{\tau}{w}$ (data taken from A3160-RJSES).

strong oscillations in the frequency dependence of the acousto-electric current. In Fig. 3.4 the data has been taken using a $0.2 \mu\text{s}$ pulse width (w) and the pulse period (τ) has been varied (similar data were taken using a variety of pulse widths, with almost identical results—the highest resolution was obtained by using the shortest pulse widths, and so that is presented here). The oscillations are seen at pulse periods such as $1.5 \mu\text{s}$, $1.7 \mu\text{s}$ and $3.5 \mu\text{s}$, as denoted by arrows. Note that there are oscillations of shorter period in the frequency response than would be expected simply from the pulse period. These occur when a reflection is present at a multiple of the pulse period, and will be discussed in Section 3.2.

The details of the oscillations in the frequency dependence of the acousto-electric current are seen more easily by taking Fourier transforms of the data, as shown in Figs. 3.5(a) and (b). A number of branches, labeled with n , can be seen due to interference of the primary SAW wave packet with subsequent pulses ($n = 1, 2 \dots$) (see Section 3.2). The peaks that occur at different time delays arise from different reflection paths. Figure 3.5(c) plots the Fourier amplitude (blue line) across the first branch ($n = 1$). The red line in Fig. 3.5(c) shows a fit to a series of Lorentzian peaks at 0.7 mm, 2.1 mm, 4.1 mm, 4.8 mm, 8.3 mm, and 9.8 mm, which are shown in Fig. 3.5(d).

The x axis in Fig. 3.5(c) was converted from a delay time into a delay length using the typical velocity of a SAW in GaAs of 2870 ms^{-1} . Note that this is different from the velocity that would be expected using the resonant frequency of the transducer ($v_{\text{saw}} = f\lambda$) and the $1 \mu\text{m}$ transducer finger-spacing period. This is because the SAW velocity underneath a metal grating is significantly affected by mass loading [38], and so would give rise to misleading results.

The prominent peaks along the $n = 1$ line can be explained as follows: when the initial SAW is generated a SAW is also sent backwards from the transducer, and reflects off the edge of the chip 1.0 mm from the transducer, leading to the 2.1 mm reflection peak (0.1 mm error may be due to uncertainty in the position of the cleaved edge). This reflected SAW is then reflected by the transducer (by Bragg reflection) and by the same edge again, generating a smaller peak at 4.1 mm. The transducer at the opposite end of the device reflects the original wave, leading to a peak at 4.8 mm, and this wave will be reflected again by the first transducer to give the 9.8 mm peak. There is no observable reflection from the edge of the chip behind the second transducer ($\sim 6.9 \text{ mm}$), suggesting that the transducer is a very efficient Bragg reflector and that the wave will be unable to pass through the transducer twice (this agrees with the high Q values we achieve with our transducers, caused by multiple internal reflections of the SAW). The origin of the weak peak at 8.3 mm is unknown. It may be due to the SAW emitted

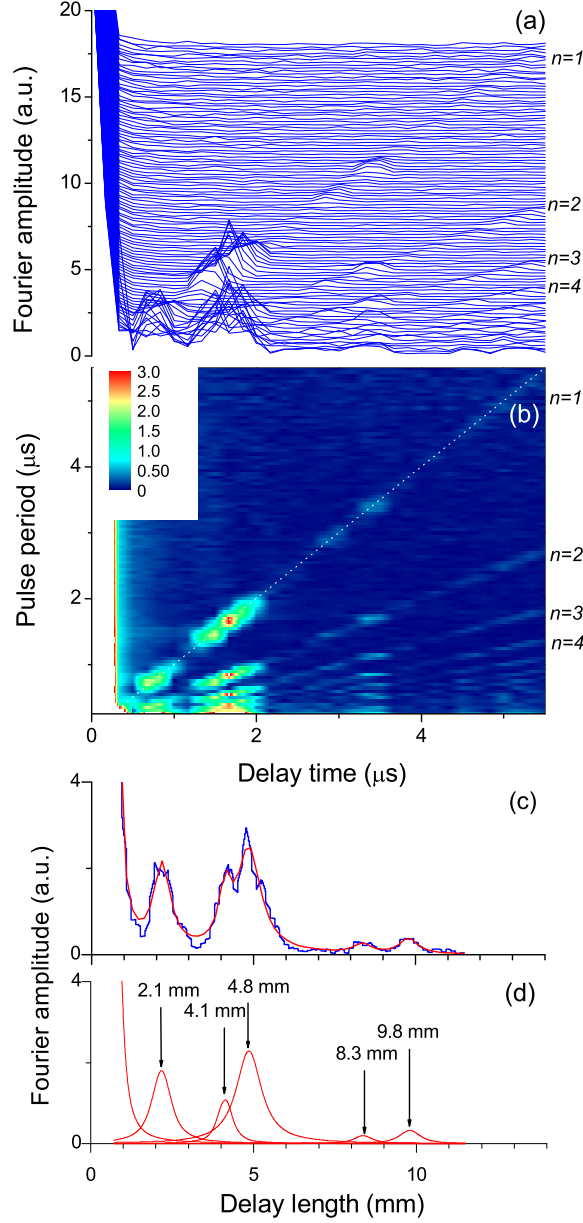


Figure 3.5: (a) Fourier transform of the acousto-electric current frequency dependence for pulse width of $0.2 \mu\text{s}$ and pulse period from $0.25 \mu\text{s}$ to $5.5 \mu\text{s}$ step $0.05 \mu\text{s}$ —traces offset vertically for clarity, data has been rescaled by $\frac{\pi}{w}$. (b) Colour plot of data in (a). (c) Blue line—trace taken along $n = 1$ (dotted line in (b)). Red line—fit to solid line using the sum of the Lorentzian peaks shown in (d) (data taken from A3160-RJSES).

backwards reflecting off the edge four times, but as we do not observe a third reflection peak at 6.2 mm, this is unlikely.

There is also a small feature at 2.5 mm which is probably due to crosstalk (the interaction between rf. pick-up and the SAW). This is weak because there is effective screening of rf. between the transducer and the device built into the design of the sample holder. The peak at 0.7 mm is not related to reflections, and is a result of the general shape of the frequency dependence.

The relative amplitudes of the peaks in Fig. 3.5(d) provide some quantitative measurement of the reflection power coefficients for each reflection type. Using r_c for the reflection from the edge of the chip, r_t for the reflection from the transducer, and t_t for transmission through the transducer, the 2.1 mm reflection path is $r_c t_t$ and the 4.1 mm path is $r_c^2 r_t t_t$. The ratio of the peak powers (found by squaring the Fourier amplitudes and integrating the result) is 0.29 ± 0.01 , therefore $r_c r_t = 0.29 \pm 0.01$. Any 6.9 mm peak ($r_c t_t^2$) is significantly smaller than the smallest feature resolved (the 8.3 mm peak) which has a power ratio to the 2.1 mm peak of 0.011 ± 0.002 , so $t_t \ll 0.01$. Assuming all the SAW power is either reflected or transmitted at the transducer this would mean $r_t \gg 0.99$ (this is an overestimate as the SAW will scatter into bulk modes at the transducer; a more accurate estimate of r_t is obtained in Section 3.2). This also suggests that $r_c \approx 0.29$.

Given the very low estimate for t_t , it is unlikely that the SAW that is reflected from the back of the chip actually passes through the transducer and then superposes with the principal SAW, as was described earlier. An alternative possibility is that when the reflected SAW impinges on the transducer it is partially absorbed by the transducer and this interferes with the generation of the principal SAW.

3.2 Multiple reflections

Because the transducers form a very efficient Bragg reflector for SAWs (see Section 3.1) it is possible for the SAW to undergo a very large number of reflections and still interfere with the principal SAW. This effect gives rise to a large amount of the ‘noise’ that is seen on the frequency response of the acousto-electric current.

Figure 3.6 shows the frequency dependence of the acousto-electric current where the pulse width w has been varied from $0.5 \mu\text{s}$ to $50 \mu\text{s}$, and the pulse repetition period τ is set to be ten times the pulse width. The ratio $\frac{w}{\tau}$ is kept constant so that the magnitude of the acousto-electric current is the same for all sweeps (this stops being the case when the pulse width is reduced to $\sim 0.5 \mu\text{s}$ because the pulse is deformed by the pass band of the transducer

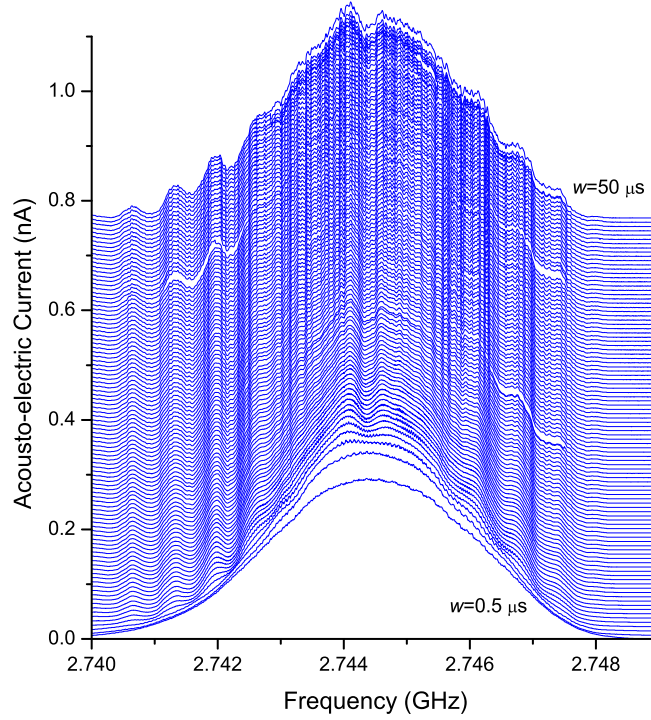


Figure 3.6: Acousto-electric current frequency dependence for a pulse width w ranging from $0.5 \mu\text{s}$ (bottom trace) to $50 \mu\text{s}$ (top trace) step $0.5 \mu\text{s}$. The ratio $\frac{\tau}{w} = 10$, where τ is the pulse repetition period—traces are offset for clarity (data taken from T636-QC10).

giving an appreciable pulse rise time at $0.5 \mu\text{s}$ pulse width as described in Kataoka *et al.* [34]).

In addition to the large-period oscillations that are described in Section 3.1, small oscillations that make up the ‘noise’ on the frequency response are reproducible between neighboring sweeps, and disappear from the traces as the pulse width becomes smaller, with the faster oscillations dying out at larger pulse widths than the slower oscillations.

The Fourier transform of these oscillations (Fig. 3.7) contains a number of peaks, with each peak only present if it corresponds to a time that is less than the pulse width used for that sweep (denoted $n = 0$ in the figure). This is because each peak in the Fourier transform is produced by a reflection, where the time delay between the main wave and the reflection results in a peak in the Fourier transform at that time delay. The reflection only interferes with the main wave if the time delay is within the pulse window, or else the main

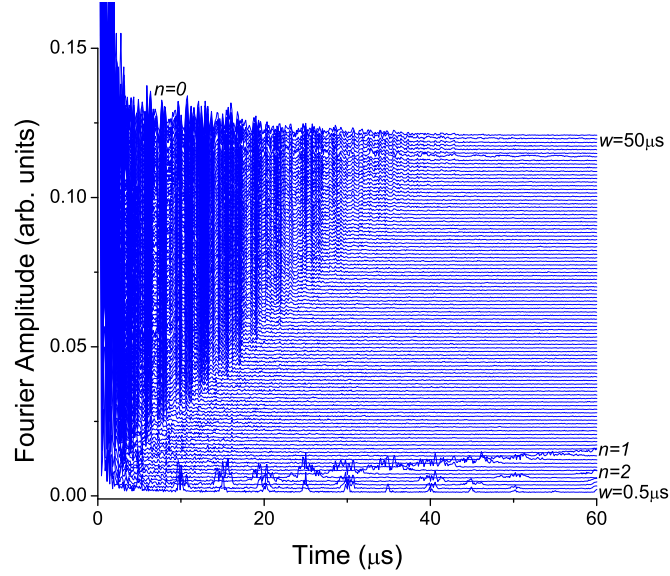


Figure 3.7: Fourier transform of Fig. 3.6—traces are offset for clarity.

SAW will no longer be present to interfere with the reflection. ‘Harmonics’ of the peaks labeled $n = 1, 2 \dots$ can also be seen on the lower traces at multiples of ten times the pulse width.

The structure of the multiple reflections was examined more closely by fixing the pulse width to $0.5 \mu\text{s}$ and varying the pulse period from $10 \mu\text{s}$ to $30 \mu\text{s}$ in $0.1 \mu\text{s}$ steps. The acousto-electric current is only produced when the main SAW is present, so the data is rescaled by the ratio $\frac{\tau}{w}$ to make the acousto-electric current comparable between sweeps. The Fourier transforms of these data (Fig. 3.8) show peaks that occur at approximately the same time as the pulse period of that sweep (as well as at ‘harmonics’, labeled $n = 2, 3$). These correspond to reflections from the previous pulse interfering with the main SAW, which can only happen when the reflection has a time delay that matches the pulse period used. The exact peak positions and heights are shown in Fig. 3.9.

The spacing of the peaks might be expected to be related to physical aspects of the device, as was found for the initial reflections. But while the peaks in Fig. 3.9 are clustered around certain time delays (i. e. the reflections are quantised to certain time delays and so must originate from specific features on the device) the magnitude and spacing of the peaks is irregular and there are substantial differences between different samples. The chaotic nature of the multiple reflection peaks cannot be explained by the SAW being

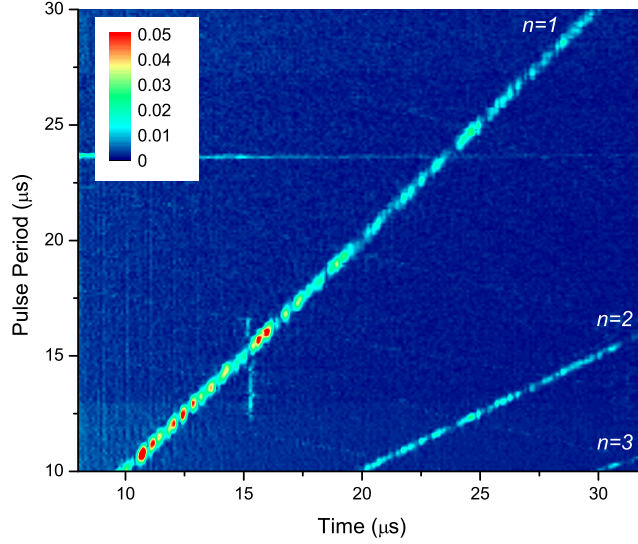


Figure 3.8: Colour plot of frequency dependence Fourier transforms for a pulse width of $0.5 \mu\text{s}$ (data taken from T636-QC10).

reflected by a large number of different features on the device and returning to the split gate by chaotic paths, because SAWs are strongly attenuated if they travel in a non-preferred crystalline direction [39]. It may be that the SAW pulse becomes broadened as it is reflected by the transducer leading to overlap between different reflected SAW packets, which could give rise to complex interference patterns.

To see how long the multiple SAW reflections would last, a $5 \mu\text{s}$ pulse width was applied to the transducer and the pulse period was varied. The acousto-electric current frequency dependencies have been rescaled and Fourier transformed in Fig. 3.10. The SAW reflections are still having an effect more than $400 \mu\text{s}$ after the initial pulse. Taking the SAW velocity as $\sim 2870 \text{ m s}^{-1}$ [38], the wave must have travelled $>1.1 \text{ m}$, requiring at least 160 reflections to have taken place without destroying the signal.

In the upper panel of Fig. 3.11 the $n = 1$ peaks have been fitted to an exponential decay function. If we assume the main reflection mechanism is the SAW being repeatedly reflected between the transducers, we can use the decay time from the exponential fit $T = 130 \pm 20 \mu\text{s}$ to estimate the power reflection coefficient $r_t = \exp(-\frac{2x}{Tv}) = 0.974 \pm 0.004$, where the distance between reflections $x = 5 \text{ mm}$, and the SAW velocity $v = 2870 \text{ m s}^{-1}$ [38].

