Acoustoelectric Charge Transport in Quasi-One-Dimensional Systems

John Cunningham

Selwyn College

University of Cambridge

Dissertation submitted for the degree of

Doctor of Philosophy

4 Jan 2000
Preface

I would like to thank several people for helping me during the last few years in Cambridge. Firstly my supervisor Mike Pepper for his constant ideas and enthusiasm concerning the SAW project. To Valery Talyanskii I extend warm gratitude both for supervising my work and acting as a source of constructive criticism. Julian Shilton helped me at the start of this work by teaching me some measurement techniques, and has provided ongoing support by way of sample fabrication over the last 2 years. For proof reading this thesis I’m indebted to Valery Talyanskii, Julian Shilton, Clare Foden and Mark Leadbeater; many thanks to you all.

I have enjoyed many useful conversations with members of the Semiconductor Physics Group over the last few years and would particularly like to thank Chris Ford, Charles Smith, Mark Leadbeater and Clare Foden for their input. Lastly, a big thank you to Deborah, Giles, Corinna and Kirill for putting up with me in the low times.

This work was funded by EPSRC, Toshiba Europe Ltd. and the Cavendish Semiconductor Physics Group.

Except where stated otherwise, this thesis contains my own original work which was not done in collaboration with others. This thesis is not substantially the same as any that I have already submitted, or am in the process of submitting, for any degree at this or another University. It is less than 60,000 words long.

John Cunningham 4 Jan 2000
Summary

The study of electron transport in mesoscopic systems has recently turned to the observation of time dependent single electron effects, where the electron transport is frequency locked to an external potential. Such devices are expected to form the basis of a standard of electric current, long sought after by the metrological community, to provide a representation of the ampere and to be compared with existing quantum standards of the volt and ohm.

This thesis details new experimental investigations of one such system. The piezoelectric interaction between an acoustic wave travelling on the surface of a GaAs heterostructure and electrons in a quasi-1D system defined therein generates a current which, under certain conditions, can be quantized in units of $e f$ where $e$ is the electron charge and $f$ the surface acoustic wave frequency. The general conditions under which this single electron acoustoelectric effect is observable are studied, and experimental results presented which demonstrate that the effect represents a possible route towards a current standard. The precision of the effect is assessed in a variety of experimental situations and device geometries. Several ways to enhance the precision of the effect are presented. Firstly a weak counterpropagating SAW beam produces a dynamic tuning of the SAW potential. Observations of a quantized acoustoelectric current are then presented in novel etched-channel SAW devices which afford a more precise current by allowing better control over the channel geometry. The presently attainable precision of the technique is at the level of 10’s of ppm. Detailed measurements are presented of the single electron acoustoelectric effect in a magnetic field applied perpendicular to the two-dimensional electron gas. Commensurability oscillations are observed for the interval of current between acoustoelectric current plateaux when the cyclotron diameter and SAW wavelength are compa-
rable. The oscillations show a particular phase dependence which results in an oscillating plateau slope as a function of applied magnetic field.

Results are also presented from measurements of the interaction between a surface acoustic wave and open 1D systems. Here the quantized current is not observed, but instead the behaviour of the measured current depends sensitively on the geometry of the channel. Two situations are possible in this regime. Interaction between the SAW and slow electrons in the uppermost 1D subband within the channel produces an oscillatory acoustoelectric current as a function of subband occupancy. These oscillations are observed in all subbands of clean constrictions for the first time. Secondly, interaction between the SAW and electrons in the device leads causes a contribution to the acoustoelectric current which is proportional to the quantized channel conductance, this contribution dominating transport in certain device geometries.


Contents

1 Low dimensional systems 5
  1.1 Confinement of Fermions ............................... 5
  1.1.1 Quantum confined energy scale ........................ 6
  1.1.2 Density of states in low dimensions .................. 7
  1.2 The Integer Quantum Hall Effect ........................ 8
  1.2.1 Landau levels ........................................ 9
  1.2.2 Edge states .......................................... 9
  1.2.3 The Fractional Quantum Hall Effect ................... 12
  1.3 Guiding centre drift resonance .......................... 13
  1.4 Quasi-1d channels ....................................... 14
  1.4.1 Conductance quantization ................................ 14
  1.4.2 Interacting electrons in 1D ............................ 15
  1.5 The Landauer/Büttiker equations ........................ 17
  1.6 Quantum dots and Coulomb charging ........................ 18
  1.7 Single electronics - electron pumps and turnstiles ...... 20
  1.8 Random Telegraph Signals .................................. 22

2 Interaction of a SAW with low dimensional systems 23
  2.1 Introduction ............................................. 23
  2.2 Rayleigh waves .......................................... 24
  2.3 Interaction of surface acoustic waves with 2D systems 24
  2.4 Commensurability oscillations ............................ 24
    2.4.1 Composite Fermions .................................. 24
    2.4.2 Electrons ........................................... 24
  2.5 SAW induced electron transport in open 1-D channels 25
    2.5.1 Coupling in the 2D-1D transition region ............ 28
  2.6 SAW induced transport in closed 1-D channels .......... 28
  2.7 Open questions in quantized acoustoelectric transport 31
## CONTENTS

### 3 Processing and measurement of SAW devices 33
   - 3.1 Device design 33
   - 3.2 Optical processing 34
   - 3.3 Ebeam processing 36
   - 3.4 Scribing and fixing 39
   - 3.5 Bonding 40
   - 3.6 Attaching to probes 41
   - 3.7 Measurement techniques 42
   - 3.8 Initial assessment 43
   - 3.9 Cryostat transfer 44
   - 3.10 Low temperature techniques 44

### 4 SAW transport in open 1D systems 49
   - 4.1 Introduction 49
   - 4.2 Summary of prior work 49
   - 4.3 Acoustoelectric current in deep HEMT layers 50
     - 4.3.1 Acoustoelectric current in open channel 53
     - 4.3.2 Exclusion of cross-talk as a possible mechanism of influence 56
     - 4.3.3 Acoustoconductance of clean quantum channels 58
   - 4.4 Acoustoelectric current in etched constrictions 61
   - 4.5 Conclusion 65

### 5 Single electron acoustoelectric effect 67
   - 5.1 Summary of results 67
   - 5.2 Acoustoelectric current quantization 68
   - 5.3 Demonstration of frequency locking 68
   - 5.4 Accuracy of quantized charge transport in Schottky gates 74
   - 5.5 The action of a d.c. bias 76
   - 5.6 Frequency response of devices 80
   - 5.7 Structure in power response of devices 83
   - 5.8 Influence of impurities in acoustoelectric current 86
     - 5.8.1 Coulomb blockade by impurities 86
     - 5.8.2 RTS noise 86
   - 5.9 Recent theoretical treatments 88
   - 5.10 Conclusion 90
CONTENTS

6 Dynamically tuned single electron transport
   6.1 Introduction ............................................. 93
   6.2 Experimental setup ................................. 93
   6.3 Sample considerations .............................. 95
   6.4 Experimental procedure ............................ 96
   6.5 Precision measurement .............................. 100
   6.6 Accuracy measurement .............................. 100
   6.7 Discussion - Dynamic tuning of SAW potential ... 101
   6.8 Summary and conclusion ........................... 104

7 Single electron acoustoelectric effect
   7.1 Summary of results ................................. 105
   7.2 Device considerations ............................... 105
   7.3 Observation of current quantization in etched constrictions 106
   7.4 Precision of quantized current in etched devices ... 107
   7.5 Robustness of etched channels to D.C. bias .......... 108
   7.6 Measurements in perpendicular field ............... 108
   7.7 Discussion ........................................... 109
   7.8 Summary and conclusion ........................... 109
Chapter 1

Low dimensional systems

This chapter reviews some of the landmarks in the field of low dimensional systems, where the confinement of Fermions leads directly to interesting physical effects. The results which will be discussed underpin the novel experimental observations described later in this thesis. Treatment of the interaction of a surface acoustic wave with low dimensional systems is discussed in the following chapter.

1.1 Confinement of Fermions

Low dimensional semiconducting systems rely upon confining electrons or holes in one or more dimensions. For Fermions the most important length scale is the Fermi wavelength, λ_f. When confined to length scales of this order a Fermion’s motion is quantized in the confinement direction. Restriction of motion in one direction can be accomplished by the crystal growth of a heterojunction: an interface between two materials of differing bandgap. The GaAs/Al_xGaAs_{1-x} material system has proved particularly useful for the formation of such structures. The similar lattice constants of GaAs and AlGaAs produce an interface that is low in defects and consequently stress free. The fraction of replaced GaAs atoms x is typically around 0.3, higher values than this produce an indirect gap. GaAs and AlGaAs both have a zinc-blende crystal structure, and the respective direct gaps are 1.427 eV and 1.427 + 1.247x (0≤x≤0.45) at 300 K [1]. High quality heterojunctions are commonly grown using epitaxial techniques such as Molecular Beam Epitaxy (MBE) or Metal-Organic Vapour Phase Epitaxy (MOVPE). The former technique was
used to grow heterojunctions for the work described in this thesis. MBE provides crystal growth conditions for the deposition of single atomic layers of material from thermal fluxes under Ultra High Vacuum conditions. The conduction band profile of a typical GaAs/AlGaAs HEMT looks like that shown in figure 1.1. Electrons from the donor layer migrate through the undoped AlGaAs buffer layer to reside near the AlGaAs/GaAs interface. Here they are confined to a two dimensional conducting sheet with quasi-metallic properties. The 2DEG which forms at the interface has the following features:

1. It has a very high mobility at low enough temperatures. Typical values are $1 \times 10^6 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$. This results from the spatial separation of electrons at the interface from the donor layer which acts as a source of Coulomb scattering.

2. The mean free path in the 2DEG is large. For a typical 2DEG a mean free path of several $\mu\text{m}$ is common. An important result of this is that when features are imposed in a 2DEG, by surface gates for example, it is easy to create a device whose critical dimensions are all smaller than the distance between non-elastic (energy changing) scattering events. This is the ballistic regime, where electrons may traverse a device in a similar manner to waves in a waveguide.

3. Only one 2D subband is usually occupied.

1.1.1 Quantum confined energy scale

The energy spacing of an electron confined to a hard walled infinite potential is a useful starting point for the discussion of a heterojunction, and can be stated [2] as:

$$E(n) = \frac{\hbar^2 \pi^2 (n + 1)^2}{d^2 2m} n = 0, 1, 2....$$  \hspace{1cm} (1.1)

where $d$ is the width of the well and $m$ is the effective mass. The total energy of an electron in such a system is given by adding the quantum confinement energy to the (unrestricted) kinetic energy in the orthogonal directions:

$$E_t = E_n + \frac{\hbar^2}{2m}(k_x^2 + k_y^2)$$  \hspace{1cm} (1.2)
The lowest lying energy level in the system will be given by

\[ E_0 = \frac{\hbar^2 \pi^2}{d^2 2m} \quad (1.3) \]

1.1.2 Density of states in low dimensions

The density of states \( N(E) \) is defined \([3, 4]\) such that \( N(E) \delta E \) is equal to the number of solutions to Schrödinger's equation in the energy interval between \( E \) and \( E + \delta E \). It can be shown \([2]\) that the following relationships are valid.

In 3D,

\[ N(E) = \frac{1}{2\pi^2} (2m/\hbar^2)^{(3/2)} E^{(1/2)} \quad (1.4) \]

2D,

\[ N(E) = \frac{1}{2\pi} (2m/\hbar^2) \quad (1.5) \]

and 1D

\[ N(E) = \frac{1}{\pi} (2m/\hbar^2)^{1/2} E^{-1/2} \quad (1.6) \]
In low dimensions the density of states at the band edge is large compared to the bulk case. This leads to the improved optical properties of low-dimensional semiconductor systems relative to their bulk counterparts.

Figure 1.2: (a) The density of states for a 3D, quasi-2D, and (b) quasi-1D system.

1.2 The Integer Quantum Hall Effect

The main thrust of modern research into low dimensional systems began with the discovery in 1979 of the quantum Hall effect by von Klitzing, Dorland and Pepper [5]. The high field Hall resistance of a two-
dimensional electron gas formed in a Si inversion layer was found to be extremely accurately quantized in units of $\hbar/2e^2$, accompanied by a drop in the longitudinal resistance to zero. While plateaux in the Hall resistance had been seen previously [6], and predicted theoretically, the major surprise was the accuracy of the quantization, which was initially shown to hold to around 1 part in $10^6$. Later experiments showed that the accuracy could be even higher, with a few parts in $10^8$ now routinely obtainable [7]. Such is its accuracy and reproducibility that in 1990 the quantum Hall effect (QHE) was adopted internationally as the primary resistance standard, with the quantized Hall plateaux now providing a worldwide representation of the SI Ohm [8].

1.2.1 Landau levels

In a low magnetic field electrons are subject to the Lorentz force and undergo cyclotron orbits with a diameter larger than the mean free path. Conversely at high magnetic field electrons may undergo many cyclotron orbits before being scattered. The continuum of possible energies at zero magnetic field reduces to a series of quantized energy levels (Landau levels) in magnetic field with energies given by

$$E_n = (n - 1/2)\hbar\omega_c$$  \hspace{1cm} (1.7)

where $\omega_c = eB/m$ is the cyclotron frequency

These levels are broadened for real systems by disorder, as shown in figure 1.3, and also by temperature.

1.2.2 Edge states

The physical reason for the accuracy of the Quantum Hall Effect can be conceptualized as the separation of charge carrying channels into edge states. In a real sample the picture presented above of Landau levels must be adjusted to incorporate edge effects. At the sample edges the potential rises steeply, and quasi-1D channels form where the Fermi energy intersects the Landau levels [9]. The electron trajectories can be considered classically as undergoing 'skipping orbits' along the sample boundary, as shown in figure 1.4. Electrons are reflected by the sharply rising potential at the sample edge.
Figure 1.3: (a) Schematic diagram of the density of states in magnetic field, with Landau levels separated by $1/2 \hbar \omega_c$. Dark areas indicate extended states; areas outside are localized at zero temperature. (b) The localization length $\xi$ as a function of energy.

Figure 1.4: The electrons in a 2DEG classically undergo skipping orbits in high perpendicular magnetic field.
The effect of disorder in the bulk can be seen in figures 1.4 and 1.5, where bumps in the potential distribution form closed loops and so do not contribute to charge transfer between ohmic contacts.

Figure 1.5: (a) Schematic of the potential distribution on a Quantum Hall plateau. The Fermi energy in the bulk is between Landau levels, and the only extended states are at the sample edges. (b) The effect of disorder in the system is to form closed loops of localized charge.

On a quantum Hall plateau the Fermi energy is situated in the centre of localised states between Landau levels in the bulk of the sample and conduction may only occur through the states at the edge. Each
edge state acts as an independent 1-d conducting channel, thereby contributing $2e^2/h$ to $\sigma_{xy}$. Edge channels in the quantum Hall regime have recently been observed directly using an optical technique with spatial resolution [10].

