PhD thesis
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Surface-Acoustic-Wave-driven
Single-Electron-Transport through
Shallow-Etched Quantum Point Contacts

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Preface

This thesis describes the work performed by me during the Ph.D. study at the Faculty of Science, University of Copenhagen, with a scholarship granted from the same institution. It presents the experimental investigations on the single-electron transport driven by surface acoustic wave. During this work I benefited from the collaboration with a number of people to whom I would like to express my gratitude.

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Chapter 1

Introduction

Single-electron devices allow the manipulation and detection of individual electronic charges. During the last two decades, they have been an object of intensive research; for a recent review, see for example Ref. 1. The considerable interest in those structures is motivated by their prospective applications in microelectronics, metrology and quantum computation technologies. This thesis describes an experimental investigation of one such system, where the single electron transport (SET) is driven by surface acoustic waves (SAWs).

Our devices are based on GaAs/AlGaAs heterostructures with a high-mobility two-dimensional electron gas (2DEG). A quantum point contact (QPC) is defined in the 2DEG by means of the shallow-etch technique. The QPC is kept in the closed regime below conductance pinch-off. Hence, the top of its potential barrier is elevated above the Fermi level of the surrounding 2DEG. The SAW propagating on the weakly piezoelectric substrate of GaAs is accompanied by a wave of electrostatic potential. Electrons are dragged across the QPC in the minima of the potential wave, travelling with the sound velocity. Under certain conditions, single or few electrons are transferred per SAW cycle and the resultant acoustoelectric (AE) current is quantized in units of \( \frac{e}{f} \), where \( e \) is the electron charge and \( f \) the SAW frequency.

The structure of the thesis is as follows. This introductory chapter 1 describes the basic properties of surface acoustic waves propagating on piezoelectric media. It also briefly reviews the existing experimental and theoretical work on the SAW-based SET devices. Chapter 2 provides details on the sample fabrication. The measurement setups and experimental techniques, together with the initial characterization of our devices, are discussed in chapter 3. The experimental results are analyzed in chapters 4-7.
Quantized steps in the acoustoelectric current can be observed as a function of the gate and bias voltage, the SAW power and frequency. The AE current characteristics with respect to the gate voltage $I(V_g)$ are presented throughout the whole thesis at fixed values of other parameters. The current dependence on the bias voltage $V_{sd}$, the SAW power $P_{RF}$ and the SAW frequency $f$ is analyzed in chapters 4, 5 and 6, respectively.

Chapter 4 describes the effect of a dc bias. The $I(V_g)$ characteristics are found to be very robust with respect to changes of the bias voltage. The slope of the quantized steps is unaffected as long as the tunnelling current, resulting from a static potential difference across the QPC, is negligible. This becomes even more apparent when the $I(V_{sd})$ characteristics are taken at fixed gate voltages. We investigate as well the regime where the AE and the tunnelling current simultaneously counterflow through the same narrow constriction of the QPC. Due to their different dependence on the gate and bias voltage, they can be controlled almost independently. We have observed the quantization of the AE current at up to ten times larger tunnelling counterflow. At large tunnelling currents, the acoustoelectric current can be strongly suppressed. However, this does not seem to be due to the electrostatic interaction between the two currents.

Chapter 5 describes the power response of our devices. Quantized steps in units of $e\hbar$ can be observed in the AE current over a broad range of microwave powers applied to the SAW transducer. At low $P_{RF}$, the onset of the $I(V_g)$ characteristics is close to the threshold voltage for the conductance. No current plateaus can be resolved at the expected multiples of $e\hbar$. However, the anomalies observed in this power range develop into pronounced quantized steps when the SAW power is increased. At very high power levels, we demonstrate for the first time the $I(V_g)$ traces with strongly suppressed lower plateaus and pronounced higher steps. We speculate on possible origins of this effect.

Chapter 6 details the frequency response of our devices. Periodic oscillations observed in the $I(f)$ characteristics are attributed to the SAW reflections from the second (unconnected) transducer. Their period $\Delta f$ corresponds to the phase change of $2\pi$ between the main and the reflected SAW beam, propagating in the opposite directions. Additionally, two separate sets of the AE transitions are distinguished within $\Delta f$. They seem to develop independently and may superpose at certain frequencies. Similar sets of transitions can also be observed when the two counterpropagating SAW beams are applied on purpose and the relative phase $\phi$ between them is varied.

Chapter 7 summarizes the results of our investigations.

1.1 Surface acoustic waves

Surface acoustic waves (SAWs) are vibrations propagating along the surface of elastic media. Since their displacement amplitude decays roughly exponentially into the bulk, the SAWs are confined to a superficial region of a
thickness comparable to their wavelength. The existence of surface acoustic waves was first demonstrated in 1885 by Lord Rayleigh\textsuperscript{2} who described one of their basic types, later called a Rayleigh wave. When such a wave propagates along a free surface of an isotropic medium, the resultant particle motion is elliptical and occurs within the sagittal plane defined by the normal to the surface and the SAW propagation direction. This is illustrated schematically in Fig. 1.1. Extensive reviews on different types of surface acoustic waves can be found, for example, in Refs. 3-6.

In piezoelectric media, the elastic deformation produces electric fields. Thus, to describe the SAW propagation on such materials, Newton’s equations of motions have to be solved together with Maxwell’s equations.\textsuperscript{7,8} In general, the solutions are mixed elasto-electromagnetic waves. However, even for strong piezoelectrics, the coupling between the elastic and electromagnetic contributions is small due to a large difference between their velocities $v_{\text{SAW}}/c \approx 10^5$. Therefore, the electrostatic approximation can be used where the electric field travelling with the SAW is considered as arising from an electrostatic potential. Figure 1.2 (a) shows the variation of such a potential with the distance from the surface.

In the first few decades following their discovery,\textsuperscript{2} the main interest in surface acoustic waves was limited to seismology and geophysics. This changed, however, with the advent of modern electronics.\textsuperscript{9} The turning point was the demonstration of an interdigital transducer\textsuperscript{10} (IDT), allowing a direct generation of surface acoustic waves on piezoelectric media. Different types of IDTs are, nowadays, used in a variety of signal processing applications.\textsuperscript{11,12} SAW filters,
resonators and delay lines are ubiquitous in radars, mobile and wireless communication systems or TV sets.

The basic design of an IDT is shown in Fig. 1.2 (b): Two comb-like arrays of interdigitated metal electrodes are deposited onto the surface of a piezoelectric material. When an rf signal is applied to the transducer, the resultant electric field periodically deforms the substrate. Those deformations superpose constructively when a resonant condition \( f_o d = v_{SAW} \) is met. Here, \( f_o \) is the frequency of the applied signal, \( d \) the periodicity of the IDT, and \( v_{SAW} \) the SAW velocity for a given propagation direction and a crystal cut. For weakly piezoelectric materials, like GaAs, a large number of electrode pairs is required to obtain high SAW amplitudes which reduces, however, the bandwidth of the transducer.

The key parameters that characterize the SAW behavior on piezoelectric substrates are the surface-wave velocity \( v_{SAW} \) and the electromechanical coupling coefficient \( K^2_{eff} \). The latter quantity describes how efficiently the material converts the energy of the applied electrical signal into the elastic energy associated with the SAW. To determine the coupling coefficient \( K^2_{eff} \) of a given material, a shift in the SAW velocity is probed for two limiting cases: along a free and a short-circuited surface. In the latter case, piezoelectric fields are assumed to be perfectly screened by means of a thin metal layer at the surface of the substrate. The coupling coefficient is then defined as:

\[
K^2_{eff} = 2(v' - v)/v = 2\Delta v/v
\]

where \( v' \) are \( v \) the velocities along the free and the short-circuit surface, respectively. The change in the velocity is, thus, a probe of piezoelectric stiffening.
of the material. For strong piezoelectrics, this can be a considerable effect: \( K^2 = 4.6 \% \) for SAWs propagating along the Z direction on Y-cut LiNbO\(_3\).

In the experiments described in this thesis, surface acoustic waves are generated along the \( \langle 011 \rangle \) direction on (100)-cut GaAs, with \( v_{SAW} = 2865 \) m/s. This direction provides the largest coupling coefficient for a weakly piezoelectric gallium arsenide, however, its value \( K^2 = 6.4 \times 10^{-4} \) is still two orders of magnitude smaller than for LiNbO\(_3\). In addition, even slight deviations (~2\(^\circ\)) from the \( \langle 011 \rangle \) propagation can result in a rapid increase in the SAW attenuation per unit length.\(^{16}\) When the SAW propagates precisely along the \( \langle 011 \rangle \) direction on (100)-cut GaAs, it can be considered as a Rayleigh wave with no transverse component. However, on moving away from \( \langle 011 \rangle \), the Rayleigh wave couples to the transverse bulk shear mode. The resultant wave is a pseudo-surface wave which no longer concentrates its energy close to the surface but leaks part of it into the bulk. As the deviation from the \( \langle 011 \rangle \) direction increases, the SAW attenuation due to the bulk mode rises rapidly.\(^{16}\) To reduce those leaky wave losses, we take special care to align our transducers along the \( \langle 011 \rangle \) direction.

### 1.2 Interaction between the SAW and charge carriers

Nearby conducting layers can affect surface acoustic waves propagating on piezoelectric substrates. Mobile carriers can dynamically screen the electric fields associated with the SAW and, thus, alter the piezoelectric stiffening. This is used, for example, to determine the effective electromechanical coupling coefficient \( K^2_{eff} \), as described in the previous section. In such case, a highly conductive metal layer is deposited on the crystal surface to assure perfect screening of the piezoelectric fields. The situation becomes more complicated for intermediate values of conductivity when the screening is less perfect. In particular, this can affect the SAW attenuation.

In an early study, Hutson and White\(^7\) investigated the propagation of bulk waves in semiconductors with homogenous conductivity \( \sigma \). They obtained the following dispersion relations for the fractional change in the acoustic wave velocity \( \Delta v/v \) and the attenuation \( \Gamma \):

\[
\frac{\Delta v}{v} = \frac{K^2}{2} \cdot \frac{1}{1 + (\omega_c/\omega)^2}
\]

\[
\Gamma = \frac{\omega}{v} \cdot \frac{K^2}{2} \cdot \frac{\omega_c/\omega}{1 + (\omega_c/\omega)^2}
\]

Here, \( \omega_c = \sigma/\varepsilon \) is the conductivity relaxation frequency. The piezoelectric coupling \( K^2 = e^2/c \varepsilon \) is derived from the elastic and dielectric coefficients of the material: \( c \) and \( \varepsilon \), respectively. \( K^2 \) obtained for bulk waves differs slightly from the coupling coefficient \( K^2_{eff} \) determined for the SAWs. When the frequency of the
applied modulation is much smaller than the relaxation frequency \( \omega \ll \omega_c \), charge carriers in the substrate are able to rapidly respond to piezoelectric fields. As a result, those fields are effectively screened. As the frequency of the modulation approaches \( \omega_c \), the carriers become too slow to follow changes of the external field. Finally, at \( \omega \gg \omega_c \), the piezoelectric field is not disturbed by the presence of mobile charges. The attenuation per unit length has its maximum at \( \omega = \omega_c \), whereas the piezoelectric stiffening (velocity shift) occurs for frequencies comparable and higher than \( \omega_c \).

Similar dispersion relations were obtained as well for surface acoustic waves propagating on semi-infinite semiconductors. Ingebrigtsen\(^\text{19}\) investigated the SAW propagation on piezoelectric insulators coated with a semiconducting film. When the film thickness \( a \) was large as compared to the SAW wavelength \( \lambda \), the attenuation and the velocity shift were described by Eqs. (1.2) and (1.3), with the relaxation frequency given by

\[
\omega_c = \frac{\varepsilon_{sp}}{\varepsilon_p + \varepsilon_s}
\]  

(1.4)

Here, \( \varepsilon_p \) and \( \varepsilon_s \) are the dielectric constants of the piezoelectric and the semiconductor. However, for thin films \( (a \ll \lambda) \), the maximum attenuation occurred at

\[
\omega_c = \frac{\sigma}{\varepsilon_p + \varepsilon_o} ak
\]  

(1.5)

where \( k = 2\pi / \lambda \) is the wavevector of the SAW and \( \varepsilon_o \) the permittivity of the free space. Thus, for thin conductive layers, the attenuation per unit length was rather dependent on conductivity \( \sigma \) than frequency \( \omega \).

Wixforth \( et\) \( al.\)\(^{18,20}\) used this result to describe the SAW interaction with a two-dimensional electron gas in a GaAs heterostructure. In their simple model, the 2DEG was considered as a thin conductive layer located at the crystal surface. This yielded the following relations for the velocity shift and the attenuation:

\[
\frac{\Delta v}{v} = K_{eff}^2 \frac{1}{2 \left(1 + \left(\sigma_{2D} / \sigma_m\right)^2\right)}
\]  

(1.6)

\[
\Gamma = k \frac{K_{eff}^2}{2 \left(1 + \left(\sigma_{2D} / \sigma_m\right)^2\right)}
\]  

(1.7)

where \( \sigma_{2D} = \sigma a \) is the sheet conductivity of the 2DEG layer. Maximum attenuation per unit length occurs at \( \sigma_m = v (\varepsilon_s + \varepsilon_o) \), see Fig. 1.3 (a).

Close to the critical conductivity \( \sigma_m \), both the attenuation \( \Gamma \) and the shift in velocity \( \Delta v / v \) are very sensitive to slight changes in \( \sigma_{2D} \). Wixforth \( et\) \( al.\)\(^{18,20}\) used this feature to probe the 2DEG magnetoconductivity \( \sigma_{xx}(B) \) in the integer quantum Hall regime. Figure 1.3 (b) shows their results as a function of perpendicular magnetic field applied to the 2DEG \( (\tilde{f} = 70\ MHz) \). In high magnetic fields, the dc
conductivity $\sigma_{xx}$ exhibits strong Shubnikov-de Haas oscillations. Both $\Delta v/v$ and $\Gamma$ follow changes in $\sigma_{xx}$ and exhibit strong peaks whenever $\sigma_{xx}$ approaches the critical conductivity $\sigma_M \approx 3.3 \times 10^{-7}$ ($\Omega \square)^{-1}$ for SAWs travelling along $\langle 011 \rangle$ direction on (100)-cut GaAs. At low filling factors $\nu$, the conductivity $\sigma_{xx}$ drops below $\sigma_M$ and double peaks can be observed in the attenuation data, see for example at $B \approx 7$ T. This is because $\sigma_{xx}$ passes $\sigma_M$ twice: on lowering and raising the conductivity. No such structure is observed in $\Delta v/v$ or $\sigma_{xx}$. The dotted lines in Fig. 1.3 (b) are the theoretical traces calculated using Eqs. (1.4) and (1.5) with $\sigma_M$ and $K_{eff}^2$ as fit parameters.

The velocity shift technique provided as well valuable information on the fractional quantum Hall effect (FQHE) in high-mobility heterostructures.\textsuperscript{21-24} For sufficiently large wave vectors and frequency ($\Omega > 700$ MHz), Willett \textit{et al.}\textsuperscript{21,22} demonstrated anomalous minima in both the velocity shift and the attenuation, which occurred at even-denominator filling factors. Those minima could not be explained within the relaxation model described above since the dc conductivity measurements suggested maxima at those sites. Hence, the anomalous minima described the enhanced dynamic conductivity. When the SAW wavevector $k$ and the frequency $\omega$ were increased (up to $\Omega \approx 11$ GHz), the conductivity was probed at smaller length scales. As a result, the anomalous minima at even-denominator filling factors deepened. For filling factor $\nu = \frac{1}{2}$, an additional structure was

Figure 1.3: (a) Attenuation $\Gamma$ per unit wavevector $k$ and (b) the fractional velocity shift $\Delta v/v_0$ as a function of the sheet conductivity $\sigma_\square$ in units of the critical conductivity $\sigma_M$. (c) SAW intensity and (d) the velocity shift with respect to the perpendicular magnetic field. Dotted lines are theoretical fits obtained from Eqs. 1.6 and 1.7. The magnetoconductivity $\sigma_{xx}(B)$ is shown in (e). Figures (a)-(b) are taken from Ref. 20, and (c)-(e) from Ref. 18.
revealed in such a minimum. It was attributed to geometric resonances of the cyclotron orbits of the composite fermions with the SAW wavelength.\textsuperscript{23} This provided strong experimental support for the Fermi surface formation at $\nu = \frac{1}{2}$, and was in good agreement with theory by Halperin, Lee and Read.\textsuperscript{25}

Rocke \textit{et al.}\textsuperscript{26} investigated the interactions between the SAW and the 2DEG in heterostructures with a tunable carrier density $n_{2D}$. To control $n_{2D}$ (and thus the 2DEG conductivity), they deposited a top gate on a 2DEG mesa. In general, a highly conductive metal layer screens piezoelectric fields at the surface, however, those fields recover with the depth into the bulk, see Fig. 1.2 (a). At the depth of half the SAW wavelength their magnitude reaches almost the same value as without the metal layer at the surface. Rocke \textit{et al.} used this property in their experiments. They designed heterostructures with thick spacer layers, where the 2DEG was buried 500 nm below the surface. This depth corresponded to around $1/7^{th}$ of the SAW wavelength of 3.4 $\mu$m, thus, a finite though reduced SAW potential was present at the heterojunction. The SAW attenuation was measured as a function of the top-gate voltage or the magnetic field. The 2DEG-induced changes in the attenuation data were clearly demonstrated even at zero magnetic fields.

### 1.3 Acoustoelectric effects

Another class of effects caused by the interaction between the surface acoustic waves and mobile carriers are acoustoelectric (AE) effects,\textsuperscript{27} where currents (or voltages) are induced as a result of energy and momentum transfer from the SAW to the carriers. Esslinger \textit{et al.}\textsuperscript{28,29} investigated acoustoelectric transport in two-dimensional electron systems in the quantum Hall regime. They observed strong oscillations of the AE current and voltage as a function of the applied magnetic field. Moreover, they showed that the current density can be expressed as:\textsuperscript{29,30}

\begin{equation}
    j = \sigma E + \Lambda Q
\end{equation}

Here, $Q = I \cdot \Gamma / v$ represents a “phonon pressure” or an average force applied on the electron system which is proportional to both the SAW intensity $I$ and the attenuation $\Gamma$. Whereas the acoustoelectric tensor $\Lambda$ is given by:

\begin{equation}
    \Lambda = \frac{1}{e} \frac{\partial \sigma}{\partial n_{2D}}
\end{equation}

where $e$ is the electron charge, and $n_{2D}$ is the carrier concentration of the 2DEG.

Shilton \textit{et al.}\textsuperscript{31,32} used the acoustoelectric method to investigate the 2DEG in very low magnetic fields. In this regime, the 2DEG conductivity is still much larger than the critical conductivity $\sigma_{xx} \gg \sigma_M$, and the 2DEG strongly screens the electric fields associated with the SAW. The velocity shift technique is, thus,
insensitive in this range since it would require measuring a small change in a large quantity. On the other hand, in the acoustoelectric method, the small quantity itself is detected. By measuring the AE current in low magnetic fields, Shilton et al.\textsuperscript{31,32} were able to observe geometric resonances of electron orbits with the SAW wavelength, similar to those due to composite fermions in the SAW-velocity-shift experiments.\textsuperscript{23}

All the experiments described above were performed on weakly piezoelectric semiconductors, mostly GaAs. Thus, the coupling between mobile charges and the SAW was small, resulting in a small modulation in the carrier density. To overcome this limitation, Rotter et al.\textsuperscript{33-35} used hybrid GaAs/ LiNbO\textsubscript{3} structures. By employing the epitaxial lift-off (ELO) technique,\textsuperscript{36} they removed the active layer (with a 2DEG) from a GaAs-based heterostructure. This film (~500 nm-thick) was then placed onto a strongly piezoelectric LiNbO\textsubscript{3} crystal in such a way that the QW was in close proximity (~30 nm) to the surface of lithium niobate. Since the electromechanical coupling coefficient of LiNbO\textsubscript{3} ($K^2_{\text{eff}} = 5.6\%$ for 128° rotated YX cut) is two orders of magnitude higher than that for GaAs, very intense SAWs could be applied in such structures. The ELO film was coated with a metal top gate which allowed the control of the 2DEG carrier density, as in Ref. 26.