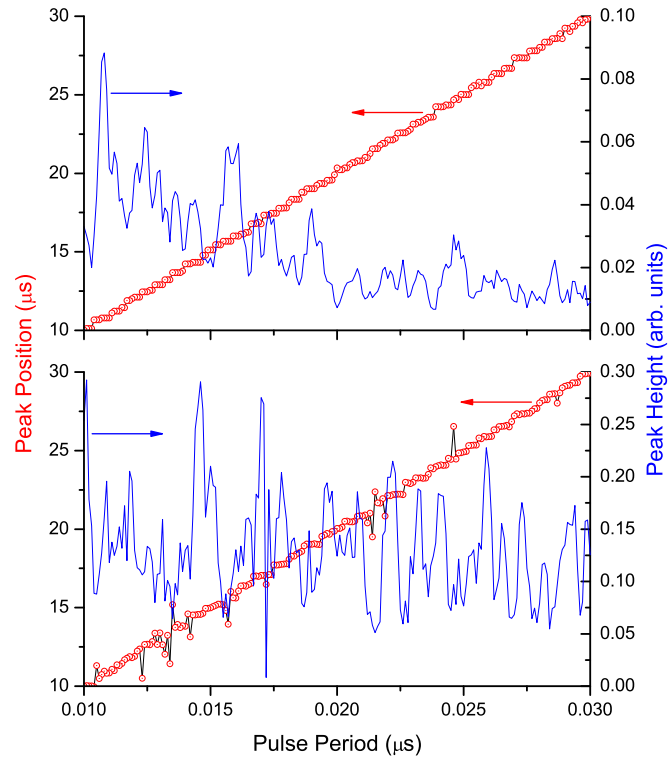


Figure 3.9: Upper panel: peak positions (open circles) and amplitudes (solid line) from Fig. 3.8 (data taken from T636-QC10). Lower panel: the equivalent data taken from A3160-TB2.

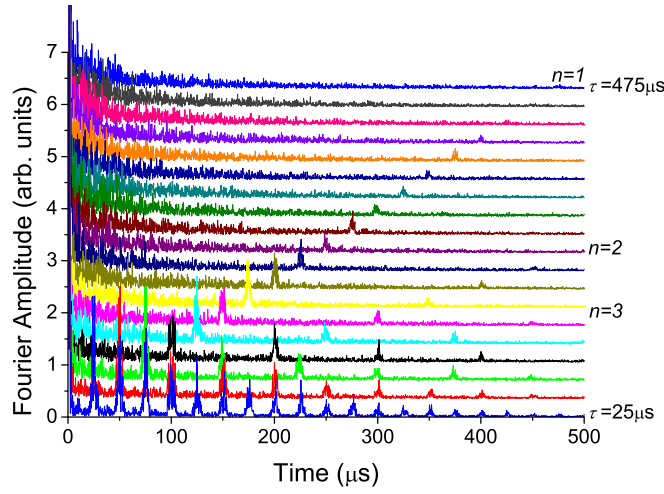


Figure 3.10: Fourier transform of frequency dependence for a pulse width of $5 \mu\text{s}$, pulse period increased from $25 \mu\text{s}$ (bottom trace) to $475 \mu\text{s}$ (top trace) at $25 \mu\text{s}$ intervals—traces are offset for clarity (data taken from A3160-TB2).

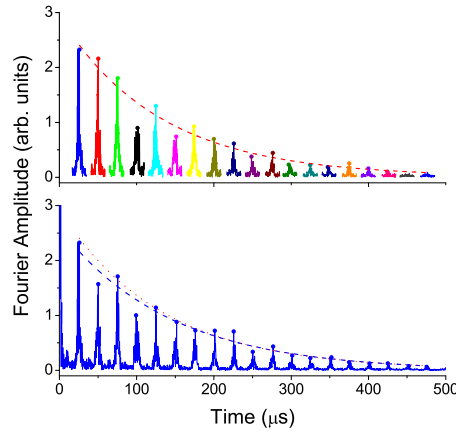


Figure 3.11: Upper trace: the first peak from subsequent time delays in Fig. 3.10. Lower trace: result for $25 \mu\text{s}$ pulse period from Fig. 3.10. Solid line shows Fourier-transform data, circles show peak maxima, dashed line shows exponential decay fitted to the peak maxima, dotted line on lower graph shows exponential decay from upper graph for comparison.

This is in good agreement with the transducer reflection coefficient found in Section 3.1 of $r_t \gg 0.99$, considering that the value derived from initial SAW reflections was known to be an overestimate as it did not take into account scattering of the SAW into bulk wave modes by the transducer.

The results from device T636-QC10 showed that the reflections only lasted for $\sim 100 \mu\text{s}$ which may have been due to the fact that the edges of the chip were intentionally roughened to dissipate the SAW, that the different wafer used to create this device may have caused greater attenuation to the SAW, or that the transducers on this sample produce less reflection because of processing variations.

There is an ambiguity as to the origins of the ‘harmonic’ features seen at multiples of the first peak in the lower traces of Fig. 3.10 (labeled $n = 2, 3, \dots$). They could be due to the reflections with time delays equal to integer multiples of the period, or if the reflected waves do not produce a linear change in the acousto-electric current, harmonics would be introduced by the Fourier transform process at multiples of the frequency of the first peak. Figure 3.11 compares the first peaks at pulse periods increasing by $25 \mu\text{s}$ between subsequent sweeps with the harmonics of a $25 \mu\text{s}$ pulse period. The peaks show great similarity in size and shape, and when the maxima from the peaks were fitted to exponential decay functions, the parameters describing both data sets were within each others’ errors. This shows that the features seen have the same cause, and so the harmonics must be a product of reflections and not an artefact of the Fourier transform.

3.3 Summary

In this chapter I have shown that oscillations in the frequency dependence of the acousto-electric current are caused by interference between reflected SAWs and the principal SAW. Using the pulse modulation technique one can control and manipulate which reflections are present in the device. Because our transducers form highly efficient Bragg reflectors, a reflected SAW may persist for over $400 \mu\text{s}$. The “noise” seen in the frequency dependence of the acousto-electric current is actually caused by multiply reflected SAWs, which are chaotic and show great variation between devices; this may limit the accuracy and reproducibility of sensitive SAW measurements.

The results presented in this chapter have been published in references [40] and [41], and were presented at the CSUK 2006 conference.

Chapter 4

Tunnel barrier device: introduction

4.1 Early tunnel barrier devices

4.1.1 Two channel device without independently controlled tunnel barrier

In reference [42], Masaya Kataoka described a SAW device that consisted of two parallel channels which met at a “tunnel barrier” created by a break in the gate separating the channels [Fig. 4.1(a)]. The injection of electrons into the two channels could be controlled independently by gates at the channel entrance, and gates on either side of the tunnel barrier could apply a potential difference between the neighbouring channels. The measurements demonstrated the ability to move electrons between the two channels [Fig. 4.1(b)], but because the tunnel barrier could not be varied without changing gates which also affected large areas of the device, tuning the tunnelling proved very difficult, and the transfer of electrons occurred only through essentially classical means.

4.1.2 Single channel device with tunnel barrier gate

Elzerman *et al.* were able to measure the spin of a single electron in a quantum dot by carrying out spin-to-charge conversion: the 2DEG outside the quantum dot was biased to a level in between the Zeeman-split energy levels of the electron in a strong magnetic field, and so tunnelling out of the dot could only occur when the electron was in the higher-energy spin state [28]. It is hoped that a similar process could be carried out with an electron

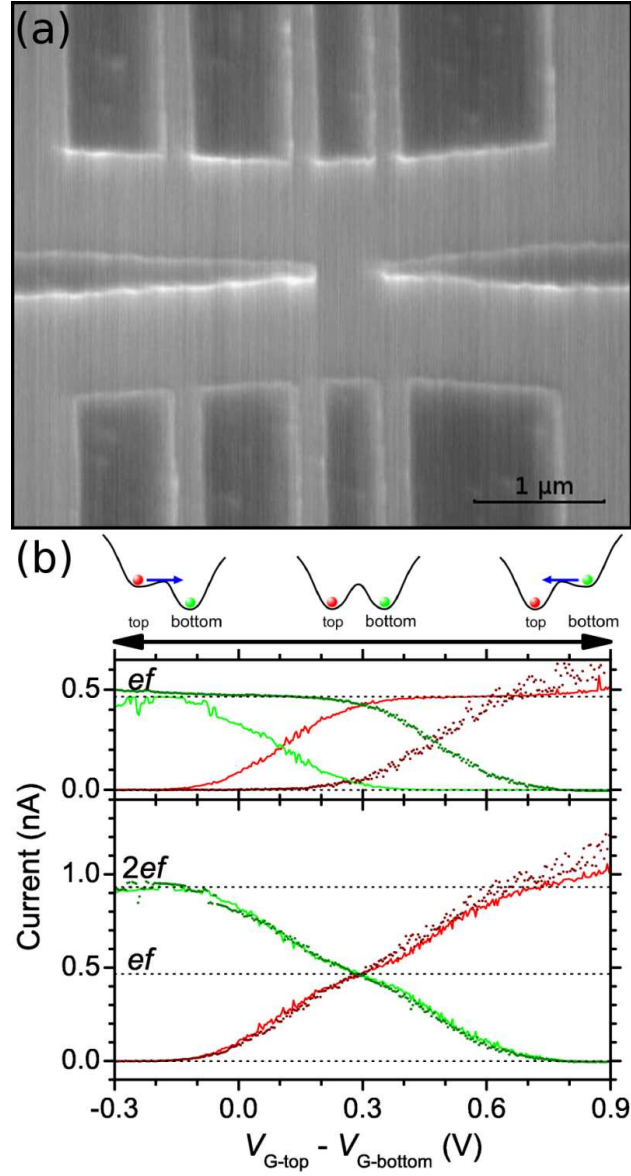


Figure 4.1: Two channel device from reference [42], without an independently controlled tunnel barrier. (a) SEM of the device gates. (b) Current outputs from the top (red) and bottom (green) channels as the channel potential difference is varied. Upper panel: A single electron per SAW potential minimum is injected into either the top channel (solid lines) or bottom channel (dotted lines). Lower Panel: Output currents (solid lines) when a single electron per SAW minimum is injected into each channel. The dotted curves are the sums of the currents shown in the upper panel for each channel (courtesy of Masaya Kataoka).

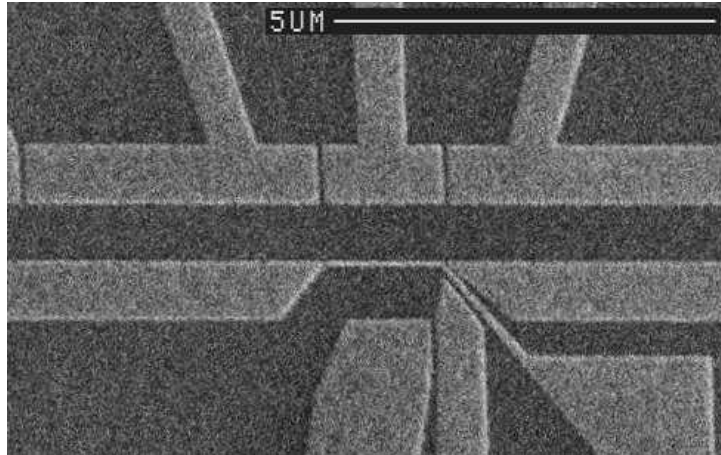


Figure 4.2: SEM image of the single channel device incorporating an independent tunnel barrier gate.

captured in a SAW-defined dynamic quantum dot. To try this I designed device which featured a single SAW channel with an independently-controlled tunnel barrier on the side (Fig. 4.2).

A fully working device was made on wafer A3160 which, when measured in a 4 K dipstation, showed that the independently-controlled tunnel barrier could be used to control the rate at which electrons crossed the tunnel barrier without adversely affecting other parts of the device. But the device became damaged during transfer between the dipstation and the microwave ^3He cryostat, and the gates started to leak to the 2DEG, so detailed measurements were not possible.

4.1.3 Quantum interferometer

Rodriguez *et al.* proposed that single-electron interferometry could be possible using electrons in dynamic quantum dots [16]. The electron wave function splits into two parallel SAW channels at a tunnel barrier structure, and after a certain distance the wave functions recombine at a subsequent tunnel barrier. The channel in which the recombined wave function resides is controlled by interference between the two channel paths, which may be altered either by applying a potential difference across the two channels, or by varying a perpendicular magnetic field and observing the Aharonov-Bohm effect [43].

An experimental device was fabricated by Masaya Kataoka which was intended to observe these effects (Fig. 4.3). This device again showed that independently-contacted tunnel barriers could be made to control the path of

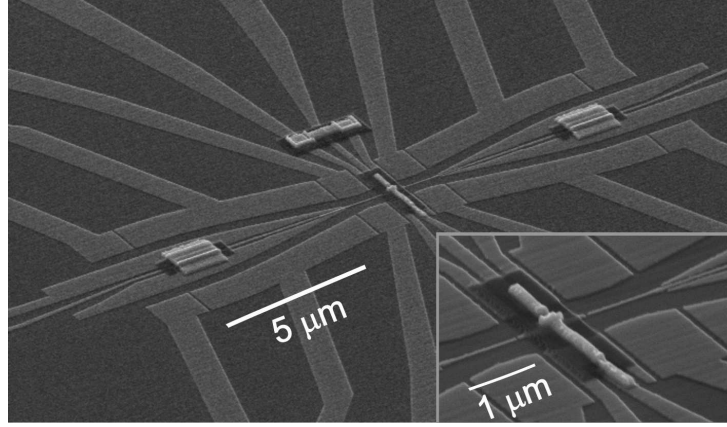


Figure 4.3: SEM image of the quantum interferometer device. Note the PMMA bridge necessary to independently contact to the central island gate (courtesy of Masaya Kataoka).

electrons through the device, but it proved impossible to tune the device into a regime where the electrons path was controlled by quantum mechanical effects rather than simply by the particular potential landscape associated with the gates around the channel exit. In addition, processing this device was highly time-consuming as PMMA bridges were necessary to independently contact to the central island gate.

4.2 T605-QC12

As a result of the earlier experiments, it was realised that the potential produced by the gates surrounding the tunnelling region would have to be very carefully controlled in order to see quantum-mechanical tunnelling effects. To do this Masaya Kataoka designed a two-channel single-tunnel-barrier device which contained six gates around the independently-controlled tunnel barrier (Fig. 4.4).

Adam Thorn produced numerical simulations of an electron within the device by solving Laplace's equation for the surface-gate geometry [44], adding a sinusoidal travelling wave to the potential to represent the passing SAW, and solving the time-dependent two-dimensional Schrödinger equation. This showed that, when the gates were tuned, the electron wave function should undergo coherent charge oscillations between the dynamic quantum dots formed in the two channels, generating a distinctive pattern in the current from the device which would be possible to observe experimentally (Fig. 4.5).

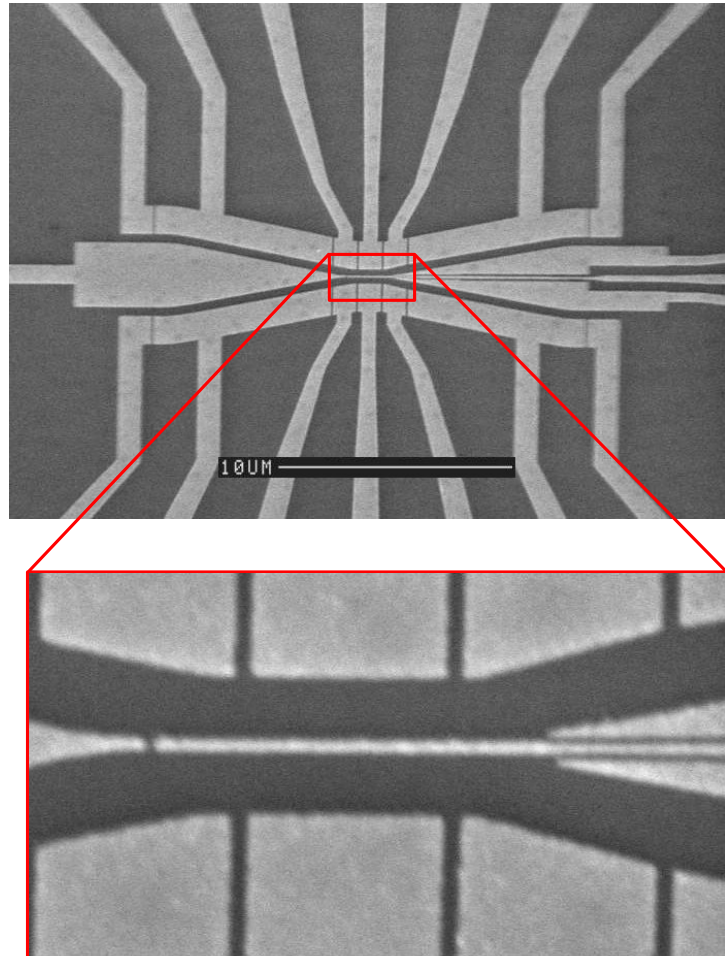


Figure 4.4: SEM images of the tunnel barrier device QC12.