The physical separation of edge states propagating in opposite directions on either side of the sample means scattering between current carrying modes can be neglected, and this explains the drop in longitudinal resistance to the zeros observed in the integer QHE. As the Fermi energy moves towards a Landau level centre bulk conduction is regained, zeros are lost in the longitudinal resistance and $R_H$ moves away from the quantized value. The accurate quantization of the Hall resistance also follows from the edge state picture. The transverse current measured will be given by the net difference in current between forward and backward moving edge states. If $\mu_i$ and $\mu_j$ are the chemical potentials on either side of the Hall bar then the net current $I_t$ is given by

$$I_t = ne^2/h(\mu_i - \mu_j)$$

where $n$ is the number of Landau levels below $E_f$ and $\mu_i - \mu_j$ is the Hall voltage. The quantized Hall resistance then follows from :

$$R_H = (\mu_i - \mu_j)/I = \frac{1}{n} \frac{h}{e^2}$$

### 1.2.3 The Fractional Quantum Hall Effect

In 1982, under extreme quantum conditions of temperature and magnetic field, further plateaus were found in the Hall resistance at values of :

$$R_H = \frac{1}{i} \frac{h}{e^2}$$

where $i = 1/3$ and $i = 2/3$. Further experiments revealed a whole series of additional plateau, all rational fractions with odd denominators. The accuracy of quantization was not as good as that observed in the integer quantum Hall effect, with around 1 part in $10^5$ for the $1/3$ state and lower accuracy for the others. The generally accepted theoretical picture of the fractional quantum Hall effect (FQHE) is that proposed by Laughlin [11]. Laughlin constructed an approximate wavefunction corresponding to a set of particles with uniform density with repel each other.
logarithmically. At special densities this system has energy gaps which correspond to the appearance of the fractional plateaus. The composite Fermion approach [12] employs a quasiparticle formed by an electron and two magnetic flux quanta. In this picture the fractional quantum Hall states are the integer states of the composite Fermions. These two approaches have been shown to be broadly compatible [13]. The FQHE is an interesting example of a many-body effect and many reviews are available (for a list see ref. [14]).

1.3 Guiding centre drift resonance

When a weak carrier density modulation with a period smaller than the mean free path is imposed on a 2DEG magnetoresistance oscillations periodic in $1/B$ can be observed in addition to the SdH oscillations. The original experiments which studied this effect were performed by two groups. Weiss et al [15, 16] used holographic illumination of samples to produce interference fringes with controllable separation, whilst Winkler et al [17] used a less versatile periodic gating technique. The oscillations dominated transport below 0.3 T and were present in both $\rho_\perp$ and $\rho_\parallel$, with a phase shift of $\pi$ distinguishing orthogonal directions. The $1/B$ periodicity of the oscillations could be expressed as a carrier density in
an analogous manner to SdH oscillations:

\[ n = \frac{e}{\pi \hbar} \Delta \left( \frac{1}{B} \right)^{-1} \quad (1.11) \]

The period of the oscillations was found to be dependent on both the 2DEG carrier density \( N \) and the modulation period set by the fringe separation \( a \). The data were in excellent agreement with the assumption that the period of the oscillations depended on a commensurability condition; the cyclotron orbit diameter being equal to an integer number of fringe periods:

\[ R_c = \frac{m^* v_f}{e} \frac{a}{B} = \frac{a}{2} \left( m + \phi \right) \quad (1.12) \]

where \( m \) was an integer and \( \phi \) a phase factor found to equal 0.17 ± 0.06 for maxima in \( \rho_{\perp} \) and 0.25 ± 0.06 for minima. The first theoretical treatment to be developed was that by Beenakker [18], who explained the effect as a classical resonance between the periodic cyclotron orbit motion and the oscillating \( E \times B \) drift of the orbit centre induced by the potential grating. Whilst this theory was sufficient to understand the \( \rho_{xx} \) oscillations it offered no explanation for those observed in \( \rho_{xy} \) and also failed to predict correctly the transition to SdH oscillations at larger \( B \). A fuller treatment which overcame these two problems was offered by Vasilopoulos and Peeters [19], who produced a quantum mechanical theory in which the bandwidth of the modulation broadened Landau levels at the Fermi energy oscillates with magnetic field. This described correctly the form of both magnetoresistance oscillations as well as predicting the transition to SdH behaviour.

1.4 Quasi-1d channels

1.4.1 Conductance quantization

The quantization of conductance in a ballistic quasi-one dimensional channel was first demonstrated in 1988 by Wharem et al [20] and van Wees et al vanWees88a. Surface Schottky gates with a narrow gap were fabricated above a 2DEG. With the application of a negative voltage the 2DEG was depleted from beneath the gate leaving a fine conducting strip
between the gate fingers. When the applied voltage was made increasingly negative the low temperature conductance was found to jump by intervals of \(2e^2/h\), the unit of one dimensional conductance.

The split gate system has been one of the most versatile experimental tools used to probe low dimensional transport, with many interesting and novel effects following from this central result. Many comprehensive reviews are available (for a list see [21]).

1.4.2 Interacting electrons in 1D

Recently the study of transport in quasi-1D systems has turned to the possibility of observing many body effects in zero field. This is the result of both the ability of MBE to produce 2D electron gases of increasing purity, and improved understanding of ballistic resistance in real 1D systems. We here mention two experiments that have demonstrated possible many-body effects. Thomas et al [22, 23] studied the ballistic resistance of split gates defined in very high mobility quantum wells and heterojunctions. The authors found up to 27 ballistic conductance plateaux and measured the Landé g factor of each. An additional quasi-plateau at around \(0.7i2e^2/h\) (where \(i\) is the subband index) was found for the lowest three subbands. This feature has become known as the ‘0.7 structure’, and had been observed previously [22], but was interpreted as an impurity effect. Thomas et al found that in a parallel magnetic field the quasi plateaux moved smoothly to the spin split-half plateaus observed previously [24], leading the authors to claim that the zero field quasi-plateaux were evidence of spontaneous spin polarization of the 1D electron gas. The 0.7 structure is better defined at lower carrier densities [23], and becomes progressively weaker with decreasing temperature below around 1 K. The authors argued that the data was consistent with a spontaneous spin polarization of the quasi-1D electron gas brought about by the exchange interaction.

Another explanation was suggested by Kristensen et al [25], who subsequently studied the 0.7 structure in constrictions formed using a shallow etching technique described later in this thesis. They initially suggested that the quasi-plateau may be the result of scattering against an excitation localized in the constriction. They were able to extract an excitation energy from the development of the 0.7 structure with increasing temper-
Figure 1.7: 15 Quantized conductance plateaux measured as a function of gate voltage for a Schottky split-gate fabricated above a deep electron layer HEMT (Cavendish wafer T214). An excitation voltage of 10 μV was used at T=300 mK. Data are corrected for series resistance of 600 Ω, chosen to align the conductance plateaux with integer values of $2e^2/h$, constituting the ohmic contact and lead resistances. Inset: the device geometry, showing dimensions of the split gate gap.

ature; this excitation energy was found to be around 1 K. The excitation was proposed to be a 1D plasmon, with a gap in its dispersion relation, which was able to absorb preferentially electrons of one spin. Later the same authors proposed that the structure arose from scattering of elec-
trons against thermally activated Bosons in the constriction [26]. An 
alternative explanation has been proposed subsequently [27], which 
involve the rapid switching of the system between two metastable states, 
one of which is spin polarized. The conductance measured experimentally 
is then seen as a time weighted average of the two states.

Another possible observation of electron-electron interaction effects in 
a quasi 1D split gate system was found by Tarucha et al [28]. The authors 
studied quantum wires of length 2-10 \(\mu\)m and reported that the quan-
tized conductance of such gates was reduced at low temperatures. The 
monotonic decrease in the plateau value they associated with Coulomb 
interactions, using a theory developed by Ogata and Fukuyama [29]. This 
theory predicts enhanced backscattering of electrons in a 1D system in 
the presence of a weak random potential, causing a suppressed value of 
conductance. The data that has been presented so far can be criti-
cized for the appearance of transmission resonances superimposed on the 
plateaux [28]. Such structure is usually indicative of an impurity poten-
tial influencing transport in the channel which makes interpretation of 
this data problematic.

1.5 The Landauer/Büttiker equations

Both the low temperature magnetotransport in a 2DEG and the quanti-
tization of conductance in a quasi-1D system can be treated using the 
formalism introduced by Landau and Büttiker. This approach treats the 
zero temperature resistance of such systems as a transmission problem. 
The basic principle is to regard ohmic contacts as source/drain and the 
geometry in between as a barrier with some transmission co-efficient. 
In the case of a split-gate system the barrier’s transmission co-efficient 
is altered by the gate potential. For the case of a contact in which the 
transport is ballistic it can be shown that for a two terminal measurement 
[21]:

\[
G = \frac{2e^2}{h} \sum_{n=1}^{N} T_n
\]  

(1.13)

where \(N\) is the number of modes at the Fermi energy and \(T_n\) is the 
fraction of electrons transmitted from one side of the point contact to
the other. The treatment of carrier transport in terms of transmission is now the framework within which many of the results in mesoscopic physics are discussed.

1.6 Quantum dots and Coulomb charging

By trapping electrons in an electrostatically defined puddle it is possible to observe zero dimensional effects. This is typically achieved either by etching away the 2DEG around a pillar [30], or by squeezing a 2DEG from above using Schottky contacts in a variation of the split-gate technique [31]. The classical charging energy is usually much larger than the quantum mechanical level separation in devices of the latter type. A schematic of such a system is seen in figure 1.8. Schottky gates form potential barriers to the transmission of electrons from one side to the other. When the barriers are made larger than the Fermi energy, electrons may be trapped forming a charge reservoir capacitively coupled to both the leads and the surface contacts. We may calculate the capacitance of the dot using a simple classical formula assuming a circular dot shape [32]:

\[ C = \frac{\pi d^2 \varepsilon \varepsilon_0}{4l} \] (1.14)

where \( l \) is the depth of the 2DEG below the surface and \( d \) is the diameter of the isolated region. For typical device parameters this gives a capacitance of order \( 2 \times 10^{-16} \text{ F} \).

To add a charge \( Q \) to a capacitance \( C \) takes an energy \( E \) given by:

\[ E = \frac{1}{2} \frac{Q^2}{C} \] (1.15)

To add a single single electron from one reservoir therefore requires an energy of \( e^2/2C \), or around 1 meV for the capacitance stated above. This energy is referred to as the charging energy of the dot and for typical device parameters is an order of magnitude larger than the quantum mechanical level separation in the dot. To tunnel into the dot electrons at the Fermi energy in the source reservoir must therefore be at least \( e^2/2C \) above the lowest unoccupied energy level in the dot, and likewise to tunnel out the Fermi energy of electrons in the drain must be less than
$e^2/2C$. The situation where current flow is stopped due to the voltage difference across the dot being less than $e^2/C$ is referred to as Coulomb blockade.

![Diagram](image)

(a)

![Diagram](image)

(b)

Figure 1.8: (a) An arrangement of surface gates used to define a quantum box in a 2DEG (as used by Ford et al [33]). The minimum separation between the large gate from the three small gates is around 0.4 $\mu$m. The white gate acts a plunger, expelling electrons from the dot when the voltage applied to it is made more negative. (b) the potential profile for such a structure biased into the Coulomb blockade regime showing the Coulomb charging energy $E_{cb}$, the Fermi energy in the leads $E_f$ and the single particle energy $E_n$.

If a plunger gate (see figure 1.8) is ramped negative the system will alternately move through Coulomb blockaded and conducting states as single electrons are expelled from the centre of the dot. This gives rise to oscillations in the tunnelling conductance measured between source and
drain contacts.

We may expand the simple picture presented here to explain the appearance of Coulomb blockade due to impurities in a split gate system. An impurity potential may act to isolate a puddle of electrons in a similar manner to that induced by surface gates [34, 35]. Peaks appear in conductance as a function of applied gate voltage near pinch-off where the screening of the impurity potential by electrons in the constriction is no longer effective. As will be seen later, the avoidance of Coulomb blockade structure due to impurities is of particular importance to the work presented in this thesis, where impurity induced current peaks could mask other single electron effects.

1.7 Single electronics - electron pumps and turnstiles

The idea of confining electrons to three dimensions lead naturally to the possibility of moving them by a time dependent change in electrostatic confinement. Many of the original ideas in this field were originated by Thouless [36], who proposed the effect of quantized electron transport in systems subjected to a slowly varying external potential.

The emphasis of this work has been the opportunity that these techniques may afford the metrological community for a standard of electric current. While quantum standards of both resistance and voltage are maintained using the Quantum Hall Effect and Josephson Effect respectively no such quantum current standard has thus far been available. The requirements of a quantum current standard are a source of current which is accurate to better than 1 part in $10^8$, of at least nanoamps in magnitude.

An additional motivation is the interest which the Silicon microelectronics industry has in reducing circuit feature size. Since the logical conclusion of the advances in microchip manufacture is the movement of single electrons Coulomb blockade and correlated tunneling are likely to become increasingly relevant as feature sizes are reduced.

The starting point for modern experimental investigation in the field of single electronics was the pioneering work of both Fulton and Dolan [37], and Kuzmin and Likharev [38]. These authors made the first observa-
tions of single electron charging in tunnel junction devices. The first observations of time correlated single electron tunnelling were performed by Delsing et al in 1989 [39, 40] with arrays of Al/oxide/Al tunnel junctions. In these experiments the junction barrier transparency was periodically modulated using a microwave signal, which gave peaks in the dynamic resistance \( R_d = dV/dI \) at low enough temperatures \( \leq 50 \text{ mK} \). The position of the peaks coincided with values of current equal to \( e f \) and \( 2 e f \), where \( f \) was the frequency of the applied signal.

Geerlings et al [41] showed in the following year that current plateaux could be induced at \( I = n e f \) in a device which they termed an electron turnstile. This device used four tunnel junctions in a row, the gaps in between forming three islands for charge to reside. The central island was capacitively coupled to a gate voltage which could be modulated at radio frequencies, and under suitable bias conditions the device produced current plateaux with a height given by the applied frequency multiplied by the electron charge. The flatness of the plateaux degraded above about 40 MHz which limited the device to plateaux 2 pA high, flat within the experimental noise level of around 2.5%. The limitation in frequency response was attributed to \( RC \) charging times, which the authors calculated as constituting a probability to miss a cycle of about \( \exp(-1/10fRC) \), giving \( 10^{-5} \) at 50 MHz for this device.

In 1990 Niu gave a theoretical examination of the feasibility of a quantum pump [42], a device which was successfully demonstrated a year later by Urbina et al [43, 44]. The principle of operation of the pump is similar to that of the turnstile except that in the pump gates are made between every junction in the array. This allows for better control over device optimization. A detailed theoretical examination of the errors in pump devices was performed by Jensen and Martinis [45]. The three main errors identified were cotunneling, thermally assisted tunneling over the Coulomb barrier, and operating at too high a frequency. By 1994 the error rate of five junction pumps under optimum conditions had been reduced to 0.5 parts per million [46]. It should be noted, however, that the current produced by pump devices was not directly measured in these experiments since it was so low, instead a capacitor charged and the voltage monitored to determine the pumping accuracy. Owing to their high accuracy but low obtainable current the focus of research into pump devices has moved away from current standards towards their use in a
capacitance standard. If pumps can accurately transfer a known number of electrons to a capacitor the voltage developed can be measured to yield a precisely known capacitance. Recent results from seven junction pumps show an error per pumped electron of around $15 \times 10^{-9}$ [47, 48], which is very close to that required to be useful in metrological capacitance applications. Although very low, the error rates measured in pumps are higher than predicted by the standard theoretical treatments by many orders of magnitude. The most likely cause is a photon-assisted cotunneling process not included in the standard model [49, 50].

1.8 Random Telegraph Signals

The presence of imperfections in AlGaAs heterostructures leads to a form of resistance noise called Random Telegraph Signal (RTS) noise. This noise is caused by defect levels situated in some crucial part of the device. Electrons may, for example, follow a hopping route from gate to 2DEG by way of several localised defect states. In a split gate system the presence of RTS noise is seen as abrupt jumps in the channel conductance [51, 52]. Provided the time constant of jumps is larger than the bandwidth of the measurement then a series of quasi-characteristics are revealed, each corresponding to one electron configuration of the system. The presence of RTS structure in both conductance and acoustoelectric current constituted a parasitic noise for the purpose of the measurements presented here.
Chapter 2

Interaction of a SAW with low dimensional systems

2.1 Introduction

This chapter summarises prior work on the interaction of a surface acoustic wave with low dimensional semiconductor systems. A surface acoustic wave propagating on a piezoelectric material produces an electrostatic wave which travels with the deformation. When this wave interacts with a low dimensional system, such as a 2DEG, the properties of both may be altered. Two types of effect are typically studied. Firstly, the attenuation and velocity shift of the surface wave after interaction contain important information about the properties of the system. Measurement of these quantities probes the linear response of the 2DEG to the AC strain field and are proportional to the SAW amplitude. The second class of phenomena are acoustolectric effects. These concern a transfer of momentum from the surface wave to the electron system the outcome of which is an acoustoelectric current in a closed measurement circuit or a voltage in open circuit. These non linear quantities are proportional to the SAW intensity rather than the amplitude. The properties of the acoustoelectric current generated in low dimensional systems will be discussed from both theoretical and experimental viewpoints.