Rotter et al.\textsuperscript{34,35} demonstrated that at very high SAW amplitudes, the 2DEG density is strongly modulated by the SAW. Hence, the linear approach used in the small-signal limit (see Eqs. 1.6-1.9) is no longer valid and needs to be replaced by a nonlinear theory\textsuperscript{34} of the acoustoelectric interactions in the 2DEG at high SAW intensities. In this regime, electrons bunch together in the travelling wells of the SAW potential, forming stripes of charge that move at the sound velocity. For small amplitudes of the surface wave, its attenuation $\Gamma$ is given by Eq. 1.7. This changes at high SAW intensities: the attenuation is strongly reduced with the intensity and its maximum shifts towards higher values of the conductivity. At the same time, the acoustoelectric current exhibits strong nonlinear behaviour as a function of the SAW amplitude. It can reach magnitudes of up to 0.7 mA.\textsuperscript{35}

1.4 Other applications

Surface acoustic waves have found numerous applications in modern semiconductor physics and technology. Acoustic charge transport (ACT) devices offer a novel approach towards electronic signal processing.\textsuperscript{37} In such systems, electrons are injected into travelling minima of the SAW potential and transferred either through a depleted channel of a field effect transistor\textsuperscript{38} or through an empty quantum well.\textsuperscript{39} In other applications, surface acoustic waves are used to dynamically modulate the mechanical, electronic and optical properties of low-dimensional semiconductor structures.
The acoustoelectric transport of electron-hole (e-h) pairs was recently demonstrated by Rocke et al.\textsuperscript{40} Their results are shown in Fig. 1.4. A laser pulse optically generates excitons in an empty quantum well embedded in a GaAs heterostructure. When a surface acoustic wave is applied and propagates across the illuminated area, the excitons are field-ionized by lateral piezoelectric fields of the SAW. A sufficiently intensive SAW traps electrons and holes in minima and maxima of its travelling potential, respectively. The spatial separation of e-h pairs strongly suppresses their recombination probability. The photoluminescence (PL) spectra taken at the illumination spot are, thus, drastically reduced with increasing SAW intensity, see Fig. 1.4 (a). The travelling potential of the surface acoustic wave can transport the trapped carriers over long distances, of order of few 1 mm. If the piezoelectric fields are screened at such a remote location, the spatial separation between electrons and holes is lifted, leading to a radiative recombination of the carriers. In the experiment, a semi-transparent metal film screens the SAW potential and an intense photoluminescence pulse is detected at this location, see Fig. 1.4 (b).

The SAW-induced ionization and ambipolar transport of electron-hole pairs has attracted a lot of interest. At low temperatures $T < 15$ K, the photoluminescence quenching was observed for both the two-dimensional excitons in a quantum well\textsuperscript{40,41} and for the three-dimensional excitons in undoped...
Variety of techniques were used to probe the exciton dissociation into free electrons and holes trapped in the moving potential minima of the SAW. In early experiments, the conductivity of those free carriers was probed using the SAW damping technique described before. In this approach, two perpendicular SAW beams were generated on the crystal: The high-intensity ‘pumping’ beam was used to field-ionize the photo-generated excitons and pump them away from the illumination spot. The low-intensity ‘probing’ beam detected the conductivity of the resultant free carriers. Further development of this method allowed imaging of the carrier density profiles with a resolution of a few acoustic wavelengths. In those measurements, the spatial position of the narrow pumping beam was adjusted by varying the frequency applied to a tapered IDT.

An alternative way was chosen by Santos et al. who measured the spatially resolved micro-reflectance and micro-photoluminescence. The first method was sensitive to the strain field and the second to the piezoelectric field of the SAW. In later studies by the same group, both those fields were probed using spatially and time-resolved PL measurements. The piezoelectric field leads to a type-II modulation in the plane of the QW, which is responsible for the spatial separation and trapping of e-h pairs, see Fig. 1.5 (b). On the other hand, the SAW-induced strain leads to a much weaker type-I modulation of the band gap and, thus, determines the excitonic recombination energies, see Fig. 1.5 (c).

Figure 1.5: Taken after Ref. 53. (a) Sample structure. (b) Calculated piezoelectric potential associated with the SAW. (c) Calculated strain-induced modulation of the electron and heavy-hole states of the conduction and valence band, respectively. (d) PL spectra in the absence of the SAW (solid line) and with the SAW (line with dots). (e) Time-resolved PL detected at the three energies indicated by the arrows in (c) and (d).
A moving lateral superlattice induced by the SAW can periodically deliver photo-generated electrons and holes to a given location on the crystal surface. Wiele et al.\textsuperscript{55} suggested a system in which this feature is used to periodically pump a quantum dot (QD) which then acts as a quasi zero-dimensional recombination center. In this scheme, when the surface acoustic wave passes the dot, the carriers trapped in the potential wells of the SAW can be captured by the QD. Since the wave delivers periodic sequences of electrons and holes, one after another, the radiative recombination also occurs in a periodic manner. A small quantum dot with only one electron and one hole level (i.e. with a single exciton state) could, thus, deliver a single photon per SAW cycle.

Bödefeld et al.\textsuperscript{56} demonstrated the first experimental results on the pumping of quantum dot arrays using the SAW. In their investigations, the SAW propagated on a mesa with InP self-organized QDs and an InGaAs quantum well underneath. Close to the driving IDT, the dots were etched away, providing a plain QW structure on about half of the sample area. The spatially-resolved PL spectra were then taken along the SAW propagation path; with and without the SAW. Their ratio indicated the change in the photoluminescence signal due to the SAW. In the QW region, no change was detected in PL since the spatially-separated electrons and holes were trapped in the potential wells of the SAW. However, on entering the region with QDs, a strong photoluminescence was observed. The dots, thus, acted as efficient recombination centers, periodically capturing the carriers from the SAW and then emitting the light.

In other studies, the radiative recombination on defects was investigated during the SAW-induced ambipolar transport in both quantum wells\textsuperscript{57} and quantum wires\textsuperscript{58-60}. Both spatially and time-resolved photoluminescence measurements were performed in order to track (in real time) the position of the charge packets, as the SAW carried them away from the illumination spot. For sufficiently strong SAW fields, the carrier recombination took place at a metal plate deposited across the quantum wire. However, for smaller SAW intensities, the charge could be captured by defect-induced trapping centers located along the surface-wave path. Electron and hole traps were identified, respectively, with qualitatively different properties: The first type captures electrons. When the holes arrive about half a SAW cycle later, they recombine with the trapped electrons. Correspondingly, the holes captured by the second type of trapping centers recombine half a wave cycle later when electrons arrive.

When the SAW transports the electron and hole packets along a quantum wire, they are additionally confined in the direction perpendicular to the SAW propagation. Three-dimensional confinement can be also achieved by combining two perpendicular SAW beams, as recently suggested by Govorov et al.\textsuperscript{51} and demonstrated by Alsina et al.\textsuperscript{62}. In such a configuration,\textsuperscript{62-64} the whole array of dynamic dots (DDs) moves along the diagonal direction between the two orthogonal SAW beams. The DDs efficiently transport electrons and holes over long distances as revealed in time and spatially-resolved photoluminescence. The
remote trapping centers can capture charge which, upon arrival of carriers of opposite polarity, recombines. Time-resolved PL taken at the trapping center locations reveal periodic light pulses with a cycle corresponding to the SAW frequency. When a trap is pumped by dynamic dots containing few carriers, Stotz et al.\textsuperscript{64} observe features which could be due to single carrier trapping and recombination.

The SAW potential can efficiently trap the photo-generated \( e^{-}h^{+} \) pairs, thus, prolonging their recombination lifetimes. In their first report on ambipolar charge transport in quantum wells, Rocke et al.\textsuperscript{40} already demonstrated an efficient delay line for light, see Fig. 1.4 (b). A photonic memory cell based on GaAs heterostructure with a QW was later demonstrated by Zimmermann et al.\textsuperscript{65,66} In these structures, the light is converted into \( e^{-}h^{+} \) pairs which are then trapped in a static potential superlattice imposed by interdigitated electrodes.\textsuperscript{67,68} When the bias voltage applied to the electrodes is removed, the potential modulation is switched off and the trapped charges released. They recombine, yielding a short and intense pulse of light. Very recently, Krauß et al.\textsuperscript{69} demonstrated photonic memory cells with the photo-generated \( e^{-}h^{+} \) pairs confined in all three dimensions. In order to achieve 3D confinement, oxide bars were deposited on the substrate prior to the deposition of the interdigitated electrodes. Oxide stripes and metal electrodes, perpendicular to each other, formed an array of 200 \( \times \) 125 optical pixels, over an area of 400 \( \times \) 500 \( \mu \)m. In their experiments,\textsuperscript{69} Krauß et al. demonstrated the storage and read-out of high quality photonic images, with the storing times of around 5 \( \mu \)s.

### 1.5 SAW-induced single-electron transport through quantum point contacts

In 1996, Shilton et al. extended their earlier investigations\textsuperscript{31,32} on the acoustoelectric effects in a 2DEG to the studies on the acoustic charge transport through a quantum point contact (QPC).\textsuperscript{70} The constriction of the QPC was electrostatically defined in the 2DEG by applying a negative voltage to the split-gate electrodes. In the open channel regime of the point contact (i.e. above conductance pinch-off), periodic oscillations were observed in the AE current as a function of the gate voltage, with minima corresponding to the quantized steps in the conductance (Fig. 1.6). This was explained in terms of the velocity matching between the SAW and slow electrons in the uppermost one-dimensional (1D) subband of the QPC. Within this model,\textsuperscript{70} only electrons with energies close to the Fermi level contribute to the acoustoelectric current. A strong interaction with the SAW takes place when their velocity approaches the sound velocity, i.e. when a new 1D subband opens.

Further studies\textsuperscript{71-73} by the same group resulted in a discovery of the integer AE effect. For gate voltages below conductance pinch-off, the acoustoelectric
current was found to be quantized in units of $e\ell$, where $e$ is the electron charge and $\ell$ the SAW frequency [Fig. 1.7 (a)]. This was attributed to trapping of a single or few electrons in the travelling minima of the SAW potential. Such packets of charge are then transferred across the potential barrier of the QPC. In the pinched-off regime, the top of this barrier is above the Fermi level and the bias-driven current flow is prohibited. A sufficiently powerful SAW can, however, drag electrons trapped in its potential minima across the barrier of the point contact. The number of electrons residing in each of those moving quantum dots is determined by the Coulomb interaction between them.

Early devices exhibiting the SAW-induced single-electron transport\textsuperscript{71-74} (called in the following the SETSAW devices) showed up to 5 quantized steps in the AE-current-versus-gate-voltage characteristics [Fig. 1.7 (a)]. Those samples were, however, plagued with the random-telegraph-signal (RTS) noise, which hindered a detailed analysis of the integer acoustoelectric effect. In later works by Cunningham \textit{et al.},\textsuperscript{75-79} the switching noise was substantially reduced. Up to $n = 15$ minima could be resolved in the AE current derivative that corresponded to the current plateaus at multiples of $ne\ell$ [Fig. 1.7 (b)].

Cunningham \textit{et al.} investigated as well the AE current behaviour in the presence of two counterpropagating SAW beams.\textsuperscript{75,77,79} A fine adjustment of the phase between those two beams enabled them to dynamically tune the moving quantum dots and, thus, to improve the precision of the current quantization.\textsuperscript{75,77,79} A significant reduction in the current slope at the first plateau was also observed when the quantum point contact was defined by shallow-etched trenches\textsuperscript{76-80} instead of the split-gates.\textsuperscript{71-75,79} In addition, when a weak magnetic field was applied perpendicularly to the 2DEG plane, the acoustoelectric current exhibited

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.6.png}
\caption{The acoustoelectric current and conductance as a function of gate voltage (after Ref. 70).}
\end{figure}
oscillations as a function of this field.\textsuperscript{76-79} They were reminiscent of those observed in Ref. 32 where the AE effects were investigated in the 2DEG.

In another study by the same group, Robinson \textit{et al.}\textsuperscript{81,82} investigated the low-frequency noise in the acoustoelectric current. When the current was away from the quantized value, Robinson \textit{et al.} observed pronounced noise due to the switching events between different impurity states. Close to the first AE plateau, the switching noise was, however, absent. Thus, the shot noise could be probed in this range and was found to be absent within the measurements errors.

Ebbecke \textit{et al.}\textsuperscript{83} managed to produce SETSAW devices operating at much higher frequencies (~5 GHz) than those used in Refs. 71-82 (~3 GHz). For a set of devices with center frequencies ranging from 1 to 5 GHz, no deterioration in precision of the quantized current was observed between them. Additionally, the quantization of the acoustoelectric-current was demonstrated for a device with two parallel quantum wires, operated at ~1 GHz. The same group investigated as well a system where the entrance to and exit from the QPC channel could be controlled by additional split gates.\textsuperscript{84} Little change was observed in the current characteristics when the shape of the QPC potential barrier was varied at the exit, i.e. on the side of the point contact where electrons were transferred to by the SAW. The current responded, however, much stronger to the modulation of the potential at the entrance to the 1D channel.\textsuperscript{84}
Recently, Fletcher et al. investigated the quantized acoustoelectric current in the limit of small rf powers ($P_{RF} < 0$ dBm). They found that the quantized steps in the current originate from the Coulomb blockade oscillations that are observed when no or very small rf power ($P_{RF} < -30$ dBm) is applied to the SAW transducer. This is illustrated in Fig. 1.8. Fletcher et al. suggested a transport mechanism alternative to the model of moving quantum dots. Within their approach, the SAW dynamically tuned the resonant states of an impurity-induced quantum dot that was formed in the vicinity of the QPC constriction. This would result in a turnstile-like operation of the device at the SAW frequency. In a more recent work, Ebbecke et al. demonstrated that similar behaviour of the AE current can be observed at low rf powers when the charge is transferred through an intentionally defined quantum dot.

### 1.6 Theoretical work on the integer acoustoelectric effect

A simple qualitative model explaining the AE current quantization was already suggested by Shilton et al. in their first experimental report. Within this picture, the travelling SAW minima are superposed on the static potential barrier of the QPC, as schematically depicted in Fig 1.9. They capture electrons at the entrance to the point contact and move up the potential hill of the QPC. Those local minima act as a chain of moving quantum dots. The number of electrons inside each dot is determined by the Coulomb repulsion between them.

Figure 1.8: (a) Grey scale coded plot of the numerical derivative $dI/dP_{RF}$ of the current with respect to gate voltage $V_g$ and power at the generator output $P_{RF}$. Grey in lower left corner corresponds to a zero derivative. Darker and lighter grey indicate positive and negative derivatives, respectively. (b) The same data as in (a) plotted with respect to the SAW amplitude instead of power. Lower panel shows the current at the lowest SAW amplitude. Taken after Ref. 85.
This qualitative explanation was further refined in a number of theoretical studies. Aizin et al. investigated the charge transport through a closed 1D wire, with one or two electrons captured in the SAW-induced quantum dot. They calculated the acoustoelectric current as a function of a dimensionless parameter \( \beta \), being the ratio between the SAW amplitude and the QPC barrier height. The stationary Schrödinger equation was solved at all times during the transport, using the adiabatic approximation. For the case of a single electron, the backward tunnelling was assumed as the only mechanism responsible for the electron escape from the dot. On increasing \( \beta \), the calculated AE current showed an abrupt step from zero to \( I_+ = e f \). Similar procedure was performed for two interacting electrons captured in the dot. The Coulomb interaction between those electrons was included into the calculations, apart from the backward tunnelling. A step-like dependence of the AE current \( I(\beta) \) was also demonstrated for this case.

The non-adiabatic effects during the formation of the moving quantum dot were investigated by Flensberg et al. Within their approach, the mechanism responsible for the development of the quantized steps in the AE current relies on the tunnelling coupling between the 2DEG and the SAW-induced dot. The SAW potential is assumed to be completely screened in the highly conductive region of the two-dimensional electron gas. On the other hand, the screening is reduced in the vicinity of the QPC. At the entrance to the constriction, the SAW forms a dot which moves away from the 2DEG at the sound velocity, as illustrated in Fig. 1.10. Therefore, the width of the tunnelling barrier between the dot and the 2DEG increases linearly with time. This results in a rapid decrease of the
tunnelling coupling with a characteristic time constant of $\tau \sim l_0/v_{SAW}$. Here, $l_0$ is the distance over which the localized wave function extends under the barrier.

Flensberg et al. estimate this time to be $\sim 10$ ps which indicates a very fast isolation of the dot from the 2DEG. As a result, the thermal equilibrium in the system cannot be maintained. This leads to an increased effective temperature of electrons in the dot and, hence, to the fluctuations of their number. Consequently, deviations can be observed from the quantized values of the acoustoelectric current. Flensberg et al. predicted the slope of the current at the first plateau $S_{\text{min}}$ to be proportional to:

$$S_{\text{min}} \propto (2E_C/T_{\text{eff}}) \exp(-E_C/T_{\text{eff}})$$

where $E_C$ is the charging energy and $T_{\text{eff}}$ the effective electron temperature in the dot. Hence, the gradient of the acoustoelectric current at the plateau is very sensitive to the ratio $E_C/T_{\text{eff}}$. Using the model by Flensberg et al., the effective temperature can be determined in the experiment by probing the slope of the AE current both at the plateau $S_{\text{min}}$ and in-between them $S_{\text{max}}$, see section 3.9.

Another approach towards acoustoelectric single-electron effect was presented by Robinson and Barnes. They used a classical model to describe the dynamics of interacting electrons in the SETSAW devices. Within this model, the moving quantum dot captures a large number of electrons ($\sim 30$) from the 2DEG reservoir. The size of the dot is reduced as it enters the QPC channel. As a result, electrons are forced out of it. At low temperature ($T < 1.7$ K), the electrons trapped inside the dot form a crystal. When one of them leaves, the remaining ones are left in an excited state and need to rearrange to a configuration with lower potential energy, as illustrated in Fig. 1.11. Approximately half of the excess potential energy is converted into the kinetic energy, resulting in heating. The temperature of electrons is elevated up to around $1.7$ K which enhances their probability to escape from the dot. This deteriorates the slope of the AE current at the quantized step. If the initial temperature is higher than $1.7$ K, the situation is different. The electron crystal melts into a more liquid-like state. In such case,
When one of the electrons leaves the dot, the evaporative cooling is observed in this system instead of heating.

Another mechanism that could explain the quantized acoustoelectric transport was investigated by Aharony et al.\textsuperscript{95} They relate the AE current quantization to the quantum adiabatic pumping of non-interacting electrons. Within their model, the external potentials due to the gates and the SAW are assumed to be completely screened in the area of 2DEG. They become effective only in the quantum wire, where their effect is modelled by a simple rectangular barrier with a superposed travelling potential of the SAW. In this approach, the electrons are never excited above the Fermi level, unlike in the models described above. The calculations by Aharony et al.\textsuperscript{95} yielded the AE current staircases as a function of the gate voltage. In the recent study by the same group, Kashcheyevs et al.\textsuperscript{96} considered as well the effects of the counterpropagating SAW beam and the source-drain bias on the AE current quantization. In particular, proper adjustment of the phase of the second beam was found to enhance to precision of the quantization.

\section*{1.7 Motivation for the present work}

The SAW-induced single-electron transport is considered to be an attractive proposal towards a quantum standard of electrical current.\textsuperscript{97} The existence of such a standard would enable to close the quantum metrology triangle of electrical units of current, voltage and resistance. This, in turn, would allow the
determination of the fundamental constants: the electron charge $e$ and Planck’s constant $\hbar$. The SAW-based approach offers much higher frequency of operation (few 1 GHz) than other electron pumps.\textsuperscript{99-101} For intrinsic reasons, the latter devices operate at frequencies of order of 10 MHz, resulting in a small output current of about 10 pA. In contrast, the SETSAW pumps can produce current in the 1 nA range. However, their accuracy\textsuperscript{75,76} (~100 ppm) still limits their metrological applications where accuracies of order of 0.1 ppm are required.

The work by Cunningham \textit{et al.}\textsuperscript{76-78} indicated that the precision of the AE current quantization can be improved if the shallow-etched technique is used to define the 1D constriction. At the time their study was presented, the fabrication of shallow-etched quantum point contacts was already well established in our group.\textsuperscript{102} In fact, the QPCs used in the SETSAW devices of Refs. 76-78 were manufactured in Copenhagen by Dr. Anders Kristensen. In the course of this work, we have demonstrated some improvement in the precision of the quantized AE current. However, the obtained accuracies are still two orders of magnitude worse than those required by the metrological community.

The SETSAW pumps could also be used as a key component of a single-photon-on-demand source. Such sources are intensively sought after\textsuperscript{103} for quantum cryptography applications.\textsuperscript{104} In the novel approach based on the SETSAW structures,\textsuperscript{105} the surface acoustic wave propagates along a lateral n-i-p junction. In the first stage, the electrons from the 2DEG reservoir (n-type region) are captured at the entrance to the QPC by the SAW-induced quantum dot (Fig. 1.12). Only single electrons per SAW cycle are allowed to pass the point contact. Unlike in the previous work on the quantized AE current, there is no 2DEG on the other side of the constriction. Instead, the surface wave injects electrons into the p-type region. The electrons can recombine there with the holes, emitting single photons.
The development of a single-photon source based on the above approach was the main objective of the European Commission FET project SAWPHOTON, in which we participated. The fabrication and characterization of the SETSAW pumps was one of our main inputs into the project. It has to be noted that another SAW based approach towards single-photon was suggested by Wiele et al. They proposed to use the static quantum dots as recombination centers for the photogenerated electron-hole pairs trapped in the SAW minima, as discussed in section 1.4.

Among other interesting proposals involving the AE current quantization is the work by Barnes et al. They suggest to use the spins of the single electrons trapped in the SAW minima as the quantum bits for the quantum computation schemes. They demonstrate the feasibility of such an approach for single and two-qubit operations. This involves a proper design of adjacent channels for the SAW-driven electrons and a pattern of magnetic and non-magnetic surface gates. Recent reports on similar schemes can be found in Ref. 107,108.
Chapter 2

Device fabrication

Figure 2.1 shows a schematic layout of our SAW-based SET devices. The sample is fabricated on a GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG) situated approximately 80 nm below the surface. The 2DEG layer is removed from most of the device apart from the mesa in the center of the chip. A quantum point contact (QPC) is defined there by two semicircular shallow-etched trenches that form a smooth constriction between the electron reservoirs to the left and to the right, respectively. Large 2DEG areas aside the QPC channel are used as side-gates, as indicated by shaded regions in Fig. 2.1. Finally, two aluminium interdigital transducers (IDTs) are deposited outside the mesa. The IDTs are facing each other and the distance between their centers is approximately 2.5 mm. The quantum point contact is in the middle of the pathway between the two transducers.