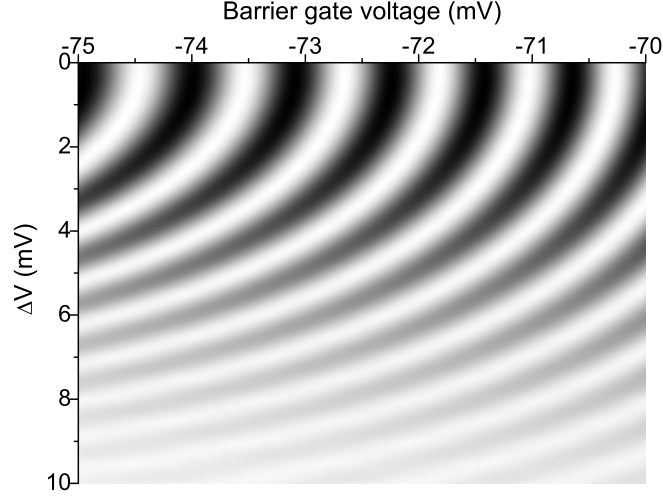


Figure 4.5: Simulation of the current out of the top channel, when $I = ef$ is injected into the top channel, as a function of the barrier gate voltage and the detuning of the voltage between the top-centre and bottom-centre gates (ΔV)—light areas indicate the electrons leaving the tunnel barrier region predominantly through the upper exit channel, whereas dark areas indicate electrons leaving predominantly through the lower exit channel. The distinctive concentric arc pattern is a result of coherent oscillations of the electron between the upper and lower channel (courtesy of Adam Thorn).

In addition, the device could be used to observe single-channel behaviour such as spin-to-charge conversion, by grounding either the upper or lower row of gates.

A fully working device was made on wafer T605 (which had mobility of $160 \text{ m}^2/\text{Vs}$ and a carrier density of $1.8 \times 10^{15} \text{ m}^{-2}$, measured at 1.5 K in the dark) by Masaya Kataoka and measured in the microwave ^3He cryostat by Masaya Kataoka and myself. The results of these measurements will be discussed in Chapters 5-8.

Chapter 5

Tunnel barrier device: measurement of non-equilibrium electron escape from dynamic quantum dots

The escape of electrons from quantum dots via tunnelling has previously been examined in static quantum dot systems over relatively long tunnelling times. Cooper *et al.* [45] measured electrons leaving an isolated non-equilibrium quantum dot over a number of seconds by detecting the change in the current flowing through an adjacent quantum point contact, and derived the tunnelling rates via statistical analysis of the length of time between successive electron escapes (Fig. 5.1). MacLean *et al.* were able to detect tunnelling times of milliseconds by measuring the time between successive electrons tunnelling onto and off a quantum dot with a quantum point contact located adjacent to the quantum dot (Fig. 5.2). These measurements are of particular interest because the electron escape process is directly analogous to α -decay in nuclear physics [47]. Using the tunnel barrier design described in Section 4.2, the escape of electrons from non-equilibrium dynamic quantum dots can be observed. The dynamic nature of the measurement means that the tunnelling time is less than a nanosecond, and through analysis of the tunnelling rates we are able to determine that dynamic dots have successfully been created in a long channel, and measure the addition energies of the dynamic quantum dots.

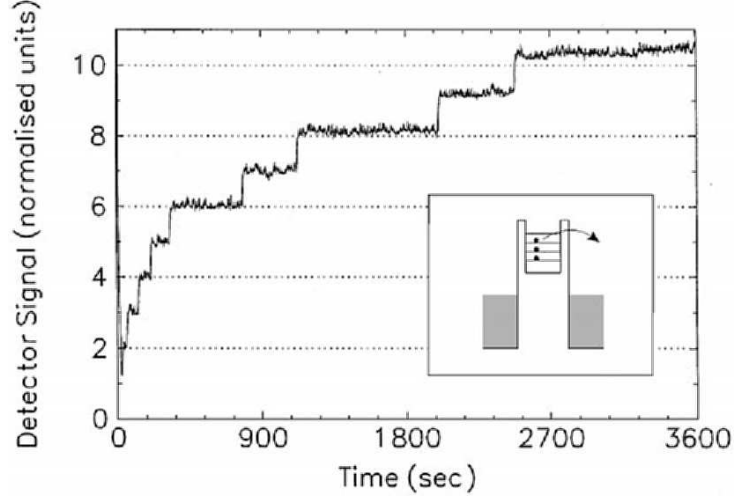


Figure 5.1: Detector signal from a quantum point contact alongside a non-equilibrium static quantum dot—each step corresponds to an electron escaping from the quantum dot. Inset: diagram of the quantum dot (taken from Cooper *et al.* [45]).

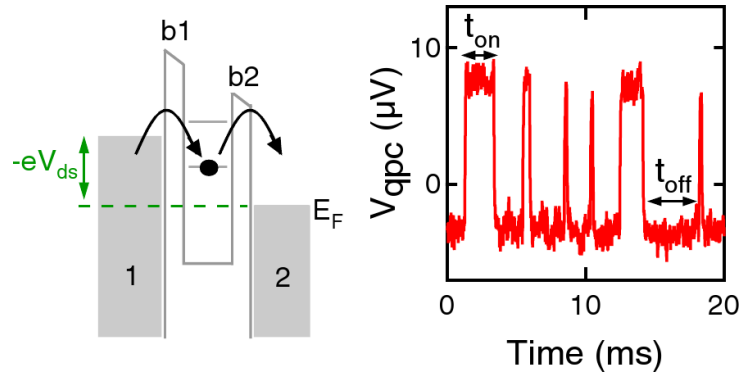


Figure 5.2: Left: diagram of a static quantum dot biased to allow electrons to flow through the dot. Right: current through a quantum point contact situated next to the quantum dot—each step corresponds to an electron entering or leaving the quantum dot (taken from MacLean *et al.* [46]).

5.1 Device operation

This measurement was carried out on device T605-QC12 (see Section 4.2) at 270 mK. An attempt was made to reduce random switching noise by applying +0.3 V to the gates as the device was cooled [33]. However, gate filters were left in place which would have the effect of strongly limiting the current that could flow through the gates. As the gates leak when warm, this meant that only a very small voltage was actually applied directly to the gates during cooldown. The random switching noise was partially reduced by this process, but the pinch-off characteristics did not change as is usually the case for cooling under bias (see Section 2.2.4).

The device set-up is as shown in Figs. 5.3, 5.4. The injector gate (G_I) is used to control the number of electrons that can enter the SAW channel. At sufficient SAW power the injected current is quantised to $I_{\text{in}} = Nef$, where e is the electron charge and f is the SAW frequency. In this regime each SAW minimum forms a dynamic quantum dot that contains N electrons, moving through the channel at the SAW velocity ($\sim 2800 \text{ ms}^{-1}$). When the dot is alongside the tunnel barrier gate (G_T), the electrons are coupled to the reservoir and tunnel out of the dot; this tunnelling process is described by Γ_n , the rate at which an electron leaves an n -electron dynamic quantum dot (Note that N is used for the number of initially injected electrons in each quantum dot, whereas n is the number of electrons in a quantum dot in the tunnel barrier region). Escape of electrons from the dot means the current I_{out} coming out of the channel is reduced by a tunnelling current I_t . The effective length of the tunnel barrier can be estimated as $\sim 1.6 \mu\text{m}$ by solving Laplace's equation for the device's surface gate voltages [44]; this means that the dynamic quantum dot is coupled to the reservoir for a tunnelling time (τ) of about 600 ps. This is an estimate of the maximum tunnelling time, it is likely that the actual tunnelling time may be smaller because there will be impurity or disorder potentials, and tunnelling will only occur at the weakest barrier potential. However, $\Gamma\tau$ is determined in the analysis of tunnel rates, so uncertainty in the exact value of τ does not effect these results. The remaining gates that define the channel are held at constant voltage throughout the experiment; these voltages have been carefully tuned to minimise any potential gradients in the channel, as large potential gradients could cause a loss of confinement in the dynamic quantum dots and lead to fluctuations from the initialised electron number N .

The dotted line in Fig. 5.5 shows I_{in} as a function of the voltage applied to the injector gate. The first three quantised plateaux can be seen at multiples of 8.7 pA, which is Nef reduced by the 1 : 50 pulse ratio used [34]. The solid lines show I_{out} for a range of voltages (V_T) applied to the tunnel barrier—the

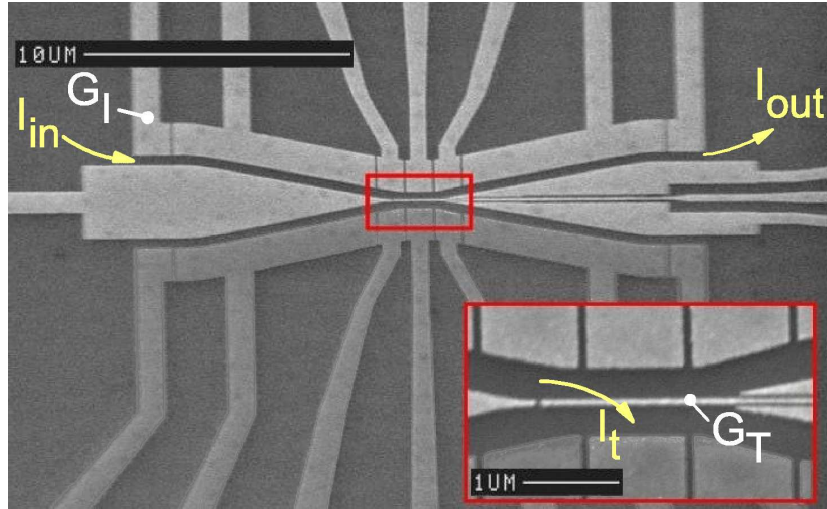
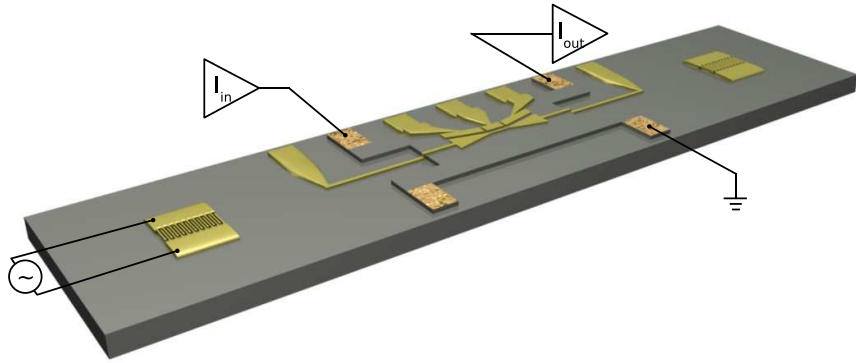


Figure 5.3: Upper panel: Schematic of the device design. Lower panel: Electron micrograph of the device's surface gates. Injector (G_I) and tunnel barrier (G_T) gates are labeled. The dark shaded gates were grounded.

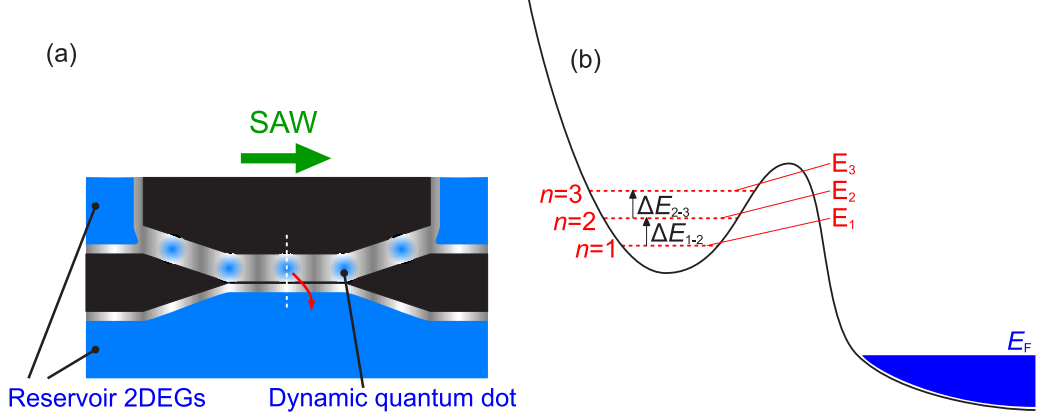


Figure 5.4: (a) Simplified experimental circuit. (b) Potential along white dotted line in (a), showing the n -dependent electron energies.

less negative the barrier voltage, the higher the rate of tunnelling out of the channel, thus the lower the value of I_{out} . The tunnelling current I_t is deduced from the difference between I_{in} and I_{out} ($I_t = I_{\text{in}} - I_{\text{out}}$).

5.2 Current ratios

In previous SAW measurements, it was not possible to demonstrate that electrons were confined in a dynamic quantum dot for the entire length of a long SAW channel (an essential feature of proposed SAW quantum circuits). An alternative possibility was that quantised charge pumping occurred at a microconstriction, but subsequently electrons could escape from the dot and freely move along the channel. In our device, if electrons were not confined in dynamic quantum dots but were free to move in an open channel, we would expect that adding up to three electrons in a SAW cycle would have a negligible effect on the energy of the system. Hence such behaviour would be unobservable and the ratio $I_{\text{in}}/I_{\text{out}}$ would be independent of N . On the other hand, if electron confinement is maintained, the energy state of the dot can vary by several meV depending on the number of electrons present and the size of the confinement potential, and thus the tunnelling rate and therefore $I_{\text{in}}/I_{\text{out}}$ should be number dependent. In Fig. 5.6 $I_{\text{in}}/I_{\text{out}}$ is shown as a function of barrier-gate voltage for $N = 1, 2, 3$. The ratio $I_{\text{in}}/I_{\text{out}}$ is strongly dependent on N , indicating that the dynamic quantum dot model correctly describes the system for at least the whole tunnel barrier region.

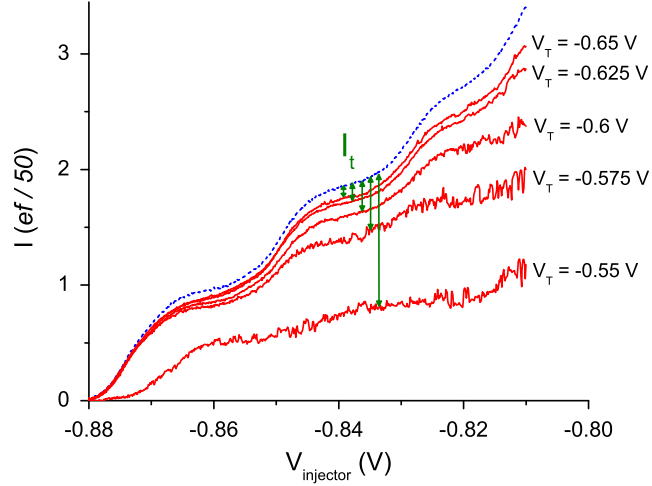


Figure 5.5: I_{in} (dotted line) and I_{out} (solid lines) dependence on injector gate voltage, for a range of barrier gate voltages. Plateaux occur when an integer number (N) of electrons occur in each SAW minimum. I_t is the difference between the two curves.