Commensurability oscillations at low magnetic fields are described for both electrons and Composite Fermions, and the discussion is then extended to higher fields. The interaction of a surface acoustic wave with an open quasi-1D system is described in detail in order to make
sense of experimental results presented later. The chapter concludes with a review of prior experimental work on quantized charge transport by surface acoustic waves and a summary of the questions which the remainder of the thesis is given over to study.

2.2 Rayleigh waves

2.3 Interaction of surface acoustic waves with 2D systems

2.4 Commensurability oscillations

2.4.1 Composite Fermions

One of the most interesting observations in a 2DES using a SAW was performed by Willet et al in 1993 [53]. The authors were able to demonstrate the presence of a Fermi surface at $\frac{1}{2}$ filling factor of the lowest Landau level by the geometrical resonance of composite Fermions with the surface acoustic wavelength. The velocity shift of the SAW was monitored as a function of perpendicular magnetic field applied to a 2DEG placed in-between SAW transducers. Oscillations developed for SAWs of high enough frequency (up to around 9 GHz), which were symmetric about $B(\nu = \frac{1}{2})$. These oscillations were attributed to the interaction of Composite Fermions with the SAW field. The oscillations were periodic in the reciprocal of an effective magnetic field $\Delta B = B - B(\nu = \frac{1}{2})$.

2.4.2 Electrons

The electron equivalent of the composite Fermion commensurability oscillations were not observed by Willet et al because the velocity shift method is insensitive at high conductivities [53]. Commensurability oscillations were, however, observed by Shilton et al [54, 55]. These experiments used a continuously applied SAW to induce an acoustoelectric current in a 2DEG. In the presence of a magnetic field the SAW induced current was modulated in an oscillatory manner similar to that measured for SAW attenuation by composite Fermions. The reason for the
increased sensitivity of the acoustoelectric method relative to the velocity shift technique is that in the latter case the observation of electron oscillations requires a small change in a large quantity to be detected, while in the former case the small quantity itself (the SAW induced current) is detected. No full theory of the modulation of acoustoelectric current by a small magnetic field has been given for electrons, while the case of Composite Fermions has attracted much interest. It is interesting to draw comparisons with the Weiss oscillations \cite{15} described in the previous chapter. To observe Weiss oscillations the resistivity components of a periodically modulated 2DEG are monitored as a function of (low) magnetic field. The similarity between the cyclotron diameter and the periodicity imposed on the 2DEG leads to oscillations in the resistivity which can largely be described using the picture of guiding centre drift resonance introduced by Beenakker \cite{18}.

\section{SAW induced electron transport in open 1-D channels}

The first measurements of acoustoelectrically driven current through a point contact were performed by Shilton \textit{et al} \cite{56}. The acoustoelectric current induced by a SAW was found to oscillate as a function of gate voltage, the maxima of the oscillations coinciding with the steps in-between conductance plateaux. A semi-quantitative explanation for the oscillations was given using the idea of velocity matching between the SAW and slow electrons in the uppermost 1-D subband of the channel (see figure 2.1)

A derivation by Galperin in the same reference gave an expression for the acoustoelectric current which oscillated as the number of occupied 1D subbands in the channel changed. In this picture only electrons at the Fermi energy with velocities close to the sound velocity could take part in the acoustoelectric current. The physical reason for the latter was given by considering the ‘effective interaction time’ \( \tau \) during which electrons with a given velocity move in an almost constant SAW field. This was given as \((qv - \omega)^{-1}\), where \( q \) is the SAW wavevector, \( v \) the electron velocity and \( \omega \) the SAW frequency. Near a resonance in current \( v = \omega/q \) so that the interaction time diverges. Electrons which are not near the
SAW/SAW interactions

Figure 2.1: Schematic diagram of the SAW and electron velocities in a 1D channel after ref. [56].

SAW velocities are unable to interact strongly with the SAW because of the small value of \( \tau \). Peaks in current appear at gate voltages corresponding to the steps in conductance because at these voltages the Fermi velocity is close to the SAW velocity. A fuller treatment along these lines was developed by Totland and Galperin in subsequent work [57] which emphasised the role of relaxation mechanisms, in particular elastic scattering within the channel and escape from the channel due to finite length. The main conclusion was that to obtain an effective SAW/electron coupling both
the electron velocity and the scattering rate must be small. A separate theoretical treatment of the acoustoelectric current in an open quantum channel was given by Gurevich [58]. This developed a quantum theory for a perfect, uniform channel using an analysis of the energy and momentum conservation laws. Giant oscillations of the current as a function of gate voltage were predicted, along with an abrupt variation of the acoustoelectric current as a function of SAW frequency at $\omega_q = 2m\omega^2/h$. For $\omega < \omega_q$ the authors predicted that an acoustoelectric current could not be generated in ballistic nanostructures. The physical reason for this was that the conservation laws forbid backscattering due to the SAW below this frequency and it should therefore be impossible to induce an acoustoelectric current. In the GaAs/AlGaAs system this frequency corresponds to 1.4 GHz, and in the work of ref. [56] a finite acoustoelectric current was measured with SAWs well below this frequency (around 900 MHz). Although some ballistic structure was found in this device, not all of the conductance plateaux were clear. Ragged structure was clearly observed in the conductance plots for the lowest few subbands presumably due to some impurity influencing transport in this regime of poor screening. It is therefore unclear as to whether this data actually contradicts theory due to Gurevich et al, which was developed solely for the case of a perfect uniform ballistic conductor.

Later theoretical work by Bo, Maao and Galerin [59, 60] attempted to reconcile the observation of a finite current with the quantum theory by allowing for two processes in the channel not previously considered; acoustically induced transitions between propagating and reflecting modes near the channel edges and short range impurity scattering within the channel. The authors found within a quantum mechanical treatment that the latter leads to a smearing of the conservation laws brought about by an electron level broadening. The presence of a finite acoustoelectric current below the expected frequency cutoff was therefore seen as an impurity induced effect. This treatment deliberately neglected the case of a very few number of impurity centres dominating transport in a small mesoscopic device, the result of which would be effectively a modification of the uniform channel geometry which was an assumption of the model. Nevertheless, the authors did demonstrate that the acoustoelectric current in an open 1-d channel should be very sensitive to scattering from random impurity centres in the quasi-1D channel. The main reason for
this is the low electron velocity of electrons participating in the current, which leads directly to a reduction in the mean free path from that of the bulk. In this picture the only way to observe the frequency cutoff would be to look at extremely short and clean 1D channels where the effect of the short range impurity potential would be negligible.

2.5.1 Coupling in the 2D-1D transition region

In addition to the oscillatory picture of acoustoelectric current arising from a SAW/electron interaction within the quantum channel the role of a finite coupling in the leads of a quantum channel has been discussed theoretically [61]. Kozub et al [61] showed that a coupling of the electron system to a 'phonon wind' in the leads of a 1D device should give rise a current through the channel proportional to the device conductance. The reason for the absence of current steps from the data of refs.[56, 62] can be appreciated from a screening argument. If the transition between 2D and 1D regions occurs in an abrupt way then the SAW potential in the device leads will be efficiently screened. If the transition occurs on over a large distance relative to the SAW wavelength we should find that a larger coupling in the device leads will be present and that the conductance quantized acoustoelectric current will dominate over the oscillations caused by interaction of the SAW with electrons within the channel. A possible observation of such a situation is demonstrated later.

2.6 SAW induced transport in closed 1-D channels

In 1996 Shilton et al extended their prior work on open 1-D channel systems to the case of a closed (pinched-off) channel. In two devices a quantized acoustoelectric current was found in an interval of gate voltage more negative than conductance pinch-off [63, 64]. The quantized current was found to occur in units of $e f$ where $e$ is the electron charge and $f$ the frequency of the surface acoustic wave. The first device in which quantization was found showed one weak plateau near $I = e f$ measured with an accuracy of 1%. A second device showed 4 clear plateaux, and the authors were able to demonstrate that the centre of the first quan-
tized plateau was within around 0.3% of the expected quantized value $ef$. The first plateau in each device showed a finite slope, but detailed observations were hampered by an RTS noise signal. Several further observations which were made prior to the start of the present work are important to mention at this stage. Firstly, the plateau of the second device were stable over ranges of microwave power, interspersed with intervals over which the quantization degraded and the RTS noise signal was found to worsen. Secondly moving the quasi-1D channel around using differential voltages applied to the split gate fingers left the plateaux largely unaffected. For both devices the quantization gradually degraded above 1.2 K, with plateaux slope increasing. One device also dramatically worsened below this temperature. The application of a source/drain bias to the channel when in the quantized regime was found to have a rather different effect on the two devices. The first device was affected by a bias as low as 1 mV, with the quantized plateau moving below the $ef$ value for one bias direction. The second device was more robust with 10 mV being needed to change the plateaux dramatically. Another important observation was that the plateaux of the first device were only visible on one cooldown of the device. Both prior (by Dr J. Shilton) and subsequent (by the author) cooldowns of this device showed no quantization, with impurity induced features clearly visible in the data. It was therefore not possible to say conclusively whether impurity effects were important for the observation of quantized acoustoelectric plateaux. The model which the authors used to qualitatively discuss the acoustoelectric current quantization was as follows; a schematic diagram is shown in figure 2.2. In the pinched-off regime the source and drain either side of the split-gate are separated by a saddle-point potential, the channel centre being at a higher potential than the Fermi energy in the 2D regions. The application of a SAW to the system results in a sinusoidal modulation of this potential landscape which travels at the SAW velocity. If this modulation is of sufficient amplitude then electrons will be transported across the barrier by the SAW. Under certain conditions the transport will be quantized. The reason for this is the Coulomb interaction between electrons in each minima, which opens up energy gaps between the states containing different numbers of electrons. The system can be thought of as a chain of moving quantum dots which form at the entrance to the constriction and then move along the channel of the split gate before
being deposited in the 2DEG on the far side of the gate. The current measured between the entrance and exit is quantized as a function of gate voltage since changing the static potential due to the gate will alter the dimensions of the quantum dots forming in the entrance to the constriction. For just one electron to be transported the energy of the second bound state must become higher than the SAW barrier behind it.
to allow it to escape.

This simple picture has acted as a starting point for some of the theoretical investigations of this system which will be discussed later. The importance of the observations can be understood in the context of the discussion of quantized current contained in the previous chapter. The crucial point is the operational frequency of the devices (near 3 GHz), some three orders of magnitude higher than that of the electrons pumps and turnstiles; such currents are high enough for metrological applications. This technique therefore represents a possible route towards a current standard. The system is also interesting as an example of an adiabatic quantum pump, such as that discussed by Thouless [36] and Niu [42]. Such a system has not been experimentally realized before, and is therefore of fundamental interest.

2.7 Open questions in quantized acouto-electric transport

Two major experimental difficulties had to be overcome at the beginning of the present work before progress could be made, and they are summarised below.

1) Reproducibility; A quantized current had been found in only two out of the tens of devices measured. Ways had to be found to improve the device fabrication and testing procedure to enable a systematic study of the quantization. The details of how this was accomplished are given in the following chapter.

2) RTS noise; The initial measurements showed a heavy RTS noise signal which strongly effected observations of the effect. It was unclear whether the RTS noise was in some way intrinsic to the quantization or whether it could be reduced or removed. A SAW current pump with fast random fluctuations would be of limited use either in the practical realization of a current standard or for a detailed investigation of the physics of the single electron transport process.

The most important questions to be answered after dealing with these problems were as follows:

1) Accuracy. If noise problems could be overcome, what would be the accuracy of the SAW induced quantization.
2) Could higher plateaux be observed and utilized for current standard applications?

3) What was the frequency, temperature dependence, source-drain bias and power dependence of such devices? What was the relationship between these parameters and could they be controlled?

4) What was the effect of a magnetic field applied to the system?

5) How did changes to the device geometry affect the quantization?

It is these questions which provided the starting point for the experimental work described in chapters 5-7 of the present thesis.
Chapter 3

Processing and measurement of SAW devices

This chapter sets out the processing techniques used in the fabrication of surface acoustic wave devices for this work. The fabrication of high frequency transducers with a split-gate presents a set of problems unique to this project, though several of the steps are standard techniques in GaAs processing. All of the work described in this thesis required the production and propagation of a powerful surface acoustic wave across a wafer surface. This necessitates a particularly careful processing regime, and the steps taken to achieve this are highlighted. The techniques used in the assessment of devices and selection of those for detailed study is then presented.

3.1 Device design

The basic design of the optical maskset used in this work was carried out by Dr. Valery Tayanskii and Dr. Julian Shilton in 1996, details of which can be found in ref. [62]. In 1998 a new mask set was designed and fabricated by the author, which incorporated several improvements and additions to this design. Surface acoustic waves are generated from transducers situated either side of a mesa containing a 2DEG. On the mesa are either six Schottky gate contacts, allowing the manufacture of three independent split gates, or an etched constriction. The most important aspect of the design is the shielding of the d.c. portion of
the chip from r.f. fields originating at the transducers. Rectification of this signal by the d.c. portion of the circuit leads to a cross-talk signal. The isolation is achieved firstly by placing transducer contacts well away (3 mm) from the mesa, and then by the use of a dielectric screen over the gate contacts, capacitively coupled to ground. The chip itself is held within an aluminum package, as described later. After solder connections have been made between transducer contacts and co-axial wires copper screens are placed over the r.f. contacts for further shielding. By this stage the chip is contained within a cavity of dimensions much smaller (≤ 5 mm) than the wavelength of microwave propagation in air for the frequencies studied (near 10 cm). All these factors allow the SAW devices measured in this work to operate in continuous wave mode, without needing a pulsed technique to separate the acoustoelectric signal from crosstalk.

3.2 Optical processing

The first stage of device fabrication is wafer growth. For the majority of work presented in this thesis wafers were selected from the supply available at the Cavendish Laboratory MBE facility, and were grown by either Dr. Dave Ritchie or Dr. Michelle Simmons. Heterojunctions with a 2D layer 1000 Å below the surface were mainly used for the closed channel work where it was important to obtain a large SAW potential and high acoustoelectric currents. Work on clean 1-d channels used deeper HEMTs with the 2DEG typically at 3000 Å. 2D dark mobilities were in the range 0.7 to 1.5 × 10^6 cm^2V^{-1}s^{-1} with carrier concentrations from 1.7 to 2.7 × 10^{11} cm^{-2}. An important criterion in the selection of wafer is that of surface morphology. High defect densities and surface roughness are expected to affect the strength of surface acoustic waves propagating across wafer surfaces. Surface roughness is parameterized by the use of an Atomic Force Microscope (AFM) operating in tapping mode. Wafers with high defect density are avoided since they cause problems with transducer fabrication later in the process.

Sections of wafer are cleaved into chips using a diamond scribe. The majority of devices produced are 2 mm × 8 mm, with six defined on the same chip. During scribing care is taken to orientate the wafer so that SAWs will be generated in the [110] crystallographic direction to take
advantage of the enhanced acoustoelectric coupling along this axis. In order to isolate a region of 2DEG and create a mesa wet etching is used. A 1.2 µm layer of Shipley Microposit 1830 resist is spun onto the cleaved wafer, which is then hardened on a hotplate for ten minutes at 115º C. A mask aligner is used to bring the covered wafer segments into direct contact with a chrome-on-glass mask before exposing the pattern using an ultraviolet lamp. The positive resist is developed away in those areas exposed by the mask. The exposed wafer surface is then etched using a dilute sulphuric acid/hydrogen peroxide mixture of composition 1:8:125 (by volume) H₂SO₄/H₂O₂/H₂O. The etch-rate which this composition gives is around 10 nm s⁻¹. The thickness of the mesa defined during the etch is determined using a standard commercial Dektak instrument.