Here, we describe the fabrication of our SETSAW devices. In general, this was a lengthy process, requiring three UV lithography stages as well as three electron-beam exposures. Although standard GaAs processing techniques were used, a lot of time and effort was spent to optimize the processing procedures and parameters. This was particularly important for fine structures of our devices: QPCs and IDTs. Due to their sub-1 μm features, they had to be patterned with the electron-beam lithography. All the device processing was performed by the author at the clean-room facilities of III-V Nanolab.

2.1 Wafer selection

Our samples were fabricated on modulation doped GaAs/AlGaAs heterostructures grown by Dr. Claus B. Sørensen in a Varian GEN-II molecular-
beam-epitaxy (MBE) system at the III-V Nanolab. In the course of this project, four high-electron-mobility-transistor (HEMT) wafers were used: HCO456, HCO533, HCO99-92 and HCO103-92. Their growth sequence and basic 2DEG parameters are listed in Table 2.1 and 2.2, respectively.

In order to select a wafer for further processing of SETSAW devices, we used a few practical criterions. First, we looked for heterostructures with a high electron mobility (typically with $\mu > 50 \text{ m}^2/\text{V} \cdot \text{s}$ at $T = 10 \text{ K}$) which should indicate a low density of impurities in those wafers. Our main motivation was to reduce the random-telegraph-signal (RTS) noise in the acoustoelectric current. This type of noise plagued our early devices, as described in section 3.6.2. Second, we checked whether the selected wafer was available in pieces that were large enough (about 11 × 13 mm) to accommodate 6-10 devices, each of 2 × 6 mm. Several samples were typically fabricated on a single chip in order to increase their reproducibility and to reduce the fabrication time. Finally, the wafer surface was inspected in the optical microscope. Scratches and/or defects were hardly desirable, especially, in the regions where IDTs or QPCs were to be located. Such defects could cause fabrication faults of those components as well as increase the propagation losses of the SAW.

The chosen wafer was cut with a diamond scriber into chips of desired size. They were typically 11 × 13 mm, large enough to contain 10 SETSAW devices. Great care was taken to obtain the SAW propagation along the $\langle 011 \rangle$ direction on (100)-cut GaAs wafers that were used by us. Even small ($\sim 2^\circ$) deviations from this direction could gravely affect the SAW propagation and result in a rapid increase of the SAW attenuation. Thus, the position of the wafer

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Figure 2.1: Schematic diagram of the sample layout: A quantum point contact (QPC) is defined in the 2DEG mesa using a shallow-etch technique. Four Ohmic contacts (1-4) provide electrical connection to the electron reservoirs on both sides of the constriction. Shaded regions are the reservoirs which serve as the side gates (G). Two interdigital transducers (IDTs) are deposited on opposite sides of the mesa.
Table 2.1: Growth sequence of four HEMT wafers used for our devices: HCO456, HCO533, HCO99-92 and HCO103-92. The position of the 2DEG plane is indicated with an arrow.

<table>
<thead>
<tr>
<th></th>
<th>HCO456</th>
<th>HCO533</th>
<th>HCO99-92</th>
<th>HCO103-92</th>
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</table>

Table 2.2: Basic 2DEG parameters for the heterostructures listed in Tab. 2.1: $\mu$ the electron mobility; $n_{2D}$ the carrier concentration; $R_c$ the square resistance; $\varepsilon_F$ the Fermi energy; $l_m$ the mean free path; and $\lambda_F$ the Fermi wavelength. All determined at $T = 10$ K in the dark.

<table>
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<th>wafer name</th>
<th>$\mu$ (m$^2$/V s)</th>
<th>$n_{2D}$ ($\times 10^{15}$ m$^{-2}$)</th>
<th>$R_c$ (Ω/□)</th>
<th>$\varepsilon_F$ (meV)</th>
<th>$l_m$ (µm)</th>
<th>$\lambda_F$ (nm)</th>
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<td>21</td>
<td>10.0</td>
<td>9.2</td>
<td>47</td>
</tr>
</tbody>
</table>
was precisely aligned in the scriber so that the cleaved edges were parallel to the base cuts of the wafer, marking the (011) directions.

### 2.2 Optical lithography

#### 2.2.1 Mesa

Electric fields accompanying the surface acoustic wave couple to mobile carriers in the 2DEG layer.\(^{18,20}\) To avoid this capacitive coupling, the 2DEG is removed from most of the sample using the wet chemical etching. During this procedure, the mesa is formed in the central part of the device, remaining the only region where the two-dimensional electron gas is left intact.

The chip cut from the HEMT wafer is rinsed in acetone, methanol and isopropanol and blown dry with nitrogen. The positive AZ 4511 resist is deposited onto the chip and spun at 4000 rpm for 40 s, yielding a 1.1 \(\mu\)m-thick film. To harden the resist, the sample is baked for 45 s at 115°C. The chip is then transferred to a Karl Süss MJB3 HP mask aligner where a mask with the mesa pattern is carefully aligned with respect to the edges of the wafer, oriented along (011) and (011) directions. The mask is brought into a direct contact with the chip and the resist is illuminated with an ultraviolet light. The AZ 400K developer removes the resist from the exposed areas and its residues are ashed for 25 s in the oxygen plasma. The wafer is then etched for 60 s in a solution of \(\text{H}_3\text{PO}_4\) (85\%) : \(\text{H}_2\text{O}_2\) (30\%) : \(\text{H}_2\text{O}\) (1:1:38 by volume). Since the etch rate of this composition is about 100 nm/min, all the wafer layers are removed down to the depth of around 100 nm. This includes the 2DEG plane located at a GaAs/AlGaAs heterojunction 70÷90 nm below the surface, depending on the chosen wafer. The mesa remains the only region where the 2DEG is intact. The sample is cleaned in acetone, methanol and isopropanol to remove the resist from the unexposed areas.

A schematic diagram of the mesa-etch procedure is illustrated in Fig. 2.2, whereas a set of three optical masks used at different stages of UV-lithography is shown in Fig. 2.3.

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**Figure 2.2**: Schematic diagram of the mesa-etch procedure: (a) resist deposition, (b) UV exposure, (c) development of the exposed resist, (d) wet etch of the exposed areas, (e) removal of the remaining resist.
Figure 2.3: Set of optical masks used for the fabrication of SETSAW devices. See text for the description of separate stages of the UV lithography.
2.2.2 Ohmic contacts

Electrical contacts to the 2DEG layer are necessary to operate the device. Hence, an around 200 nm-thick sandwich of metals (Ge/Au/Ni/Au) is deposited onto selected parts of the mesa. After annealing, a eutectic alloy is formed which diffuses into the wafer. This provides an n-type Ohmic contact to the two-dimensional electron gas. Note that the thick metal sandwich is also deposited outside the mesa, as shown in Fig. 2.3. Some of those additional metallized areas are used as thick bonding pads to the interdigital transducers; others form large contacts which are grounded during the measurements of the AE current.

Figure 2.4 schematically illustrates the ‘lift-off’ procedure which is performed in order to fabricate the Ohmic contacts. The sample is thoroughly cleaned, and the AZ 4511 resist is spun onto the chip as in the previous lithographic stage. An optical mask with the pattern of Ohmic contacts (Fig. 2.3) is used during the UV exposure. The resist is developed in the AZ 400K developer. Its residues are ashed in the oxygen plasma and then removed in a solution of \( \text{NH}_3 : \text{H}_2\text{O} \) (25% : 1:15 by volume). The sample is rinsed in millipore water and immediately afterwards mounted into the electron-beam evaporator. The chamber of the evaporator is pumped down to \( 10^{-7} \) torr. Four layers of metal are then subsequently deposited onto the sample: 40 nm of germanium, 60 nm of gold, 27 nm of nickel and 200 nm of gold. During this process, a crystal gauge controls the growth rate and the thickness of the evaporated metal. The sample is taken out of the evaporator and immersed into acetone. Acetone dissolves the resist, thus, lifting off the metal from the unexposed areas. The metal sandwich is only left in regions illuminated with the ultraviolet light. If the lift-off is slow, the acetone is heated or ultrasound is applied. The sample is cleaned and placed into a furnace where metal layers are annealed for 1 min at \( T = 420°C \) under a constant flow of nitrogen. Ohmic contacts are then tested with the HP 4145B semiconductor parameter analyzer.
2.2.3 Optical metallization for the transducers

The interdigital transducers are defined by electron-beam lithography. However, they are not directly connected to the metal pads deposited outside the mesa while processing the Ohmic contacts (see Fig. 2.3). This is because an approximately 70 nm-thick metallization of the IDTs could break at the edges of those ~200 nm-thick contacts. Therefore, a much thinner Cr/Au (15 nm/60 nm) metallization is deposited onto the chip during a separate stage of UV lithography, partially overlapping the thick contacts (Fig. 2.3). The same ‘lift-off’ procedure is employed as the one described in the previous section.

2.3 Electron beam lithography

The fine components of our devices, QPCs and IDTs, are defined with the electron beam lithography, using JEOL JSM-6320F scanning electron microscope (SEM) with a field emission electron gun. The position of the electron beam is controlled by the Raith Elphy-III control box. The electrostatic Deben Research beam blanker can remove the electron beam from the exposure area. The structures are patterned using the Raith Elphy software.

The processing steps are similar to those described for the optical lithography. The sample is thoroughly cleaned to remove any contamination from its surface, in particular, to get rid of hard-baked resist residues from the previous processing stages. The chip is kept in hot acetone for approximately 4-5 min, and rinsed in methanol and isopropanol. It is then ashed for 20 s in the oxygen plasma and deoxidized in HCl (18%) for 30 s. After rinsing in millipore water, the sample is left for 7 min on a hot-plate at \( T = 185^\circ C \). A positive PMMA resist, sensitive to the electron irradiation, is then spun onto the chip for 60 s at 6000 rpm. Different PMMA solutions (in anisole) are used to define quantum point contacts and interdigital transducers. A thick layer of resist is required for a satisfactory lift-off when 60÷70 nm-thick electrodes of the IDTs are to be deposited onto the chip. Therefore, a 6%-solution of PMMA is chosen in such case, yielding a resist film of about 180 nm. On the other hand, when the quantum point contacts are to be defined by the shallow-etch technique, 2% PMMA is used. In both cases, the electron-beam-sensitive resist is hard-baked on a hot plate at \( T = 185^\circ C \). The baking time is 5 min and 20÷30 min when the QPCs and the IDTs are to be patterned, respectively. This concludes the sample preparation prior to the e-beam exposure.

2.3.1 Shallow-etched quantum point contacts

In our devices, quantum point contacts are defined by two shallow-etched semicircular trenches\(^{102}\), which form a smooth constriction between electron reservoirs, as illustrated in Fig. 2.5 (a). Since the trench depth is about 50-60 nm,
only the heavily n-doped active layer is etched away. The AlGaAs/GaAs interface, at which the 2DEG layer is formed, is left intact (see Tab. 2.1 for the growth sequence of our heterostructures). However, the surface states deplete the two-dimensional electron gas underneath the trenches.

During the exposure, the scanning electron microscope is operated at an acceleration voltage of 30 kV. The SEM magnification is set to 1100× which results in a write-field size of 66 × 66 µm. The aperture and condenser lenses are adjusted in such a way that the resulting e-beam current is about 35÷50 pA. The QPCs are drawn in a single pass of the electron beam. The exposed resist is developed for 60 s in a solution of methyl isobutyl ketone (MIBK) in isopropanol (1:3 by volume); post-baked for 7 min at 185°C; and ashed for 6 s in the oxygen plasma. The trenches are then etched for 25 s in a solution of H₃PO₄ (85%) : H₂O₂ (30%) : H₂O (1:1:38 by volume). Thus, an approximately 50 nm-thick layer is removed from the wafer in the exposed areas.

The trenches etched in our devices are typically ~200 nm-wide. Most of them have a 1 µm-long straight segment added at the center of the constriction, as shown in Fig. 2.5 (a). In the course of this project, different radii of curvature of the semicircular sections were used. Table 3.1 lists those values for eight SETSAW devices that exhibited the AE current quantization. The geometrical width of the QPC channel formed by the two shallow-etched trenches was typically around 200÷250 nm [Fig. 2.5 (a)].
2.3.2 Interdigital transducers

The electron-beam lithography is also used to define the IDTs on opposite sides of the 2DEG mesa. Each transducer consists of 80 pairs of interdigitated fingers, typically, with a spacing of \(d \approx 1.15\ \mu m\) between electrodes of the same polarity. This yields a fundamental SAW frequency of \(f_o \approx 2.5\ GHz\).

The definition of a large grating of closely spaced electrodes is hindered by the proximity effect. Electrons backscattered from the wafer can irradiate the resist outside the center of the e-beam. A partial exposure from the neighbouring areas builds up, setting a limit for the minimum spacing between patterned features. To correct for the proximity effect, the IDT electrodes in our designs are only 0.04 \(\mu m\) wide. After their exposure and metal deposition, ~0.2 \(\mu m\)-wide fingers are, however, acquired in the final structures. To prevent the over- or underexposure of the resist due to unstable electron-beam currents, the same finger pattern is drawn in four consecutive passes.

In the course of this project, we managed to fabricate interdigital transducers with the electrode spacing of down to \(d \approx 0.9\ \mu m\). Nevertheless, most of our IDTs had a pitch of \(d \approx 1.15\ \mu m\). A large portion of the transducers was fabricated in a single-stage e-beam process, where both fingers and contact pads connecting electrodes of the same polarity were exposed at the same time. However, using this method, we sporadically encountered problems with lifting-off the metal from the areas between electrodes. Towards the end of the project, a two-stage scheme was thus preferred, where fingers and their contact pads were exposed in two separate electron-beam-lithography sessions.

In the single-stage process, a Cr/Al (15 nm/65 nm) metallization is deposited onto the sample. When the two-stage method is chosen, about 65 nm-thick fingers of aluminium are fabricated in the first stage. After the second e-beam exposure, Cr/Au (15/65 nm) pads are added, which connect electrodes of the same polarity with the large-area Cr/Au contacts previously defined by the optical lithography (see section 2.2.3). In fact, the e-beam-defined pads are large enough (200 \(\times\) 60 \(\mu m\)) to be fabricated using the optical lithography, too. However, standard developers used in our laboratory for the UV resists are based on KOH or NaOH. Thus, when those developers are applied, aluminium fingers are dissolved in the areas exposed to the ultraviolet light.

2.4 Sample mounting

When all the device components are fabricated, a chip containing 6-10 samples is cleaved into individual devices (2 \(\times\) 6 mm). The samples are mounted onto copper chip carriers (Fig. 2.6), being a copy of holders designed at the Cavendish Laboratory by Dr. Valery Talyanskii and Dr. Julian Shilton. The main idea behind this design\textsuperscript{75} is to reduce the crosstalk by confining the sample into a
metal cavity with dimensions much smaller than the wavelength of the airborne rf signal (of order of 10 cm at 2.5 GHz).

A silver epoxy is used to attach the sample to the chip carrier. Such a conducting layer reduces the bulk wave reflections from the bottom of the device and improves the thermal contact between the sample and the holder. Pieces of ceramic packages with large bonding pads are glued to the chip carrier. The Karl Süss bonder is used to make an electrical connection between those pads and the dc contacts on the sample. The chip carrier is then mounted onto a copper block with two microwave SMA connectors (Suhner 23 SMA-50-0-13 receptacles with coaxial end), as shown in Fig. 2.6. Thin gold wires are bonded directly to the gold-plated inner conductors of the SMA connectors and to the pads on the holder that are in electrical contact with one of the two sets of the IDT electrodes. The other set of electrodes is bonded to the sample holder itself. Gold wires connect as well the dc contacts on the chip carrier with the corresponding contacts on the copper block. When the bonding is completed, a copper shield is placed on top of the sample holder and finally confines the sample within a small metal cavity.

The copper block with an attached chip carrier can be easily mounted onto our probes. The SMA jacks of the block are connected with their counterparts at
the end of the microwave lines on the probe. On the other hand, retractable plugs connect the dc contacts of the block with the dc wiring of the probe. Once the sample is found to show the AE current quantization, it is not removed from such a fixing. New devices are then mounted on other carriers/blocks. This allows a fast replacement of the investigated samples or their transfer between different probes. At the same time, this ensures that the electrical connections are not altered during a transfer.
Chapter 3

Device characterization

Due to the large number of relevant parameters, the characterization of SETSAW devices is a complex task. Quantized AE current can be studied as a function of the gate and bias voltage, SAW amplitude and frequency. Those different types of measurements are analyzed in detail in the following chapters. Here, we describe the initial stages of the device characterization. That includes an assessment of the main components of the SETSAW device: 1) When the surface acoustic wave is not yet applied, the conductance \( G(V_g) = \frac{dI(V_g)}{dV_{sd}} \) as well as the \( I(V_{sd}) \) characteristics provide information on the properties of the quantum point contact. 2) When the SAW is on, the efficiency of the transducers is determined from the transmittance measurements. Those experiments are followed by initial scans of the AE current with respect to the SAW frequency \( f \) and to the gate voltage \( V_g \). They allow us to determine the passband of the driving transducer and make an attempt to find the quantized AE plateaus in units of \( e_f \).

3.1 Low temperature systems

Measurements performed in the course of this study were carried out in three different cryogenic systems, all fitted with microwave coaxial lines for SAW-related experiments. A bulk copper holder described in section 2.4 could be directly attached to the SAW lines in any of those three systems. Therefore, a sample transfer to either of them did not require to break the bonding wires or to dismount the copper lids covering the chip carrier. Such design of the cryogenic systems and the retractable sample holders reduced to minimum any risk of damage to the device that could occur during repetitious mount/dismount procedures.
Preliminary measurements of the SETSAW devices were performed in a helium dewar at $T = 4.2$ K. In the experiments where the SAW was applied, a special care had to be taken not to immerse the device into the liquid $^4$He, which dampened the SAW. The position of the probe with respect to the surface of the liquid helium was adjusted while taking the transmittance spectra (see section 3.5 for details). The probe was lowered until the transmittance peak at the correct centre frequency was dampened, thus indicating that the surface of the liquid was reached. The probe was then raised a little to recover the transmittance peak.

The majority of our measurements were performed in the second cryogenic system with $\sim 1.7$ K base temperature. This small $^4$He fridge was designed by Dr. Kurt Gloos and fabricated at our laboratory’s Central Workshop by Mr. Carsten Mortensen. Its design is based on a standard dipping probe that is inserted into a helium dewar. The sample space of such a modified probe is contained inside a vacuum can where a 1 K pot is additionally located. Prior to loading it into the $^4$He dewar, the can is pumped, and then filled with a small amount of $^4$He exchange gas. When the probe is inside the dewar, the 1K pot is filled with liquid helium. By pumping it, its boiling point is reduced below 4.2 K. The resulting base temperature of $\sim 1.7$ K is measured by an Allen Bradley carbon resistor thermometer located at the 1 K pot and a Matsushita carbon resistor at the sample holder. Two stainless steel microwave coaxes go from the top of the probe (at room temperature) down to the 1 K pot. Below that point, they are replaced with copper coaxes in order to provide good thermal contact between the 1 K pot and the sample holder.

The simplicity of the operation as well as a short time necessary for the sample replacement was a key advantage of this refrigerator. It allowed testing a large number of samples in a short time at temperatures down to 1.7 K. On the other hand, longer measurement sessions at base temperature were only limited by the amount of helium that was left in the dewar. In other words, the measurements at 1.7 K were possible as long as the entrance to the tube supplying liquid $^4$He into the 1 K pot was above the $^4$He surface in the dewar. Our 100 dm$^3$ helium containers were sufficient for around four weeks of continuous measurements, when large rf powers of up to 15 dBm were applied to the SAW transducers. After that time, though the base temperature of 1.7 K could no longer be reached, approximately 30 dm$^3$ of liquid $^4$He were still left in the dewar.

The third cryogenic system at our disposal was an Oxford Instruments $^3$He top-loaded cryostat with a base temperature of 300 mK. This refrigerator was located at the Department of Physics of Technical University of Denmark (DTU) in Lyngby. In order to use it for the SAW-related experiments, a new insert with two stainless steel rf lines was ordered from Oxford Instruments by Dr. Rafael Taboryski from Danish Institute of Fundamental Metrology (DFM).

The operation principles of this commercial cryogenic system can be found in Ref. 110. In order to cool the sample space below 4.2 K, the 1 K pot is filled with $^4$He from the main bath and pumped to reduce the vapour pressure. Its
temperature drops then to 1.2 K. In the next step, a charcoal sorption pump is heated to ~45 K to release $^3$He gas which it contains. The $^3$He gas condenses on the cold 1 K pot and runs down to the sample space. When all gas is condensed, the heater wound around the sorption pump is turned off. The sorption pump starts to work and reduces the vapour pressure above the liquid $^3$He. The sample temperature goes down to ~300 mK.

As in the case of the dipping station, care had to be taken not to immerse the sample into the liquid $^3$He. However, we rarely performed the SETSAW experiments at the base temperature. When the cryostat was operated at around 300 mK, a powerful microwave signal (up to +15 dBm) caused a very fast (10-20 minutes) boil-off of the liquid $^3$He and a correspondingly abrupt increase in temperature. Therefore, to perform the measurements in more stable conditions, we only operated the fridge at relatively high temperature of ~1.2 K. The sorption pump was then kept at ~30 K to release sufficient amount of $^3$He exchange gas and keep the sample in good thermal contact with the 1 K pot. However, even then the read-out of the temperature sensor (located close to but not on the sample holder) increased to around 1.7 K when the microwave power of around +15 dBm was applied to the SAW transducer.