5.3 Rate equation analysis

Control of the tunnelling rate of electrons leaving a quantum dot is needed for understanding and manipulating the quantum states within the dot. We can deduce the tunnelling rate Γ_n of an n -electron dynamic quantum dot by comparing our measurements with rate equations. Within the tunnelling region, the probability (P_n) for having n electrons in the dot varies with time according to $\frac{dP_n}{dt} = \Gamma_{n+1}P_{n+1} - \Gamma_nP_n$ (each dynamic quantum dot is assumed to undergo an independent tunnelling event—there is a $\sim 1\,\mu\text{m} \sim 50\,\text{meV}$ barrier between electrons in neighbouring dots so there will be no wave function overlap, and the Coulomb energy of two electrons $\sim 1\,\mu\text{m}$ apart is only $\sim 100\,\mu\text{eV}$ which should have little effect). Assuming that the tunnel rates Γ_n remain constant over the duration of tunnelling τ_n , that on the $I_{\text{in}} = Ne f$ plateau there are exactly N electrons in each SAW minimum, and that no electrons are able to tunnel back into the dot, $I_{\text{out}} = ef \sum_{n=1}^N nP_n$

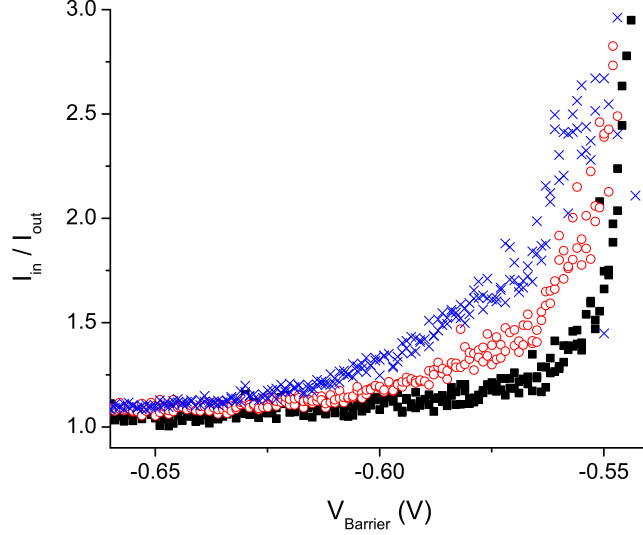


Figure 5.6: The ratios $I_{\text{in}}/I_{\text{out}}$ as a function of barrier gate voltage, taken from the I_{in} plateau corresponding to $N = 1$ (■), $N = 2$ (○) and $N = 3$ (×).

can be calculated as:

$$I_{\text{out}} = ef e^{-\Gamma_1 \tau_1} \quad (N=1)$$

$$I_{\text{out}} = ef \left(2e^{-\Gamma_2 \tau_2} + \frac{\Gamma_2}{\Gamma_1 - \Gamma_2} (e^{-\Gamma_2 \tau_2} - e^{-\Gamma_1 \tau_1}) \right) \quad (N=2)$$

$$I_{\text{out}} = ef \left[3e^{-\Gamma_3 \tau_3} + \frac{2\Gamma_3}{\Gamma_2 - \Gamma_3} (e^{-\Gamma_3 \tau_3} - e^{-\Gamma_2 \tau_2}) + \frac{\Gamma_2 \Gamma_3}{\Gamma_2 - \Gamma_3} \left(\frac{1}{\Gamma_1 - \Gamma_3} e^{-\Gamma_3 \tau_3} - \frac{1}{\Gamma_1 - \Gamma_2} e^{-\Gamma_2 \tau_2} + \frac{\Gamma_2 - \Gamma_3}{(\Gamma_1 - \Gamma_2)(\Gamma_1 - \Gamma_3)} e^{-\Gamma_1 \tau_1} \right) \right] \quad (N=3)$$

The assumption of exactly N initial electrons is not perfect, as imperfect quantisation in the SAW current leads to some dynamic quantum dots having $N+1$ or $N-1$ electrons [48], and there is a small possibility that electrons may be transferred between adjacent dynamic quantum dots after initialisation. However, both of these processes should only affect a small percentage of dynamic quantum dots, and because $I_{\text{in}} = Nef$ there must be equal numbers

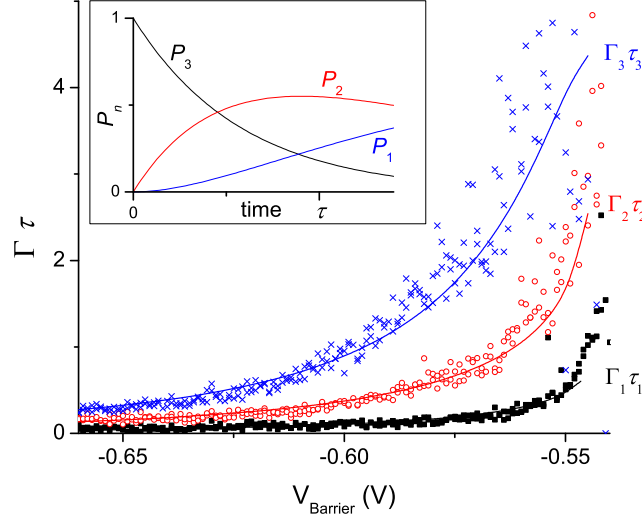


Figure 5.7: Dependence of the calculated tunnelling rates Γ_n on barrier gate voltage for one (■), two (○) and three (×) electrons in the dynamic quantum dot, normalised by the tunnelling time τ_n . The solid lines show fits based on the tunnelling probability of non-interacting electrons incident on a saddle-point potential, as described in the text. Inset: Example of the time-evolution of P_n for $3ef$ injection, using tunnel rates for $V_T = -0.575$ V.

of $N+1$ and $N-1$ dynamic quantum dots whose effects would tend to cancel each other out, so the errors caused by this assumption should be less than the measurement errors in our system. Using these equations, the values of $\Gamma_n \tau_n$ are calculated as a function of barrier gate voltage in Fig. 5.7. The tunnelling rate is varied over an order of magnitude by a single gate, which shows great promise for making future SAW quantum devices.

5.4 Saddle point tunnelling model

The data in Fig. 5.7 are fitted using the analytical solution for the transmission probability of non-interacting electrons through the saddle-point poten-

	$\frac{2E_n - \hbar\omega_y}{\hbar\sqrt{2\alpha\omega_x/m^*}} (V^{\frac{1}{2}})$	$\frac{2\alpha V_0}{\hbar\sqrt{2\alpha\omega_x/m^*}} (V^{-\frac{1}{2}})$	$E_n - \frac{1}{2}\hbar\omega_y$ (meV)
$n = 1$	0.0013 ± 0.0004		0.27 ± 0.08
$n = 2$	0.015 ± 0.002	3.050 ± 0.017	2.9 ± 0.4
$n = 3$	0.084 ± 0.006		17.0 ± 1.2

Table 5.1: Fitting parameters from Fig. 5.7, used to derive the addition energies of the dynamic quantum dot.

tial $V(x, y) = V_0 - \frac{1}{2}m^*\omega_x^2 + \frac{1}{2}m^*\omega_y^2$ [49, 50]:

$$T_{i,j} = \delta_{i,j} \frac{1}{1 + e^{-\pi\epsilon}}$$

$$\text{where } \epsilon = \frac{2[E_n - \hbar\omega_y(i + \frac{1}{2}) - V_0]}{\hbar\omega_x}$$

V_0 is the potential at the centre of the barrier, m^* is the effective mass of the electron, ω_x (ω_y) controls the curvature of the barrier perpendicular (parallel) to the barrier, $\delta_{i,j}$ is the Kronecker delta function, E_n is the energy of the incident electron and, assuming the electron tunnels through the one-dimensional ground state, the sub-band index $i = 0$. The transmission probabilities are converted to tunnelling probabilities by multiplying by a free parameter which describes the number of attempts the electron makes at tunnelling in the time τ , and the other terms in the expression can be related to changes in the tunnel barrier voltage (V_T) by assuming a simple capacitor model: $\Delta V_0 = \alpha_{V_0}\Delta V_T$ and $\frac{1}{2}m^*\Delta\omega_x^2 = \alpha_{\omega_x}\Delta V_T$ where each α is a constant relating the coupling of the gate to the barrier potential; ω_y is determined by the SAW potential amplitude and so remains constant. An estimate of $\alpha_{V_0} = 0.62 \pm 0.01$ is obtained by applying a bias potential to the 2DEG until a breakdown current starts to flow through the upper channel, which is expected to occur when the Fermi energy of the 2DEG is level with the top of the barrier. From the fitting parameters in Table 5.1, the addition energies $\Delta E_{n \rightarrow n+1}$ for n electron dynamic quantum dots are found to be $\Delta E_{1 \rightarrow 2} = 2.6 \pm 0.4$ meV and $\Delta E_{2 \rightarrow 3} = 14.1 \pm 1.3$ meV (these errors are from the fitting; there may be other errors caused by the assumptions in the model that have not been accounted for).

The energy of the dynamic quantum dot will be increased by a Coulomb repulsion when adding an electron to the dot. The constant interaction model of a quantum dot predicts $\Delta E_{n \rightarrow n+1} = e^2/C + \Delta\epsilon_{\text{sp}}$ with a capacitance C , at equal gate voltages and where $\Delta\epsilon_{\text{sp}}$ is the single-particle energy spacing (for a discussion of Coulomb energies within quantum dots,

including the limitations of this constant-interaction model, see Section 1.1.2 and Ref. [3]). This predicts the ratio $\Delta E_{2\rightarrow 3}/\Delta E_{1\rightarrow 2} \approx 1$, whereas we find $\Delta E_{2\rightarrow 3}/\Delta E_{1\rightarrow 2} = 5.4 \pm 1.0$. The difference is too large to be attributed solely to the single-particle energy—the large variation in addition energies may be due to the complexities of the exchange and Coulomb interactions in few electron quantum dots which would require a self-consistent theory of electron-electron interactions to model accurately. Note that the distance from quantum dot to reservoir 2DEG is greater in dynamic quantum dots than in previous static quantum dot measurements, which will reduce the screening of the Coulomb interaction by the reservoir and could result in larger electron-electron effects. However, the very large discrepancy may also suggest that assumptions in the saddle-point tunnelling model (e.g. ignoring electron-electron interactions in the tunnelling process or assuming the rate is only sensitive to the potential at the tunnel barrier) are affecting the calculation, but while the measured addition energies may contain inaccuracies due to the approximations incorporated into the model, the energies are of comparable order of magnitude to those measured in static few-electron quantum dots [51, 2].

5.5 Summary

Observations of tunnelling on a $\lesssim 600$ ps timescale have been demonstrated by confining electrons in dynamic quantum dots using a SAW. Tunnel rates were determined from the currents flowing through the device by using rate equations. The tunnel rates are dependent on the barrier voltage applied and on the number of electrons in the dot; fitting these dependencies to a saddle point tunnelling model gives addition energies which are attributed to the Coulomb interaction. The physical behaviour of electrons confined to dynamic quantum dots is found to be similar to that of electrons in static quantum dots, indicating that dynamic quantum dots can provide an additional method of probing the fundamental behaviour of electrons in quantum dots.

These results have been published in references [52] and [53], and have been presented at the APS March Meeting 2007 and EP2DS 2007 conferences.

Chapter 6

Tunnel barrier device: coherent charge oscillations

It is a feature of quantum mechanics that, when any particle is perturbed from its ground state into a combination of excited states, the states will undergo unitary evolution. As phase differences accrue between different states, the overall particle wave-function oscillates coherently between those states. The high frequency of these oscillations makes them very difficult to observe using traditional pulsed-gate techniques, and to date the coherent time-evolution of an electron has only been seen using double-dot systems containing tens of electrons in each dot [54]. However, by using surface-acoustic-wave-defined dynamic quantum dots, very short gate operations can be applied to the dot using static gates, so we are able to see the effects of the coherent evolution of the electronic state as the barrier is lowered adiabatically.

6.1 Observation of oscillations in the tunnel current

After the experiments described in Chapter 5, the device was warmed up and re-cooled with a +0.3 V bias applied to all the gates using a SMU signal source, with compliance set to 200 μA , which further reduced random switching noise and also shifted the pinch-off characteristics by 0.3 V, so the gates were defined at zero bias (see Section 2.2.4). The experimental set-up was as shown in Fig. 6.1, with the top channel pinched off and an open one-dimensional electron gas in the bottom channel. Electrons were injected into the device through the top channel, while the entrance to the bottom channel was pinched off to prevent any current flowing, as shown in Fig. 6.2.

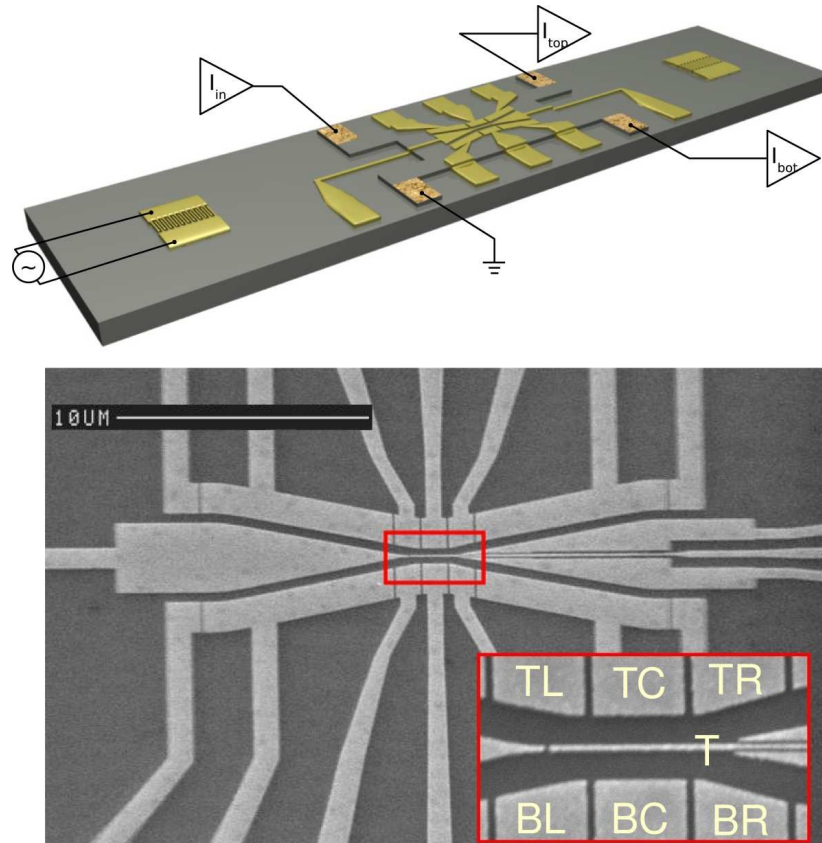


Figure 6.1: Upper panel: Schematic of the device design. Lower panel: SEM images of the device's surface gates. The gates are labelled top-left (TL), top-centre (TC), top-right (TR), bottom-left (BL), bottom-centre (BC), bottom-right (BR), and tunnel barrier (T).

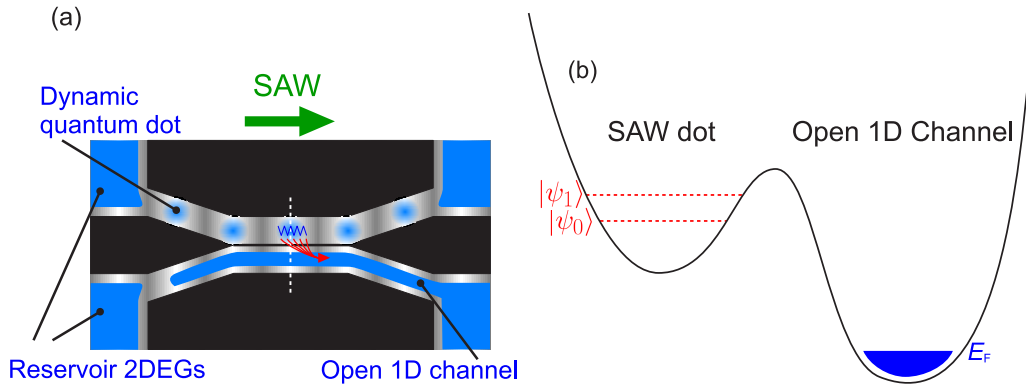


Figure 6.2: (a) Simplified experimental circuit. (b) Potential along white dotted line in (a), showing the ground state ($|\psi_0\rangle$) and first excited state ($|\psi_1\rangle$) energies.

When the tunnel barrier is tuned to allow a small amount of tunnelling, and a single electron is injected, the tunnel rate can be increased by applying an increasingly negative voltage to the top centre gate (TC on figure). As the gate is made more negative, the dynamic dot is squeezed against the barrier, increasing the energy of the confined electron, and therefore increasing the tunnel rate. An example of this is shown in Fig. 6.3; while at first inspection the current out of the top channel appears to decrease smoothly, as would be expected from simple electron tunnelling behaviour, closer inspection reveals that there are a number of small oscillations in the output current. This is seen more clearly by calculating a smoothed background I_{smoothed} using the Matlab *csaps* command, and subtracting this from the original trace to give $\Delta I_{\text{out}} = I_{\text{out}} - I_{\text{smoothed}}$. ΔI_{out} , shown in Fig. 6.3, contains four distinct oscillations (visibility $\lesssim 1\%$). These oscillations are reproducible, as seen from taking a number of sweeps at different voltages applied to the other gates (Fig. 6.4).

6.2 Coherent evolution model

If potential which confines a particle is changed slowly, the change is adiabatic: the particle will remain in its initial state, although the wave function which describes this state will change. But if the potential changes abruptly, a transition may occur from the particle's initial state to a different state or states, allowing the wave function to remain largely unchanged.