The following three stages require the use of a ‘lift-off’ procedure. Photo-resist is patterned to form a shadow mask for material evaporated onto the surface of the chip. The resist is then stripped leaving a pattern as shown in figure 3.1. Shipley 1830 resist is used for each of these patterning stages, with exposure again performed using an ultraviolet mask aligner. Material is evaporated onto the patterned substrate using Edwards evaporators at a background pressure of around 1x10⁻⁶ mbar. Ceramic boats are heated to provide a thermal flux of metal onto the regions of substrate exposed through the resist pattern. A crystal gauge determines the thickness of metal deposited during evaporation, and a manual shutter is used to cut off the source when the desired thickness has been reached.

To contact the 2D gas at the heterojunction interface ohmic contacts are defined in the mesa. To give a good resist undercut after development samples are soaked in chlorobenzene for 5 minutes prior to developing. This has the effect of hardening the upper layer of the resist and improves the undercut of the resist profile. After developing the pattern 100 nm of a Au/Ge/Ni alloy is then deposited by evaporation and the chips annealed at a temperature of 480 ºC for 3 minutes. Split gates and transducers are made in two stages. An optical lift-off procedure is first used to deposit a 20/80 nm thickness of NiCr/Au. Finer features are formed later using electron beam lithography. Of particular importance during the optical procedure is the need to maintain an undercut resist profile during patterning. If this due not happen a wall of optical material can be formed at the edge of the pattern which will shear through any
overlying material deposited later. This is shown in figure 3.2. To optimise the profile constant attention must be paid to the concentration (and therefore age) of the chlorobenzene and resist used, adjusting the processing conditions if these factors change.

The final stage of optical processing again uses the lift-off procedure, this time to form an isolating screen above the gate material. In the evaporation 300 nm of GeₓO is used, followed by a 20 nm layer of gold (x is a value between 1 and 2 representing the non-stoichiometric nature of the compound).

3.3 Ebeam processing

The principle behind electron beam lithography of metal features is similar to that used in the optical lift-off procedure, a patterned resist being
from the linkpads. The latter allowed more latitude in the exposure but tried to improve transducer yield including the use of bi-layer resists and a two stage process fabricating transducer fingers in a separate stage from the link pads. The latter allowed more latitude in the exposure but
was eventually abandoned as a high enough yield of 1 μm interdigital pitch transducers could be fabricated in a single stage process. Using a
high beam current of 100 pA with a single 180 nm layer of P5 resist the present yield is around 80%. Devices are developed in a methyl isobutyl ketone : IPA (1:3 by volume) mixture typically for around 10 seconds. A series of progressively dosed boxes were drawn at the same time as transducers to act as a guide for developing the exposed pattern. This reduced variations in finger width caused by changes in dose and developer concentration or temperature between processing runs. Split Schottky gates were fabricated using standard e-beam techniques discussed at length in many of the thesis available from our group. Particular care was taken to obtain a smooth profile edge along the channel.

Some of the etched gates discussed in this thesis were fabricated by Dr. A. Kristensen using a JEOL microscope at the Niels Bohr Institute in Copenhagen. After a 5 minute pre-bake at 180°C a 4% solution of PMMA is spun at 6000 rpm for 60 seconds to give a thickness of around 150 nm. The resist is baked for 5 minutes at 180°C before exposure. Care is taken during the drawing procedure not to expose the central gate region to the electron beam, the correct drawing field is found by relative positioning of the SEM stage from known marks on the sample. An accelerating voltage of 30 kV with a beam current of around 50 pA is used in drawing the gate. The pattern is developed in an MIBK/IPA (1:3 by volume) mixture for 60 seconds. After rinsing in IPA and inspection of the developed pattern the channel is etched using H₃PO₄ : H₂O₂ : H₂O (1:1:38 by volume) which gives an etch rate of around 50-60 nm per minute. The time is adjusted to ensure that the etch goes below the depth of the dopant layer. A typical gate etched using this process is shown in figure 3.4.

### 3.4 Scribing and fixing

After optical and e-beam processing is complete wafer segments are cleaved into individual chips using a diamond scribe. They are then fixed into purpose built chip carriers using spots of silver dag and GE varnish. GE varnish acts as a glue and silver dag reduces crosstalk. Several different designs of chip carrier have been used. The design of each was based around the need to ensure both isolation of the d.c. contacts from airborne r.f. fields and easy transfer between the four cryostats used. Later designs allow more d.c. contacts to be made to the mesa
whilst offering better isolation from crosstalk.

3.5 Bonding

After devices are mounted connections are made from the chip to the carrier using a thermosonic ball bonder. The chip package is placed on the heated stage of this machine, above which a metal arm holding a ceramic capillary is situated. A thin gold fibre is threaded through this capillary. The idea is to make a link between the d.c. contact pads on the mesa and an array of gold contact pads on the chip package using this wire.

First the arm of the bonder is brought down onto the mesa’s gold bond pad. An ultrasonic discharge melts the end of the gold thread forming a link to the contact pad. The arm is then moved to the contact pad on the chip package and lowered again. Compression and a second discharge forms this bond before the gold wire is snapped by a second arm moving into the thread. An electrostatic discharge between the second arm and the end of the gold wire forms a ball at the end of the gold thread ready
for the next bond. In the early stages of this project the ball bonder was the source of many damaged split gates, whose small capacitance rendered them particularly susceptible to electrostatic discharge.

Connecting all D.C. contacts together on the chip package before bonding reduced the possibility of damage due to differences in voltage across the arms of a split gate. Bonding all ohmic contacts before gates removed the need for any electrostatic discharges after bonding the split-gates. If several gates were present all split gate arms on one side of a device were bonded before the other side, leaving at least 2 minutes between each arm. This reduced the possibility of damage due to discharge, possibly from surface states holding charge after a bond. In addition the sparking unit was always switched off before making a bond. The electrostatic discharge that forms a ball may have been responsible for some split-gate damage, so care was taken to only make a ball when the devices were well away from the arm assembly. After employing all of these safety features the rate of device destruction on the bonder fell from around 1 in 3 to a negligible rate.

3.6 Attaching to probes

Next the chip packages are mounted on a copper mounting where microwave connections are made to copper co-axial lines using low temperature SMA microwave connectors. D.C. contacts are soldered to twisted pairs. The rigidity of our low temperature microwave co-axial lines necessitates different assemblies for perpendicular and parallel field experiments. A diagram of the two types of mounting is shown in Figure 3.5

After soldering r.f. contacts copper screens are placed over the co-axial lines and screwed down. The idea is to form a cavity for the samples whose dimensions are small relative to the wavelength of applied r.f. signal in free space. This reduces any airborne r.f. signal that could be rectified by the d.c. wires leading to spurious cross-talk induced signals. Once screwed into a copper mounting samples are not removed until complete characterization has taken place. They are transferred between cryostats in the same disk without demounting. This was found to ensure repeatability in the sensitive microwave measurements. Prior to the adoption of this method problems were found when cross talk suppression changed
between mounting configurations. Lastly the copper mounts containing the sample are attached to a cryostat for measurement. Microwave connections are made using low temperature SMA connectors throughout. D.C. wires are taken from the disks in twisted pairs to terminate at room temperature in standard BNC connectors.

### 3.7 Measurement techniques

The most common measurements performed in the course of this work have been conductance and acoustoelectric current measurements. A two terminal conductance measurement is typically performed at a constant excitation voltage, chosen to be low enough to avoid electron heating by the current produced. Typical values are between 10 and 100 μV. An oscillator is used to provide both the excitation voltage (and division) and a reference signal for a lock-in amplifier. The majority of conductance measurements have been performed using a EG+G lock-in amplifier which has an internal pre-amp outputting 10^6 V/A. Between sample ohmic contacts and the pre-amp input a D.C. blocking capacitor is used to prevent the (≤1 mV) pre-amp burden voltage from producing spurious currents. Typical lock-in measurement frequencies are around 80 Hz chosen to avoid mains pickup. The analogue voltage output of the lock-in is read with a CIL microsystems analogue-to-digital converter (ADC), and recorded using an Acorn Archimedes computer running software written in-house by Dr. C. Ford. Gates are controlled by this software through a Iotech digital-to-analogue converter (DAC). Microwave filters are used to reduce high frequency noise. The resolution of the gate voltage (normally 0.25 mV up to 1 V) is improved using a voltage dividing arrangement of resistors. Leakage currents are monitored when necessary using a Keithley Source/Measure unit, which simultaneously outputs voltage and measures induced current. Acoustoelectric current measurements are performed across a 2DEG in several ways. Firstly, a lock-in amplifier can be used by pulse modulating the microwave signal. This technique is useful in measurements where the burden voltage of a D.C. setup can influence results; in measurement on open 1-d channels for example. The disadvantage is usually a loss of accuracy and increased noise relative to a d.c. setup, and the latter are therefore preferred in acoustoelectric current quantization experiments. A Stanford Research
systems SR530 low-noise current preamplifier or a Keithley SMU have both proved to be useful. The Stanford instrument can operate for 15 hours on its internal batteries, a facility used extensively in the sensitive assessment of current steps.

3.8 Initial assessment

The initial assessment of a device is carried out in a He dewar. Measurements of microwave transmittance are made across the delay line formed by the two transducers on either side of a device. A peak in transmittance appears as a sample is cooled. On hitting liquid’s surface SAWs are immediately damped and a sudden drop in transmittance is observed. The probe is then raised slightly to allow a measurement of acoustoelectric current or lowered further to ensure that the temperature is as low as possible for conductance measurements. At this stage ohmic contacts are checked for good $\leq 2\,\text{k}\Omega$ contact resistance and gates are swept individually to check for leakage with a SMU. Next two terminal conductance measurements are performed to observe ballistic 1-d plateaus in the constriction. In some devices several plateaus in the conductance can be observed at 4 K. The other important assessment at this stage is to check for any RTS structure. Wafers that consistently show RTS structure in gate characterization are avoided. Next acoustoelectric current is measured for each transducer. If the device has two transducers the approximate centre frequency can be deduced from the earlier transmittance measurement and used as a starting point to find the peak in current from either transducer alone. Very low current levels are observed before gate definition so a voltage of $-0.3\,\text{V}$ is generally applied to the gates to allow current to be induced between ohmic contacts on either side of the gate. After finding the peak in current at the centre of the passband of each transducer the magnitude of the current is then measured as a function of gate voltage for several microwave powers. This measures the transducer efficiency at producing current both in open channel and, when applicable, beyond conductance pinch-off. The process is repeated for each gate on a chip.
3.9 Cryostat transfer

After testing a device at 4.2 K to ensure that transducers, gates and ohmic contacts are all working correctly devices are transferred on their copper disk to one of three systems: a top loading $^3$He cryostat, a 1.2 K glass cryostat or a $^3$He/$^4$He dilution refrigerator. Care is taken to avoid electrostatic damage to the gates whilst remounting. During soldering devices the soldering iron, user, probe, copper disk and tweezers are all grounded. After cooling to 1.2 K the checks detailed above are repeated to ensure that no change has occurred since dipping. Detailed measurements can then begin.

3.10 Low temperature techniques

The majority of the measurements contained in this thesis were performed using a single-shot Oxford $^3$He cryostat with sliding seal insert. This system uses $^3$He to cool samples to around 300 mK. The cost of $^3$He is such that it must be recycled in the cryostat. A schematic diagram of the system is shown in figure 3.7. To cool the sample space below 4.2 K $^4$He is bled from the main bath into the 1 K pot and pumped to reduce its boiling point to 1.2 K. The charcoal sorb is heated at the same time to evaporate the few ccs of $^3$He which it contains. This condenses on the 1 K pot and runs down into the sample space. When all the $^3$He has condensed the sorb is cooled by turning off its heater. This reduces the vapour pressure above the liquid $^3$He and the sample temperature drops to around 300 mk. Hold time at base temperature largely depends on the heat load in the sample space, several hours being typical for the majority of microwave experiments described here. When the $^3$He charge has fully evaporated it must be recycled by heating the sorb before recooling. The probe uses a sliding seal arrangement with vacuum lock to allow sample changeover is a matter of around 6 hours. Copper co-axial transmission lines were used to connect microwave fittings in the sample space to the room temperature microwave source.
Figure 3.5: Schematic of the bonding configuration (a) and 2 types of mounting used to orientate the magnetic field (b) perpendicular and (c) parallel to the 1D channel. Misorientation of samples due to the fixed co-axial lines is limited to around ±5 degrees. D.C. connections were made from the contacts shown in (a) to small PCB's on the rear side of the copper mounts (not shown) and then along the length of the cryostat probe in twisted pairs.
Figure 3.6: The experimental setup used to perform low-noise measurements of device conductance at 300mK. For acoustoelectric current measurements in closed channel a D.C. low noise current preamplifier was used in place of the lock-in and signal generator.
CHAPTER: 3 PROCESSING AND MEASUREMENT

—

innervacuumchamber_

sorb
at 40K  at 4K

pumped liqued
4He in 1K pot

diagramoftheprocessusedtocoolsamples to 300 mK
inthe top loading $^3$He cryostat, after ref [65].
Chapter 4

SAW transport in open 1D systems

4.1 Introduction

A surface acoustic wave traveling over a GaAs/AlGaAs heterostructure may induce a d.c. current through a quasi-one dimensional channel defined within it. Experimental results are presented from two types of device. The first are rectangular Schottky split gates fabricated above a deep HEMT, the second semicircular constrictions formed using a shallow etching technique. For the former devices clear oscillatory behavior are found as a function of gate voltage for all subbands in the constrictions. In the latter the acoustoelectric current resembles the device conductance. The observations demonstrate the importance of point contact geometry in determining the form of the measured acoustoelectric current and are discussed within the theoretical frameworks which have been developed recently.

4.2 Summary of prior work

To the author’s knowledge the only observations of an acoustoelectrically driven d.c. current in a quasi-1D system prior to the present work were performed by Shilton et al in 1996 [56, 62] who found an oscillatory acoustoelectric current as a function of gate voltage for some subbands in a quasi-1D constriction. The data were affected by the appearance of reso-
nances presumed to be caused by impurities in the channels measured. In particular the reduced screening at low subband occupancy meant that impurity effects dominated transport in the lowest few subbands, leading to unreplicable structure. The lowest subband was found to be particularly susceptible to impurity effects in the experiments of refs. [56, 62], which was unfortunate since other contemporaneous results had shown interesting effects in this regime of gate voltage [22].

For higher subbands the current was found to display oscillatory behavior as a function of gate voltage which was interpreted as being due to a matching of velocities between the SAW and slow electrons in the uppermost subband of the constriction. Prior theoretical work on the acoustoelectric effect in open 1-D quantum channels has been summarized in chapter 2.

4.3 Acoustoelectric current in deep HEMT layers

The manufacture of clean 1D systems has been an object of much interest in the semiconductor physics community since the first observations of transport in split-gate systems. Approaches have been adopted in to improve the number and flatness of conductance plateaux by reducing potential fluctuations in the constriction. One of the most successful techniques has been the use of deeper electron layers, where a large buffer layer is used to increase the separation between dopant atoms and the electron channel. This improves the quality of the channel and has allowed the observation of up to 26 1D subbands in devices formed using the split-gate technique [22].