The fact that this $^3$He refrigerator was bound to operate above 1.2 K whenever the SAW was applied as well as its location outside our own laboratory made us perform majority of our measurements in the in-house built cryogenic system described before. This small fridge had a base temperature only slightly higher than 1.2 K. Moreover, in either system, the rf power for generating the SAW raised the 2DEG temperature. More details on the rf heating effects observed in our devices are provided in section 3.9, where the 2DEG itself was used as a temperature sensor.\textsuperscript{111}

### 3.2 Measurement setup and data acquisition

Figure 3.1 shows schematically a typical voltage-controlled measurement setup used in the course of this work. In general, it allowed us to measure the current $I$ flowing between the source and drain contacts of the quantum point contact. In particular, when this was the AE current generated by the SAW, the microwave signal applied to the SAW transducer was not pulse-modulated. In other words, a dc technique was always used to measure the AE current across a pinched-off QPC.

However, in addition to the current, we frequently recorded its derivatives with respect to the gate voltage $dI/dV_g$ (transconductance) and to the source-drain bias $dI/dV_{sd}$ (conductance). Those derivatives were measured using standard lock-in techniques. Depending on the measurement configuration (and its goals), the excitation amplitudes were set to $dV_g = 0.1\div1$ mV and $dV_{sd} = 0.01\div1$ mV at 10÷130 Hz (though typically at 17 Hz and 117 Hz).
Figure 3.1: Schematic diagram of the measurement setup. The voltage signals are generated by the digital-to-analogue converters (DAC) and/or signal generators. Opto-couplers (opto) are used to break the ground loops. Voltage dividers enhance the resolution of the signal applied to the sample. The output current from the sample is collected by a current preamplifier which transforms it into a voltage signal. Its dc component is detected directly by the analogue-to-digital converter (ADC). The ac components are detected by lock-in amplifiers whose outputs are connected to other ADCs.
The components of the circuit diagram 3.1 are briefly discussed here. 16-bit National Instruments (NI) digital-to-analogue converters (DACs) supply the dc voltages to the circuit. The DACs provide voltages in the range between $-10$ V and 10 V with 16-bit resolution. The ac signals are generated with a HP 3325A signal generator or internal oscillators of the lock-ins. All input signals run through Burr-Brown ISO-100 optical isolation amplifiers (opto-couplers) powered on batteries. The opto-couplers isolate the electrical setup from the surrounding, effectively breaking the ground loops. The signals are divided and added in appropriate voltage dividers, which enhance their resolution. Selection of the divider boxes depends on the measurement configuration. For example: 1:4 division is typically used for the dc component of the gate voltage, and $1:10^3$ for its ac component. The signals then run through Ferroperm ceramic low-pass ($\pi$) filters, and are applied to the appropriate contacts of the QPC.

The output current is measured with an Ithaco DL1211 low-noise current-preamplifier, which converts the current into a voltage signal. For AE current measurements, its amplification is typically set to $10^9$ V/A. The output signal then runs through another opto-coupler. The signal is then split, and its dc component is read with a 16-bit NI analogue-to-digital converter (ADC). The ac component(s) are measured with lock-in amplifiers (EG&G Princeton 5208 or 5210 or Stanford SR530 are available). The analogue voltage outputs of the lock-ins are also read with NI ADCs.

The measurement setup is controlled with a ‘sweepVfPstep’ program that was created by me in the NI LabView environment. The program provides extensive control over the available output signals: dc voltages (from NI DACs); rf power and frequency (from Agilent 8648D or HP 8673B synthesized signal generators). Input signals are read from the NI ADCs.

In the ‘2D’ operation mode, up to three different output signals can be swept simultaneously. If required, the only link between those three independent signals can be the number of measurement steps and the sweep delay. On the other hand, up to 8 different input signals can be collected simultaneously. They can be adequately rescaled and plotted with respect to the applied output signals or, if necessary, to the other input signals. Up to three signals (transformed or not) can be recorded with respect to a specified parameter. However, an option exists to record all the input and output signals in their raw form.

In the “3D” mode, it is also possible to step values of up to three independent outputs, while sweeping other outputs (also up to three). It is very useful when a precise measurement is required with respect to one parameter at fixed values of another parameter. This allowed us, for example, to collect simultaneously the $I(V_g, P_{RF})$ and $dI(V_g, P_{RF})/dV_g$ characteristics (see chapter 5) or the $I(V_g, f)$ and $dI(V_g, f)/dV_g$ characteristics (see chapter 6). Large matrices of data (with $10^4 \div 10^6$ data points) were typically taken during such measurements, which could last from 3 to 15 hours.
3.3 Conductance without the SAW

In an early stage of a SETSAW device characterization, we measured the conductance (without the SAW) of the quantum point contact, \( G(V_g) = d(I(V_g))/dV_{sd} \). Those measurements provided preliminary information on the QPCs’ properties. We were particularly interested in determining the pinch-off gate voltage, below which the 1D channel of the point contact was closed. Apart from the conductance, we also monitored the leakage current to the gates. If the gate-voltage range between a low-\( V_g \) threshold for leakage and the conductance pinch-off was smaller than around 200 mV, the device was discarded from further SETSAW experiments. This was because, in order to observe pronounced quantization of the AE current, large rf powers (~10 dBm) had to be applied to a SAW transducer. At those power levels, the onset of the SAW-driven current was about \( \Delta V_g = 100 \div 200 \text{ mV} \) below pinch-off for \( G \). On increasing the microwave power, the current onset could be further lowered towards more negative gate voltages. Therefore, we chose only those devices which did not exhibit parasitic leakage currents in the \( V_g \)-range relevant for SETSAW experiments.

For the conductance measurements, we used the same setup as illustrated in Fig. 3.1. A small \( \sim 10 \mu \text{V} \) ac voltage was applied to the source contact of the QPC, while the drain contact was kept at the virtual ground of the current preamplifier. The frequency of the ac excitation was normally 117 Hz. The resolution of the ac and dc components of the bias voltage was improved by incorporating voltage dividers (1:10\(^4\) and 1:10\(^3\), respectively) into the corresponding signal lines. No ac modulation was applied to the gate voltage, and the DL1211 current preamplifier was typically set to 10\(^6\) V/A.

Figure 3.2 (a) shows examples of the conductance characteristics for three SETSAW devices: HC0103-92-31022-2B, 2C and 2E. The data are corrected for a 600 \( \Omega \) series resistance of the contact pads and the 2DEG. The conductance traces show plateaus at regular intervals, however, considerably below the ideal multiples of \( 2e^2/h \). This deviation from the expected value cannot be overcome by simply correcting for a larger series resistance, which only results in an increasing spacing in \( G \) between consecutive plateaus. Similar reduction in the conductance quantization was previously observed in studies on long quantum wires,\(^{112-114}\), and attributed to additional electron scattering inside the channels and an enhanced role of electron-electron interactions. This could also be a plausible explanation for our long QPCs. Additionally at temperatures \( T \ll 2 \text{ K} \), all the investigated devices exhibited pronounced conductance fluctuations [Fig. 3.2 (b)], which would indicate the presence of impurities in the vicinity of the constriction.

Fine features in the conductance are easier to resolve in its derivative \( dG/dV_g \). Figure 3.2 (c) shows a grey scale coded plot of \( dG/dV_g \) as a function of the gate and bias voltage. The data were taken for sample 2E at 1.7 K. Dark regions correspond to plateaus in \( G(V_g) \), whereas light colour indicates transitions between those plateaus.
Figure 3.2: Conductance $G$ as a function of gate voltage $V_g$. (a) Traces acquired for samples HCO103-92-30122-2B, 2C and 2E at $T = 1.7 \, \text{K}$. The data were corrected for series resistance of 600 $\Omega$. (b) The conductance measurements taken at three indicated temperatures for sample HCO99-92-21024-2A. The data were not corrected for series resistance. (c) Grey-scale coded plot of the conductance derivative $dG/dV_g$ with respect to gate voltage $V_g$ and source-drain bias $V_{sd}$ for sample HCO103-92-30122-2C. Dark (light) indicates low (large) magnitude of the conductance derivative. $T = 1.7 \, \text{K}$. 

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Plots of this type are often used to reveal the energy shifts of consecutive 1D subbands. In Fig. 3.2 (c), a series of diamonds can be resolved in \( \frac{dG}{dV_g} \), with their centers positioned along a horizontal line at \( V_{sd} = 0 \). Crossings between the transition lines that occur at zero bias indicate gate voltages for which the \( n \)-th subband \( \varepsilon_n \) is well aligned with the chemical potentials on both the source and drain side of the quantum point contact. On the other hand, crossings that occur away from \( V_{sd} = 0 \) are a direct measure of the subband energy spacing at fixed gate voltage. For example, \( \varepsilon_3 - \varepsilon_2 \approx 2.2 \, \text{mV} \) at \( V_g \approx 215 \, \text{mV} \) [Fig. 3.2 (c)]. Our shallow-etched devices with long QPC channels typically exhibited \( \varepsilon_1 - \varepsilon_0 \approx 2\div4 \, \text{mV} \).

### 3.4 Estimating the barrier height below conductance pinch-off

Another type of information was acquired from the \( I(V_{sd}) \) characteristics of our quantum point contacts (Fig. 3.3). Analysis of such data allowed us to estimate the barrier height of a closed QPC at a certain gate voltage below conductance pinch-off. In those experiments, the QPC was operated in the closed-channel regime, where (at zero bias) the top of its lowest 1D subband was elevated above the Fermi level. The bias voltage was applied to the source contact, while the drain was kept at the virtual ground by the current preamplifier. Figure 3.3 shows examples of the \( I(V_{sd}) \) characteristics for two of our devices. Different curves were taken at fixed values of the gate voltage. Qualitatively, the \( I(V_{sd}) \) characteristics recorded by us resemble those from Ref. 119. At low bias voltages close to \( V_{sd} = 0 \), no charge is transferred across the constriction. The current starts to flow (and its magnitude steeply rises) only when the critical bias voltages are reached: \( V_+ \) for positive and \( V_- \) for negative polarity.

In our experiments, \( V_\pm \) are typically detected at a small, arbitrary chosen current of order of \( 10 \, \text{pA} \). Note that the traces shown in Fig. 3.3 are not symmetric. For all \( I(V_{sd}) \) characteristics obtained by us, the magnitude of \( V_+ \) was larger than \( V_- \). Moreover, the slope of the current traces was always higher for negative than for positive bias. Those results did not depend on which side the QPC was grounded and which side was biased. This excludes a simple geometric asymmetry of the constriction as a plausible explanation for this effect. On the contrary, similar results obtained when the source and drain contacts were exchanged would rather indicate that our QPCs are quite symmetric.

To allow electron tunnelling or thermal activation across an initially pinched-off quantum point contact, the height of its potential barrier, \( H = E - m\Delta \max(\mu_s, \mu_d) \), has to be reduced to a few meV. Here, \( E \) is the maximum energy of the first 1D subband and \( m\Delta \max(\mu_s, \mu_d) \) denotes the higher of the two chemical potentials: \( \mu_s \) of the source contact, and \( \mu_d = \varepsilon_F \) of the drain. For clarity,
we set the zero of the energy axis at the bottom of the conduction band on the drain side of the QPC.

At a fixed gate voltage, a positive bias applied to the source contact reduces its chemical potential \( \mu_s = \epsilon_s - eV_{sd} \) and lowers the maximum energy of the QPC barrier. This is schematically illustrated in the upper inset to Fig. 3.3 (a). Since the experimental data suggest almost linear relationships in the investigated voltage range, we describe the energy change of the potential maximum by \( dE = -\alpha e dV_{sd} \). For a large positive bias, only the barrier defined with respect to the chemical potential on the drain side, \( H = E - \epsilon_t \), determines the current flow (from drain to source). Its height changes with the bias voltage as \( dH = dE = -\alpha e dV_{sd} \). At the critical voltage \( V_c \), the barrier height is reduced to \( H = \Delta E \), where \( \Delta E \) is a small energy difference of a few meV. It is low enough to allow

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Figure 3.3: Current \( I \) with respect to source-drain bias \( V_{sd} \) for sample (a) HCO103-92-30122-2B and (b) HCO103-92-30122-2C. \( T = 1.7 \) K. Different traces were recorded at fixed gate voltages: (a) from \(-100\) to \(-80\) mV in steps of \(2\) mV, and (b) from \(-70\) to \(+70\) mV. Lower insets in (a) and (b) show critical bias voltages \( V_+ \) (open symbols) and \( V_- \) (solid symbols) at which the current reaches the threshold of \( I_+ = 100 \) pA and \( I_- = -100 \) pA, respectively. Upper inset in (a) shows a schematic potential landscape through the center of the QPC for: (dotted line) zero bias, (upper solid line) a negative bias, and (lower solid line) a positive bias applied to the source contact on the left.
electron transport to the source and depends on the current threshold chosen for determining $V_\pm$. Therefore, the energy difference between the potential maximum for the critical voltage $V_+$ and the potential maximum for zero bias is $E(V_+) - E(0) = (\varepsilon_F + \Delta E) - E_0 = -\alpha \, e V_+$. 

On the other hand, a negative bias voltage lifts the chemical potential on the source side of the QPC and, simultaneously, raises the top of the barrier as described above by $dE_+ = -\alpha \, e \, dV_{sd}$. Note that, for negative polarity, the relevant barrier height is determined with respect to the chemical potential on the source side of the QPC. This barrier changes as $dH_+ = dE_+ + e \, dV_{sd} = -(\alpha - 1) \, e \, dV_{sd}$. At the critical voltage $V_-$, electrons start to flow from source to drain. At this condition, the barrier height is $H = \Delta E$. Thus, the energy difference between the top of the potential barrier for the critical voltage $V_-$ and the potential maximum for zero bias is $E(V_-) - E(0) = (\varepsilon_F - e V_- + \Delta E) - E_0 = -\alpha \, e V_-$. 

Combining the above two equations for the change in the barrier height for $V_+$ and $V_-$ yields $\alpha = -V_- / (V_+ - V_-)$. As a practical exercise, one can derive this parameter from the current-voltage characteristics of Fig. 3.3. For the trace taken for sample 2C at $V_g = -70$ mV [Fig. 3.3 (b)], we determine critical bias voltages at threshold currents of $I_+ = 100$ pA and $I_- = -100$ pA for positive and negative biasing, respectively. This yields $V_+ = 292$ mV, $V_- = -80$ mV, and $\alpha \approx 0.2$. Note that $\alpha$ is rather insensitive to the threshold currents at which critical voltages $V_\pm$ are read out.

The deviation of this parameter from the ideal value of $\alpha = 0.5$ indicates asymmetry introduced by the bias voltage. For a positive bias applied to the source contact, the constriction width on the source side of the QPC is reduced as compared to the case for $V_{sd} = 0$. This additionally heightens the potential barrier and is known as self-gating. A negative bias has the reverse effect, and results in a widening of the QPC channel. Therefore, a bias of a higher magnitude is required for positive polarity to obtain the same reduction in the barrier height as for negative polarity ($\alpha < 0.5$). Moreover, the bias voltage drops non-uniformly across the quantum point contact. In a classical model, the voltage drops proportionally to the inverse width of the constriction. As a result, when the bias voltage is applied, the spatial position of the potential maximum moves along the QPC channel.

Lower insets to Figs. 3.3 (a) and (b) show critical voltages $V_\pm$ determined from the main figures at $I_\pm = \pm 100$ pA. Note that below a certain gate voltage ($V_g < -85$ mV for sample 2B, and $V_g < 30$ mV for sample 2C), critical biases are linearly shifted with respect to $V_g$. For device 2C, we obtain $dV_+ = -2.5 \cdot dV_g$ and $dV_- = +0.6 \cdot dV_g$ for positive and negative polarity, respectively. This allows us to relate the change in the QPC barrier height with a shift in the gate voltage: $dH = dE = -\beta \, e \, dV_g$. For positive biasing, the same modulation of the barrier height can be achieved by changing $V_{sd}$ at a fixed gate voltage: $dH = -\alpha \, e \, dV_{sd}$. This yields $\alpha \, dV_{sd} = \beta \, dV_g$. The corresponding relations for negative source-drain
biases are \( d\mathcal{V} = -(\alpha - 1) \cdot dV_{sd} \) and \( (\alpha - 1) \cdot dV_{sd} = \beta \cdot dV_g \), respectively. For sample 2C, this yields \( \beta = +2.5 \cdot \alpha = -0.6 \cdot (\alpha - 1) \approx 0.5 \).

It is interesting to note that, for our devices, we estimate much lower conversion factors between the gate and bias voltages in the open-channel range: \( dV_{sd} \approx 0.01 \cdot dV_g \). Those estimates are based on bias spectroscopy measurements similar to those presented in Fig. 3.2 (c) in section 3.3.

## 3.5 Transmittance

All our devices had a pair of uniform IDTs deposited on opposite sides of the quantum point contact, see Fig. 2.1. Such sample design allowed us to perform transmittance measurements and, thus, to roughly assess the efficiency of both transducers.

The two IDTs formed a SAW delay line: the SAW generated by one of them (transmitter) could be detected by the second one (receiver). The ratio between output and input power of such a delay line was determined in the transmittance measurements. However, apart from the efficiency of the IDTs, the

![Figure 3.4: Transmittance of the SAW delay line formed by the two IDTs. The data for three different samples is shown, as indicated in the figure. \( T = 1.7 \text{ K} \).](image-url)
insertion loss of the delay line depended as well on: how well the transducers were aligned; how close their fundamental wavelengths were; and on the SAW propagation loss due to the surface roughness. Therefore, transmittance experiments provided only rough information on the efficiency of a separate transducer.

Figure 3.4 shows transmittance spectra obtained for three SETSAW devices at 1.7 K. To acquire those characteristics, we used an Agilent E4402B spectrum analyzer with a tracking generator. The spectrum analyzer both supplied the rf power to the driving transducer and measured the output power from the second IDT.

The fundamental center frequency $f_0 \approx 2470$MHz, around which the main peaks are centered in Fig. 3.4, corresponds to the IDT finger spacing $d$ between electrodes of the same polarity: $f_0 d = v_{SAW}$, where $v_{SAW}$ is the SAW velocity. The $\sin(x)/x$ structure visible in the shown transmittance traces is, in fact, expected for a SAW delay line with a well aligned pair of bidirectional IDTs. This is because the frequency response (around the first harmonic) of a single uniform transducer is given by $|H_{in}(f)| \approx |\sin(x)/x|$, where $x = N_p \pi (f-f_0)/f_0$, and $N_p$ is the number of electrode finger pairs in the IDT. The total response of a delay line depends, however, on both input and output IDTs: $|H(f)| = |H_{in}(f)| \cdot |H_{out}(f)|$. Therefore, the fact that the transmittance characteristics of our devices resemble $|\sin(x)/x|$ structures, indicates a close match in the periodicities $d$ of the transducers. Note as well the small variations in the observed center frequencies $f_0$ between different devices shown in Fig. 3.4. This indicates good reproducibility during the fabrication process for transducers with nominally the same periodicity.

For our SETSAW devices, the transmittance at the center frequency was typically around $-50$ dB at 2 K. The best devices showed, however, transmittances of around $-40$ dB, as shown in Fig. 3.4 for sample HCO100-92-30625-2A.

The transmittance measurements could be as well performed at room temperature. This was usually sufficient to verify the quality of the delay lines, although the transmittance was typically lower by around 10 dB with respect to the results obtained at 2 K. The room temperature measurements were, however, crucial for proper fixing of the copper lids that covered the chip carrier (see section 2.4 for details on sample mounting). Those shields were supposed to reduce the spurious crosstalk in both the transmittance and in further AE current experiments. While monitoring the transmittance, the position of the copper shields was corrected in such a way that the background signal in the transmittance was reduced (away from the center frequency) to around $-90 \div -100$ dB, see Fig. 3.4.

### 3.6 Acoustoelectric current below conductance pinch-off

Interdigital transducers can generate, via piezoelectric effect, elastic waves on the surface of gallium arsenide. The same piezoelectric interactions are
responsible for the fact that the mechanical component of the SAW is accompanied by a travelling wave of the electrostatic potential. This is crucial for transport phenomena that are the scope of our study. In particular, the SAW can induce the current flow across a closed quantum point contact.

Figure 3.5 shows examples of the SAW-driven AE current $I$ with respect to the gate voltage $V_g$. The $I(V_g)$ traces, taken at the indicated SAW frequencies and powers, are drawn together with the conductance characteristics $G(V_g)$ taken without the SAW. At sufficiently high microwave powers, the onset of the AE current is well beyond the conductance pinch-off. For example for sample 2C in Fig. 3.5, the difference between those two onsets is $\Delta V_g \approx -200$ mV. In section 3.4, we already suggested a simple method to estimate the barrier height of a closed QPC. Using those estimates, we find that, for the $I(V_g)$ traces shown in Fig. 3.5, the AE current starts to flow across the point contact when the top of its potential barrier is about 100 meV above the Fermi level.