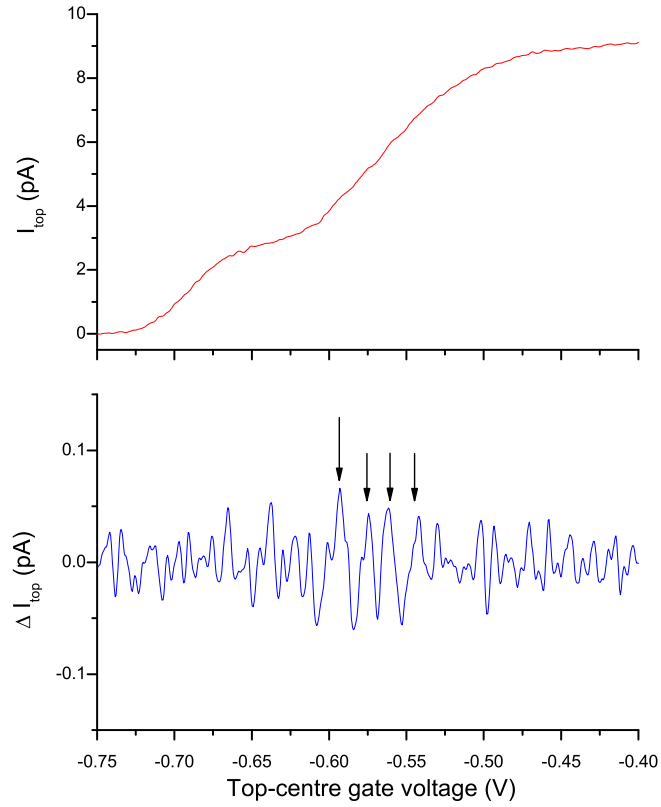


Figure 6.3: Top panel: the current out of the top channel as a function of top-centre gate voltage. As the top-centre gate voltage is made more negative, the electrons are squeezed against the tunnel barrier, and so the tunnel current increases and the current out of the top channel decreases. Bottom panel: the current out of the top channel as a function of top-centre gate voltage where a smoothed background has been removed. Four oscillations can be seen in the current, denoted by the arrows.

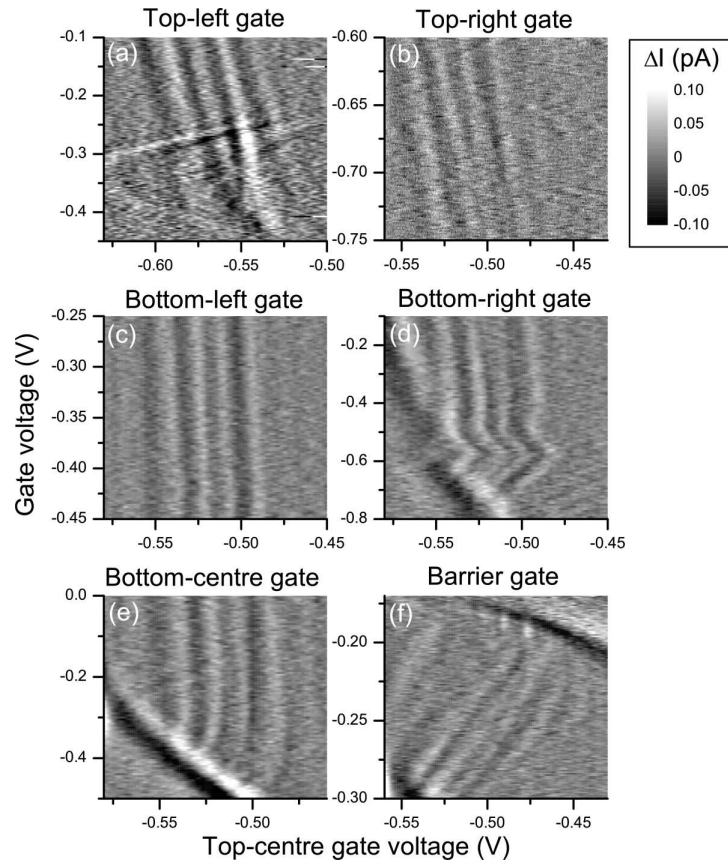


Figure 6.4: Dependence of ΔI on the gate voltages around the tunnel barrier region. The oscillations are most sensitive to the top-centre gate and the barrier gate, demonstrating that the origin of the oscillations must occur in this region.

In the tunnel barrier device, if the tunnel barrier is suddenly lowered the electron can be excited into a linear superposition of the single-particle states of the dynamic quantum dot. In particular, the electron will mainly be in the ground state and first excited state, both because the wave function is less likely to be excited into higher excited states, and because any portion of the wave function excited into higher states will be able to tunnel across the barrier into the reservoir quickly. The symmetric combination of the ground state ($|\psi_0\rangle$) and first excited state ($|\psi_1\rangle$) results in the wave function being located predominantly in the left side of the dynamic quantum dot ($|\psi_L\rangle$), whereas the antisymmetric combination results in the wave function being located predominantly in the right side of the quantum dot ($|\psi_R\rangle$):

$$|\psi_L\rangle = \frac{1}{\sqrt{1+\alpha}} (|\psi_0\rangle + \alpha |\psi_1\rangle)$$

$$|\psi_R\rangle = \frac{1}{\sqrt{1+\alpha}} (|\psi_0\rangle - \alpha |\psi_1\rangle)$$

These states are shown in Fig. 6.5. If the wave function is excited into $|\psi_L\rangle$ when the tunnel barrier is lowered, then the wave function will evolve unitarily; i.e. the wave function oscillates between $|\psi_L\rangle$ and $|\psi_R\rangle$ at a frequency of $f = \Delta\varepsilon_{0\rightarrow 1}/\hbar$, where $\Delta\varepsilon_{0\rightarrow 1}$ is the difference in energy between $|\psi_0\rangle$ and $|\psi_1\rangle$, as shown in Fig. 6.6.

Because the tunnelling length, and therefore tunnelling time, is fixed in our system it is not possible to observe the oscillations as a function of time. However, by changing the voltages applied to the gates the confinement potential of the dynamic dot may be changed in the region in which the oscillations are taking place. If the confinement of the dynamic quantum dot is increased, the energy gap $\Delta\varepsilon_{0\rightarrow 1}$ increases and the oscillations occur more quickly, and an extra portion of oscillation occurs before the end of the tunnelling region. If this additional portion of oscillation is when the electron is in state $|\psi_L\rangle$ then there is little overlap between the dynamic quantum dot state and the reservoir states, and so little tunnelling will occur for this additional portion. But when the electron is in state $|\psi_R\rangle$ it has a larger overlap with the reservoir states, so if the additional portion of the oscillation is when the electron is in state $|\psi_R\rangle$ there will be increased tunnelling. Hence, the tunnelling current out of the dynamic quantum dot will oscillate as the confinement potential is changed. Note that the tunnelling time that is used in simulations to give similar behaviour to experiments is of order 40 ps rather than the 600 ps predicted by solving Laplace's equation for the gate geometry used [44]. The ideal device potential is modified by disorder and impurities potentials, which could introduce a weakness to the barrier at a certain position along its length. Because tunnelling is exponentially

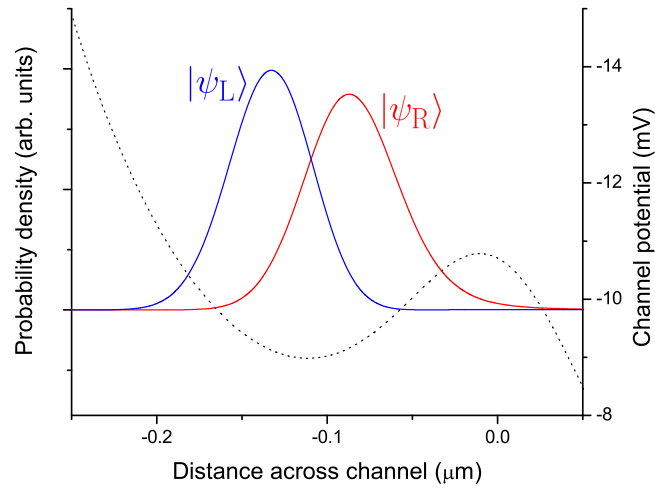


Figure 6.5: Examples of states $|\psi_L\rangle$ (blue) and $|\psi_R\rangle$ (red), for the channel potential shown by the dotted line. The overlap of the state $|\psi_R\rangle$ with the revoir states to the right side of the barrier is much larger than the overlap of the state $|\psi_L\rangle$ and the reservoir states, so that the rate of electron escape from the dynamic quantum dot is higher when the electron is in state $|\psi_R\rangle$ (courtesy of Adam Thorn).

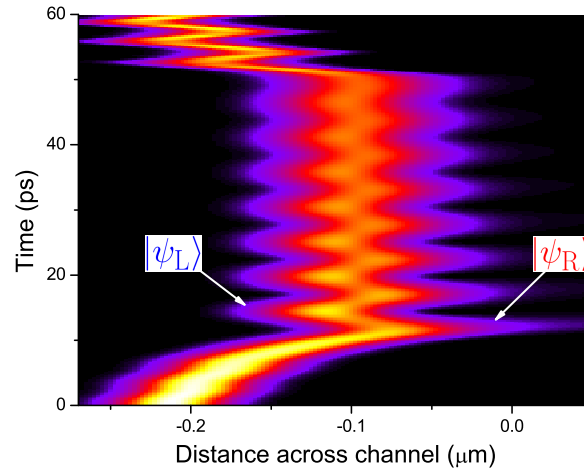


Figure 6.6: Numerical simulation of the electronic wave-function position as a function of time (a brighter colour shows a greater probability density). The tunnel barrier is lowered between 0 ps and 10 ps, held at a constant height for 40 ps during which time tunnelling occurs, and then raised between 50 ps and 60 ps. (courtesy of Adam Thorn).

dependent on the barrier height, electrons could escape at a weak point in the barrier when the gate voltage is too negative to allow tunnelling along the majority of its length. This makes it likely that the tunnelling time for the electron escape could be much less than 600 ps.

The data shown in Fig. 6.4 can be explained in this way: As the top-centre gate voltage is made more negative, the dynamic quantum dot is more strongly coupled to the external reservoir and the confinement within the dot is less strong; this makes $\Delta\varepsilon_{0\rightarrow 1}$ lower, and so oscillations are seen as a function of top-centre gate voltage. The top-left and top-right gates affect the tunnelling region in a similar way, but because they are more distant from the tunnelling region the period of oscillation in gate voltage is considerably greater [Figs. 6.4(a, b)]. The oscillations appear to move to more negative values of top-centre gate voltage as the top-left and top-right gate voltages are made less negative, because this gives the same overall $\Delta\varepsilon_{0\rightarrow 1}$ when the effect of all gates is considered. When the tunnel barrier gate is made more negative, the confinement of the dynamic quantum dot is made stronger and so $\Delta\varepsilon_{0\rightarrow 1}$ is increased (these dependencies of $\Delta\varepsilon_{0\rightarrow 1}$ on the various gates are confirmed by solving the Laplace equation for the gate geometry used [44]). Therefore, to achieve the same $\Delta\varepsilon_{0\rightarrow 1}$ the voltage applied to the top-centre gate must also be made more negative, as seen in Fig. 6.4(f). The gates below the channel [Figs. 6.4(c-e)] have virtually no effect on the oscillations at low voltages: this is because an electron gas resides in the lower channel which can electrostatically screen out any effect of the lower gate potentials. When the bottom-centre gate voltage reaches approximately -0.3 V it suddenly starts to affect the oscillations, which is probably caused by the lower channel becoming depleted, and so then making the bottom channel gate more negative effectively increases the size of the barrier. The zig-zag feature associated with making the bottom-right gate very negative is not fully understood, but it is probably related to closing off the exit region of the bottom channel so that it charges up, changing the electric potentials in the device.

6.3 Other possible models

The oscillations observed in the tunnelling current have been explained in terms of the coherent evolution of the electronic wave function in the dynamic quantum dot (Section 6.2). But there are many mechanisms which can give rise to oscillations in complex semiconductor devices. Here I will examine a number of such possibilities and explain why they are unable or unlikely to explain the features that have been observed.

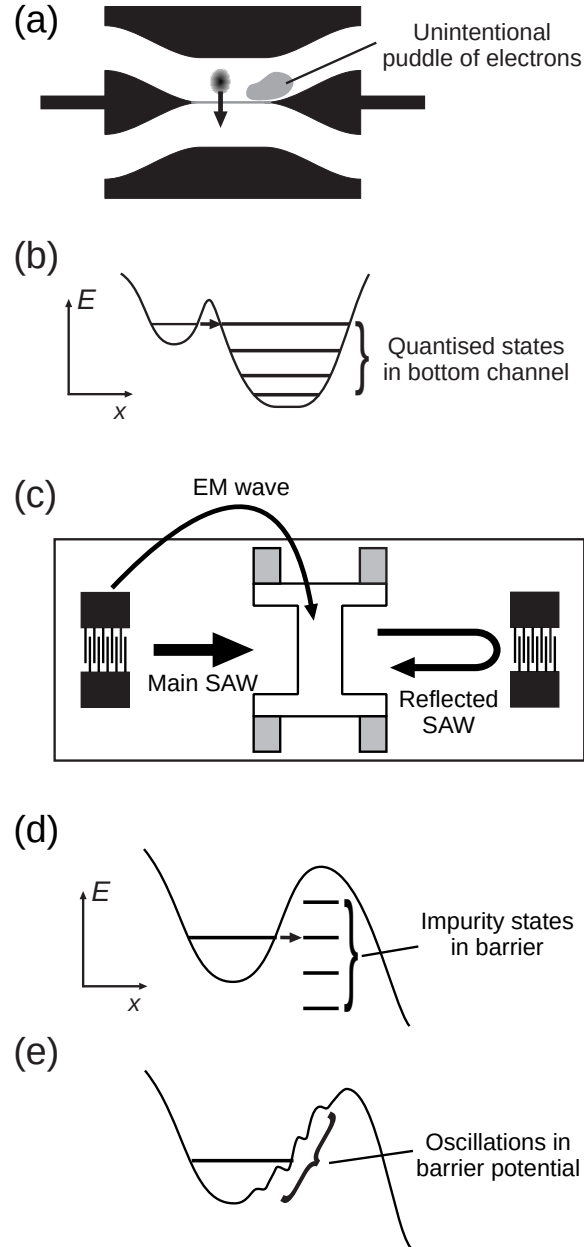


Figure 6.7: Alternative models which could give rise to oscillatory features in the tunnel current. (a) Charging of a puddle of electrons near the barrier region. (b) Resonances with states in the lower channel. (c) Crosstalk or reflection effects. (d) Impurity states within the barrier (e) Oscillations across the barrier potential.

6.3.1 Charging in the SAW channel

The gates that define the upper channel are carefully tuned to try and avoid the possibility that electrons could be forced out of the dynamic quantum dots by a sudden change in potential, but it is very difficult to be sure that this is the case. If a puddle of electrons is able to form in the channel [Fig. 6.7(a)] then as the gates are swept, the size of the puddle will change, but this change can only be by an integer number of electrons. This discrete charging may give rise to oscillatory features as the gate is swept. But in this case it would be expected that sweeping any gate negatively would squeeze the puddle and so as the barrier gate is made more negative the oscillations would move to less negative top gate voltages. As this does not happen [Fig. 6.4(f)], the charging explanation cannot account for the oscillations. This also disproves any charging models which are not in the plane of the 2DEG, for example, the ionization of impurities.

6.3.2 Electronic states in the lower channel

The density of states of a Q1DC contains strong peaks as each subband is crossed, and it is also possible that as the entrance and exit of the lower channel became closed a large quantum dot could be formed. If the energy level of the dynamic quantum dot is aligned with a large peak in the density of states outside the dot it could lead to enhanced tunnelling from the dot [Fig. 6.7(b)]. Therefore, if the dynamic quantum dot energy relative to the base of the lower channel changed, oscillations in the tunnelling current may be created. However, these resonances would be strongly dependent on the confinement potential in the lower channel, and so it would not be possible that the bottom-centre gate could be changed by 0.3 V without substantially affecting the oscillations [Fig. 6.4(e)]. Therefore the oscillations seen cannot be caused by resonances in the bottom channel.