The major drawback in the use of deep layer HEMTs for high frequency SAW work is the decay length of the SAW beneath the wafer surface, which is typically close to the SAW wavelength [66]. A lower acoustoelectric current is therefore expected in wafers with a deeper electron layer since the acoustoelectric current depends on SAW magnitude. In the results described in this chapter SAWs of around 1 μm wavelength were excited, and the depth of the electron layer was at most 0.3 μm. Wafer T353, used extensively in the present work, was grown with the matrix sequence shown in figure 4.1.
Figure 4.1: Cross sectional representation of Cavendish wafer T353 grown using the indicated matrix materials.

The depth of the 2DEG in this wafer is three times larger than that used in the work of ref. [63], and the low temperature mobility assessed from Hall bars made from the same material is $2.2 \times 10^{11}$ cm$^2$V$^{-1}$s$^{-1}$, nearly ten times higher. The improved quality of this wafer relative to that used in previous SAW investigations is evident from the numerous conductance plateaux observed in split gates made from this material. Six devices were measured, and the qualitative features of the acoustoelectric current were similar with the exception of pinch-off voltage, which fluctuated by around 1 V between nominally identical gates. The acoustoelectric current in the cleanest two constrictions (out of a total of 15 gates measured) judged by the number and flatness of the conductance plateaux will now be discussed.

In figure 4.2 the acoustoelectric current generated by transducers on either side of a split-gate is shown along with the delay line transmittance. This observation demonstrated the feasibility of using deep HEMTs for SAW work. The magnitude of the peaks in figure 4.2 is lower than that obtained in shallow (100 nm) HEMT structures by around 50% for similar power levels, and low current was a general feature of all of the
samples made from this wafer. The most likely explanation is the depth of the electron layer, though increased surface roughness due to growth conditions cannot be excluded. The position of the peak in figure 4.2 agrees to within 1% with that expected from the transducer period and
the SAW velocity on GaAs. The direction of induced current agrees with that expected for SAW transported electrons. The acoustoelectric origin of the peaks is also apparent in the damping of the resonance when the sample is immersed in liquid He and the lack of other resonances in the range D.C. to 5 GHz. Samples drawn by e-beam with nominally identical transducers produce resonant peaks with around 0.1% variation in observed centre frequency. Such a small difference can be explained by small variations in sample orientation during the writing procedure, as discussed in the previous chapter.

4.3.1 Acoustoelectric current in open channel

Figures 4.3 and 4.4 show the conductance and open channel acoustoelectric current as a function of gate voltage for two split gates on wafer T353. The gates were drawn with dimensions \( w=0.7 \mu m, l=0.7 \mu m \), yielding a channel length comparable to the SAW wavelength after taking into account depletion fields. The conductance is well behaved, with up to 19 plateaux observable. The subtraction of a constant series resistance is found to align the conductance plateaux to within 1% of \( 2e^2/h \). The sub-band separation of the lowest two subbands in the two gates was found to be 1 and 2 meV for samples T353a and T353b respectively using the standard technique of applying a sufficient source-drain bias to obtain half-plateaux [67].

The main features of the acoustoelectric current are now discussed. Clear oscillatory structure is found for all subbands in the constrictions. The position of minima in acoustoelectric current coincides with the centre of the conductance steps. No irreproducible structure is observed for the lower subbands, in contrast to ref. [63]. The oscillatory structure is maintained over a wide range of microwave power, from the lowest level at which an acoustoelectric current was measured (-15 dBm and -18 dBm in samples a and b respectively) up to the range in which the conductance started to smear (above 5 dBm) as described below. Of particular relevance to the data described later in this chapter is the observation that the oscillations show no plateaux in-between maxima. A rising background current is observed, the origin of which is unclear. It is possible that this current represents a semi-quantized contribution from the device leads since it appears to roughly proportional to the de-
Figure 4.3: (a) Conductance of Schottky gated device T353a measured using a 10 μV excitation voltage in a two-terminal configuration. T=300 mK. The data are corrected for a 900 Ω series resistance, comprised of the ohmic contact and 2D lead resistances, chosen to align the plateaux to $2e^2/h$. (b) Acoutoelastic current measured through the constriction. Microwaves were applied at a source power of -5 dBm at a frequency of 2.693 GHz, the latter coinciding with the peak in the transducer response.
Figure 4.4: Data taken in a similar manner to the previous figure for a second sample T353b. (a) Conductance of device measured using a 10 μV excitation voltage in a two-terminal configuration. T=300 mK. The data are corrected for a 600 Ω series resistance, comprised of the ohmic contact and 2D lead resistances, chosen to align the plateaux to 2e²/h. (b) Acoustoelectric current measured through the constriction. Microwaves were applied at a source power of -5 dBm and a frequency of 2.682 GHz, the latter coinciding with the peak in the transducer response.

vice conductance. Against this argument is the fact that the minima of the oscillations do not monotonically increase as a function of opening
the channel, as shown in figure 4.3. Much better evidence for an open channel current quantized in a similar manner to the conductance will be given later. It is interesting to discuss the amplitude of the acoustoelectric current oscillations as a function of gate voltage, since in prior work the amplitude of the oscillations has been dominated by impurity effects. The amplitude of the oscillations is seen to decrease as the channel is opened. The most likely explanation for this behaviour is simply the reduced subband spacing for the higher subbands. Note that the conductance is smoothed for higher subbands in a similar manner.

4.3.2 Exclusion of cross-talk as a possible mechanism of influence

The parasitic rectification of microwave signals by the gate contacts is a process which was important to suppress for the purpose of the measurements contained in this thesis. Details of the mask design used to achieve this aim have been given in the previous chapter.

In ref. [63] a large cross-talk signal meant that the simultaneous action of cross-talk and SAW signals could not be excluded from the data. In particular the acoustoelectric current was found to oscillate sharply as a function of frequency within the transducer passband. The modulation period as a function of frequency agreed with that expected from interference between the SAW signal and direct line-of sight r.f. pickup by the gate. The size of this oscillation constituted a large proportion of the signal and it was therefore unclear to what extent the oscillations as a function of gate voltage could be attributed to cross-talk. This point was acknowledged in ref. [63]. For all samples measured in the present chapter no discernible change in the gate voltage position of features in open-channel acoustoelectric current was found over the transducer passband. A typical set of traces for sample T353a is shown in figure 4.5.

Such data can be used to exclude cross-talk from the mechanism which is responsible for the oscillations as a function of gate voltage. Two pieces of evidence are used to support this claim. Firstly, the cross-talk contribution was found to be at most 25% of the total signal for device T353a and T353b, this figure being the change in the measured current over one cross-talk induced 1.4 MHz oscillation near the centre of the transducer passband. This change in current over the oscillation

56
Figure 4.5: Data taken over a range of frequencies near the centre of the transducer passband. (a) The current as a function of gate voltage, subsequent traces offset by 45 pA. The value of current beyond pinch-off is used to indicate the source frequency on the y axis. (b) The gate voltage positions of minima in acoustoelectric current oscillations for the same data as in (a). The positions of the oscillations are independent of the cross-talk signal. Sample is T353b, T = 300mK.

period is up to four times smaller than that observed as a function of gate voltage. Secondly, alterations in frequency do not affect the gate voltages at which the extrema in the oscillations occur. This is shown in figure 4.5 (b). Because of these two points it is reasonable to neglect cross-talk as a mechanism responsible for the oscillations as a function of gate voltage.
4.3.3 Acoustoconductive loss of clean quantum channels

Another measurement which gives information concerning the interaction of the SAW with the electrons in a 1-D system is the acoustoconductance. This is the contribution to the conductance which is due to interaction between phonons and the charge carriers.

At SAW powers well above that those shown in figures 4.3 and 4.4 the conductance plateaux are found to smear appreciably. This is shown in figure 4.6. Tuning the applied microwave frequency to outside of the transducer passband removes the smearing effect. From this we may exclude direct local heating of the sample by microwave power as a process responsible for the smearing effect, though the possibility of the SAW itself inducing heating in the sample cannot be excluded by this measurement. A separate way of looking for possible heating effects is to monitor the 2D SdH amplitude as a function of SAW power. No change in the SdH amplitude was found over the range of microwave powers applied. A possible explanation for the observations can be made in the context of a smearing process whereby the 1-D subband structure is affected by the action of the powerful SAW. Intuitively one might expect such perturbation to become apparent when the amplitude of the SAW is comparable to the subband spacing. The subband spacing of the first two subbands in these samples was found to be 1±0.1 meV using the method of Patel et al [67]. The transmittance of the delay line formed by both transducers showed a peak of near -60 dB at the middle of the passband. Assuming that the two transducers had similar efficiency, which is reasonable since the acoustoelectric current that they generated was similar, this indicates a loss of 30 dBm for each transducer. For 8 dBm (the point at which the traces became smooth) we have an unscreened SAW intensity of around -22 dBm. If the correct interpretation of the data is the fast perturbation of the 1D subband structure in the presence of a SAW causing a smoothing of the conductance then we may equate -22 dBm with the subband spacing and use this as a coarse indication of the SAW potential in the 1D channel at this power level.

In ref. [68] the acoustoconductance of a quantum channel longer than the SAW wavelength was treated theoretically. The main finding was a contribution to the conductance from the SAW which oscillated as a func-
function of subband occupancy monitored by the gate voltage, the largest was monitored and negative oscillations in the conductance were found as a function of gate voltage for the indicated range of continuously applied SAW powers (T=300 mK). Frequency of the microwave source is set to coincide with the peak in transducer response at 2.693 GHz. Consecutive traces are offset by 77 μS for clarity. Power levels above -2 dBm are found to smear the conductance plateaux. Below this power level no change is visible in the data. Above 8 dBm the conductance is smooth with only hints of lower subbands visible in the data. Moving the applied microwave frequency to outside of the transducer passband removes the smearing effect.

The change in the conductance of the channel due to 20 ns long heater pulses was monitored and negative oscillations in the conductance were found as function of subband occupancy monitored by the gate voltage, the largest
Figure 4.7: (a) The conductance measured using a low frequency (80 Hz) two terminal lock-in technique as a function of gate voltage for several applied microwave powers at a frequency coincident with the peak in transducer response. Device is T353a, T=300 mK. The SAW is applied continuously. High SAW powers are found to perturb the subband structure sufficiently to smear the conductance plateaux. (b) The frequency dependence of the conductance with powerful (8 dBm) SAW applied. Consecutive traces moving up the page are taken with an increment in gate voltage of 13 mV. The conductance is found to increase in the regime of powerful SAW production for high subbands and decrease for the lowest subbands (i = 1, 2). Near pinch-off the conductance becomes positive once more under the action of the SAW.

reduction in conductivity being found for gate voltages in-between the QPC plateaux. Simple heating of the channel from the pulses was excluded from the measurements by plotting the temperature dependence of the conductance which behaved in a different manner to the change in conductance due to the ballistic phonons interacting with the channel; ΔG due to heating showed oscillations about ΔG=0, whereas the ΔG measured due to ballistic phonon impact with the channel showed only negative oscillations with maxima at the steps in QPC conductance. The authors argue that the reason for their observed reduction in G under the influence of the phonon signal is increased backscattering within the
channel. In our case direct heating of the sample from one end by the r.f. signal has been excluded by considering the frequency response of the smearing effect and heating of the 2D electron gas by the SAW is excluded by the absence of any change in the SdH amplitude. It is interesting to note that the smearing effect leads to an increase in conductance for the upper subbands in the constriction, whereas for the lowest subband increasing microwave power leads to a reduction in the measured conductance. This is shown in figure 4.7 (a). Figure 4.7 (b) shows an alternative way of measuring the SAW induced contribution to the conductance where the frequency of the microwave source is swept around the SAW resonance. The data shows a similar picture under reverse of the SAW direction brought about by swapping transducers. There was no change in the 2D conductance as a function of SAW power, as measured by the conductance of the channel with no gate voltage applied. The data of ref. [70] also show a possible change in sign of the phonon-conductance oscillations for higher subbands, but the authors made no comment concerning this feature of the data.

4.4 Acoustoelectric current in etched constrictions

The generation of an acoustoelectric current through a curved geometry quasi-1D shallow etched constriction is demonstrated. The form of the open channel acoustoelectric current as a function of subband occupancy is then discussed.

Constrictions were formed as described in the previous chapter using the shallow etching of a pattern drawn using electron beam lithography. The pattern chosen was similar to that of refs. [25, 26]; semicircular etched trenches of radius 5-10 \( \mu \text{m} \) and wall to wall separation 250 nm defined a channel whose narrowest point was 200 nm wide. Ohmic contacts were made to the semicircular sections of 2DEG which acted as gates, as shown in figure 4.8.

The ballistic conductance regime of similar gates has been studied in the work of refs. [25, 26], the main emphasis being upon the structure found at 0.7 \( 2e^2/h \), along with the relatively high temperature operation of such gates afforded by their wide subband separation. The high sub-
Figure 4.8: SEM micrograph of an etched constriction. Semicircular etched trenches of radius 5μm define the channel and adjacent pieces of 2DEG act as in-plane gates. SAWs are launched from interdigital transducers located 2mm away on either side of the constriction.

Band separation is thought to arise from the extra lateral confinement afforded by an in-plane gate relative to that imposed from above in a Schottky gate. 1μm interdigital pitch transducers were fabricated facing the channels in an identical manner to those used in the Schottky gated devices described above.

Conductance was again measured using a standard low frequency two-terminal lock-in technique. Around 90% of devices tested showed clear 1-D conductance steps in multiples of 2e²/h as a function of positive gate voltage. The high yield of devices showing conductance plateaux indicates that the etching process used is an accurate and reproducible
way to define QPCs. A positive gate voltage is needed to open the channels, which are depleted at zero gate bias by surface states in the etched trenches. Chips fabricated in a nominally identical manner showed small ($\pm 0.1$ V) variations in the turn-on voltage. A likely explanation is variations in roughness in the side-walls defining the constrictions. In order to observe an acoustoelectric current in the low SAW intensity regime discussed in this chapter channels were opened by the application of a positive voltage to the pieces of 2DEG which acted as gates.

Measurements of device conductance and acoustoelectric current were taken sequentially as a function of gate voltage for a range of SAW intensities and frequencies within the transducer passband. In the initial stage of this investigation problems were found with unstable gate characteristics, gate pinch-off voltage shifting by up to 0.1 V between consecutive sweeps. In order to obtain characteristics stable over a period of weeks open channel measurements were only taken after a gate-training period of several hours during which time the channels were repeatedly opened up to $i = n - 1$ where $n$ was the highest obtainable subband in the constriction and then closed to 0.2 V beyond (more negative than) pinch-off voltage. After 10 hours of this procedure open channel characteristics were found to be stable and reproducible. Only data taken after this stabilizing procedure will be discussed.

In the following, as above with acoustoelectric current measured in rectangular Schottky gates, only the regime of microwave power well below that required to smear the conductance is discussed. The qualitative features the current in both types of constriction remains constant (but different) in this regime.

The open-channel acoustoelectric current measured as a function of gate voltage shows plateaux between peaks, as shown in figure 4.9. The peaks coincide with the region in-between conductance plateaux, in a similar manner to the peaks of the oscillations in rectangular gates described above. We therefore attribute the peaks to a similar mechanism, namely velocity matching between slow electrons in the uppermost 1D subband with the SAW velocity. The plateaux in acoustoelectric current, which are only found for the semicircular constrictions, are found to coincide with the flat sections of the conductance plateaux. Data taken for two devices is shown in figure, with similar data available for all other devices which showed good conductance plateaux. The contri-
bution from cross-talk to the signal is even lower than that found in the Schottky gated devices discussed earlier, probably due to the recessed nature of the etched constriction. We can therefore exclude crosstalk from the mechanism responsible for the plateaux.

The observation of current steps rather than oscillatory behaviour as a function of gate voltage can be attributed to SAW-electron coupling in the semicircular trenches of the constriction, and provides some experimental support for the ideas discussed by Bo et al in ref. [59]. In this picture a 'phonon wind' in the leads of the device couples to the electron system. This produces a quantization which will be superimposed upon the oscillating pattern which is due to the piezoelectric coupling in the channel itself. The relative contribution to the measured current from the leads and the channel will then determine whether steps, oscillations, or both are seen in the measured current.