This already indicates that the SAW can drag electrons across a high potential barrier of a closed constriction. Ultimately, the quantization of the AE current can be observed in the gate-voltage interval beyond conductance pinch-
off, with current plateaus appearing at multiples of $e\ell$ (Fig. 3.5). A simple transport mechanism explaining this effect was proposed by Shilton et al. in their first report\cite{71} on the quantization of the AE current. According to this model, electrons are trapped at the entrance to the constriction in local minima of the SAW potential. Such ‘moving quantum dots’ travel with the sound velocity up the potential hill of the point contact. The occupancy of a single dot is determined by the Coulomb interaction between electrons that populate it.

A qualitative picture of ‘moving quantum dots’ by Shilton et al.\cite{71} is still considered as a predominant model to explain the integer AE effect. Different aspects of this proposal were later discussed in a number of experimental\cite{71-79} and theoretical\cite{88-94} studies. The deviations from perfectly flat AE plateaus were attributed there to electron tunnelling or thermal activation either out of\cite{94} or into the moving quantum dot.\cite{90} Recently, Fletcher et al.\cite{85-87} suggested an alternative mechanism involving a static quantum dot, which is either impurity-induced\cite{85} or fabricated on purpose.\cite{86} Within this model, potential barriers of a static dot are tuned by the SAW, resulting in a turnstile-like operation of the device. However, this picture might be limited to low SAW powers.

### 3.6.1 Finding plateaus in the AE current

The search for AE plateaus in the $I(V_g)$ characteristics is not an easy task. This is because a large number of relevant parameters needs to be tuned: the gate and bias voltage; SAW power and frequency; and (for the two-SAW-beam configuration) the phase between two counterpropagating SAW beams. Normally, a large number of scans within the mentioned parameter space is necessary in order to find quantized steps in the AE current or discard the device.

Here, we describe initial checks and procedures related with the AE current measurements. In those experiments, we used either Agilent 8648D or HP 8673B signal generator as a microwave source, and the AE current was measured using the electrical circuit of Fig. 3.1. The main components of the device, IDTs and a QPC, were characterized in preliminary transmittance and conductance measurements. The $G(V_g)$ characteristics [Fig. 3.2 (a)-(b)] provided information on the pinch-off gate voltage; whereas the transmittance data (Fig. 3.4) gave rough information on the rf frequencies at which the SAW transducers should be operated. Having this knowledge, the gate voltage on the QPC was set beyond the conductance pinch-off (typically ~100 mV below it), and a powerful SAW of around +10 ÷ +15 dBm was applied to the transducer. A frequency scan was then performed to determine the efficiency of each transducer. Examples of the $I(f)$ characteristics are shown in Fig. 3.6. Note periodic ~1.1 MHz oscillations in those traces. Similar beating was present for our other SETSAW devices and could also be found in works by others. We attributed this interference pattern to a weak standing wave that forms when the main SAW beam interacts with a
counterpropagating beam reflected from the second IDT (see section 3.8 for further details on this issue).

The AE current-versus-frequency characteristics were inspected for any indications of quantized steps. The situation was fairly straightforward, if a flattening at roughly $ef$ was spotted in the $I(f)$ trace. We concentrated then on a frequency interval of around 5 MHz that contained current peaks with such ‘kinks’. In the next step, the $I(V_g)$ characteristics (similar to those in Fig. 3.5) were taken at fixed frequencies from this range. Those frequencies were varied in small steps of $\Delta f = 0.01 \div 0.1$ MHz. To enhance the resolution of the current plateaus, we monitored as well the transconductance, $dI(V_g)/dV_g$. Thus, we were able to acquire precise $I(V_g,f)$ and $dl(V_g,f)/dV_g$ maps, and to verify the presence of the AE transitions. Once the quantized steps in the AE current were found for a particular device, extensive scans were started over the entire space of relevant parameters. Those results are detailed in the following chapters.

Figure 3.6: Acoustoelectric current $I$ with respect to SAW frequency $f$ for device (a) HCO103-92-30122-2E and (b) HCO99-92-21024-2A. The measurements were performed at the indicated gate voltages below conductance pinch-off. The rf power was applied either to the transducer on the same side as the source contact of the QPC (left, negative $I$) or to the IDT on the opposite side than the source (right, positive $I$). In all traces, the pronounced 1.1 MHz or 2.2 MHz beating can be observed within the transducer passband. $T = 1.7$ K.
The situation was more complicated if there were no apparent ‘kinks’ at $e\ell$ in the preliminary $I(f)$ traces. In the example shown in Fig. 3.6 (a) [right IDT], one would have to focus on a broad frequency interval from around 2455 MHz to 2475 MHz. Within this 20 MHz range, the current peaks are of comparable height. If we arbitrarily narrowed this interval, we could risk overlooking some of the AE plateaus that we were still searching for. However, a detailed $I(V_g, f)$ scan over that large a frequency range would be extremely time consuming (in excess of 12 hours). It could be quicker and more rewarding to vary other controllable parameters, such as the rf power or phase between the two counterpropagating SAW beams. Therefore, we developed the following procedure for finding the AE plateaus.

We concentrate on frequencies at the base of the $I(f)$ peaks. As an example, take a peak at around 2458.9 MHz in Fig. 3.6 (a) [right IDT]. Although it spreads from ~2458.0 to ~2459.2 MHz, we would not measure the $I(V_g)$ characteristics at fixed frequencies from this entire interval. Instead, we would narrow our selection and focus on two smaller ranges: (2458.0, 2458.4) and (2459.0, 2459.2) MHz, where the broadest AE plateaus are expected to be found in the $I(V_g)$ characteristics. This is based on our empirical observations that are discussed in chapter 6. A relatively large step of 0.1 MHz step is then chosen for frequency variations. Other peaks are checked in a similar way. If the quantized steps are still not revealed in the $I(V_g)$ characteristics, the SAW power is increased by 1 dBm and the whole procedure is repeated. It has to be noted that, on subsequent cool-downs, this search procedure might have been necessary even for devices that already exhibited the current quantization.

### 3.6.2 Working SETSAW devices

Figure 3.7 shows examples of the $I(V_g)$ and $dI(V_g)/dV_g$ characteristics for all eight SETSAW devices, for which we have managed to observe the AE current quantization in units of $e\ell$. This is only a small fraction of samples that we attempted to manufacture. In general, the fabrication of our SETSAW devices was a lengthy process, which included three separate e-beam exposures and a number of steps by means of optical lithography. All the processing stages were completed for in total 106 devices. The samples with disqualifying faults (broken IDTs; leaking QPCs: QPCs which did not open, etc.) were discarded. The remaining 45 samples were tested for the AE current quantization.

Devices fabricated on wafer HCO456 (four upper panels in Fig. 3.7) were plagued with the random telegraph signal (RTS) noise. A good example would be the trace for sample HCO456-11125-2C in Fig. 3.7, where the AE current randomly switches between two or more values. The RTS noise is usually attributed to switching events between metastable states of the impurities that are close to the center of the constriction. This modulates the QPC potential and, thus, affects the charge transport across it. In our experiments, this was a hardly
Figure 3.7: (black) Acoustoelectric current $I$ and (light) transconductance $dI/dV_g$ as a function of gate voltage $V_g$ for eight working SETSAW devices.
The switching noise was almost completely absent for devices manufactured on wafers HCO99-92 and HCO103-92 (four lower panels in Fig. 3.7). In particular, three samples fabricated on the latter heterostructure, HCO103-92-30122-2B, 2C, and 2E, proved to be of an outstanding quality. It is not clear why devices based on wafers HCO99-92 and HCO103-92 were not susceptible to the random telegraph signals while samples fabricated on wafers HCO456 and HCO533 (not shown) exhibited pronounced RTS noise. The growth sequence of all four heterostructures was very similar, see section 2.1. The main difference was the enhanced 2DEG mobility for wafers HCO99-92 and HCO103-92 ($\mu \approx 100$ m$^2$/Vs) as compared to HCO456 and HCO533 ($\mu \approx 50$ m$^2$/Vs). It has to be noted that, for all four of them, there was little evidence of RTS noise in the conductance characteristics of quantum point contacts (without the SAW).

Table 3.1: Basic properties of the quantum point contacts and the SAW delay lines for eight devices shown in Fig. 3.7. Each QPC was defined by shallow-etched trenches with the indicated radius of curvature. Most of the constrictions had a straight section at their centers. Center frequencies of the SAW delay lines as well as the transmittance at those frequencies were determined at $T = 1.7$ K.

<table>
<thead>
<tr>
<th>sample name</th>
<th>QPC radius (µm)</th>
<th>straight segment (µm)</th>
<th>center frequency $f_0$ (MHz)</th>
<th>transmittance at $f_0$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCO456-11122-2BI</td>
<td>5</td>
<td>1</td>
<td>2525</td>
<td>-64</td>
</tr>
<tr>
<td>HCO456-11124-2B</td>
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<td>1</td>
<td>2497</td>
<td>-45</td>
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<tr>
<td>HCO456-11125-2C</td>
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<td>1</td>
<td>2485</td>
<td>-70</td>
</tr>
<tr>
<td>HCO456-11125-2D</td>
<td>5</td>
<td>1</td>
<td>2480</td>
<td>-48</td>
</tr>
<tr>
<td>HCO99-92-21024-2A</td>
<td>5</td>
<td>1</td>
<td>2468</td>
<td>-53</td>
</tr>
<tr>
<td>HCO103-92-30122-2B</td>
<td>5</td>
<td>1</td>
<td>2468</td>
<td>-54</td>
</tr>
<tr>
<td>HCO103-92-30122-2C</td>
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<td>1</td>
<td>2469</td>
<td>-53</td>
</tr>
<tr>
<td>HCO103-92-30122-2E</td>
<td>10</td>
<td>0</td>
<td>2468</td>
<td>-51</td>
</tr>
</tbody>
</table>

desirable effect, which could obscure the AE transitions that we wanted to investigate.

The switching noise was almost completely absent for devices manufactured on wafers HCO99-92 and HCO103-92 (four lower panels in Fig. 3.7). In particular, three samples fabricated on the latter heterostructure, HCO103-92-30122-2B, 2C, and 2E, proved to be of an outstanding quality. It is not clear why devices based on wafers HCO99-92 and HCO103-92 were not susceptible to the random telegraph signals while samples fabricated on wafers HCO456 and HCO533 (not shown) exhibited pronounced RTS noise. The growth sequence of all four heterostructures was very similar, see section 2.1. The main difference was the enhanced 2DEG mobility for wafers HCO99-92 and HCO103-92 ($\mu \approx 100$ m$^2$/Vs) as compared to HCO456 and HCO533 ($\mu \approx 50$ m$^2$/Vs). It has to be noted that, for all four of them, there was little evidence of RTS noise in the conductance characteristics of quantum point contacts (without the SAW).
3.7 Relation between conductance and transconductance in the region of acoustoelectric quantization

We have already pointed out that a major tuning of relevant parameters is necessary to find quantized steps in the acoustoelectric current, $I$. Therefore, in addition to $I$, we frequently recorded its derivatives with respect to the gate voltage $dI/dV_g$ (transconductance) and to the source-drain bias $dI/dV_{sd}$ (conductance). This was mainly done to enhance the resolution of current plateaus. Standard lock-in techniques were used, and the excitation amplitudes were $dV_g = 0.1 \pm 1$ mV at 17 Hz and $dV_{sd} = 0.01 \pm 1$ mV at 117 Hz. As usual, the drain contact was kept at the ground by the current preamplifier.

In the region of the AE quantization, we found that the ratio between conductance and transconductance is constant with respect to the gate voltage (Fig. 3.8). It depends, however, on whether the QPC is biased on the same or on the opposite side as the active IDT.
Inset to Fig. 3.8 (a) shows a simplified layout of our devices. The IDT generates a surface acoustic wave, which drags charge across the potential barrier of the QPC. Electrons are taken from a reservoir connected with contact ‘3’ (on the same side of the constriction as the transducer), and are transferred across the QPC into the reservoir connected with contact ‘1’. Thus, the resulting AE current has a negative sign if the source contact in our electrical setup is contact ‘3’. When the source is at contact ‘1’, the current is positive. This is illustrated in Fig. 3.8 (a) for sample HCO103-92-30122-2C. The AE current is plotted there with respect to the gate voltage for both source-drain configurations.

Figure 3.8 (b) shows the corresponding conductance and transconductance traces as well as the ratio between them. When the source and drain contacts are exchanged, the transconductance characteristics change their sign; however, their magnitude remains the same. On the other hand, the conductance preserves the sign but changes its magnitude. A larger value is obtained when contact ‘3’ near the active IDT is biased.

For a QPC in the closed-channel regime, the ratio between conductance and transconductance not only is independent of the gate voltage [Fig. 3.8 (b)],
but also of the SAW power and frequency [Fig. 3.9 (a)]. For sample 2C, we found it to be about \(-1.75\) and \(0.4\) when the source was at contact ‘3’ and ‘1’, respectively. Figure 3.9 (b) shows that the same ratios between conductance and transconductance were obtained without the SAW when the bias voltage was swept. They were \(-1.75\) for negative and \(0.4\) for positive biasing, respectively.

Note that for both the SAW-driven (Fig. 3.8) and the bias-driven currents [Fig. 3.9 (b)], larger magnitudes of \(\frac{dI/dV_{sd}}{dI/dV_g}\) are acquired when electrons flow from source to drain. We have already accounted for it while discussing the \(I(V_{sd})\) characteristics of closed QPCs with no SAW applied (see section 3.4). The apparent asymmetry in those characteristics was attributed to the self-gating, which alters the width of the constriction on the biased side. This additionally heightens the QPC potential barrier for positive biases and lowers it for negative biases.

### 3.8 Counterpropagating SAW beams

At gate voltages below conductance pinch off, the \(I(f)\) characteristics of our devices exhibited sharp oscillations with a period of around 1.1 and 2.2 MHz, as illustrated in Fig. 3.6. Similar interference patterns were already observed in the experiments\(^{72,73,75,79}\) by the Cambridge group. They were typically attributed to the SAW reflections from the second (unconnected) IDT.

The AE current oscillations could also result from another spurious signal: the electromagnetic feedthrough (crosstalk). When an rf power is applied to the SAW transducer, a part of it can be irradiated and picked up by the gates of the quantum point contact, thus modulating its confinement potential. This electromagnetic wave, propagating at the velocity of light, almost instantaneously reaches the QPC. On the other hand, the SAW travels at the sound velocity of \(v_{SAW} \approx 2800\) m/s on the GaAs substrate. Hence, the frequency modulation in the AE current, which results from the interference between those two signals, depends on the distance \(L_1\) between the driving transducer and the QPC: \(\Delta f = v_{SAW} / L_1\). For our samples with \(L_1 \approx 1.25\) mm, the expected modulation due to the crosstalk would thus be \(\Delta f = 2.2\) MHz.

The SAW can also interfere with another SAW beam that reaches the point contact from the opposite side. This additional beam originates from the SAW reflections from the second transducer. The phase difference between the two beams that meet at the point contact depends then on a double distance \(2L_2\) between the QPC and the transducer from which the main beam is reflected. For our devices \(2L_2 \approx 2.5\) mm (\(= 2L_1\)), which yields a frequency modulation of \(\Delta f \approx 1.1\) MHz. This is, in fact, the oscillation period that we normally observe in our \(I(f)\) characteristics, see Fig. 3.6.

The SAW reflection from another transducer is a well identified design problem in SAW filters, known as a triple transit echo\(^{12,13}\). However, the same
effect can also be used to enhance the efficiency of the transducer by putting a reflector behind it. Typically, this is another IDT with the same finger spacing as the driving transducer but with shorted electrodes. An unconnected IDT can also be used.

3.8.1 Previous work by others

The second SAW beam, propagating in the opposite direction than the main beam, can also be generated on purpose. This issue was investigated by Cunningham et al. who applied a microwave signal to both transducers forming a SAW delay line. Thus, the relative magnitude and phase between the two resulting SAW beams could be controlled and adjusted. While varying the phase, Cunningham et al. observed notable changes in the \( I(\sqrt{g}) \) characteristics. For some phase settings, the slope of the first AE plateau was markedly reduced, indicating an enhanced precision of the AE current quantization. At other phases, the plateau flatness degraded while the position of the current step moved away from the expected value of \( I = \varepsilon f \).

J. Cunningham et al. attributed those changes in the AE current to shifts in the position of the standing wave nodes and antinodes with respect to the entrance to the QPC channel. In the experiment, this position can be directly controlled by adjusting the phase between the two counterpropagating SAW beams. The standing wave alters the shape of a moving quantum dot that transfers electrons across the QPC. This dynamic tuning is synchronized with the SAW cycle. At a correct phase setting, the shape of the dot can be improved when it passes the critical point in the constriction, where the electron occupancy of the dot is determined. In contrast, the gate voltage statically changes the potential barrier of the QPC. Thus, the shape of the dot can be improved for some times within the SAW cycle and worsened for others.

The effect of the second SAW beam on the AE current was recently addressed in a theoretical study by Kashcheyevs et al. The AE transport is modelled there by an adiabatic quantum pumping of non-interacting electrons. When a counterpropagating SAW beam is included into the calculation, the onset of the AE current is found to periodically change its position along the \( \sqrt{g} \)-axis. It reaches the lowest gate voltages when the phase difference between the two beams is \( \varphi = 0 \); whereas at \( \varphi = \pi \) the current onset is at the largest value of \( \sqrt{g} \). The flatness of the AE plateaus is found to enhance at those special phase settings and to degrade between them.

3.8.2 Altering the phase of the second SAW beam

The experiments with two controllable SAW beams propagating in opposite directions across a quantum point contact were also performed by us. In those measurements, we used the same electrical setup as in Fig. 3.1. The only difference was an additional microwave line connected to the second IDT. An rf
Figure 3.10: Sample HCO103-92-30122-2E. (black) Acoustoelectric current $I$ and (light) transconductance $dI/dV_g$ as a function of gate voltage $V_g$. The data in consecutive panels were measured for different phase shifts between the main and the counterpropagating SAW beam in steps of about 18° (the last two traces completing the 360° cycle are missing). The power applied to the main IDT was $P_{RF} = +13.5$ dBm. For the second IDT, this source power was attenuated by 8 dB. $f = 2459.4$ MHz, $T = 1.2$ K.
signal from the generator was split up and simultaneously applied to both transducers. A phase shifter and a 0-110 dB attenuator were built into the line to the second IDT. This allowed us to control the relative magnitude and phase between the applied rf signals. Apart from the AE current \( I \), we frequently recorded its derivatives with respect to the gate voltage \( dI/dV_g \) (transconductance) and to the source-drain bias \( dI/dV_{sd} \) (conductance). This was particularly useful when the adjustment of the phase was necessary to optimize the slope of the AE plateau.

Figure 3.10 shows the AE current and the (numerical) transconductance with respect to the gate voltage. Current traces were taken at a fixed value of the phase of the second SAW beam. For consecutive panels, this value is incremented in steps of around 18° (the last two traces completing a 360°-cycle are missing). One can immediately notice that the AE current strongly responds to changes in the phase between counterpropagating SAW beams. Compare for example the number of the AE plateaus per gate-voltage-interval in panels 7 and 15. On the other hand, the current slope at the plateau can be strongly reduced for some settings of the phase, see for example panel 7.

We have found that the evolution of the \( I(V_g) \) characteristics in response to the incremented phase of the second SAW beam resembles closely the changes observed in \( I(V_g) \) when the frequency is varied. We address this issue in chapter 6 where those two dependencies are compared. Their common features are highlighted there, in particular, the abrupt transitions in the \( I(V_g) \) characteristics that occur within narrow intervals of frequency or phase. An example would be a disappearing step at \( I=I+ef \) in panels 7 through 9 of Fig. 3.10. Moreover, two separate sets of the AE plateaus can be distinguished in our data.

Here, it will suffice to say that common features observed in the phase and frequency responses of our devices support the argument that the 1.1 MHz-oscillations in the \( I(f) \) characteristics (Fig. 3.6) are due to the interference between two counterpropagating SAW beams. The main beam is generated by the driving transducer. The second one is either generated by the IDT on the opposite side of the QPC or results from the SAW reflections from this second transducer. The 1.1 MHz-modulation in frequency in Fig. 3.6 is, thus, equivalent to the phase change of \( 2\pi \) between the two counterpropagating SAW beams.

### 3.8.3 Reduction of the current slope at the plateau

We often used the two-SAW-beam configuration to improve the flatness of the AE current plateaus, and thus enhance their resolution. Here, we report on the largest number of quantized steps that we were able to resolve in the AE current-versus-gate voltage characteristics (Fig. 3.11). We also present the results of slow, detailed scans of \( I(V_g) \) at the first AE plateau (Figs. 3.12 and 3.13). Those measurements were performed in order to determine the precision of the current...
quantization. All \(I(V_g)\) characteristics presented in this section were acquired upon application of two counterpropagating SAW beams.

Figure 3.11 shows an outstanding example of an \(I(V_g)\) characteristic with \(n = 20\) current plateaus near multiples of \(\eta \text{ef}\). The first 8 steps are visible with the naked eye, the rest can be resolved in the transconductance, \(dI/dV_g\). Prior to this measurement, the phase of the second SAW beam was optimized in order to produce the flattest achievable plateau at \(I = \text{ef}\) (for given values of the rf power and frequency). Fine tuning was performed by monitoring the transconductance signal while sweeping the phase. The current slope at the first plateau was reduced to around 1.5 pA/mV. The \(I(V_g)\) characteristic presented in Fig. 3.11 was measured at such an optimum condition.