6.3.3 Cross-talk and reflection effects

As discussed earlier (Chapter 3), cross-talk and reflections of the SAW can lead to oscillatory features in the acousto-electric current [Fig. 6.7(c)]. It could be argued that in a complicated SAW circuit these processes may cause the oscillations we see in the tunnelling current. But the effects of cross-talk and reflections can be removed by altering the pulsing conditions of the microwave signal applied to the transducer. Figure 6.8 shows the dependence of the oscillations on microwave signal frequency at pulse lengths of 10 μ s and 900 ns. At a pulse length of 900 ns, by the time that the SAW

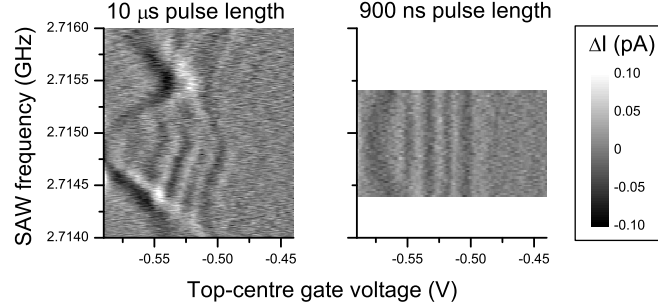


Figure 6.8: Dependence of ΔI on the frequency of the microwave signal applied to the transducer, for pulse widths / periods of $10\ \mu\text{s} : 500\ \mu\text{s}$ (left) and $900\ \text{ns} : 45\ \mu\text{s}$ (right).

has travelled from the transducer to the device the microwave signal applied to the transducer is switched off, and so there can be no crosstalk effects present. While crosstalk clearly causes the position of the oscillations to shift, when there is no crosstalk or reflections present the oscillations persist, so neither of these is related to the origin of the oscillations.

6.3.4 Impurity effects

It is possible for accidental impurities to be incorporated into the heterostructure and to affect the transport properties of the device. Resonant tunnelling through states in an impurity in the barrier potential or oscillations across the barrier potential caused by the impurity potential could both lead to oscillations in the tunnelling current. It is not possible to totally rule out these possibilities from the measurements that we are able to make, but it can be said that the probability of an impurity or set of impurities causing four nearly-periodic oscillations in only one region of the tunnelling current is highly unlikely given that there is no evidence for similar oscillations elsewhere. However, this is not surprising for the case of the coherent oscillation model, as a number of parameters must be exactly right for the oscillations to be visible i.e. there must be sufficient tunnelling current to observe the oscillations, but if the tunnelling current is too high then the first excited state will tunnel out of the dot and so the interference between first excited state and the ground state will not be visible.

6.4 Summary

Reproducible oscillations are seen in the tunnelling current from single-electron dynamic quantum dots. These oscillations have low visibility ($\lesssim 1\%$), are approximately periodic, and are most strongly dependent on the voltages applied to the top-centre and barrier gates. The most likely explanation for these oscillations is that the electron is excited into a superposition of ground and excited states when the barrier is suddenly lowered, and these states then interfere as they evolve coherently, leading to oscillations in the position of the electron wave function in the dynamic quantum dot. This model explains all the behaviour seen as the various gate voltages are varied, whereas other models which might be proposed to explain the oscillations can be said to be either incorrect or highly unlikely.

These results demonstrate the benefit of using dynamic quantum dots to observe high-frequency effects which would be very difficult to observe using traditional static quantum dot techniques. They have been published in references [55] and [56], and were presented at EP2DS 2007 by Masaya Kataoka.

Chapter 7

Tunnel barrier device: charge sensing

The charge of electrons confined within a quantum dot affects the local potential landscape through its capacitive coupling. The conductance of a narrow constriction (quantum point contact) alongside the quantum dot is therefore sensitive to changes in the electron occupation of the dot [57] (Fig. 7.1). This fact has proved highly useful in probing the fundamental properties of confined electrons in static quantum dots, such as non-equilibrium tunnelling rates [45, 46], excited states [58], electron transport statistics [59, 60] and the properties of electron spins [28, 61]. It will be useful to have an equivalent non-invasive charge detection scheme for dynamic quantum dots created by surface acoustic waves; for example, to tune and monitor separate parts of a multi-stage SAW circuit.

7.1 Device operation

The device set-up is shown in Fig. 7.2. The SAW channel, defined by gates G_{C1} - G_{C6} , is depleted, and the SAW carries electrons through this channel in dynamic quantum dots, as shown in Fig. 7.3. The occupation of each dynamic quantum dot in the SAW channel is controlled by the injector gate (G_I)—as the voltage applied to the injector gate (V_{injector}) is swept the acousto-electric current through the SAW channel (I_{SAW}) takes on quantised values of $I_{\text{SAW}} = nef$ where n is the integer occupation number of electrons in each dynamic quantum dot, e is the electron charge, and f is the frequency of the SAW (typically ~ 3 GHz) [11]. The electrons are carried along the channel to the barrier region by the dynamic quantum dots (the SAW channel gate voltages C_1 - C_6 have been carefully tuned to avoid any abrupt changes in

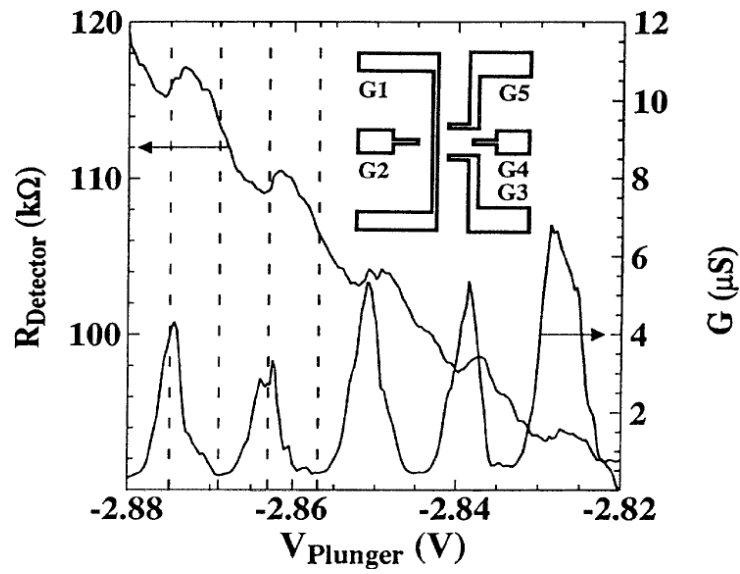


Figure 7.1: Coulomb blockade oscillations of conductance through the dot (G) and resistance of the split gate detector circuit (R_{Detector}) as a function of plunger gate voltage (V_{Plunger})—steps in the detector circuit are caused by electrons entering the quantum dot. Inset: diagram of device—the quantum dot is formed between gates G1, G3, G4 and G5; the detector constriction is formed between gates G1 and G2 (taken from Field *et al.* [57]).

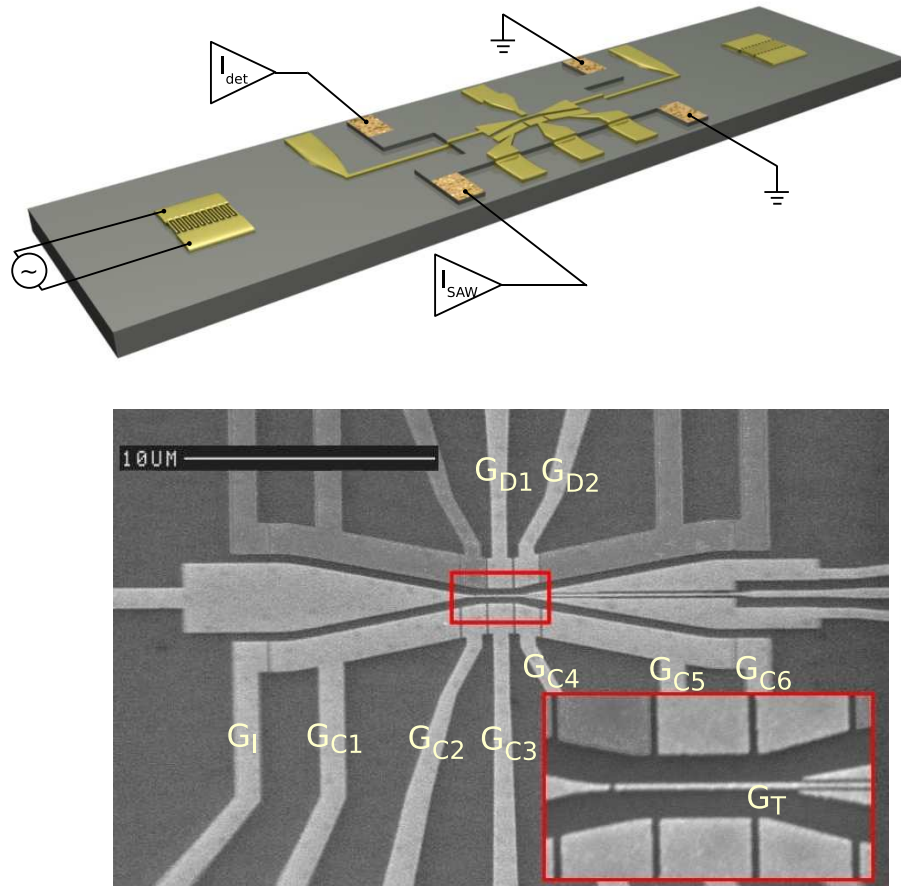


Figure 7.2: Upper panel: Schematic of the device. Lower panel: Scanning electron microscope image of the device surface gates. The gates are labeled as detector channel gates (G_{D1} and G_{D2}), tunnel barrier gate (G_T), injector gate (G_I), SAW channel Gates (G_{C1} - G_{C6}). Dark shaded gates were not used in this experiment, and were held at a voltage of +0.3 V (i.e. undefined).

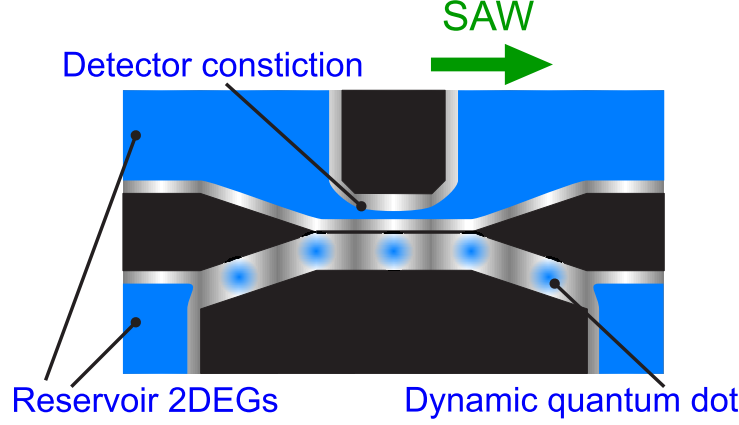


Figure 7.3: Simplified experimental circuit.

the gradient of the electric potential, which could otherwise lead to electrons escaping from the dynamic quantum dots [62]). A sufficiently negative bias is applied to the tunnel barrier gate (G_T) that no electrons can escape across the barrier between the channels [52]. However, the charge of the electrons in the SAW channel will couple capacitively to the detector channel constriction, defined by gates G_{D1} and G_{D2} . Therefore the current that is driven through the detector channel by the SAW can be used to monitor the occupation of the dynamic quantum dots in the top channel.

7.2 Observation of charge sensing

Figure 7.4 shows the effect of sweeping the injector gate. The SAW channel current shows plateaux at multiples of 8.7 pA, which is $I_{SAW} = nef$ reduced by the 1 : 50 pulse ratio [34]. I_{det} can be seen to clearly follow the features in I_{SAW} , despite the fact that the gate being swept is $\sim 8\mu\text{m}$ away from the detector circuit and would therefore be expected to have a negligible influence over the detector current. However, I_{det} is sensitive to changes in the local potential landscape. The electrons which make up the acousto-electric current are carried through the channel in dynamic quantum dots, and so they are out of equilibrium with the reservoir 2DEGs, and the charge is localised within a small area in the SAW confinement potential. This means that the additional charge contained in the dynamic quantum dots increases the local electric potential, and so as the current carried in the dynamic quantum dots past the detector constriction is increased the constriction is closed, and the magnitude of the detector current decreases.

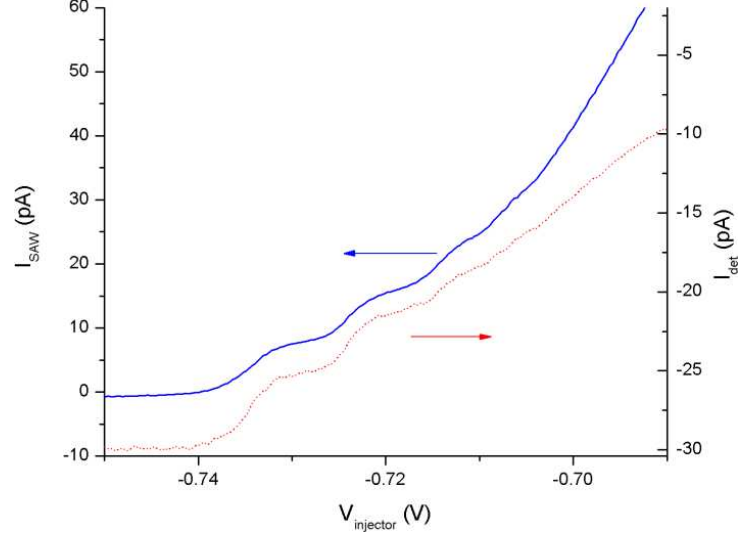


Figure 7.4: Current produced in the SAW channel (solid line) and detector constriction (dotted line) as a function of the injector gate voltage.

Note that the current through the detector circuit is negative. This is because the channel is sufficiently open for the current to be dominated by crosstalk (current generated by the interaction between the free-space electromagnetic wave and the SAW), rather than being a true acousto-electric current—the crosstalk current is more sensitive to changes in the local potential landscape than the acousto-electric current, and also has the advantage that it is approximately linear over tens of picoamp variation and so gives a uniform sensitivity, whereas if an acousto-electric current was used in the detector circuit then the current plateaux would lead to a non-uniform sensitivity. Crosstalk may produce positive or negative currents depending on the phase difference between the free-space electromagnetic wave and the SAW [12, 34, 41]; in this data the frequency chosen to produce best quantisation in the SAW channel happens to produce a negative current in the detector channel.

Figure 7.5(a) shows the differential of the SAW channel current as a function of the injector gate voltage and the power applied to the transducer. Acousto-electric current plateaux are clearly visible as the dark bands in the plot. Figure 7.5(b) shows the equivalent data for the detector channel - the features in the SAW channel current are reproduced in the detector constriction current (the voltage applied to the detector gate (D_1) is adjusted to reset the detector constriction current to -10 pA at the start of each sweep,

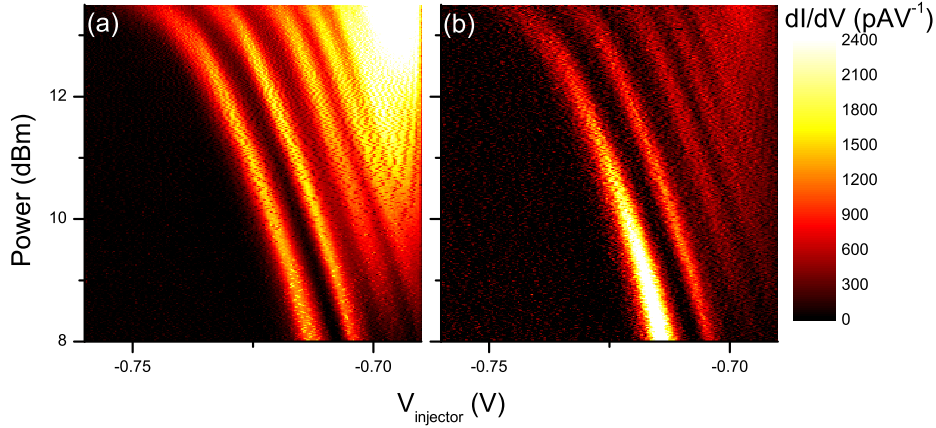


Figure 7.5: The differential of the current in the (a) SAW channel, and (b) detector constriction, with respect to the injector gate voltage.

because the detector channel current is strongly sensitive to the transducer power).

To demonstrate that it is the non-equilibrium charge in the dynamic quantum dots that controls the detector channel current, the voltages applied to the SAW channel gates C_2 - C_6 were backed off so that electrons could enter the channel. In this regime the electrons are pumped over the constriction at the injector gate, but after the injector constriction there are free electrons in the channel. These free electrons will screen the SAW potential, and so there are no dynamic quantum dots confining the electrons as they pass the detector. The differentials of the SAW channel and detector constriction are shown in Fig. 7.6. The SAW channel behaves in a similar way to that shown in Fig. 7.5, but the detector current does not record any features, as there is no non-equilibrium charge confined in dynamic quantum dots to change the channel current. This demonstrates that it is the non-equilibrium charge confined to dynamic quantum dots which creates an effect in the detector current, and not merely the fact that a current is flowing through the SAW channel.