In a rectangular gated system the SAW potential is expected to be screened out in the 2D leads since their size is much larger than the Bohr radius \( a_B = E\hbar^2 / m^2 e^2 \) [59]. For a gate of the curved geometry investigated in this section the transition from the 2D to 1D region in open channel will be smoother than in a typical rectangular gated device. Crucially, the length of the leads which has a width \( < a_B \) is expected to be much larger in the case of the curved geometry. The SAW potential is therefore not expected to be as effectively screened in the leads of the curved geometry, allowing a more effective SAW-electron piezoelectric interaction in this region of the constriction. Interaction in the leads of a quasi-1D device in the open-channel regime has been treated theoretically by Kozub et al [61] in the phonon wind model mentioned earlier. The main result was the prediction of a drag on the electrons in the leads of the device. Current steps were predicted, with plateaux corresponding to gate voltages for which QPC conductance was quantized. The current arising from the phonon wind in the leads is given by:

\[
I = \sum_n \int_{E_n}^{E_n} \hat{J}_{e-ph}^\text{drag}(E_{nk}) \left( \frac{\partial f_0(E_{nk})}{\partial E_{nk}} \right) T_n(E_{nk}),
\]  

(4.1)

where \( \hat{J}_{e-ph}^\text{drag} \) is the electron-phonon collision integral in the device leads which provides a force on the electrons.
The form of the acoustoelectric current has been studied for two types of open quasi-1D system. The use of high quality deep HEMTs enabled the
observation of clear oscillatory behaviour in the acoustoelectric current for all subbands in quasi-1D rectangular Schottky gated constrictions. The data confirm the role of slow electrons in the uppermost subband of the constriction in determining the acoustoelectric response of a split-gate system and can be understood within the framework introduced by Galperin. A powerful SAW is found to smear the low frequency conductance plateaux. This is not due to heating of the sample, and may be explained in the context of a fast perturbation to the 1D subband structure. In etched channel devices with semicircular leads the form of the acoustoelectric current is found to be dramatically different. An acoustoelectric current with a contribution proportional to the quantized conductance is found. The observations are qualitatively consistent with a recent model in which an electron/SAW coupling in the leads produces the quantization. The results demonstrate the importance of quantum point contact geometry in determining the form of the acoustoelectric current observed in open channel conditions.
Chapter 5

Single electron acoustoelectric effect

5.1 Summary of results

The application of a surface acoustic wave to a quasi 1-D channel formed in a GaAs/AlGaAs heterostructure produces quantization of the acousto-electric current in units of $I = ef$ where $e$ is the electron charge and $f$ the surface acoustic wave frequency. A study is presented of the quantization effect in 11 devices formed using the split-gate technique. The effect is firstly shown to be reproducible and not dependent upon impurities for its observation. In cleaner channels quantization is observed for integer occupation numbers up to $n = 17$. The frequency dependence of the current measured near the plateau centre shows conclusively locking of the electron transport to the SAW potential. The integer acoustoelectric effect is studied as a function of source drain bias, power and frequency. Any of these parameters may be independently changed to observe steps quantized in units of $I = ef$. Interesting structure in acoustoelectric current occurs as a function of SAW power when the SAW amplitude is insufficient to transport an integer number of electrons. A smooth transition between $I = nef$ and $I = (n - 1) ef$ is observed as a function of decreasing SAW power in this regime. The susceptibility of devices to source-drain bias is dependent on the length of channel used to define the constriction. The shape of the quantized acoustoelectric plateaux in the absence of RTS noise is discussed, and typical values of the precision of the quantization effect presented. Impurity effects which degrade de-
vice performance are also discussed; Dirty channels show coulomb blockade peaks reproduced in acoustoelectric current and no quantization is found. The chapter finishes with a discussion of the relationship between the experiments and the presently available theoretical treatments of the quantization effect.

### 5.2 Acoustoelectric current quantization

In 11 of the 14 devices measured RTS noise was either absent or limited to switching times well outside that required to influence the tuning process. Table 1 shows the relevant device parameters. The main features of the quantized acoustoelectric current in these devices will now be discussed. In all cases a quantized acoustoelectric current was found only for the regime of gate voltage more negative than the pinch off value of conductance. This is consistent with electrons being forced over the static barrier formed by the split-gate potential. For gate voltage beyond conductance pinch-off, which co-incides with a dip in acoustoelectric current, the acoustoelectric current shows a peak followed by a series of plateaux (see figure 5.1).

The origin of the peak is the reduction in screening of the SAW potential as the channel conductance becomes very low. The most numerous plateaux were found in device T404a. Figure 5.2 (a) shows the acoustoelectric current measured between two ohmics on either side of the gate for the quantized regime. The current is observed to decrease in a stepwise manner with increasingly negative gate voltage applied to the split-gate. To emphasise the presence of higher plateaux the derivative of the same data is shown in figure 5.2 (b).

### 5.3 Demonstration of frequency locking

In any given device the SAW transducer bandwidth (around 2 MHz) is such that it is not possible to demonstrate the change in $ef$ plateau height as a function of frequency. Using the techniques described in the previous chapter transducers were fabricated in the range 0.95 to 1.1 $\mu$m, giving a range over which the frequency locking of single electron transport could easily be demonstrated as a change in the value of current.
### Table 5.1: The main parameters for 14 devices which show quantization of the acoustoelectric current. The accuracy and precision of measurement are defined in the text.  
1 Precision of device affected by RTS noise.  
2 Device discussed in later chapter

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gate geometry width, length (μm)</th>
<th>Wafer ( \mu (\text{cm}^2\text{V}^{-1}\text{s}^{-1}) ), ( N (\text{cm}^{-2}) )</th>
<th>Current (nA)</th>
<th>Frequency (GHz)</th>
<th>Precision (± % / mV)</th>
<th>Accuracy (± %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T404a</td>
<td>1.1, 0.7</td>
<td>1.1, 2.2</td>
<td>0.429735</td>
<td>2.68220</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>T404b</td>
<td>1.5, 0.7</td>
<td>1.1, 2.2</td>
<td>0.42624</td>
<td>2.67781</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>T404c</td>
<td>1.5, 0.7</td>
<td>1.1, 2.2</td>
<td>0.42819</td>
<td>2.67571</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>T404d</td>
<td>1.5, 0.7</td>
<td>1.1, 2.2</td>
<td>0.4288</td>
<td>2.67571</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>T404e</td>
<td>0.7, 0.7</td>
<td>1.1, 2.2</td>
<td>0.44</td>
<td>2.73100</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>T404f</td>
<td>0.7, 0.7</td>
<td>1.1, 2.2</td>
<td>0.4615</td>
<td>2.88700</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>A1758a</td>
<td>0.8, 0.6</td>
<td>0.89, 1.7</td>
<td>0.42133</td>
<td>2.63060</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>A1758b</td>
<td>0.8, 0.6</td>
<td>0.89, 1.7</td>
<td>0.450</td>
<td>2.80364</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>A1470i</td>
<td>0.7, 0.95</td>
<td>0.75, 2.7</td>
<td>0.431</td>
<td>2.71330</td>
<td>0.02</td>
<td>1.4</td>
</tr>
<tr>
<td>A1470s</td>
<td>0.7, 0.25</td>
<td>0.75, 2.7</td>
<td>0.432</td>
<td>2.71410</td>
<td>0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>A1470b</td>
<td>0.7, 0.25</td>
<td>0.75, 2.7</td>
<td>0.43293</td>
<td>2.70925</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Cop1</td>
<td>0.2, curved</td>
<td>1.0, 2.0</td>
<td>0.43586</td>
<td>2.71625</td>
<td>50 ppm</td>
<td>0.15</td>
</tr>
<tr>
<td>Cop2</td>
<td>0.2, curved</td>
<td>1.0, 2.0</td>
<td>0.434</td>
<td>2.69980</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Cop3</td>
<td>0.05, curved</td>
<td>1.0, 2.0</td>
<td>0.42998</td>
<td>2.68737</td>
<td>50 ppm</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Figure 5.1: The regime of quantized acoustoelectric current for sample T404a
(a) The device conductance, showing the smearing of the lowest conductance plateaux at high SAW powers as discussed in the previous chapter. The increment between consecutive traces was xxx dBm. The -50 dBm trace is also shown to indicate the effect of removing the SAW on conductance. (b) The acoustoelectric current measured at a microwave source frequency co-incident with the transducer’s resonance (2.67571 GHz). T = 1.2K.

measured at the plateau centre over many devices. This is shown in figure 5.4. The data show the experimental value of current from the
Figure 5.2: (a) The quantized acoustoelectric current measured in device T404a. Data were taken at 1.2 K after optimization by tuning the applied microwave frequency and power as described in the text. Acoustoelectric current was monitored between two ohmics on either side of the split gate using a battery operated preamplifier. (b) The numerical derivative of the same data as in (a) which emphasises the presence of higher plateaux.

plateau centre in all of the devices which showed quantization. In the case of devices which showed a finite slope the centre of the flattest segment was chosen as the experimental value of current. The error bars represent the calibration uncertainty in the measurement equipment. The straight line is equal to $ef$ where $e$ is the electron charge and $f$ the applied microwave frequency. All data points are found to lie along this line within the measurement error, clearly demonstrating frequency
Figure 5.3: The gate voltage derivative of acoustoelectric current plotted against acoustoelectric current for the first ten plateaux in device T404a. Minima correspond to quantized acoustoelectric current plateaux centres. $T=1.2$ K.
dependent locking of electron transport to the applied microwave signal.

Figure 5.4: Frequency locking of the electron transport measured in 14 devices. Data points each represent the current measured at the centre of the first plateau. Error bars indicate the calibration error of the various instruments used. Inset: Deviation of the data points from the expected quantized value. All points with error bars lie along the line $\ell_f$. 
5.4 Accuracy of quantized charge transport in Schottky gates

For all devices measured the precision of quantization was determined after optimization of the microwave conditions. Optimum conditions were found initially of the two main parameters - SAW frequency and power. We monitored the acoustoelectric current as a function of gate voltage and incremented these two parameters iteratively to obtain the flattest achievable plateaux. All data which will be discussed were taken at 1.2 K; cooling the devices to 300 mK has not shown any improvement in plateaux slope. A possible reason for this observation is discussed later in this chapter in the context of the model by Flensteg.

In all the Schottky gated devices measured we have found that the first plateau shape is such that an inflection point occurs at the plateau centre. Part of the plateau around the inflection point within a several millivolt interval of gate voltage can be approximated well by a straight line. The flatness of a plateau can therefore be quantified by a fractional slope $\Delta I/\Delta V$, the latter being expressed as percent per mV or parts per million. The length of this segment is typically 1-2 mV in gate voltage so that a value of the slope expressed in % per mV or ppm/mV gives at the same time the imprecision of the current in % or ppm. In the case of four devices the first quantized plateaux showed a distinctive flat straight section, and the imprecision could then be assessed in a straightforward way. In order to obtain a more accurate assessment of the acoustoelectric plateaux in these four samples we used, in addition to slow continuous sweeps of gate voltage, a ‘stop and wait’ technique. In this technique gate voltage was held constant for 10 secs during which time approximately 100 readings of gate voltage were taken. The gate voltage was then incremented, data taking turned off for several seconds in order to allow for the effect of any instrumental damping, and the process repeated across the whole plateau. This allowed us to obtain the mean and standard deviation of the current for a series of consecutive gate voltage increments on the plateau. We then define the imprecision of the plateau as an interval of current which includes all the means with standard deviations taken at each gate voltage on the flat section.

The best results obtained in a Schottky gated device using one SAW beam are shown in figure 5.5. The first plateau in this sample showed a
Figure 5.5: (a) An enlargement of the first acoustoelectric current plateau for sample A1470b. Data were taken using the 'stop and wait' technique described in the text. Inset: the first plateau with a dotted line showing the quantized value $e_f$. (b) Data from (a) (main figure) averaged over time at each gate voltage. Error bars indicate the standard deviation of current at each gate voltage point.
straight segment at the plateau centre which allowed us to determine an imprecision of around ± 200 ppm. An enlargement of the first plateau for this sample is shown in figure 5.5 (b). The noise on the data in figure 5.5 (b) is that produced by the 16 bit analogue digital converter used to measure the analogue output of the current preamplifier. The exact value of the quantized current for this sample \( I = e f = 434.8 \) pA differs by 0.23 /435.8 pA, the deviation being well within the quoted accuracy of the ammeter. In figure 5.5 (b) the data are presented after averaging over the readings taken at each value of gate voltage. The horizontal dashed lines show the ‘imprecision interval’. The data for other samples measured is shown in table 1. These samples showed an inclined segment of approximately 1 mV in length at the plateau centre and we define the imprecision as an interval of current which includes all the experimental points in this segment. The most likely explanation for the difference in the form of the plateau centres for different samples is the impurity potential in the vicinity of the channel.

5.5 The action of a d.c. bias

Devices were also measured with a source/drain bias applied whilst monitoring the acoustoelectric current. The results of these investigations are now discussed. Such measurements are important for several reasons. Firstly they provide some information concerning the internal impedance of the devices as current sources. For a current standard a high internal impedance is obviously desirable. A second reason for interest is that they contain some information concerning the single electron transport mechanism. It is found that plateaux in units of \( ef \) may be observed as a function of d.c. bias for fixed gate voltage. This indicates that the geometry of the dots which form in the entrance to the constriction can be deformed using the source-drain bias in such a way that we may move the system through suitable conditions for the observation of single electron electron transport. A schematic of the system under the action of a source/drain bias \( V \) is shown in figure 5.6. Similar representations have been used for the case of open channel transport, in the work of Patel et al for example [67]. The application of such a bias may be used to probe the subband structure of a split-gate in open channel conditions as described in chapter 1 by changing the number of 1D subbands con-
ducting in the two directions through the constriction. In the case of an open channel conductance measurement the application of a dc bias has been interpreted in the context of Glazman et al's model [72]. The source/drain bias alters the chemical potential in the source and drain of the device away from the Fermi energy according to: \( \mu_{\text{source}} = E_F + \beta eV_{sd} \) and \( \mu_{\text{drain}} = E_F - \beta eV_{sd} \). Assuming a symmetric bias drop across the constriction \( \beta = 0.5 \). Below the last 1D subband in conductance the value of \( \beta \) required to fit experimental data is known to drop linearly until at pinch-off \( \beta = 0 \) V [73]. Since current steps occur are only found in the regime well beyond conductance pinch-off the bias drop for the measurements presented here will also occur with \( \beta = 0 \) V. Bias was applied in series with the devices using the internal voltage sources of the ammeters which were used to monitor current: a Keithley SMU and a Stanford battery operated pre-amp. The effect of a d.c. bias applied to the entrance of constrictions whilst in the quantized regime is shown in figure 5.7. The pinch-off voltage is found to move negatively with increasing negative dc bias; the form of the first few plateaux remaining similar over some range of dc bias. The shape of the upper plateaux are deformed first, indicating that the device impedance changes with gate voltage as we may expect if the width and/or length of the static barrier increases with applied negative gate voltage.

In order to assess the effect of changes in channel length on the current plateaux devices were fabricated using a mask design with the facility for multiple split-gates on each chip. A comparison of different gate geometries under similar SAW conditions is then possible. Results are shown in figure 5.7 for two gates on the same device with different length channels. Identical SAW power levels were applied to the channels to obtain this data, though a small change in the applied frequency was used to obtain optimum conditions for transport across each constriction. The length of both Schottky split gates was assessed after electrical measurement using an SEM and found to be 0.25 \( \mu \)m and 0.95 \( \mu \)m respectively. The width of both channels was 0.7 \( \mu \)m. The pinch-off voltage in acoustoelectric current at zero bias for the two channels is -1.32 V and -2.01 V, the longer channel pinching off at more positive voltage. The corresponding pinch-off voltages for conductance, which we will define as the point where the conductance dropped below 1 \( \mu \)S with no SAW applied, are -1.26 V and -1.94 V.
Figure 5.6: Schematic diagram showing the application of a source/drain bias to a device in the quantized acoustoelectric current regime. The source and drain are defined in terms of the SAW-induced transport direction. The factor $\beta$ is the ratio of bias dropped on either side of the constriction as discussed in the text; in the quantized regime $\beta = 0$.