Figure 3.11 clearly demonstrates the capabilities of a SETSAW device, which can deliver current quantized in units of \(\text{ef}\). This explains considerable interest of the metrological community in these structures as potential candidates for a quantum standard of electrical current. Their key advantage is their high operational frequency of around 2.5 GHz, which results in currents in the 1 nA
range, high enough for metrological applications. However, a major obstacle still needs to be overcome in order to consider the implementation of a SETSAW device as a current standard. Namely, the finite slope of the AE current at the quantized step limits the precision of the quantization, which still needs to be improved to meet metrological requirements.

Figure 3.12 shows a series of measurements, in which we attempted to precisely determine the current slope at the first plateau. Prior to those experiments, we optimized the device parameters (the SAW frequency, power and phase of the second beam) in order to obtain the flattest step at $I=I^\text{eff}$. All ac excitations ($dV_{sd}$ or $dV_g$) were disconnected from the sample to reduce the amount of electrical noise.

First, a broad sweep in the gate voltage was performed to roughly determine the position of the AE plateau with respect to the gate voltage. This is shown in the inset to Fig. 3.12 (a). A 6 mV-wide interval in $V_g$ was then selected around the region of minimum slope in the current. Another measurement was carried out over this narrower gate-voltage range. To precisely assess the current quantization, 200 readings of $I$ were taken at a fixed value of $V_g$ over 5 seconds. The gate voltage was then increased by 10 µV and, after a delay of 2 s, another data set was taken. Figure 3.12 (a) shows the result of this procedure. The data
from the third measurement is shown in Fig. 3.12 (b). In this case, the $V_g$-interval was further decreased to around 1 mV, and the sweep step was lowered to 2.5 µV. For each of the data points in Fig. 3.12 (a) and (b), the standard deviation of the mean current was calculated and plotted as error bars. Those bars are, however, obscured in Fig. 3.12 (a) due to too large a scale on the current axis. In Fig. 3.12 (b), every tenth error bar is shown to keep the figure legible.

A straight segment with a pronouncedly reduced slope can be distinguished in the AE current around $V_g \approx -48$ mV [Fig. 3.12 (a)]. It is approximately 1.5 mV-wide and has a small slope of around 0.06 pA/mV (or 150 ppm/mV if we normalize it to the expected current of $e_f = 393.86$ pA). At the center of the segment, the current is 394.695 pA, that is 0.21% above the theoretical value. This is within the accuracy of the current amplifier and the analogue-to-digital converter of about ±1 pA.

A demand exists to compare the precision of the AE current quantization between different devices, especially those fabricated with different techniques. However, the results of measurements similar to those presented here have to be approached with a certain caution. The slope of an AE plateau, determined in pA/mV, might not be a good quantity to compare between devices with a clearly different capacitive coupling to the gates. On the other hand, selecting a flat section in the current trace and basing the precision quote on this selection might turn out to be rather arbitrary.

Figure 3.13: Sample HCO103-92-30122-2E. Acoustoelectric current $I$ as a function of gate voltage $V_g$. Detailed measurement in the region of minimum gradient in (a) indicates negative slope at the first plateau (b). Two counterpropagating SAW beams were applied. The main IDT at $P_{RF} = +13.5$ dBm, the second at $P_{RF} = +5.5$ dBm, $f = 2460.62$ MHz, $T = 1.2$ K.
To complete this discussion, we present yet another example of a precise measurement of the AE current with respect to the gate voltage (Fig. 3.13). Again, the current was scrutinized at the first plateau in order to find its minimum slope. The same technique was used as for acquiring the data in Fig. 3.12. This time, however, not only did we observe a finite slope of the current, but this was a negative slope with respect to the gate voltage. It is not yet understood what the exact physical origin of this effect is.

### 3.9 2DEG resistance as a temperature sensor

In our devices, clear AE plateaus at \( I = n_{\text{ef}} \) are typically observed at high microwave powers of order of 10 dBm. This may radically increase the sample temperature, as indicated for example by a fast and vehement boil-off of liquid \(^3\)He when the top-loaded cryostat is operated at \( T_0 = 300 \text{ mK} \) (see section 3.1). Therefore, a reliable assessment of the device temperature is crucial for further investigation on the acoustoelectric effects.

A quantum-mechanical theory by Flensberg et al.\(^90\) predicts an elevated effective temperature of the SAW-driven electrons with respect to the temperature of the remote 2DEG. Using this model, the effective temperature can be estimated from:

\[
\frac{S_{\text{min}}}{S_{\text{max}}} \approx 4 \exp\left(-\frac{E_{\text{C}}}{kT_{\text{eff}}}\right)
\]

where \( S_{\text{min}} \) is the minimum slope at the \( n \)-th AE plateau; \( S_{\text{max}} \) the maximum slope between the \( I = n_{\text{ef}} \) and \( I = (n-1)_{\text{ef}} \) transition; and \( E_{\text{C}} \) the charging energy of a moving quantum dot. The effective temperature is defined as \( T_{\text{eff}} = \sqrt{T^2 + T'^2} \), where \( T \) is the 2DEG temperature and \( T' \propto 1/\tau \) depends on a characteristic time constant \( \tau \) of the tunnelling coupling between the moving dot and the 2DEG. In Refs. 92,93, the effective temperatures were determined experimentally at relatively low microwave powers of \( P_{\text{RF}} \approx 0 \text{ dBm} \), yielding \( T' \approx 2 \text{ K} \). For our devices operated at much higher power levels (\( P_{\text{RF}} \approx 10 \text{ dBm} \)), such an analysis yielded temperatures of around 6 K.

We also probed heating effects using a more direct method, where the 2DEG resistance was used as a built-in temperature sensor. All the measurements described in the following were performed in vacuum, using a \(^4\)He refrigerator with a base temperature of \( T_0 = 1.7 \text{ K} \).

The inset to Fig. 3.14 (a) shows a simplified layout of our 2DEG mesa with a shallow-etched QPC in its center. Contacts 1 and 2 provide electrical connections to the electron reservoir on the right-hand side of the QPC, whereas contacts 3 and 4 to the reservoir on the left. The resistance \( R_{34} \) between the latter pair of contacts is calibrated against the temperature of the cold plate to which the sample is attached. At \( T_0 = 1.7 \text{ K} \), \( R_{34} \approx 600 \Omega \). No rf signal is applied to the SAW
The quantum point contact is pinched off, electrically separating the 2DEG reservoirs on both sides. The temperature is measured by an Allen Bradley resistor attached to the cold plate. Figure 3.14 (a) shows typical calibration curves $\Delta R_{34}(T)$ acquired by us for sample HCO103-92-30122-2E. When the base temperature is elevated from 1.7 K to 4 K, the 2DEG resistance increases by around 12 $\Omega$, exhibiting a $\Delta R_{34} \propto T^4$ dependency.

Using the temperature calibration of the 2DEG resistance $\Delta R_{34}(T)$, we can determine the thermal coupling between the sample and the cold plate. Figure 3.14 (a) shows typical calibration curves $\Delta R_{34}(T)$ acquired by us for sample HCO103-92-30122-2E. When the base temperature is elevated from 1.7 K to 4 K, the 2DEG resistance increases by around 12 $\Omega$, exhibiting a $\Delta R_{34} \propto T^4$ dependency.

An electrical current flowing between contacts 1 and 2 heated the 2DEG on the right-hand side of the QPC, while $\Delta R_{34}$ was monitored on the left side of the constriction. The dotted line is a linear fit to the data.

Using the temperature calibration of the 2DEG resistance $\Delta R_{34}(T)$, we can determine the thermal coupling between the sample and the cold plate. The electron reservoirs on both sides of the (closed) QPC are electrically separated from each other. An electrical current is passed between contacts 1 and 2, thus Joule heating the 2DEG to the right via its finite resistance $R_{34}$. The resistance $R_{34}$ of the 2DEG to the left is then probed with respect to the Joule heat $P_{\text{Joule}}$ injected into the reservoir to the right, as shown in Fig. 3.14 (b). A linear dependence $\Delta R_{34} \propto P_{\text{Joule}}$ is found. When the calibration curve of Fig. 3.14 (a) is used, this yields $P_{\text{Joule}} \propto T^4 - T_0^4$. This could be attributed to a thermal boundary resistance $R_{12}$ between the semiconducting substrate of the sample and the copper transducer.
chip carrier. Taking $P_{\text{Joule}} = A \sigma_K (T^4 - T_0^4)$ and a geometrical cross section of the sample $A \approx 1 \text{ mm}^2$, the thermal boundary conductance $\sigma_K = 2.5 \text{ W K}^{-1} \text{ m}^{-2}$ is of the correct order of magnitude, see for example Ref. 125.

Finally, the Joule heating is turned off and an rf signal is applied to the SAW transducer. The 2DEG resistance $R_{34}$ is measured with respect to the output power of the microwave generator $P_{RF}$, as shown in Fig. 3.15 (a). Figure 3.15 (b) shows the Joule heating $P_{\text{Joule}}$ corresponding to this resistance. $P_{\text{Joule}}$ is derived from the linear fit $\Delta R_{34}(P_{\text{Joule}}) \propto P_{\text{Joule}}$ to the data of Fig. 3.14 (b), extrapolated above $0.5 \text{ mW}$. We estimate that approximately 3 mW ($\sim 5 \text{ dBm}$) are dissipated in the sample while applying $P_{RF} = 10 \text{ dBm}$ to the generator output. As a result the temperature rises to around $T = 6 \text{ K}$ (Fig. 3.15), well above the base temperature.

Changes in the 2DEG resistance indicate that heating due to the AE or the tunnelling current flowing across the QPC is negligible. When 100 nA hot electrons at 100 mV are injected from the reservoir on the right into the 2DEG on the left, the resistance $R_{34}$ indicates only a small temperature increase of less than 0.1 K at $T = 5 \text{ K}$. This is consistent with earlier reports on similar QPC devices.\textsuperscript{111}
Chapter 4

Action of the source-drain bias

In order to observe the quantized acoustoelectric current, the quantum point contact needs to be operated in the closed-channel regime. The SAW drags electrons across the potential barrier of the QPC, the top of which is elevated above the Fermi level. The absolute value of the resulting AE current can be adjusted by: altering the QPC barrier height using the gate voltage (chapters 3-6); varying the depth of the dynamic SAW potential (chapter 5); as well as by sweeping the SAW frequency (chapter 6) or the phase of a counterpropagating SAW beam generated by another transducer (section 3.8). Quantized steps can also be observed in the AE current when the bias voltage is swept at fixed values of other parameters.

In this chapter, we describe the effect of a finite source-drain bias on the quantized AE current. First, we describe changes observed in the $I(V_g)$ characteristics taken at different values of $V_{sd}$. Then, we demonstrate the AE current quantization while sweeping the bias voltage. Finally, we investigate the case, when the bias voltage reduces the QPC barrier height to the level at which the tunnelling current starts to flow in the opposite direction to the SAW-driven current. Since those two contributions to the total current depend in a distinctively different way on the bias and gate voltage, they can be separated at least over a certain range of parameters.

4.1 The $I(V_g)$ characteristics taken at fixed bias voltages

Figure 4.1 (a) shows the AE current with respect to the gate voltage for sample HCO103-30122-2C. Different $I(V_g)$ traces were taken at fixed values of the bias voltage. In those measurements, the biased (source) contact was located on
the same side of the constriction as the active IDT. The drain on the opposite side of the QPC was kept at the virtual ground by the current amplifier. In such a configuration, the SAW transferred electrons from source to the drain, and the resulting AE current had a negative sign. Current derivatives, conductance $\frac{dI}{dV_{sd}}$ and transconductance $\frac{dI}{dV_{g}}$, were measured simultaneously with $I$, and are shown in Fig. 4.1 (b). Their ratio $\left(\frac{dI}{dV_{sd}}\right)/\left(\frac{dI}{dV_{g}}\right)$ with respect to the gate voltage is shown in Fig. 4.1 (c).

Large negative bias voltages (down to $V_{sd} = -300$ mV) applied to contact 3 near the active IDT do not deform plateaus in the AE current. The $I(V_{g})$ traces and their derivatives are, however, shifted along the $V_{g}$-axis towards more negative gate voltages, which looks as if they were displaced parallel to each other. This feature was already demonstrated by Cunningham et al. in Refs. 76,79. A positive bias voltage applied to contact 3 shifts the $I(V_{g})$ traces towards higher values of the gate voltage. Eventually, the current reverses its polarity and starts to flow in the

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Figure 4.1: Sample HCO103-92-30122-2C. (a) Acoustoelectric current $I$ as a function of gate voltage $V_{g}$. The solid curves were recorded at fixed bias voltages $V_{sd}$ from $-300$ to $+100$ mV in steps of $50$ mV. The bias voltage was applied to contact 3 on the same side of the QPC as the active IDT. The dashed lines are the traces from Fig. 4.2 (a), measured with the source at contact 1. (b) Conductance $\frac{dI}{dV_{sd}}$ (upper curves) and transconductance $\frac{dI}{dV_{g}}$ (lower curves) with respect to gate voltage $V_{g}$, recorded simultaneously with the current traces in (a). The ratio $\left(\frac{dI}{dV_{sd}}\right)/\left(\frac{dI}{dV_{g}}\right)$ is shown in (c). $P_{RF} = +13$ dBm, $f = 2464.78$ MHz, $T = 1.7$ K.
opposite direction. Similar behaviour of the \( I(V_g) \) characteristics can be observed when the source and drain contacts are exchanged. This is illustrated in Fig. 4.2. In this case, however, a negative bias shifts the \( I(V_g) \) curves towards more positive gate voltages. The total current reverses its polarity at sufficiently high values of negative bias.

The displacement of the \( I(V_g) \) characteristics along the gate-voltage axis can be related to the change in the QPC barrier height in response to the applied bias. For the SAW-driven current, the direction of electron flow is determined by the direction of the SAW propagation. Therefore, only the barrier height on the side of the incoming SAW matters. On the other hand, the bias voltage changes the chemical potential on the biased side of the constriction as well as the maximum energy of the barrier. Thus, depending on the polarity of the bias voltage, the relevant barrier is defined either with respect to the chemical potential

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\* See section 3.4. We analyze there the \( I(V_{sd}) \) characteristics of closed quantum point contacts (with no SAW applied) and use those data to estimate the QPC barrier height.
of the drain (for positive $V_{sd}$) or the source (for negative $V_{sd}$). At sufficiently large bias voltages, the respective barrier is low enough to allow electron tunnelling across the constriction. The AE and the tunnelling contribution to the total current can thus flow in the same or in the opposite direction, depending on polarity of the applied bias.

Figure 4.1 depicts a situation when the source contact is on the same side of the constriction as the active IDT. Therefore, the barrier relevant for the SAW-driven transport is defined with respect to the chemical potential $\mu_s$ of the source. A negative bias voltage reduces its height and shifts the onset of the $I(V_g)$ curves towards more negative values of the gate voltage. A positive bias acts oppositely. It increases the barrier height on the source side of the QPC and shifts the onset of the AE current towards more positive values of $V_g$. At large magnitudes of a positive bias, electron tunnelling from drain to source becomes possible. Since it is in the opposite direction than the SAW, the total current reverses its sign, as it happens for $V_{sd} = +100$ in Fig. 4.1.

Figures 4.1 (c) and 4.2 (c) show the ratio between conductance and transconductance $\frac{dI/dV_{sd}}{dI/dV_g}$, which remains constant as long as the total current is purely acoustoelectric. Deviations from this constant occur when the tunnelling contribution to the total current develops. Note that the absolute value of $\frac{dI/dV_{sd}}{dI/dV_g}$ changes on exchanging the source and drain contacts [from about $-1.75$ in Fig. 4.1 (c) to about $+0.4$ in Fig. 4.2 (c)]. This is in line with our observations from section 3.7.

### 4.2 Quantized acoustoelectric current with respect to the source-drain bias

Figure 4.3 shows examples of current-versus-bias-voltage characteristics (with the applied SAW) for three of our devices: HCO103-92-30122-2A, 2B and 2C. Different $I(V_{sd})$ traces were taken at fixed values of the gate voltage, $V_g$. For all three samples, the source was situated at contact ‘3’ near the active IDT.

At small gate voltages, quantized AE steps at multiples of $\varepsilon f \approx 395$ pA are clearly visible in the $I(V_{sd})$ characteristics of Fig. 4.3. For example, see traces taken at $V_g = 90 \div 110$ in Fig 4.3 (b). On lowering a positive bias voltage, the barrier height of the QPC potential is reduced on the source side of the constriction and the AE current starts to flow from source to drain. An increase in the gate voltage, at which an $I(V_{sd})$ characteristic is taken, shifts the onset of the AE current towards larger values of $V_{sd}$. However, at sufficiently positive bias voltages $V_{sd} = V_+$ (depending on the gate voltage), the current reverses sign and becomes positive, which indicates tunnelling across the QPC in the direction opposite to the SAW propagation. See, for example, the trace taken at $V_g = 110$ mV in Fig. 4.3 (b), where the onset of the (negative) AE current is at $V_{sd} = 90$ mV and the onset of (positive) tunnelling current is at $V_+ = 105$ mV. Both
those values were read out at arbitrarily chosen currents of $-10$ and $+10$ pA, respectively.

Figure 4.4 shows the same $I(V_{sd})$ data as in Fig. 4.3 (b) along with the current derivatives: conductance $dI(V_{sd})/dV_{sd}$ and transconductance $dI(V_{sd})/dV_g$; as well as the ratio between them $(dI/dV_{sd})/(dI/dV_g)$. Note that at large tunnelling counterflow, the AE plateaus are no longer visible in the total current but can still be resolved in current derivatives. A good example would be the trace taken at $V_g = 150$ mV. Again (see previous section and section 3.7), the ratio between conductance and transconductance remains constant as long as either the acoustoelectric or tunnelling contribution dominates the total current. This is shown in Fig. 4.4 (d).

All $I(V_{sd})$ curves as well as their derivatives can be displaced along the $V_{sd}$-axis to match either at low bias voltages where the tunnelling contribution to the total current is small [Fig. 4.5 (a)] or at large bias voltages where the AE current is negligible [Fig. 4.5 (b)]. In both cases, the corresponding displacement $\delta V_{sd}$ is
proportional to the gate voltage but with a different slope, as illustrated in the inset to Fig. 4.5 (b). Note that those two slopes agree fairly well with different ratios \( (\frac{dI}{dV_{sd}})/(\frac{dI}{dV_g}) \) obtained for the acoustoelectric and tunnelling regime, [Fig. 4.4 (d)].

Similar results are obtained when the source contact is located on the opposite side of the constriction than the transducer (Fig. 4.6). In such a configuration, the AE current has a positive polarity (the SAW drags electrons from drain to source) and is increased when the source-drain bias is incremented. At negative biases, the tunnelling contribution is negative. Matching the traces in the acoustoelectric and tunnelling regime is again possible; however, the required shifts in the bias voltage are interchanged with respect to the previous case. This is shown in the inset to Fig. 4.6 (c). When contact ‘1’ is biased, the same shift \( \delta V_{sd} \)
(except the sign) is necessary to match the $I(V_{sd})$ curves in the acoustoelectric regime as it is required for adjusting the tunnelling current when contact ‘3’ is biased, and vice versa. This again indicates that both shifts are closely related.

4.3 Separating the two counterflowing currents

The transition range between purely acoustoelectric and tunnelling current is an interesting case of a dual charge transport. In this range, two different electron currents flow simultaneously in opposite directions across the same narrow constriction of a quantum point contact. They both depend on the bias and gate voltage, however, in a distinctively different ways. This offers a chance to separate them and study their possible interactions. The tunnelling current originates from a static potential difference across the QPC and varies exponentially with the gate and bias voltage. On the other hand, the acoustoelectric current is due to the SAW, which traps a single or few electrons inside the travelling minima of its potential. Those minima move with the speed of sound and transfer electrons across the static barrier of the QPC. Hence, the quantized steps in the AE current at $l = n\delta f$.

Figure 4.7 shows the positions of the transconductance minima from Fig. 4.4 (b), as well as the total current at those minima. At low values of the gate voltage (below $V_g = 120$ mV), current plateaus approach the expected multiples of
Figure 4.6: Sample HCO103-92-30122-2C. (a) Acoustoelectric current $I$ and (b) transconductance $dI/dV_g$ with respect to bias voltage $V_{sd}$. The 13 curves in each of those panels were recorded at fixed gate voltages from 0 to $-120$ mV in steps of 10 mV. The bias voltage was applied to contact 1 on the opposite side of the QPC than the IDT. Panels (c) and (d) show the AE current and the transconductance traces from (a) and (b), respectively, displaced along the bias voltage axis to match at large voltages where the tunnelling contribution is small. $P_{ee} = +13$ dBm. $f = 2464.78$ MHz, $T = 1.7$ K.
For higher gate voltages, the counterflowing tunnelling contribution starts to dominate the total current, reversing its sign. At low countercurrent, the AE plateaus can still be resolved in the current. See, for example, the $I(V_{sd})$ trace taken at $V_g = 130$ mV in Fig. 4.4 (a). However, the magnitude of the current steps seems to be smaller than the expected multiples of $e\phi_f$. At larger countercurrent, the AE steps cannot longer be resolved in the total current but minima still appear in current derivatives: $dI(V_{sd})/dV_{sd}$ and $dI(V_{sd})/dV_g$. For example, see traces taken at $V_g = 150$ mV in Fig. 4.4.