It was hoped that the detector circuit could be calibrated by applying a bias to the free electron gas in the open channel to pinch off the detector constriction; however the results obtained from this method proved counter-

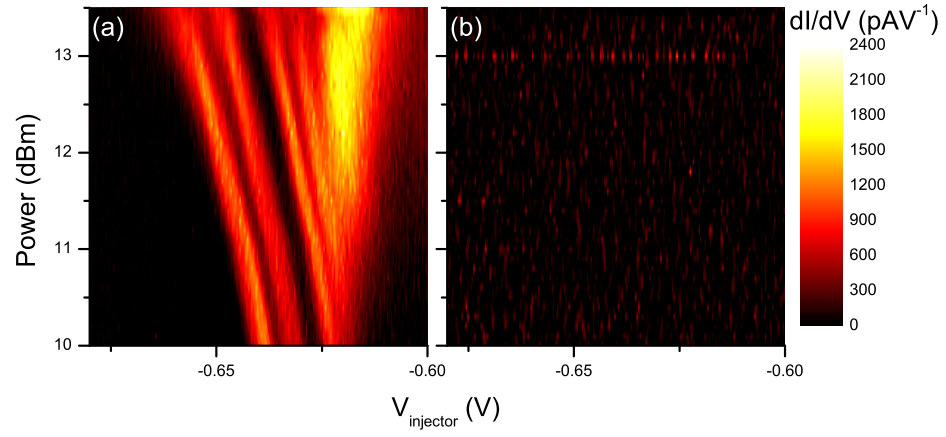


Figure 7.6: The differential of the current in the (a) SAW channel, and (b) detector constriction, with respect to the injector gate voltage, where the SAW channel gate voltages have been backed off to allow an open one-dimensional channel of electrons to form in the SAW channel.

intuitive. It is likely that the electronic configuration of a series of SAW-defined dynamic quantum dots is sufficiently different to that of an open one-dimensional channel that no useful comparisons can be drawn between the two.

7.3 Summary

In this chapter I have demonstrated that a detector circuit may be used to observe the occupation of a SAW-defined dynamic quantum dot. The measurement is carried out non-invasively by using the effect of the change in the local electric potential caused by the non-equilibrium charge contained in the dynamic quantum dot. This technique is analogous to the widely-used experimental technique of charge detection with a quantum point contact, and as increasingly complex SAW devices are developed, non-invasive charge detection is likely to become instrumental for testing each component of a multiple-stage SAW circuit.

The work presented in this chapter is expected to form a future publication.

Chapter 8

Tunnel barrier device: miscellaneous results

Dynamic quantum dot devices are still in their infancy, and as such they exhibit a large amount of behaviour that is not fully understood. In this chapter I will summarize a number of such observations that have been made on device T605-QC12.

8.1 Lorentz-force dependent tunnelling

The behaviour of the acousto-electric current in a perpendicular magnetic field exhibits a number of interesting features, as shown in Fig. 8.1. The most striking is that, in a certain region (labeled MDT on the figure), the tunnelling current depends strongly on the magnetic field: the line joining points of equal amounts of tunnelling current has a gradient of $\sim 5.9 \text{ TV}^{-1}$. The most likely explanation for this is the effect of the Lorentz force acting on the electron. A dynamic quantum dot moves through the device at $v \sim 2800 \text{ ms}^{-1}$, carrying the electron with it. An electron travelling through a magnetic field B feels the Lorentz force $F_{\text{Lorentz}} = e(\mathbf{v} \times \mathbf{B})$, which, in the rest frame of the electron, acts like an equivalent extra electric field of $E_{\text{Lorentz}} = vB$ if the electron is moving perpendicularly to the magnetic field. The two channels are separated by approximately the width of a single channel (400 nm), meaning that the effect of the magnetic field on a dynamic quantum dot in the tunnelling region is equivalent to an extra 1.1 mVT^{-1} . The gradient of the line which marks the onset of magnetic-field-dependent tunnelling has an experimental value of -5.9 TV^{-1} , but the effect of changing the gate voltage is not simply to apply a linear force to the electron, so it is difficult to compare this value with the Lorentz-force theory.

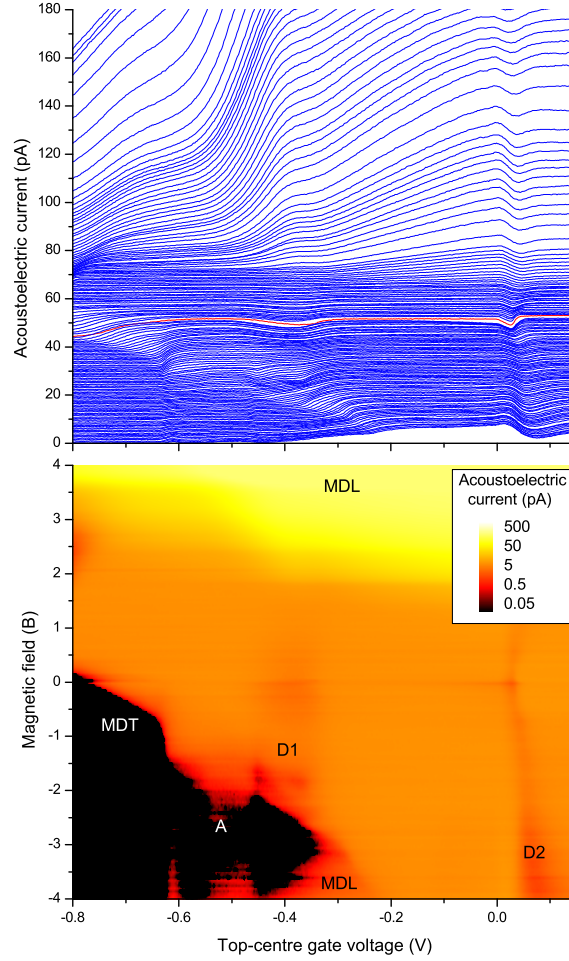


Figure 8.1: Top panel: Current measured coming out of the top channel, as a function of top-centre gate voltage, for magnetic field varying from 4 T (top) to -4 T (bottom) step 0.05 T; zero-field trace is shown in red (Traces are offset vertically for clarity). Bottom panel: Colour plot of the data shown in the upper panel. The following distinctive regions have been labeled: MDT—magnetic field dependent tunnelling, thought to be caused by the Lorentz force acting on the confined electron in a dynamic quantum dot. A—region between -0.4 V and -0.6 V gate voltage, where magnetic field dependence of tunnelling is much less strong, for unknown reasons. D1, D2—dips in the acousto-electric current at gate voltages of -0.40 V and +0.05 V which are possibly due to subtle changes in the potential gradients of the device as the gate voltages are varied. MDL—Magnetic-field dependent leakage current, where high magnetic fields appear to increase the current flowing from the reservoir 2DEG outside the tunnel barrier into the channel.

In addition to the magnetic-field-dependent tunnelling, Fig. 8.1 also exhibits a region between -0.4 V and -0.6 V where the magnetic-field dependence is much less strong (labeled A on Fig. 8.1); dips (i.e. increases in current escaping across the barrier) at -0.40 V and +0.05 V (labeled D1, D2 on the figure), which may be caused by subtle changes in the potential gradients along the SAW channel as the gate voltage is changed; and leakage from the reservoirs into the SAW channel at high magnetic fields (labeled MDL on the figure), which is examined further in Section 8.2.

8.2 Leakage into the SAW channel

When an electron gas exists in the lower channel, if the top-centre or tunnel barrier gate voltages are relaxed then the bottom of the upper channel may fall below the Fermi energy of the electron gas. When this occurs a leakage current flows into the upper channel. This leakage current may be monitored by applying a large negative voltage to the injector gate to prevent current entering the device, so the only current flowing out of the top channel is the leakage current.

8.2.1 Magnetic-field dependent oscillations of the Fermi energy

As the magnetic field is swept, a number of steps appear in the leakage current (Fig. 8.2). The spacing of these steps appears to be related to the filling factors, which occur whenever a Landau level in the bulk 2DEG is full. It is known that the velocity of a SAW can be strongly affected by the conductivity of the 2DEG over which it travels, and so at integer filling factors one would expect to see a change in the travel time of the SAW [9]. Any change in the time it takes the SAW to reach the device will change the phase difference between the SAW and the electromagnetic free-space wave which causes crosstalk, so steps in the leakage current could be explained by this. But the effects of crosstalk can be eliminated by shortening the SAW pulse to below 900 ns; when this is done, steps in the leakage current are still clearly visible (Fig. 8.2). The most likely cause of these steps is the oscillations in the Fermi energy of the 2DEG outside the barrier, which occur as the magnetic field is increased past integer filling factors.

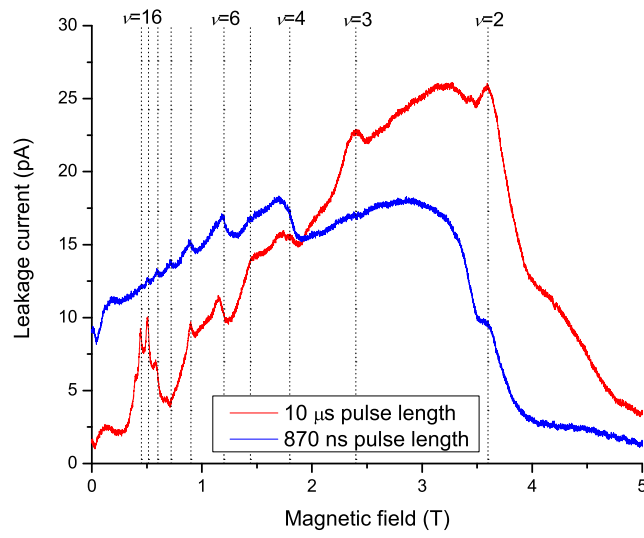


Figure 8.2: Leakage current dependence on the applied perpendicular magnetic field, for pulse widths / periods of $10\ \mu\text{s}$: $500\ \mu\text{s}$ (red) and $870\ \text{ns}$: $43.5\ \mu\text{s}$ (blue). Steps occur when the Landau level filling factor (ν) is an integer.

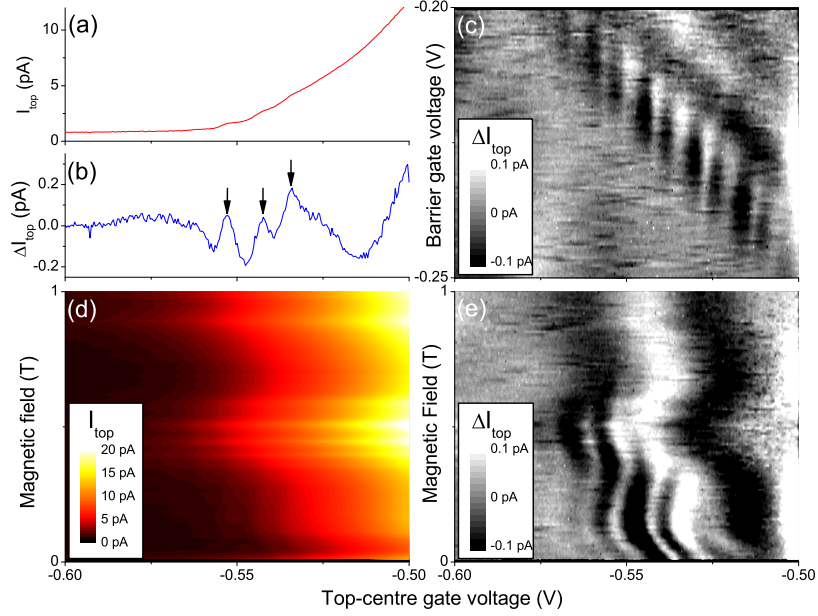


Figure 8.3: Oscillations in the leakage current. (a) The leakage current into the top channel as a function of top-centre gate voltage. (b) ΔI_{top} , the difference between I_{top} and a smoothed background; arrows denote the positions of oscillation maxima. (c) ΔI_{top} as a function of top-centre and barrier gates. (d) The leakage current as a function of the applied perpendicular magnetic field. (e) ΔI_{top} as a function of the applied perpendicular magnetic field.

8.2.2 Oscillations in the leakage current

The leakage current can be analysed by removing a smoothed background from the total current to highlight small variations in the current, as described in Section 6.1. When this is carried out, oscillations in the leakage current can also be seen (Fig. 8.3). However, these oscillations behave differently to those seen in the tunnelling current out of dynamic quantum dots, as described in Chapter 6, and their origin is unknown. In particular, the oscillations appear to be completely independent of the barrier gate voltage [Fig. 8.3(c)], which makes it unlikely that the oscillations have any origin in effects around tunnelling region. But the magnetic field dependence of the oscillations makes it unlikely that their origin is related to effects in the reser-

voir 2DEG as well: the magnetic-field-dependent steps in the leakage current described in Section 8.2.1 are seen in Fig. 8.3(d) as strong horizontal lines, but they are totally absent from the oscillations in Fig. 8.3(e). Assuming the steps are caused by changes in the Fermi energy of the reservoir 2DEG, such changes should be visible in any process arising from the 2DEG region.

Chapter 9

Conclusions and suggestions for future work

9.1 SAW reflections

SAW reflections are the cause of oscillations in the frequency dependence of the acoustoelectric current. By using the pulse modulation technique, the reflections that are present in the device can be controlled. Transducers form highly efficient Bragg reflectors and so reflected SAWs may persist for very long times. Because multiply reflected SAWs are chaotic and show great variation between devices, they may limit the accuracy and reproducibility of sensitive SAW measurements.

The effects of reflections can be minimised by using pulse conditions that avoid major sources of reflections, but this will be a compromise against the need for long pulses to provide good quantisation and high enough duty ratios to produce a measurable current. The fact that reflections lasted for a much shorter length of time in one sample than another suggests that there is considerable scope for designing samples to minimise the effects of reflected SAWs, for instance by increasing the distance between the transducers and the edge of the chip, by adding material to dampen the reflected wave, using wafers that attenuate the SAW more strongly, or by using Bragg reflectors to change the direction of the reflected SAW into a non-preferred crystalline direction, in which it would be strongly attenuated [39]. The techniques of pulse modulation and Fourier analysis presented here will be required to characterise the success of each of these measures.

9.2 Tunnel barrier devices

Surface acoustic waves can be used to form dynamic QDs in relatively large and complex devices. Independently-contacted tunnel barrier gates can be used to control the tunnelling rate out of the QD by more than an order of magnitude. By monitoring the currents which flow through the device, the physics of the tunnelling behaviour out of individual dynamic QDs can be deduced; because of the very short tunnelling time (600 ps or less), physical behaviour can be observed which would be very difficult to see using other techniques, such as the coherent oscillations of the electron which are induced when the barrier is lowered adiabatically. The non-equilibrium charge within the dynamic QD affects the local potential landscape, and this can be used to sense the charge contained in the QD remotely. Dynamic QD devices have not received much study, and there are numerous other effects which can occur in dynamic QD electron transport which are not fully understood.

The results obtained from device T605-QC12 were all obtained using just a single SAW channel. This is because, if both the top-centre and bottom-centre gates were made sufficiently negative to completely deplete the 2DEG in the tunnel barrier region, the resulting potential around the tunnel barrier region's entrance was too high to allow any electrons to be injected by the SAW, and all incoming electrons were reflected back into the source 2DEG.

A different gate geometry with, for example, a narrower gap between the top-centre and bottom-centre gates than the gap on the incoming channels, may solve this problem and allow the device to operate with both channels simultaneously. This would then create dynamic double quantum dots, which are necessary to observe the simulated charge-oscillation pattern (Fig. 4.5) and to see effects such as spin-blockade.

Measurements on device T605-QC12 were unable to resolve different spin states in the spin-charge conversion experiment described in section 4.1.2. The reason for this is that the bare potential of a gated heterostructure system deviates from the ideal case because of disorder potentials caused by, for example, inhomogeneous dopant distributions and ionised impurities. The base of the channel and the tunnel barrier are very close to each other and so will see virtually the same disorder potential, which means that the tunnelling rate from a non-equilibrium dot will be largely unaffected by disorder. But a 2DEG can screen any underlying disorder potential and so the dynamic QD would in effect see a different Fermi energy outside the QD depending on how far it had travelled along the tunnel barrier, making the final measurement the average of a number of different situations. If the disorder potential is greater than the Zeeman splitting of the electron spins, spin-charge conversion will not be possible. To try and eliminate this problem it will therefore

be necessary to either increase the Zeeman splitting through the use of a high g-factor material [63, 64], or to reduce the disorder potential by using, for example, an dopant-free heterostructure [65].