The shorter channel, shown in figure 5.7 (b), is found to be more susceptible to d.c. bias than the longer channel. Around -3 mV applied to the channel entrance is sufficient to dramatically worsen the plateaux slope, whilst around +1 mV is sufficient to open the channel to transport against the SAW direction. The longer channel, shown in panel (a) of the same figure, is much more stable with the application of applied to the channel entrance of -8 mV being needed to visibly alter the first
Figure 5.7: Quantized acoustoelectric current measured in two split gates on the same chip fed from the same SAW transducer. A static dc bias was applied relative to the entrance of the channels. The longer gate, shown in (a) with a channel length \( l = 0.75 \, \mu m \), was found to be less susceptible to the influence of a static dc bias applied relative to the channel entrance than the shorter length channel, \( l = 0.35 \, \mu m \), shown in (b). Applied SAW power for both gates was 10 dBm, with tuned frequencies of 2.7141 GHz for (a) and 2.7133 GHz for (b). Gate widths were both 0.8 \, \mu m, T=1.2 K.

plateaux slope. For both devices applying a positive bias to the channel entrance is found to open the channels to transport against the SAW direction. This behaviour may be understood with reference to figure 5.6.
as the peak of the saddle point moving below the chemical potential in the drain. A current will then flow opposing the direction of SAW transport. Interestingly a quantized contribution to the total current can still remain, as shown by the plateaux structure in the negative current direction of figure 5.7 (a) and (b). This is the result of adding the quantized SAW current to the bias induced current. For wider split-gate channels than those presented in the data of figure 5.7 we find a smaller affect on current with the application of a static dc bias, consistent with a longer barrier giving higher device impedance. Data for such a Schottky gated device is shown in figure 5.8. Later in the present thesis SAW transport in etched constrictions is discussed. These channels have shown an extreme robustness against dc bias relative to Schottky gated devices.

Figure 5.8: The application of a d.c. bias to the entrance of device T404a ($t = 0.7 \mu m$, $w = 1.1 \mu m$). $T=1.2$ K. Microwave power applied = 10 dBm. 10 mV of positive bias is found to perturb only the fourth step indicating an enhanced device impedance relative to the devices shown in figure 5.7.

5.6 Frequency response of devices

The effect of incrementing the applied microwave frequency over the transducer passband was measured as the initial part of the optimization
procedure for each device. A typical result is shown in figure 5.9.

Figure 5.9: The current step regime in device A1758b measured as a function of gate voltage with frequency incremented by 50kHz in-between sweeps. T=1.2K. The pinch-off voltage is seen to oscillate as a function of frequency with a periodicity of approximately 0.7 MHz as discussed in the text.

In devices where the centre frequency of the two transducers was
well aligned the pinch-off voltage was found to oscillate with a period of around 0.7MHz as shown. This is explained as the effect of a weak reflected SAW from the second (unconnected) transducer and is discussed at length in the following chapter, where an intentionally generated secondary SAW beam is used to control the quantization. Devices with only one transducer, or with transducers of mismatched frequency do not show this oscillation. Such a device is shown in figure 5.10. Since the pinch-off voltage does not oscillate it is possible to observe current steps as a function of swept microwave frequency. The resulting SAW potential decreases away from the centre of the transducer passband so the situation is similar to altering the microwave source power at fixed frequency.

**Figure 5.10:** The current step regime in device T404a as a function of swept source frequency with gate voltage incremented by 200 µV between consecutive sweeps. T = 1.2 K. This device had transducers with a large difference in operational frequency allowing the observation of quantization with swept SAW frequency within the transducer passband. Current plateaux are shown as a bunching of the curves near $n = ef$. 

82
5.7 Structure in power response of devices

For all devices which show acoustoelectric current quantization there are ranges of microwave powers over which the quantization as a function of gate voltage can be observed. These are interspersed with regions of power in which the slope of the current plateaux increases dramatically; for decreasing power a smooth transition between the $n e_f$ and $(n - 1)e_f$ plateaux is observed. Such structure is shown for two devices in figure 5.11. Some devices show some evidence of two transitional regions between quantized regimes of power. Such a device is shown in figure 5.11. This behaviour is not at present understood.

Increasing microwave power in the current step regime always moves channel pinch-off to more negative values of gate voltage. This may be understood intuitively as an increase in the the depth of the SAW minima forming in the entrance to the 1D channel with increasing SAW amplitude. Increasing the SAW amplitude will also increase the amount by which the lateral split-gate barrier is pulled down in every SAW cycle. An increase in the size of the static barrier is therefore required to reduce the well size and current after an increase in SAW power. An interesting consequence of this behaviour is that the current steps occurs not only as a function of gate voltage, but also as a function of SAW power for a static potential barrier. This is shown in figure 5.12 for device A1758a.

Typical barrier heights separating source and drain in the gate voltage domain beyond conductance pinch-off were estimated in ref. [74]. A factor $\alpha$ was introduced to relate the applied gate voltage to the measured barrier height. The value $\alpha$ was shown to be of order 0.5. In our Schottky gated devices the regime of quantized current occurs at around 50 mV beyond conductance pinch-off with no SAW applied, yielding a static barrier height of around 25 meV. A typical value of the unscreened SAW potential was made in the previous chapter, around 1 meV being typical. A reasonable picture of the potential landscape is therefore a small SAW induced modulation of the conduction band superposed on a much larger static barrier due to the gate.
Figure 5.11: The regime of microwave power for two devices in which a smooth transition between quantized plateaux may be observed. Horizontal lines indicate the expected quantized values of current at $I = n e f$. The transition regions are indicated by dashed lines as a guide to the eye. $T = 1.2$ K. Device in (a) is A1758a, (b) is A1758b. Device A1758b shows more numerous, flatter plateaux.
Figure 5.12: The quantized current regime for device A1758a measured as a function of swept SAW power. Gate voltage was incremented by 1 mV between consecutive sweeps.
5.8 Influence of impurities in acoustoelectric current

5.8.1 Coulomb blockade by impurities

In several devices the current quantization was absent despite the observation of a large acoustoelectric current beyond conductance pinch-off. These devices all showed poor conductance quantization with impurity induced resonances superimposed on the quantized conductance plateaux. One such device is shown in figure 5.13. Impurity induced coulomb blockade peaks are visible below the first 1-d subband, as well as a random telegraph signal which switches between two metastable states with a time constant of a few minutes. The acoustoelectric current measured through the constriction also shown in figure 5.13. The gate voltage positions of the peaks and dips in conductance were observed to coincide with those observed in acoustoelectric current. The gate voltage position of the peaks are unaffected by changes in either the applied microwave power or frequency within the transducer passband. Increasing the applied microwave power increases the magnitude of the oscillations and smears the structure. It is apparent from data such as this that the absence of extensive coulomb blockade structure is a prerequisite for the observation of current steps since both phenomena occur in the interval of gate voltage beyond conductance pinch-off.

5.8.2 RTS noise

RTS noise can have a major parasitic influence on the characteristics of many mesoscopic devices. Single electron SAW devices are also susceptible, and this source of noise was important to suppress for the purpose of our measurements. It is not yet possible to state why some wafers should be particularly susceptible to RTS noise. Some devices showed regimes of power in which RTS noise was highly evident, which may indicate that the SAW itself is responsible for the observation of RTS noise. This agrees with the observation that two devices showed no evidence of RTS noise in conductance measurements whilst a heavy RTS noise signal was found in acoustoelectric current beyond pinch-off. It is therefore insufficient to perform a conductance measurement on a split gate to assess
Figure 5.13: Acoustoelectric current and conductance of a constriction showing both RTS switching and Coulomb blockade behaviour. Peaks in acoustoelectric current co-incident with peaks in conductance. T=100 mK.

whether a wafer is suitable for measurements of acoustoelectric current quantization.
5.9 Recent theoretical treatments

In the period since this work was started several theoretical treatments of relevance to the experiments described above have appeared. Very recently SAW induced single electron transport in a split-gate system has been studied theoretically by Flensberg et al [75, 76]. The authors have modelled a mechanism for the appearance of the current plateaux which relies upon a time-dependent tunneling coupling to the leads of the device. A schematic is shown in figure 5.14. The authors argue that the SAW potential in the leads can be ignored due to effective screening by the 2DEG. An abrupt transition is therefore assumed to occur at the channel entrance with the SAW potential rising rapidly. In this model the time dependence of the SAW profile at the channel entrance is sufficient to periodically fill SAW wells if the barrier drags the conduction band below the Fermi energy in the channel leads for half of the SAW cycle.

![Diagram showing the instantaneous electrostatic potential ψ in Flensberg et al.'s model, taken from ref. [75]. The x axis corresponds to the Fermi level; the location x₁ of the SAW induced potential minimum moves to the right with sound velocity. The dashed line indicates the wave function of the trapped electron. l₀ is the decay length of the wave function under the potential barrier.](image)

The authors calculate a tunnelling probability for electrons between
the dots formed at the entrance to the channel and the leads. Since
the distance from the dot to the 2DEG increases linearly with time, the
tunnelling probability of electrons moving from the dot back to the 2DEG
in the entrance should decrease exponentially as the SAW barrier forms
at the rear of the dot.

The authors emphasise that the dot becomes isolated from the 2DEG
e xtremely fast within their model - on a time scale of around 5 ps. The
authors claim that this is similar to the level spacing in the dot, which
implies that the devices have a fast built-in time dependence of the cou-
pling to the leads. The authors compare this to the rise/fall times of
sharp voltage pulses used to modulate the gate voltages in other experi-
ments [77] which are an order of magnitude larger. Parameters of the
model include the relative magnitudes of the SAW potential and static
barrier shape. The main prediction that the authors make is that the
width of the transition region between current plateaux should saturate
to a value determined by the inverse switching near at around 1 K; lower-
ing the temperature further would have no effect on the quantization.
This is tentatively supported by our experimental data. The main diffi-
culty with these measurements is that small temperature changes usually
produce a small change in the transducer response, forcing a retuning of
the SAW parameters to obtain optimum plateaux flatness once more.
None of the devices measured showed an improvement in plateaux slope
on cooling from 1.2 K to 300 mK. In the case of 3 devices the plateaux
slope worsened and incrementing the SAW frequency and power was not
sufficient to reduce the slope back to the 1.2 K level. A possible expla-
nation for the latter behaviour may be the additional disorder that a
reduction in temperature is expected to bring about. In the case of every
device warming to 4 K from 1.2 K increased the device slope; within
Flensberg el al’s model this may be understood as a thermal activation
process over the rear of the dot into the lead region. The possibility of
dots isolating electrons below the Fermi energy is not considered since
the SAW potential is assumed to be negligible here. At the same time the
tunneling process which the authors discuss should be dependent upon
the specific form of the potentials chosen to represent transport in this
region of the constriction. The screening of a SAW by the electron gas
in a metallic Schottky split-gate is complicated, and has been discussed
by Aizin et al [78]. Indeed, these numerical calculations indicate that
the SAW potential in the entrance to the channel may not be negligible as Flensberg et al have stated, but rather have a value of at least one half of the unscreened SAW amplitude. It is unclear to what extent the inclusion of gradually changing screening in the entrance to the channel would alter the claims made by Flensberg concerning the predicted slope saturation near 1 K. It does, however, seem likely that any change in the form of the potentials involved will affect the modelling of what is a complex transport mechanism whose theoretical investigation is still obviously in its infancy.

The problem of electron transport by a potential minimum over a static barrier has also been theoretically investigated in recent work by Maksym [79]. This involved a one-dimensional quantum mechanical approach. The electron transfer per SAW cycle was calculated by solving the time-dependent Schrödinger equation. For static barriers larger than 1 meV the accuracy of transport was found to improve smoothly with barrier height. The accuracy in the high barrier regime was found to be well fitted by $\alpha \exp(-\beta \sqrt{V_0})$ with $\alpha = 0.81 \pm 0.07$ and $\beta = 4.76 \pm 0.05$. A quantization of around 50 ppm, demonstrated later in this thesis, is predicted for a static barrier height $\geq 5-10$ meV. For larger barriers even more accurate quantization is predicted, of the order of 1 part in $10^{10}$ for a barrier height of around 20 meV (see figure 5.15).

## 5.10 Conclusion

The quantized acoustoelectric current has been studied in 14 devices. The large number of devices which showed the quantization indicates that current steps are a reproducible effect not dependent upon a particular impurity configuration for their observation. RTS noise which affected prior measurements of the quantized current was absent from roughly two thirds of the devices measured, indicating that it is not intrinsic to the observation of the effect. The influence of a static D.C. bias has been studied, with measurements indicating that a longer electrostatic potential increases device impedance. The precision of Shottky gated devices as a source of quantized current in the absence of RTS signals was measured and typical values of this quantity presented.

Data discussed in this chapter have been published in refs. [80, 81], and were presented at EP2DS97 and CMMP 96.
Figure 5.15: The accuracy of quantisation at plateau centres as a function of static barrier height in Maksym’s model, taken from ref [79].
Chapter 6

Dynamically tuned single electron transport

6.1 Introduction

This chapter details experiments performed using counter-propagating surface acoustic waves to produce single electron transport in a split gate system.

After the observation, detailed in the previous chapter, that a weak standing wave could affect the transport through the SAW/split-gate system the possibility existed that an intentionally generated counterpropagating SAW could be used to influence the accuracy of current produced by devices of this kind. In this chapter the realization of such a scheme is demonstrated. The principle result of this work is that a weak counterpropagating SAW can be used to adjust the shape of quantized acoustoelectric current steps, improving the precision of the quantization. The experiment allows the concept of dynamic tuning of the SAW potential to be introduced, and the results are discussed within this framework.

6.2 Experimental setup

The experimental setup used in this investigation was designed to allow the launching of two coherent, counterpropagating surface acoustic waves with independently controllable phase and amplitude. A diagram of the experimental setup is shown in figure 6.1.

93
Figure 6.1: The experimental setup used to generate two counterpropagating surface acoustic waves travelling across a device. The microwave source was an HP83620A, amplifier a Mini-Circuits ZHL with 27dB gain and phase shifter made by MA/Com. The HP manufactured attenuator provided independent control of the power applied to each transducer. All microwave links outside the cryostat were made using low-loss copper co-axial lines.

The signal from an R.F. generator is split and one of the resulting
signals phase shifted and attenuated relative to the other. Each signal is fed to one of the transducers on either side of the device, which is situated in a $^3$He cryostat. This setup allows experiments to be performed using either one or two SAW beams. The phase shifter allows the phase of the second SAW beam to be adjusted over a complete $2\pi$ interval relative to the first SAW beam.

6.3 Sample considerations

Devices with two working transducers were needed for study. Aside from this obvious necessity, devices were also only considered for this experiment if the gate characteristics showed no discernible RTS structure. The qualitative features discussed below have been observed on several other devices, but results from the most stable device, T4043, are presented here. This device had the additional benefit that there was a small difference in the resonant frequency of the two transducers. This meant that any reflected beam from the second transducer was extremely weak (the 0.7MHz oscillation referred to in the previous chapter was absent), and could be safely neglected in the following consideration. This is illustrated by figure 6.2, where plots of the acoustoelectric current from either transducer are shown. These plots were taken at a gate voltage of -1V which corresponded to open channel conditions. The magnitude of the peaks in Fig. 6.2 is related to both the efficiency of the transducers and any asymmetry present in the split-gate. From this data it is clear that when one transducer is connected to the source the reflected beam is negligible. When both transducers were connected to the source it was possible to compensate for the off-resonance excitation of one transducer by applying a sufficiently large microwave signal from the source. The arrangement therefore allowed the exploration and comparison of both ‘one-beam’ and ‘two-beam’ regimes of the device’s operation.