Even at a large tunnelling countercurrent, we attribute minima in conductance and transconductance to the integer acoustoelectric effect. This becomes apparent in Fig. 4.7, where positions of the minima are mapped with respect to the gate and bias voltage. Those positions vary linearly with $V_g$ and $V_{sd}$ both in the region where the tunnelling is negligible and where it starts to dominate the total current. Thus, the AE current is quantized even at large tunnelling countercurrent. The maximum tunnelling current, at which we could detect the AE anomaly while positively biasing contact ‘3’ on the same side of the QPC as the IDT, was about ten times larger than $e\phi_f = 395$ pA. We could also resolve the AE anomalies when contact ‘1’ on the opposite side of the constriction was biased. However in this case, a large slope of the tunnelling current (see Fig. 4.6) made it very difficult to separate the AE contribution.

In principle, the pure tunnelling current could be determined by simply turning off the SAW. In fact, we have found that the $I(V_{sd})$ characteristics taken at
fixed gate voltage without the SAW have the same slope in a semi-logarithmic plot as those taken while applying the surface acoustic wave. They are, however, displaced along the $V_{sd}$-axis, as if the SAW lowered the effective barrier of the quantum point contact. We attribute it to the rf heating and changes to the QPC potential that are due to the travelling minima of the superposed SAW potential. Therefore, we use another method to determine the tunnelling current when the surface acoustic wave is on.

We have already indicated that the $I(V_{sd})$ characteristics (with the SAW on) as well as their derivatives can be displaced in such a way that they match in the region where the tunnelling dominates, as illustrated in Fig. 4.5 (b) for the transconductance. We attribute the asymptotic curves, which are approached by those shifted characteristics, to the tunnelling current $I_T$ and its derivatives $dI_T/dV_g$ and $dI_T/dV_{sd}$. Similar procedure can be performed for the purely AE range where the tunnelling is negligible, as shown for the transconductance in Fig. 4.5 (a). Thus, in principle, we know the ideal behaviour of the tunnelling and the acoustoelectric current as well as their derivatives.

However, a brief analysis of the data from Fig. 4.4 indicates that subtracting the asymptotic $I_T$ from the total current $I$ yields smaller magnitudes of the AE current than expected from the region where the tunnelling is negligible. Or, in other words, when the AE current from the purely AE regime is compared with the measured $I$, the resulting tunnelling current is larger than expected from the experimentally determined asymptote for $I_T$. But we do not know a priori which part is affected most, whether the tunnelling current suppresses the AE current, or vice versa, or whether they both suppress each other.

To quantify those observations, we calculate the purely acoustoelectric current $I_{AE} = I - I_T$, under the assumption that the asymptotic $I_T$ is not affected by the AE contribution. Figure 4.8 illustrates the whole procedure. To enhance the resolution, the derivatives are used instead of the current. In Fig. 4.8 (a), the asymptotic $dI_T/dV_{sd}$ is subtracted from the measured conductance $dI/dV_{sd}$, yielding the AE contribution $dI_{AE}/dV_{sd}$. The latter is then integrated to obtain the AE current $I_{AE}$. Figure 4.8 (b) shows results of such an integration for traces taken at different gate voltages. Note the decreasing magnitude of the AE current plateaus for increasing counterflow, which is in line with our preliminary observations for sample 2C.

Such an analysis was performed for three of our devices: HCO103-92-30122-2B, 2C and 2E. Figure 4.9 summarizes those results. The AE current $I_{AE} = I - I_T$ is determined using the same method as described above. Its magnitude at the centers of the AE plateaus is plotted in Fig. 4.9 with respect to $I_T$. For sample 2B, a tunneling current of $I_T \leq 0.5$ nA does not affect $I_{AE}$. For larger tunnelling currents, the AE current at the plateaus is linearly reduced. For $I_T \geq 1$ nA, it saturates at about half of the expected value. For sample 2C, the AE current at the first four plateaus is strongly suppressed even at the lowest values of the tunnelling counterflow. It eventually saturates when $I_T \geq 0.6$ nA; however, at
lower AE currents than it occurs for device 2B. In case of sample 2B and 2C, the saturation can be unambiguously resolved only for the first two quantized steps. On the other hand, the relative reduction \(1 - \frac{I_{AE}(I_T)}{n\epsilon_f}\) is the same for each of the \(n = 1 \div 4\) plateaus. For sample 2E, the AE current at the first plateau is unaffected by tunnelling currents of up to about \(I_T \approx 4\) nA, that is about ten times larger than \(\epsilon_f\). For quantized steps of higher index \(n\), the magnitude of \(I_{AE}\) not only is not reduced but becomes larger than expected. This could be an artefact, resulting from an increased uncertainty of the tunnelling current at large counterflow.

The data for device 2B can be considered as a combination of results of sample 2C and 2E: At low values of \(I_T\), the AE current remains unaffected, as for device 2E. When the tunnelling current is increased, the magnitude of the acoustoelectric current is linearly reduced and saturates at large values of the tunnelling counterflow as for sample 2C.
4.4 Possible interaction between the tunnelling and acoustoelectric current

The reduction of the AE current observed for samples 2B and 2C could result from a distortion of the static potential barrier of the point contact due to the bias voltage. This could increase the probability of errors in the SAW-driven electron flow, reducing the slope of the AE plateaus. However, as long as the tunnelling contribution to the total current is negligible, the plateau flatness is not affected over a very wide range of bias voltages, see Figs. 4.1 and 4.2.

The suppression of the AE current could also indicate an interaction between the tunnelling and the acoustoelectric current that counterflow through the same narrow constriction of the QPC. For example via backscattering of the SAW-driven electrons on the tunnelling electrons, or vice versa. The latter scenario, where an electron trapped in the SAW minimum backscatters a tunnelling electron, seems rather unlikely. This would require a transfer of twice
the Fermi momentum while the SAW-driven electrons have barely any momentum as compared to their hot tunnelling counterparts. On the other hand, backscattering an electron residing in a moving quantum dot would require only a small momentum transfer which would not affect the tunnelling current. However, this could also be unlikely due to a large velocity mismatch between the tunnelling electrons propagating at the Fermi velocity $v_F \approx 230 \text{ km/s}$ and those transferred by the SAW at the sound velocity $v_{\text{SAW}} \approx 3 \text{ km/s}$. When both currents have similar magnitudes, it is rather unlikely for a tunnelling electron in the QPC to hit a SAW-driven electron. Thus, backscattering should be negligible, in line with results for sample 2E (Fig. 4.9).

While passing the point contact, the tunnelling electrons could also be trapped in the travelling SAW minima, increase the kinetic energy of electrons already residing there, and thus enhance their probability of escape. This could result in a reduction of the AE current as observed for devices 2B and 2C (Fig. 4.9). Since the inelastic mean free path (of order\textsuperscript{126} of $h v_F/k_B T \approx 2 \mu \text{m}$ at $T = 5 \text{ K}$) is comparable to the length of the QPC channel, few such events could occur during the transition time of a tunnelling electron. At large bias voltages, the inelastic mean free path should be even further reduced due to the excitation of LO phonons at multiples of 36 mV, see Ref. 111. We have not observed, however, any anomalous behaviour of $I_{AE}(I_T)$ at those bias voltages. Therefore, we consider the suppression of the AE current due to the inelastic scattering of the tunnelling electrons as negligible.

The $I_{AE}(I_T)$ characteristics could also reflect a complex potential landscape of our long QPCs. When the point contact is operated in the closed or nearly-closed regime, its channel becomes depleted of the conduction electrons. This reduces the screening of the impurity potentials,\textsuperscript{127-129} which could affect the exact shape of the QPC barrier. The formation of an impurity-induced static quantum dot affecting the SAW-driven charge transport was, for example, reported in Ref. 85.
Chapter 5

Power response

In order to study the power response of our devices, we perform detailed measurements of the acoustoelectric current as a function of both the gate voltage and the rf power applied to the SAW transducer. Over a broad range of microwave powers, we observe quantized steps in either the $I(V_g)$ or $I(P_{RF})$ characteristics. However, our experiments reveal rather a complicated pattern of the AE transitions which cannot be easily explained within the existing theories on the SAW-induced single-electron effect. For example, we demonstrate the $I(V_g)$ characteristics taken at large SAW powers where the lower AE plateaus (e.g. $n \leq 3$) are only weakly indicated in the current traces while the higher steps ($n > 3$) are still well-pronounced. In addition, we probe the transconductance which enables us to analyze the evolution of the AE plateaus on increasing the SAW amplitude. Different sets of the quantized steps are distinguished.

5.1 Prior work by others

The effect of the SAW power on the quantized acoustoelectric current was already investigated by Shilton et al.\textsuperscript{71} In those early experiments, the $I(V_g)$ characteristics were measured at fixed values of the microwave power. When the power was increased, the onset of the AE current shifted towards lower values of the gate voltage. This could be intuitively explained: The moving quantum dots were deeper and, thus, could transfer electrons across a higher potential barrier of the QPC. In the later studies by the same group,\textsuperscript{72-74,79} smooth transitions between the $n\sigma f$ and the $(n+1)\sigma f$ plateaus were, additionally, observed in the $I(V_g)$ characteristics taken at the increasing power levels. This is illustrated in Fig. 5.1. In the transitional regions, the current plateaus appeared away from the expected
multiples of $e_f$. Moreover, their slopes were much steeper than those for plateaus at $l = nef$. No explanation was, however, provided for this effect.

A complex structure of similar transitions was recently demonstrated by Fletcher et al. $^{85-87}$ Their results indicated that the quantized current steps observed at high SAW powers developed from the Coulomb blockade oscillations at low powers. When the numerical derivative of the current $dI(V_{g}, P_{RF})/dP_{RF}$ was plotted on a colour-scale-coded plot (Fig. 1.8), a highly regular V-shaped fan pattern of the transition lines (maxima in $dI/dP_{RF}$) was revealed. Those lines originated from the conductivity peaks in the low-SAW-power, high-conductance region and spread out towards high-SAW-power, low-conductance region where the quantized steps formed in the current near multiples of $e_f$. Fletcher et al. $^{85}$ associated their device behaviour at low power levels with the formation of an unintentional static quantum dot due to an impurity potential close to the entrance to the QPC. They proposed a transport mechanism alternative to the model of moving quantum dots $^{71,72}$ travelling with the SAW velocity. Instead, the SAW would dynamically tune the resonant states of the static dot, resulting in a turnstile-like operation of the device at GHz frequency.

In an earlier report on the integer acoustoelectric effect, Cunningham $^{79}$ considered the absence of the Coulomb blockade oscillations as a necessary condition for the AE current quantization. Fletcher et al. $^{85}$ concluded the opposite. They emphasized that the quantized AE current was not observed in their devices during the cool-downs for which the Coulomb blockade oscillations were not present. Such a strong dependence on a suitable configuration of random impurity potentials could explain the low yield of working SETSAW devices.
5.2 Experimental details

Quantized steps in the acoustoelectric current can be observed as a function of the gate and bias voltage, the SAW power and frequency. However, such a large number of relevant parameters makes it difficult to find the AE plateaus in the first place. The whole search procedure is described in section 3.6.1. In most cases, the bias voltage is set to zero, and the \( I(V_g) \) characteristics are taken at different values of the rf power and frequency. Hence, the power scans are routinely performed in our experiments. They are, however, carried out within a rather limited range of the microwave power applied to the SAW transducer (from around +10 to +15 dBm) and in large steps (around 0.5±1 dBm). Here, we present a much more detailed study of the AE current response to the applied SAW power. The same three devices are investigated as in chapter 4, namely HCO103-92-30122: -2B, -2C and -2E.

The acoustoelectric current \( I \) was measured simultaneously with the transconductance \( dI/dV_g \) as a function of both the gate voltage and the rf power. Since a large number of data points (~200 000) was required to obtain a sufficient resolution, each of those measurements was carried out over several hours (8÷14 h). The ac modulation applied to the gate was \( dV_g = 0.5 \) mV at 117 Hz. The experiments were performed in vacuum at the base temperature of 1.7 K of our refrigerator. The 2DEG temperature increased, however, to ~6 K (section 3.9) when the rf signal of about +10 dBm was applied to one of the transducers.

The transitions observed in either \( I(V_g, P_{RF}) \) or \( dI(V_g, P_{RF})/dV_g \) were strongly dependent on the SAW frequency. However, for a specific sample and fixed settings of other controllable parameters (such as \( f, V_{sd}, \varphi \)), the \( I(V_g, P_{RF}) \) characteristics were well reproducible during the same cool-down of the device. When the sample was thermally cycled to the room temperature, the characteristics differed distinctively from those obtained with the same parameter settings during other cool-downs. However, their general structure remained qualitatively similar.

5.3 Effect of the SAW power on the \( I(V_g) \) characteristics

Figure 5.2 shows the \( I(V_g) \) characteristics taken at different rf powers for sample 2E. During the measurements, the active IDT was on the same side of the QPC as the drain contact. Additionally, a small dc bias of \( V_{sd} = -100 \) µV was applied to the source. The voltage-driven current could, thus, be observed even in the absence of surface acoustic waves.

When the SAW is turned off, the current starts to flow for gate voltages above the pinch-off (\( V_g \approx -20 \) mV). The negative bias applied to the source determines the polarity of the resultant current. The plateau above \( V_g > -10 \) mV
corresponds to the first quantized step in the conductance. Note as well the periodic oscillations in the gate-voltage interval between the current onset and the plateau. Their resemblance to the Coulomb blockade peaks could suggest the presence of an impurity-induced quantum dot in the vicinity of the constriction.

When the SAW is turned on, the $I(V_g)$ characteristics remain unaffected as long as the rf power is below $-30$ dBm. Therefore, only the traces acquired at higher power levels are shown in Fig. 5.2. Above $-30$ dBm, a broad peak starts to form at $V_g = -10$ mV in the negative total current. On increasing the SAW power, the peak shifts its position along the $V_g$-axis towards lower values of the gate voltage. It is unclear whether this peak should be attributed to the velocity matching mechanism discussed for the AE charge transport in the open 1D channels\textsuperscript{70,71} or rather to the rectifying behaviour of the constriction due to the presence of an impurity.\textsuperscript{130,131} As the magnitude of the peak rises, the superposed periodic oscillations do not disappear. They become, however, more difficult to resolve because of the large background signal.

Figure 5.2: Sample HCO103-92-30122-2E. Current $I$ versus gate voltage $V_g$. Two traces were taken without the SAW at a small bias voltage of $-50$ $\mu$V (dotted line) and $-100$ $\mu$V (thick solid line). An rf signal of 2468.90 MHz was later applied to the SAW transducer on the same side of the QPC as the drain contact. Seven traces were recorded at fixed levels of microwave power from $-20.2$ dBm to $+9.8$ dBm in steps of 5 dBm (from right to left; $V_{sd} = -100$ $\mu$V). Only the traces at $+4.8$ dBm and $+9.8$ dBm showed current quantization in units of $e_\mathrm{f}$. $T = 1.7$ K.

\begin{center}
\includegraphics[width=\textwidth]{Figure5.2.png}
\end{center}
Figure 5.3: Sample HCO103-92-30122-2E. (a) Acoustoelectric current $I$ as a function of gate voltage $V_g$. The curves were measured for different rf powers $P_{RF}$ applied to the SAW transducer, in steps of 0.2 dBm. Consecutive dashed traces are spaced by 2 dBm. The roughly vertical dotted line at $V_g \approx \pm 50$ mV marks the division between different sets of AE plateaus, as discussed in the text. Note the disappearance of the lowest plateaus for the traces taken at high powers. For example the curve taken at $P_{RF} = +11.6$ dBm (thick solid line) shows little indications of the first three plateaus at $\pm 3\sigma f$ while plateaus at $4\sigma f$ can still be resolved with a naked eye. (b) The same data plotted with respect to the rf power at fixed gate voltages. The source contact was on the opposite side than the active IDT. $f = 2468.90$ MHz, $V_{sd} = -100$ $\mu$V, $T = 1.7$ K.
At power levels above 0 dBm, the current reverses its sign on decreasing the gate voltage. Quantized steps in units of $\Delta I = \phi f \approx 400$ pA start to appear at low values of $V_g$. For example, the trace taken at $P_{RF} = +9.8$ dBm shows at least three clear AE plateaus in the gate-voltage interval between the current onset ($V_g \approx -110$ mV) and the conductance pinch-off ($V_g \approx -25$ mV). The latter threshold is roughly indicated by the crossover of the current slope from the positive to the negative polarity. In the purely AE regime below the conductance pinch-off, the SAW determines the direction of the electron flow. Since the active transducer is located on the same side of the QPC as the drain contact, the acoustoelectric current has a positive sign. This explains the observed change in the current polarity when the surface acoustic waves become the main driving mechanism.

5.4 Quantized regime

Figure 5.3 (a) shows a typical set of the $I(V_g)$ characteristics in the gate-voltage interval where the quantized AE plateaus are well defined (sample 2E). On incrementing the microwave power from $P_{RF} = 0$ dBm, the onset of the acoustoelectric current shifts towards lower values of the gate voltage. Quantized steps are weakly pronounced in the current traces until another set of broad plateaus appears at power levels above $P_{RF} > +2$ dBm. The dotted line at $V_g \approx -50$ mV marks a division between those two different sets of the quantized steps. Another interesting feature is visible above $P_{RF} > +9$ dBm: The slope of the current becomes very steep at the current onset and up to four consecutive plateaus seem to be missing while those of the higher order are still present. For example, the first three plateaus ($n \leq 3$) are difficult to resolve in the current trace taken at $P_{RF} = 11.6$ dBm (thick solid line). However, at least three steps of higher order ($n \geq 4$) are still well visible at gate voltages above $V_g > -160$ mV.

The data of Fig. 5.3 (a) can also be plotted with respect to the rf power applied to the SAW transducer. This is illustrated in Fig. 5.3 (b) the AE current quantization as a function of the SAW power is clearly demonstrated. For certain gate voltages, some of the AE plateaus seem to be missing in the current traces. See, for example, the $I(P_{RF})$ traces taken at $V_g = -76$ mV and $V_g = -156$ mV. The maximum power of $P_{RF} = +13.8$ dBm was arbitrarily chosen to avoid possible damage to the IDT.

Figure 5.4 (a) shows another set of the $I(V_g)$ characteristics (sample 2C). Note a different behaviour of the acoustoelectric current at low levels of the rf power ($P_{RF} < +6$ dBm): The current does not change its polarity at high gate voltages ($V_g > -100$ mV). This is because the bias-driven electron flow is in the same direction as the SAW propagation. At high power levels ($P_{RF} > +11$ dBm) and small gate voltages ($V_g < -200$ mV), another set of the AE plateaus appears in the current traces. Not only are those steps away from the expected multiples of...
Figure 5.4: Sample HCO103-92-30122-2C. (a) Acoustoelectric current $I$ as a function of gate voltage $V_g$ for different SAW powers in steps of 0.2 dBm. Consecutive dashed lines are separated by 2 dBm. (b) Colour-scale coded plot of transconductance $dI/dV_g$ with respect to gate voltage $V_g$ and SAW amplitude $V_{SAW}$. See text for details on the conversion method used to rescale the logarithmic $P_{RF}$-axis (inset) into the linear $V_{SAW}$-axis (main figure). Dark (light) indicates large (small) transconductance. $f = 2469.20$ MHz, $T = 1.7$ K.
\( ef \approx 400 \text{ pA} \) but they are spaced in intervals smaller than \( \sqrt{2} ef \). However, their spacing increases on incrementing the microwave power. At \( P_{\text{RF}} > +14 \text{ dBm} \), the quantized steps eventually reach the expected values of \( I = n ef \).

Higher AE plateaus are easier to resolve in the current derivative. Figures 5.4 (b) and 5.5 show colour-scale coded plots of the transconductance \( \frac{dI}{dV_g} \) with respect to the gate voltage and the rf power. Those characteristics were measured at the same time as the acoustoelectric current of Figs. 5.4 (a) and 5.3, respectively. Plots of that type enable us to map the transitions between different quantized steps in the AE current, many of which are obscured in the current characteristics. To further improve the resolution, the vertical axes of Figs. 5.4 (b) and 5.5 are scaled linearly with respect to the SAW amplitude rather than to the SAW power.

The magnitude of the electrostatic potential of the SAW \( V_{\text{SAW}} \) at the crystal surface can be evaluated from the following expression:

\[
V_{\text{SAW}} = \frac{2 P_{\text{SAW}} \lambda_{\text{SAW}}}{\gamma_o w}
\]

where \( P_{\text{SAW}} \) is the SAW power, \( \lambda_{\text{SAW}} \) the wavelength, and \( w \) the beam width of the surface acoustic wave. The characteristic admittance \( \gamma_o \) is independent of the beam width. For surface acoustic waves propagating along the (011) direction on the (100)-cut surface of GaAs, it is equal to \( \gamma_o = 3.1 \text{ mS} \). The SAW power can be estimated from the transmittance measurements (section 3.5) under an assumption that both IDTs forming the SAW delay line have the same efficiency. However, this might result in an underestimate of the SAW power and, hence, the amplitude. On the other hand, the 2DEG plane is located \( \sim 80 \text{ nm} \) below the crystal surface. For the SAW wavelength of \( \lambda_{\text{SAW}} \approx 1.2 \text{ \mu m} \), the magnitude of the SAW potential at the 2DEG is, thus, reduced by approximately a half, see Fig. 1.2 (a).

The amplitude of the SAW potential in Figs. 5.4 (b) and 5.5 is calculated from Eq. 5.1 for given rf powers applied to the SAW transducer. The transmittance of around \(-50 \text{ dB} \) is taken into account, whereas the width of the SAW beam is \( w \approx 60 \text{ \mu m} \). The obtained values are treated only as an estimate and are, therefore, denoted as arbitrary units (1 a.u. \( \sim 1 \text{ mV} \)). Once the power axis is rescaled, the transconductance data is linearly interpolated at the evenly spaced positions on the amplitude scale.