Appendix

Abbreviations

2DEG two-dimensional electron gas

CB conduction band

DI deionised

E_F Fermi energy

HEMT high-electron-mobility transistor

IPA isopropyl alcohol

MIBK Methyl isobutyl ketone

MOSFET metal-oxide-semiconductor field-effect transistor

PMMA polymethyl methacrylate

Q1DC quasi-one-dimensional channel

rf radio frequency

RTS random telegraph signal

SAW surface acoustic wave

SMU Source-Measure Unit

Mathematical symbols

C gate capacitance

$\delta_{i,j}$ Kronecker delta function

e electron charge

E_a energy of the a^{th} electron

$\Delta E_{a \rightarrow a+1}$ addition energy of the a^{th} electron

ε_a single particle energy of the a^{th} state

$\Delta \varepsilon_{a \rightarrow b}$ energy difference between the single particle states $|\psi_a\rangle$ and $|\psi_b\rangle$

f frequency applied to the transducer to generate the SAW

$\hbar$ Planck constant divided by 2π

λ wavelength of the SAW

m^* effective mass of an electron ($m^* \approx 0.067m_e$ in GaAs, where m_e is the electron mass in free space)

μ electrochemical potential

N, n number of electrons in a quantum dot or dynamic quantum dot

$|\psi\rangle$ electron wave function

$T_{i,j}$ transmission coefficient where indices i, j label the incoming and outgoing electron sub-bands

U total energy of the system

V_G voltage applied to gate G

ω_x parameter describing the curvature of a parabolic potential in the x direction

Bibliography

- [1] C. H. W. Barnes. Quantum electronics in semiconductors. Part III lecture course, Cambridge University, 2005.
- [2] M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng, and Z. Wasilewski. Addition spectrum of a lateral dot from coulomb and spin-blockade spectroscopy. *Physical Review B*, 61(24):R16315–R16318, June 2000.
- [3] L. P. Kouwenhoven, D. G. Austing, and S. Tarucha. Few-electron quantum dots. *Reports On Progress In Physics*, 64(6):701–736, June 2001.
- [4] K. Nishi, T. Anan, A. Gomyo, S. Kohmoto, and S. Sugou. Spontaneous lateral alignment of $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ self-assembled quantum dots on (311)B GaAs grown by gas source molecular beam epitaxy. *Applied Physics Letters*, 70(26):3579–3581, June 1997.
- [5] J. A. H. Stotz, R. Hey, P. V. Santos, and K. H. Ploog. Coherent spin transport through dynamic quantum dots. *Nature Materials*, 4(8):585–588, August 2005.
- [6] Lord Rayleigh. On waves propagated along the plane surface of an elastic solid. *Proceedings of the London Mathematical Society*, 17:4, 1885.
- [7] C. Campbell. *Surface acoustic wave devices and their signal processing applications*. Academic press, London, 1989.
- [8] J. Heil, I. Kouroudis, B. Luthi, and P. Thalmeier. Surface acoustic-waves in metals. *Journal Of Physics C-Solid State Physics*, 17(13):2433–2447, 1984.
- [9] A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp. Surface acoustic-waves on $\text{GaAs Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures. *Physical Review B*, 40(11):7874–7887, October 1989.

- [10] R. L. Willett. Experimental evidence for composite fermions. *Semiconductor Science And Technology*, 12(5):495–524, May 1997.
- [11] J. M. Shilton, V. I. Talyanskii, M. Pepper, D. A. Ritchie, J. E. F. Frost, C. J. B. Ford, C. G. Smith, and G. A. C. Jones. High-frequency single-electron transport in a quasi-one-dimensional GaAs channel induced by surface acoustic waves. *Journal Of Physics-Condensed Matter*, 8(38):L531–L539, September 1996.
- [12] 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. Single-electron transport in a one-dimensional channel by high-frequency surface acoustic waves. *Physical Review B*, 56(23):15180–15184, December 1997.
- [13] J. T. Janssen and A. Hartland. Recent measurements of single electron transport of surface acoustic wave devices at the NPL. *IEEE Transactions On Instrumentation And Measurement*, 50(2):227–230, April 2001.
- [14] J. Ebbecke, N. E. Fletcher, T. J. B. M. Janssen, F. J. Ahlers, M. Pepper, H. E. Beere, and D. A. Ritchie. Quantized charge pumping through a quantum dot by surface acoustic waves. *Applied Physics Letters*, 84(21):4319–4321, May 2004.
- [15] J. Ebbecke, N. E. Fletcher, T. J. B. M. Janssen, H. E. Beere, D. A. Ritchie, and M. Pepper. Acoustoelectric current transport through a double quantum dot. *Physical Review B*, 72(12):121311, September 2005.
- [16] R. Rodriguez, D. K. L. Oi, M. Kataoka, C. H. W. Barnes, T. Ohshima, and A. K. Ekert. Surface-acoustic-wave single-electron interferometry. *Physical Review B*, 72(8):085329, August 2005.
- [17] C. H. W. Barnes, J. M. Shilton, and A. N. Robinson. Quantum computation using electrons trapped by surface acoustic waves. *Physical Review B*, 62(12):8410–8419, September 2000.
- [18] C. H. W. Barnes. A pseudo-spin surface-acoustic-wave quantum computer. *Philosophical Transactions Of The Royal Society Of London Series A-Mathematical Physical And Engineering Sciences*, 361(1808):1487–1492, July 2003.
- [19] C. L. Foden, V. I. Talyanskii, G. J. Milburn, M. L. Leadbeater, and M. Pepper. High-frequency acousto-electric single-photon source. *Physical Review A*, 62(1):011803, July 2000.

- [20] J. R. Gell, P. Atkinson, S. P. Bremner, F. Sfigakis, M. Kataoka, D. Anderson, G. A. C. Jones, C. H. W. Barnes, D. A. Ritchie, M. B. Ward, C. E. Norman, and A. J. Shields. Surface-acoustic-wave-driven luminescence from a lateral p-n junction. *Applied Physics Letters*, 89(24):243505, December 2006.
- [21] R. P. Feynman. Simulating physics with computers. *International Journal Of Theoretical Physics*, 21(6-7):467–488, 1982.
- [22] P. W. Shor. Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. *Siam Journal On Computing*, 26(5):1484–1509, October 1997.
- [23] D. P. DiVincenzo. *Scalable Quantum Computers*, chapter 1, pages 1–14. Wiley-VCH, 2000.
- [24] L. M. K. Vandersypen, M. Steffen, G. Breyta, C. S. Yannoni, R. Cleve, and I. L. Chuang. Experimental realization of an order-finding algorithm with an NMR quantum computer. *Physical Review Letters*, 85(25):5452–5455, December 2000.
- [25] Z. Zhao, Y. A. Chen, A. N. Zhang, T. Yang, H. J. Briegel, and J. W. Pan. Experimental demonstration of five-photon entanglement and open-destination teleportation. *Nature*, 430(6995):54–58, July 2004.
- [26] H. Haffner, W. Hansel, C. F. Roos, J. Benhelm, D. Chek-al kar, M. Chwalla, T. Korber, U. D. Rapol, M. Riebe, P. O. Schmidt, C. Becher, O. Guhne, W. Dur, and R. Blatt. Scalable multiparticle entanglement of trapped ions. *Nature*, 438(7068):643–646, December 2005.
- [27] J. H. Plantenberg, P. C. de Groot, C. J. P. M. Harmans, and J. E. Mooij. Demonstration of controlled-not quantum gates on a pair of superconducting quantum bits. *Nature*, 447(7146):836–839, June 2007.
- [28] J. M. Elzerman, R. Hanson, L. H. W. van Beveren, B. Witkamp, L. M. K. Vandersypen, and L. P. Kouwenhoven. Single-shot read-out of an individual electron spin in a quantum dot. *Nature*, 430(6998):431–435, July 2004.
- [29] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard. Coherent manipulation of coupled electron spins in semiconductor quantum dots. *Science*, 309(5744):2180–2184, September 2005.

- [30] F. H. L. Koppens, C. Buizert, K. J. Tielrooij, I. T. Vink, K. C. Nowack, T. Meunier, L. P. Kouwenhoven, and L. M. K. Vandersypen. Driven coherent oscillations of a single electron spin in a quantum dot. *Nature*, 442(7104):766–771, August 2006.
- [31] D. Loss and D. P. DiVincenzo. Quantum computation with quantum dots. *Physical Review A*, 57(1):120–126, January 1998.
- [32] M. Kataoka, R. J. Schneble, A. L. Thorn, C. H. W. Barnes, C. J. B. Ford, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper. Single-electron population and depopulation of an isolated quantum dot using a surface-acoustic-wave pulse. *Physical Review Letters*, 98(4):046801, January 2007.
- [33] M. Pioro-Ladrière, J. H. Davies, A. R. Long, A. S. Sachrajda, L. Gaudreau, P. Zawadzki, J. Lapointe, J. Gupta, Z. Wasilewski, and S. Studenikin. Origin of switching noise in GaAs/Al_xGa_{1-x}As lateral gated devices. *Phys. Rev. B*, 72(11):115331, September 2005.
- [34] M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, H. E. Beere, D. A. Ritchie, and M. Pepper. The effect of pulse-modulated surface acoustic waves on acoustoelectric current quantization. *Journal Of Applied Physics*, 100(6):063710, September 2006.
- [35] A. M. Robinson and C. H. W. Barnes. Classical dynamics of electrons in quantized-acoustoelectric-current devices. *Physical Review B*, 63(16):165418, April 2001.
- [36] J. Cunningham, V. I. Talyanskii, J. M. Shilton, M. Pepper, M. Y. Simmons, and D. A. Ritchie. Single-electron acoustic charge transport by two counterpropagating surface acoustic wave beams. *Physical Review B*, 60(7):4850–4855, August 1999.
- [37] P. Utko, K. Gloos, J. B. Hansen, and P. E. Lindelof. An improved 2.5 ghz electron pump: Single-electron transport through shallow-etched point contacts driven by surface acoustic waves. *Acta Physica Polonica A*, 103(6):533–538, June 2003.
- [38] Y. Takagaki, E. Wiebicke, P. V. Santos, R. Hey, and K. H. Ploog. Propagation of surface acoustic waves in a GaAs/AlAs/GaAs heterostructure and micro-beams. *Semiconductor Science And Technology*, 17(9):1008–1012, September 2002.

- [39] W. D. Hunt, R. L. Miller, and B. J. Hunsinger. Slowness surface measurements for zero-degree and 5-degree [100]-cut GaAs. *Journal Of Applied Physics*, 60(10):3532–3538, November 1986.
- [40] M. R. Astley, M. Kataoka, R. J. Schneble, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, H. E. Beere, D. A. Ritchie, and M. Pepper. Examination of surface acoustic wave reflections by observing acoustoelectric current generation under pulse modulation. *Applied Physics Letters*, 89(13):132102, September 2006.
- [41] M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, H. E. Beere, D. A. Ritchie, and M. Pepper. Examination of multiply reflected surface acoustic waves by observing acoustoelectric current generation under pulse modulation. *Physical Review B*, 74(19):193302, November 2006.
- [42] M. Kataoka, C. H. W. Barnes, C. J. B. Ford, H. E. Beere, D. A. Ritchie, D. Anderson, G. A. C. Jones, and M. Pepper. Single-electron transfer between double quantum dots defined by surface acoustic waves. *Physica E-Low-Dimensional Systems & Nanostructures*, 34(1-2):546–549, August 2006.
- [43] Y. Aharonov and D Bohm. Significance of electromagnetic potentials in the quantum theory. *The Physical Review*, 115:485–491, 1959.
- [44] J. H. Davies, I. A. Larkin, and E. V. Sukhorukov. Modeling the patterned 2-dimensional electron-gas - electrostatics. *Journal Of Applied Physics*, 77(9):4504–4512, May 1995.
- [45] J. Cooper, C. G. Smith, D. A. Ritchie, E. H. Linfield, Y. Jin, and H. Launois. Direct observation of single-electron decay from an artificial nucleus. *Physica E*, 6(1-4):457–460, February 2000.
- [46] K. MacLean, S. Amasha, I. P. Radu, D. M. Zumbuhl, M. A. Kastner, M. P. Hanson, and A. C. Gossard. Energy-dependent tunneling in a quantum dot. *Physical Review Letters*, 98(3):036802, January 2007.
- [47] J. Martorell, D. W. L. Sprung, P. A. Machado, and C. G. Smith. Model of single-electron decay from a strongly isolated quantum dot. *Physical Review B*, 63(4):045325, January 2001.
- [48] A. M. Robinson and V. I. Talyanskii. Shot noise in the current of a surface acoustic-wave-driven single-electron pump. *Physical Review Letters*, 95(24):247202, December 2005.

- [49] M. Büttiker. Quantized transmission of a saddle-point constriction. *Physical Review B*, 41(11):7906–7909, April 1990.
- [50] J. N. L. Connor. *Molecular Physics*, 15:37, 1968.
- [51] S. Tarucha, D. G. Austing, T. Honda, R. J. vanderHage, and L. P. Kouwenhoven. Shell filling and spin effects in a few electron quantum dot. *Physical Review Letters*, 77(17):3613–3616, October 1996.
- [52] M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper. Energy-dependent tunneling from few-electron dynamic quantum dots. *Physical Review Letters*, 99:156802, 2007.
- [53] M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper. Measurement of coulomb-energy-dependent tunneling rates in surface-acoustic-wave-defined dynamic quantum dots. *Physica E (accepted for publication)*.
- [54] T. Hayashi, T. Fujisawa, H. D. Cheong, Y. H. Jeong, and Y. Hirayama. Coherent manipulation of electronic states in a double quantum dot. *Physical Review Letters*, 91(22):226804, November 2003.
- [55] M. Kataoka, M. R. Astley, A. L. Thorn, D. K. L. Oi, C. H. W. Barnes, C. J. B. Ford, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper. Coherent time evolution of a single-electron wave function. *(to be published)*.
- [56] M. Kataoka, M. R. Astley, A. L. Thorn, C. H. W. Barnes, C. J. B. Ford, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper. Investigation of single-electron dynamics in tunnelling between zero- and one-dimensional states. *Physica E (accepted for publication)*.
- [57] M. Field, C. G. Smith, M. Pepper, D. A. Ritchie, J. E. F. Frost, G. A. C. Jones, and D. G. Hasko. Measurements of coulomb blockade with a non-invasive voltage probe. *Physical Review Letters*, 70(9):1311–1314, March 1993.
- [58] J. M. Elzerman, R. Hanson, L. H. W. van Beveren, L. M. K. Vandersypen, and L. P. Kouwenhoven. Excited-state spectroscopy on a nearly closed quantum dot via charge detection. *Applied Physics Letters*, 84(23):4617–4619, June 2004.

- [59] S. Gustavsson, R. Leturcq, B. Simovic, R. Schleser, T. Ihn, P. Studerus, K. Ensslin, D. C. Driscoll, and A. C. Gossard. Counting statistics of single electron transport in a quantum dot. *Physical Review Letters*, 96(7):076605, February 2006.
- [60] T. Fujisawa, T. Hayashi, R. Tomita, and Y. Hirayama. Bidirectional counting of single electrons. *Science*, 312(5780):1634–1636, June 2006.
- [61] R. Hanson, L. H. W. van Beveren, I. T. Vink, J. M. Elzerman, W. J. M. Naber, F. H. L. Koppens, L. P. Kouwenhoven, and L. M. K. Vandersypen. Single-shot readout of electron spin states in a quantum dot using spin-dependent tunnel rates. *Physical Review Letters*, 94(19):196802, May 2005.
- [62] M. Kataoka, C. H. W. Barnes, H. E. Beere, D. A. Ritchie, and M. Pepper. Experimental investigation of the surface acoustic wave electron capture mechanism. *Physical Review B*, 74(8):085302, August 2006.
- [63] D. R. Mace, M. P. Grimshaw, D. A. Ritchie, A. C. Churchill, M. Pepper, and G. A. C. Jones. The growth and physical-properties of high-quality pseudomorphic $\text{In}_x\text{Ga}_{1-x}\text{As}$ HEMT structures. *Journal Of Crystal Growth*, 127(1-4):601–605, February 1993.
- [64] M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, M. Godfrey, I. Farrer, D. A. Ritchie, M. Pepper, D. C. Unitt, and S. N. Holmes. Quantised acousto-electric current in an InGaAs quantum well. (*to be published*).
- [65] R. H. Harrell, K. S. Pyshkin, M. Y. Simmons, D. A. Ritchie, C. J. B. Ford, G. A. C. Jones, and M. Pepper. Fabrication of high-quality one- and two-dimensional electron gases in undoped GaAs/AlGaAs heterostructures. *Applied Physics Letters*, 74(16):2328–2330, April 1999.