Acoustoelectric current was measured using a Stanford SR570 battery operated pre-amplifier with accuracy ±0.7% quoted by the manufacturer. This instrument may be operated for up to 14 hours using its internal batteries, and was found to give lower noise levels than both a Keithley 236 SMU instrument and an EG+G 5209 lock-in amplifier. The Stanford instrument was calibrated using standard resistors and an electronic standard cell supplied by the U.K. National Physics Laboratory, and found
Figure 6.2: The acoustoelectric current measured at definition of the split gate for both transducers on sample T4043. A small difference of around 6MHz in the resonant frequency of the two transducers can be seen. Power applied to each transducer was +10dBm. The second transducer was disconnected in each case T=1.25K.

to be within its manufacturer's stated accuracy. In the following discussion we quote ±0.7% as the accuracy of the measurements since daily fluctuations were found to affect the Stanford instrument’s calibration within this range.

6.4 Experimental procedure

Initially the device was operated in ‘single beam’ geometry. Optimum conditions of SAW power and frequency were found using the iterative procedure set out in the previous chapter. The result of this optimization is shown in figures 6.3 and 6.4.

Up to 13 plateaus in acoustoelectric current were observed in the this device. To completely stabilize the device it was operated continuously for several weeks. During this time no signal that could be attributed to RTS noise was observed. The frequency which produced the flattest steps was found to coincide with the centre of the more powerful transducer's
passband. The flattest plateaus were limited to ±0.2% per mV of gate voltage over a region roughly 2mV in length as discussed in the previous chapter. Within this 2mV section the current varied linearly with gate voltage.

After optimization in single-beam mode experiments were performed using two-beams by connecting the second transducer. The presence of the second SAW beam dramatically influenced the shape of the acoustoelectric current plateaus.

The relative amplitude of the two SAW beams was controlled using the attenuator shown figure 6.1. With the attenuator at 0dB and frequency set to the centre of the more powerful transducer’s passband.
Figure 6.4: The first plateau in more detail for single beam geometry. The straight line is a best fit to the data along the 2mV flattest section of the plateau. The slope of this line is equivalent to 0.12% per mV.

the relative power of the forward (quantizing) versus backwards (tuning) beams was around 1:10 as assessed from the mismatch in centre frequencies seen in figure 6.2.

A typical series of traces taken at constant power for two SAW beams is shown in figure 6.5. The phase of the second SAW beam was incremented by approximately 24 degrees between each panel running across the page. The shape of the acoustoelectric current plateaus can be adjusted by the phase shift of the second weak SAW beam relative to the first. The phase shifter allowed the phase of the second SAW beam to be adjusted over a complete $2\pi$ interval relative to the first SAW beam. The slope on the plateau alters abruptly with the phase of the second SAW beam. This indicates that the second SAW beam is changing the shape of the SAW minima in the entrance to the channel as discussed later. As the slope on the plateau is reduced the plateau centers approach the expected quantized value from below.
Figure 6.5: Graphs for different phase shifts between the main and counter-propagating SAW beams. The source power was +9.5dBm for all plots. For (a) the attenuator was set to 0dB, whilst in (b) the attenuator was set to -3dBm to give a less powerful counterpropagating SAW beam. The difference in phaseshift between consecutive panels is 24 degrees. Reducing the power of the counterpropagating beam is seen to reduce its tuning influence on the plateau.
Decreasing the power applied to the secondary transducer by a factor of 2 (attenuator=-3dB) reduced both the amplitude of the oscillation in pinch-off voltage and the flattening of the plateaus (figure 6.5). Setting the attenuator to -9dB, equivalent to reducing the power applied to the secondary transducer by a factor of 8, was sufficient to remove the tuning influence of the second SAW. No change in the form of the plateaus could then be detected by changing the phase of the second SAW beam.

6.5 Precision measurement

To assess the best plateau flatness obtainable in two-beam geometry the phase was incremented around the conditions shown in panel 11 of figure 6.5(a). Within around 10 degrees of this panel the straight inclined segment seen in single beam geometry separated into two straight parallel lines separated by a region of very low slope. Further data were taken under these SAW conditions in stop-and-wait mode, incrementing gate voltage by 100 μV and then waiting for ten seconds at each gate voltage in which time 100 data points were recorded. The result is seen in figure 6.6, where the mean and one standard deviation of the current recorded at each of these gate voltages is shown. The range of the standard deviations within the flattest region of the plateau then provided a convenient measure of the precision of the device, as discussed in the previous chapter. This range is equivalent to ±50 parts per million of the ideal quantized value $ef=429.695pA$. The precision of the measurement was at this level limited by the digital quantization of the DAC used to record data from the pre-amp, which quantized at a value of current equivalent to ±25ppm.

6.6 Accuracy measurement

In the detailed measurements described above the accuracy of measurement equipment was ±0.7%. After the experiments detailed above were complete the device was subsequently transferred to the UK National Physics Laboratory. Measurements by Dr. J.T.Jansen of the plateau centre in single beam geometry showed that the centre of the inclined slope differed from the ideal quantized value $ef$ by -188(±12) ppm with
Figure 6.6: Graph obtained using the ‘stop and wait’ technique for optimal phase shift between the main and counterpropagating SAW beams. The attenuator was set to 0dB, source power was +9.5dBm after the amplifier shown in figure 6.1

a Type A uncertainty of ±5ppm. Experiments in two beam geometry are yet to be performed, but note that the effect of tuning the plateaus using a second SAW is to elevate the centre of the plateau.

6.7 Discussion - Dynamic tuning of SAW potential

The system of two superimposed SAWs described above can be considered as the addition of a powerful travelling wave with a weak standing wave. By adjusting the phase of the signal applied to the second transducer the position of this standing wave is adjusted with respect to the static channel potential. The observation that a 2nd weak counterpropagating SAW can be used to influence the accuracy of current quanti-
zation in the split-gate system is in agreement with the simple model previously used to describe the mechanism behind single electron transport as presented in previous chapters. The mechanism responsible for the separation of the system into quantized levels is the appearance of Coulomb gaps between single particle levels in the energy spectrum of the dots transferred across the gate. Crucially, for the first plateau there will be some important interval of time in the SAW cycle during which the system separates from two to one electrons.

![Diagram](image)

**Figure 6.7:** Proposed mechanism for the improvement in accuracy of the SAW devices under the influence of a counterpropagating SAW beam. The system can be thought of as the superposition of a powerful travelling wave with a weak standing wave. Moving the position of the standing wave relative to the channel entrance changes dynamically the shape of the potential wells formed at the entrance to the channel.

This is illustrated in figure 6.7 at the entrance to the channel. The well shape (width and depth of the wells) at this interval of time will determine the accuracy of single electron transport. Reducing the well
width will enhance the Coulomb gap between energy levels in the dots, making the system less susceptible to changes in the static potential due to the split-gate. A static tuning of the well shape, such as can be effected by changing the gate voltage or altering the gate shape may improve the well shape for this process in one interval of time in a SAW cycle but degrade it in another. The addition of a weak counterpropagating SAW beam acts as a tuning device if it influences the well shape at this critical time in the SAW cycle in such a way that the probability of errors in the transport process is reduced. By adjusting the phase of the second SAW beam the position of the nodes and antinodes forming the weak standing wave will be moved relative to the channel entrance. This can be thought of as a dynamic tuning since the change in well shape brought about by the tuning influence of the secondary SAW occurs at an interval of time synchronized with the SAW cycle in contrast to the static tuning brought about by a change in gate potential which does not.

It is interesting to compare the technique presented in this chapter for improving the accuracy of single electron transport in a SAW device to the techniques which have been proposed for improving the accuracy of single electron pumps. The main error mechanisms in the electron pump are cotunneling, thermal activation and (at high enough frequencies) RC response. In refs. [82, 83] the authors showed in a numerical investigation that the accuracy of pumps could be adjusted by the use of a step-like driving potential rather than the triangular wave usually used [44]. Cotunneling of electrons was supressed and the accuracy improved by a factor between 20 and $10^4$, dependent on drive frequency. The similarity to point out is in the concept of tuning the time dependent potential profile of the device to reduce error mechanisms. No theoretical treatments of SAW devices has yet included the effect of a counterpropagating SAW on error mechanisms. It would be interesting to extend the theoretical work by Flensberg [76] to the presence of a weak standing wave in addition to the quantizing wave. It seems likely that such a treatment would alter the non-adiabatic correction to the quantized current discussed in this paper.
6.8 Summary and conclusion

Experiments have been performed using a system which launches two coherent counterpropagating surface acoustic waves at a split gate. The slope of the quantized acoustoelectric current plateaus can be altered using the tuning influence of the weaker wave. Under ideal conditions the slope of the first plateau can be reduced to ±50 ppm of the ideal quantized value \( e_f \). This represents a substantial (40x) improvement in the precision of the current delivered by the device relative to single beam geometry. An interpretation of the data is given in terms of a dynamic tuning of the SAW potential at the entrance to the split-gate channel which influences the well shape in such a way that transport errors are reduced. The coherent secondary SAW causes a dynamic tuning of the well shape, altering the well shape at an interval of time synchronized with the primary SAW beam.

The results of this chapter have been published in Ref.[80], and were presented at the 22nd International Conference on Low Temperature Physics.
Chapter 7

Single electron acoustoelectric effect

7.1 Summary of results

Observations of a quantized acoustoelectric current in etched constrictions are presented. The quantized current in etched constrictions displays superior precision (around ±50ppm in single beam geometry) and robustness to d.c. bias relative to that observed in Schottky gate defined channels. The effect on the quantization of a magnetic field applied perpendicular to the 2DEG is investigated for the first time. A change in plateau slope is observed which oscillates as a function of magnetic field, the position of the oscillations being dependent on a commensurability condition. The implication of the observations is discussed.

7.2 Device considerations

In the work described in this chapter constrictions were formed using the shallow-etching technique described in this thesis. An adjustment was made to the semicircular etched trenches discussed earlier by the addition of a 1μm straight segment to the centre of the channel. This alteration was made to ensure that when fully depleted the channel was at least of the same length as the surface acoustic wavelength. Prior to this modification no acoustoelectric current quantization was found in any of the etched channels measured. After the addition of a straight
segment to the channel pattern a quantized acoustoelectric current was observed in three devices. The qualitative features of all three devices were similar, with a quantized acoustoelectric current generated for gate voltages in heavily pinched-off channel conditions. One of the devices suffered from a heavy RTS noise signal which affected assessment of the device precision so the following discussion will be limited to the two devices which showed no RTS noise in the quantized regime. Devices were fabricated from a heterojunction with a 1000 Å deep electron layer having a low temperature dark mobility of $1.0 \times 10^{11}$ cm$^2$V$^{-1}$s$^{-1}$ and carrier concentration $1.9 \times 10^{11}$cm$^2$.

### 7.3 Observation of current quantization in etched constrictions

Figure 7.1 (a) and (b) show the channel conductance for the measured devices. The lowest conductance plateaux in both devices are found to be disturbed. The similarity of the traces may indicate that the introduction of the straight segment to the channel is responsible for this perturbation from the ideal flat plateaux observed earlier in simple semicircular trench devices.

A quantized acoustoelectric current was again observed in the regime of gate voltage more negative than conductance pinch-off. A large acoustoelectric current was induced with no sign of cross-talk in the measured signals. This is shown in figure??.

It is interesting to note that the pinch-off voltage for acoustoelectric current was between xxx and xxxmV beyond conductance pinch-off at a SAW power of 10 dBm in these devices. We note that the quantized current plateaux observed here occur in a region of gate voltage up to 600mV beyond conductance pinch-off. In comparison the corresponding values for Schottky gates were under 100 mV.
Chapter: 7  
Etched Constrictions

![Graph](image-url)

Figure 7.1: The conductance of semicircular/straight segment QPC devices (a) Copen1 and (b) Copen2 measured at 1.2 K with no SAW applied. The data are corrected for a series resistance of 1.2 kΩ, comprised of the ohmic contact and 2D lead resistances, chosen to align the conductance plateaus to $2e^2/h$.

### 7.4 Precision of quantized current in etched devices

After optimization of the applied microwave power and frequency using a slowly swept gate voltage device slope was assessed using the 'stop-and-wait' procedure discussed earlier. These data are shown in Figure ?? and ???. All data were taken at 1.2 K; lowering the temperature to 300 mK was not found to improve the plateaux in a similar manner to the observations discussed earlier for Schottky gates. The gates show a precision of around ±50 ppm of the ideal quantized value, which represents a large improvement in the precision of quantized current relative to that observed in Schottky gates.

After measurement by the author at the Cavendish laboratory sample Copen1 was measured at the National Physical laboratory by Dr. J. T. Jansen. These measurements indicated that the centre of the first current plateaux was within xxx of the ideal quantized value.
7.5 Robustness of etched channels to D.C. bias

Another indication that the size of the static barrier in etched constrictions is much larger than in Schottky gated devices is their robustness to D.C. bias. Typical data is presented in figures ?? and ?. In the case of device Copen1 the application of some xxx mV to the device entrance was insufficient to disturb the shape of any of the plateaux. Sample Copen2 required a bias of xxx mV to disturb the conductance plateaux.

7.6 Measurements in perpendicular field

The effect of applying a small perpendicular magnetic field to a device in the current step regime is now discussed. Data were taken on two of the etched devices described above (samples Copen 1 and Copen2), as well as on a Schottky gated device as discussed below. The quantitative behaviour of each gate was similar with the exception of pinch-off voltage. shown in figure ??. Oscillations in acoustoelectric current are found to develop for the interval of current in-between quantized acoustoelectric plateaux. The oscillations have a $1/B$ periodicity and are reminiscent of the geometric resonance found previously in a 2DEG between the SAW wavelength and cyclotron diameter. For values of current near $nef/2$ the oscillations have identical phase to those measured through an open channel (see figure ??). However, as the gate voltage is made more positive the oscillations change phase by $\pi$, with the interesting observation that at a field corresponding to a cylotron diameter just smaller than the SAW wavelength the plateaux becomes flatter. The improvement in plateaux slope is a factor of around 4, as shown in figure xxx. Assuming that the filling of SAW wells occurs at the entrance to the channel from electrons at the Fermi energy in the leads these observations indicate that the perpendicular magnetic field alters one or more of the error mechanisms responsible for deviation from an ideal flat plateau.
7.7 Discussion

No full mechanism for these observations described above has yet been found, though a qualitative extension of the theory by Gumbs has been proposed. Here the xxx. Smooth entrance - increased adiabaticity, smooth metal gates should replicate this provided screening is not more important - \( \tilde{\omega} \) here we get a relatively large SAW potential in the leads as evidenced by the open channel quantization of acoustoelectric current and can be expected by the lack of any metal in this region of the device. reasons for the improvement - \( \tilde{\omega} \) G.Gumbs' chat Schottky gates, other etched gates. Implications for other geometries.

7.8 Summary and conclusion

A quantized acoustoelectric current is demonstrated in three constrictions with an in-plane gate formed using a shallow etching technique. The quantized current in such gates shows a superior precision and robustness to D.C. bias relative to rectangular Schottky gated devices without any need for a secondary SAW beam. The precision is equivalent to around ±50 ppm of the ideal quantized value. The dependence of the acoustoelectric current on a magnetic field applied perpendicular to the growth interface is measured for the first time. Commensurability oscillations are observed which result in an oscillating device slope. Data are presented which show a reduction in the device slope relative to zero field conditions for values of field such that the cyclotron radius is just smaller than the SAW wavelength. The data indicate that a small magnetic field can be used to positively influence the device performance as a source of quantized current.

The results contained in this chapter are accepted for publication in refs.[84, 85]
Bibliography


115