### 5.5 Structure of the AE transitions

The transconductance characteristics reveal rather a complicated pattern of the AE transitions. Towards an economy of words, we use the term AE plateau...
Figure 5.5: Sample HCO103-92-30122-2E. Colour-scale coded plot of transconductance $\frac{dI}{dV_g}$ with respect to gate voltage $V_g$ and SAW amplitude $V_{SAW}$ measured simultaneously with the AE current shown in Fig. 5.3. Dashed lines indicate transconductance maxima that are not well resolvable within the chosen colour scale. Three regions are distinguished (TYPE A, B, and C) where the transconductance minima corresponding to current plateaus show different behaviour with respect to $V_g$ and $P_{RF}$, as discussed in the text. $f = 2468.90$ MHz, $V_{sd} = -100$ µV, $T = 1.7$ K.
interchangeably with the transconductance minimum. On the other hand, the transition lines are the transconductance maxima, marking the regions in-between the quantized steps in the acoustoelectric current. In the following description of the basic features observed in the \( \frac{dI(V_g,P_{RF})}{dV_g} \) characteristics, we use data of Fig. 5.5 as a representative example for all three investigated samples.

Basing on similarities in their behaviour, we distinguish three types of transition lines (Fig. 5.5). Such a notation, though rather arbitrary, enables us to refer more precisely to specific transitions. Due to their superior flatness, the AE plateaus separated by lines of TYPE \( B \) are typically scrutinized in the experiments on the precision of the current quantization (Figs. 3.12-3.13). However, quantized steps at expected values of \( I = n e f \) can also be observed in regions of TYPE \( A \) and TYPE \( C \).

The transition lines of TYPE \( A \) appear at the lowest levels of the applied microwave power. On few occasions, a weak V-shaped structure was found in this power range (Fig. 5.6), resembling the fan patterns of Refs. 85-87. In those cases, lines of TYPE \( A \) originated from periodic oscillations in the current (Fig. 5.2). This could suggest a relation between those transitions and an impurity-induced static quantum dot or an impurity-induced potential in general.

At sufficiently high SAW amplitudes (\( P_{RF} > -1 \) dBm in Figs. 5.3 and 5.5), the total current and its derivative reverse their sign on decreasing the gate voltage. (Note that the change in the current polarity occurs only if the bias applied to the source contact drives the charge in the opposite direction than the SAW.) Plateaus of TYPE \( A \) start to form in the current. They are, at first, away from the expected values and eventually approach \( I = n e f \) when the SAW power is increased (Fig. 5.3).

The lines of TYPE \( B \) start to appear at power levels higher than those for which the transitions of TYPE \( A \) become first apparent. In the intermediate range of the microwave power (\( P_{RF} \in (+1,+9) \) dBm in Fig. 5.5), those two sets of transitions behave in a distinctly different way: Lines of TYPE \( A \) run parallel to each other and are densely spaced with respect to the gate voltage. Current steps corresponding to the transconductance minima of that type are weakly pronounced in a steeply rising current. Moreover, their position with respect to the gate voltage is only slightly affected when the SAW amplitude is varied. In contrast, broad AE plateaus of TYPE \( B \) shift their position along the \( V_g \)-axis in response to much smaller changes in the SAW power. This distinction becomes, however, less clear at higher power levels (\( P_{RF} > +9 \) dBm in Fig. 5.5). In this regime, the lines of TYPE \( A \) are still densely spaced but their slope becomes similar to the slope of the lines of TYPE \( B \), see Fig. 5.5. As a result, at high SAW amplitudes, both sets of transition lines separate broad plateaus in the \( I(V_g) \) characteristics (or narrow plateaus in the \( I(P_{RF}) \) traces).

Transitions of TYPE \( C \) appear at high SAW powers and low gate voltages (\( P_{RF} > +10 \) dBm and \( V_g < -150 \) mV in Fig. 5.5). In our experiments, we usually observed only a very weak indication of current plateaus of TYPE \( C \). In most cases,
the first few quantized steps seemed to be missing in the \( I(V_g) \) characteristics taken at large SAW powers. At the same time, the higher plateaus (of \textsc{type} A or B) were still present and well pronounced in the current traces, see Fig. 5.3. In other words, the AE current appeared to be \textit{cut off} below a certain value of the gate voltage. It has to be noted that this threshold voltage was very sensitive to the variations in the SAW frequency, see chapter 6.

Clear plateaus or transition lines of \textsc{type} C were observed only in some of the \( I(V_g,P_{RF}) \) and \( dI(V_g,P_{RF})/dV_g \) characteristics acquired by us (Fig. 5.4), in the regime of high SAW powers and low gate voltages. The resolved plateaus of \textsc{type} C were densely spaced with respect to the gate voltage, in contrast to the broad steps of \textsc{type} A and B in the same range of microwave power. Surprisingly, this situation was very similar to the one observed at lower SAW amplitudes, where the two sets of clearly different plateaus were present in the \( I(V_g) \) characteristics: broad steps of \textsc{type} B and densely-packed plateaus of \textsc{type} A.

Different transition lines can cross each other. However, only the crossings between lines of \textsc{type} B can usually be resolved in the raw transconductance data. In order to reveal others, the positions of the transconductance maxima and minima are mapped on a colour-scale coded plot of the acoustoelectric current. This is shown in Fig. 5.7 where possible crossings between different transition

Figure 5.6: Sample HCO103-92-30122-2E. Colour-scale coded plot of transconductance \( dI/dV_g \) with respect to gate voltage \( V_g \) and SAW amplitude \( V_{SAW} \). V-shaped structure of the transition lines is weakly visible at small amplitudes. See for example the transconductance maximum at \( V_g \approx -35 \text{ mV} \) and \( P_{RF} = -5 \text{ dBm} \) which splits on increasing the rf power, forming a V-shaped pattern. \( f = 2468.90 \text{ MHz}, V_{sd} = -100 \mu \text{V}, T = 1.7 \text{ K} \).
Figure 5.7: Sample HCO103-92-30122-2E. Colour-scale coded plot of current $I$ versus gate voltage $V_g$ and SAW amplitude $V_{SAW}$. Different colours indicate current intervals of $\Delta I = 400 \text{ pA} = \epsilon f$. Open (full) symbols mark the position of the minima (maxima) in the transconductance $dI/dV_g$. The numbers label the current plateaus. This is another way of presenting the same data as in Fig. 5.3 (current) and 5.5 (transconductance) which enables us to resolve the crossings between different transition lines (transconductance maxima), as discussed in the text. $f = 2468.90 \text{ MHz}$, $V_{sd} = -100 \mu \text{V}$, $T = 1.7 \text{ K}$. 

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of \text{T}y\text{pe B} and \text{A} are indicated with thick solid lines. The lines of \text{T}y\text{pe C} are not analyzed in this example since they are hardly discernible in the data.

Note the evolution of different sets of the transconductance minima. In particular, the set marked with black pentagons attracts a special attention: At microwave powers exceeding $P_{\text{RF}} > +10 \text{ dBm}$, those minima indicate the sixth plateau in the acoustoelectric current (Figs. 5.7 and 5.8). On decreasing the SAW amplitude, the current at those minima is, however, notably reduced. Below $P_{\text{RF}} < +3 \text{ dBm}$, they indicate the first AE plateau!

When a crossing occurs between different transition lines, they change their character. For example, at around $P_{\text{RF}} = +5 \text{ dBm}$ and $V_g = -70 \text{ mV}$ in Fig. 5.7, the line separating the current onset and the first plateau turns into a division line between the first and the second step in the AE current. Moreover, it becomes possible to “skip” the first plateau and directly enter the second. A similar feature was reported by Fletcher \textit{et al.} \textsuperscript{85}: At low power levels, they observed an ordered structure of transition lines which crossed each other. This was attributed to the resonant tunnelling through an impurity-induced quantum dot. The transitions discussed here occur, however, at much higher SAW powers where the validity of this transport mechanism is still disputed.

Figure 5.8: Sample HCO103-92-30122-2E. (open symbols) The actual current $I$ at the transconductance minima indicated in Fig. 5.7 as a function of (a) gate voltage $V_g$ and (b) SAW amplitude $V_{\text{SAW}}$. The solid lines are guide to eye.
Figure 5.9: Sample HCO103-92-30122-2C. (a) Acoustoelectric current $I$ as a function of bias voltage $V_{sd}$ for different SAW powers in steps of 0.2 dBm. Consecutive dashed lines are separated by 2 dBm. (b) Colour-scale coded plot of conductance $dI/dV_{sd}$ with respect to bias voltage $V_{sd}$ and rf power $P_{RF}$ applied to the SAW transducer. Dark indicates large magnitudes of (negative) conductance and light indicates small magnitudes. The bias voltage was applied to the source contact on the same side of the QPC as the active IDT. $f = 2474.95$ MHz, $V_g = -250$ mV, $T = 1.7$ K.
It is interesting to note that, when the source-drain bias is varied instead of the gate voltage, features similar to those described above can still be observed in both the current $I(V_{sd}, P_{RF})$ and the conductance $dI(V_{sd}, P_{RF})/dV_{sd}$ (Fig. 5.9). This includes: different types of transition lines, crossings between them, and even the cut-off behaviour. In view of the results presented in chapter 4, this similarity to the $I(V_g, P_{RF})$ and $dI(V_g, P_{RF})/dV_g$ characteristics is, however, not a surprising observation: The bias voltage is another means to alter the barrier height of the point contact.

### 5.6 Possible role of random potentials

The enhanced role of impurity or ionized-donor potentials in the vicinity of our long ~1÷3 µm quantum point contacts was already indicated in section 3.3, while discussing the conductance characteristics without the SAW. Our devices show strong conductance fluctuations at temperatures $T \ll 2$ K (Fig. 3.2). Smooth conductance steps observed at higher temperatures are often accompanied with an additional structure near pinch-off (Fig. 3.2). After corrections for series resistance, the conductance plateaus are spaced in regular intervals. They are, however, considerably below the expected multiples of $G_o = 2e^2/h$. This apparent reduction in the conductance quantization could also be attributed to the disorder in our long quasi-1D channels, as concluded for similar systems in Refs. 112-114,132.

The effect of the disordered background should be even more pronounced in the gate-voltage interval near and below conductance pinch-off, that is in the region relevant for the AE current quantization. As the 1D channel is depleted of the conduction electrons, screening of the nearby random potentials is reduced. Hence, they can affect the transport properties of the device.

Periodic peaks observed in the $I(V_g)$ characteristics measured without the SAW or at low SAW powers (Fig. 5.2) could be another indication of the complex potential landscape of our constrictions. When the SAW power is increased, those current oscillations can transform into the AE plateaus of TYPE A (Fig. 5.6). This resembles the experimental observations by Fletcher et al. 85,87

An impurity potential located away from the center of the QPC (on the side of the incoming SAW) could also be a plausible explanation for the cut-off behaviour observed in the $I(V_g)$ characteristics taken at high SAW powers (Figs. 5.3 and 5.5). In such a simplistic picture, the broad potential hill of the QPC would determine the number of electrons transferred per SAW cycle, as in the standard model of moving quantum dots. 71 Above a certain gate voltage, the presence of a nearby impurity would not affect the SAW-driven electron transfer across the QPC, as long as the conduction electrons can go around the impurity-induced potential. A decrease in the gate voltage would reduce its screening by the 2DEG. The impurity could then block the sideway access to the QPC
entrance. Hence, the electrons would have to be transferred across the potential barriers of both the impurity and the point contact. Such a picture would have an interesting implication at high SAW powers: Above the threshold value of the gate voltage, when the impurity no longer blocks the QPC entrance, the height of the potential barrier of the point contact could already be low enough to allow the transport of more than one electron in a deep SAW minimum.

It is still unclear to us whether the presence of the disordered background potentials enhances or suppresses the SAW-driven single-electron transport. Nevertheless, the long constrictions of our devices can hardly be perceived as clean quasi-1D channels. The disorder-related features were observed in both the conductance and the current characteristics. Despite it, we were able to observe very clear $I(V_g)$ staircases with an impressive number of up to 20 quantized steps in the AE current (Fig. 3.11). Under certain conditions, our devices showed as well some of the flattest plateaus ever reported (Fig. 3.12). On the other hand, the yield of working SETSAW devices was extremely low (section 3.6.2). A large number of samples did not produce quantized steps in the AE current although their geometrical layout, fabrication procedures as well as the conductance and the transmittance characteristics were very much the same as for the devices described in this study.

In view of those problems with acquiring working devices, the random factor suggested by Fletcher et al.\textsuperscript{85} would seem a particularly attractive explanation. They related the AE quantization with a favourable configuration of random impurity potentials: quantized steps in the current were observed only during the cooldowns for which the Coulomb blockade oscillations were present. One could imagine as well an opposite scenario where an impurity near the entrance to the constriction does not promote the quantized current flow but prevents it. It would be of considerable interest if the effect of the impurity potentials was included into the existing theoretical models of the SAW-driven single-electron transport.\textsuperscript{88-91,94-96}
Chapter 6

Effect of the SAW frequency

When the SAW frequency is varied within the transducer passband, our devices show pronounced oscillations in the acoustoelectric current, see Figs. 3.6 and 6.1. Two mechanisms are typically considered in order to explain those interference patterns (section 3.8). First, a direct pick-up of the microwave signal that is irradiated from the SAW transducer. Since our IDTs are located about 1.25 mm from the quantum point contact, this would result in the current oscillations with a period of around 2.2 MHz. Second, the SAW reflections from the transducer on the other side of the QPC. In such case, the main and the reflected SAW beam produce a standing wave at the point contact. In our devices, this mechanism would result in a frequency modulation of about 1.1 MHz, as the round trip from the QPC to the IDT is approximately 2.5 mm. This is, in fact, the dominating period of the current oscillations observed for our samples (Fig. 6.1).

The effect of the second SAW beam can be conveniently investigated in the experiments where two counterpropagating beams are applied on purpose. This technique was developed by Cunningham et al.\textsuperscript{75,79} and also used in our studies, see section 3.8. When the phase of the second SAW beam is varied with respect to the main beam, the nodes and antinodes of the standing wave change their position. This can be of particular importance at the entrance to the constriction or, in general, at the positions where the number of electrons transferred per SAW cycle is determined.

In this chapter, we present detailed measurements of the acoustoelectric current and the transconductance with respect to both the gate voltage and the SAW frequency. The current oscillations with a modulation of about 1.1 MHz are clearly visible in our data. However, within this period, two frequency intervals can be distinguished where different sets of the AE plateaus seem to prevail. We compare those results with the experiments where two counterpropagating SAW
Figure 6.1: Acoustoelectric current $I$ versus SAW frequency $f$ for samples: (a) HCO103-92-30122-2C; (b) HCO103-92-30122-2E; (c) HCO456-11124-2B; and (d) HCO99-92-21024-2A. The data were taken at different values of the gate voltage $V_g$ below pinch-off for conductance, as indicated in figures. $T = 1.7$ K.
beams are applied at a fixed frequency and the phase between them is varied. We also point out similarities between the \( I(V_g, f) \) and the \( I(V_g, P_{RF}) \) characteristics.

### 6.1 Device HCO103-92-30122-2C

Figure 6.2 shows the acoustoelectric current \( I \) measured as a function of gate voltage \( V_g \). The SAW frequency was incremented by 0.05 MHz between consecutive sweeps in \( V_g \). During the measurement, a microwave signal of \( P_{RF} = 9.8 \text{ dBm} \) was applied to the driving IDT. \( T = 1.7 \text{ K} \).

Figure 6.2: Sample HCO103-92-30122-2C. Acoustoelectric current \( I \) measured as a function of gate voltage \( V_g \). The SAW frequency was incremented by 0.05 MHz between consecutive sweeps in \( V_g \). During the measurement, a microwave signal of \( P_{RF} = 9.8 \text{ dBm} \) was applied to the driving IDT. \( T = 1.7 \text{ K} \).

The detailed structure of the observed AE transitions is again better visible in the colour-scale-coded plot of the transconductance \( dI/dV_g \), as shown in
Figure 6.3: Sample HCO103-92-30122-2C. Grey-scale coded plot of transconductance $dI/dV_g$ with respect to SAW frequency $f$ and gate voltage $V_g$. The transconductance was measured simultaneously with the AE current shown in Fig. 6.2. Dark (light) indicates small (large) values of the current derivative. Note pronounced oscillations with a period of 1.1 MHz. In addition, two smaller intervals can be distinguished within this period where different sets of AE plateaus seem to prevail. Solid and dotted arrows indicate frequencies around which one set is replaced by another. See text for details. $P_{ef} = +9.8$ dBm, $T = 1.7$ K.
Fig. 6.3. Note that the AE plateaus do not evolve smoothly over the entire interval of 1.1 MHz, being the dominating period of the current oscillations. On increasing the SAW frequency, the broad plateaus (with respect to the gate voltage) can be abruptly replaced by densely-packed quantized steps. The frequencies around which such events occur are indicated in Fig. 6.3 with solid arrows, spaced by approximately 1.1 MHz. Another type of events is marked with the dotted arrows. Within a narrow frequency interval around them, the acoustoelectric current dramatically shifts its onset along the gate-voltage axis. This displacement can be as large as $\Delta V_g \approx 50$ mV over $\Delta f \approx 0.2$ MHz, as it occurs for $f = 2467.8$ MHz.

The frequency response of the $I(V_g)$ and the $\frac{dI}{dV_g}$ characteristics is shown in more detail in Fig. 6.4: When the SAW frequency is incremented from 2465.7 MHz, the first plateau in the AE current broadens with respect to the gate voltage. At the same time the current onset shifts towards smaller values of $V_g$. At $f = 2465.9$ MHz, the first quantized step can no longer be resolved in either the AE current or the transconductance. (This frequency is marked with a solid arrow in Fig. 6.3.) On further increase in frequency, the AE plateaus start to reappear in the $I(V_g)$ traces of Fig. 6.4. They are much less pronounced than those below $f = 2465.9$ MHz, as both their slope and their number per gate-voltage interval is increased. They evolve smoothly until about $f = 2466.7$ MHz (dotted arrow in Fig. 6.3). Around this frequency, the onset of the $I(V_g)$ traces shifts drastically towards lower gate voltages. For the characteristics obtained at $f = 2466.6$ and 2466.8 MHz, this displacement is as large as $\Delta V_g \approx 40$ mV. Above 2466.7 MHz, another set of quantized steps starts to develop in the AE current. The new set corresponds to the one below 2465.9 MHz. Thus, a full cycle in the frequency domain is completed.

Solid and dotted arrows in Fig. 6.3 indicate frequencies around which one of the two presumably independent sets of the AE plateaus in $I(V_g)$ seems to replace the other. Two frequency intervals are, thus, distinguished within a period of 1.1 MHz. A more detailed analysis of our data leads to an even more puzzling observation. At some frequencies, plateaus belonging to both sets can appear simultaneously in $I(V_g)$, as if they were superposed on each other. This becomes apparent when one of those two sets forms the current plateaus at the expected multiples of $n \omega f$ while the other produces quantized steps away from those values. It has to be noted that the latter type of plateaus is usually weakly pronounced in the $I(V_g)$ traces and needs to be resolved in the transconductance, as described in the following.

In Fig. 6.5 (a), we map the positions of the transconductance minima from Fig. 6.3 on a colour-scale-coded plot of the acoustoelectric current. The exact current at the corresponding plateaus is plotted in Fig. 6.5 (b). Note that, for some SAW frequencies, the transconductance minima indicate more than one plateau in $I(V_g)$ within an interval of $\Delta I = \omega f$. See for example for $f = 2465.8$ MHz in Fig. 6.5 (a). Figure 6.5 (b) reveals that such a situation can result from a simultaneous occurrence of two different sets of the AE plateaus which respond in
a distinctively different way to the change in frequency. For example, focus on the following range \( f \in [2465.7; 2465.9] \text{ MHz} \). On increasing the SAW frequency within this interval, one plateau in \( I(V_g) \) remains at the expected value of \( I_{ef} \approx 400 \text{ pA} \) while another set of quantized steps appears at lower and lower currents. Note a regular spacing (close to \( \Delta I = ef \)) between consecutive plateaus belonging to the latter set. Despite changes in the current magnitude, this spacing is maintained. Within the selected frequency interval, the plateau observed at \( I = I_{ef} \) is broad and well pronounced with respect to the gate voltage, see Fig. 6.4. On the other hand, the steps away from the expected multiples of \( ne_{ef} \) are barely indicated in the \( I(V_g) \) characteristics.

Figure 6.4: Sample HCO103-92-30122-2C. (black) AE current \( I \) and (light) transconductance \( dI/dV_g \) as a function of gate voltage \( V_g \). 16 graphs show selected traces from Figs. 6.2 (current) and 6.3 (transconductance), with the SAW frequency incremented by 0.1 MHz between consecutive panels. \( P_{RF} = +9.8 \text{ dBm}, T = 1.7 \text{ K} \).
Figure 6.5: Sample HCO103-92-30122-2C. (a) Colour-scale coded plot of acoustoelectric current $I$ with respect to SAW frequency $f$ and gate voltage $V_g$. Different colours indicate current intervals of $\Delta I = 400 \text{ pA} = \sigma f$. Open (full) symbols mark the position of the minima (maxima) resolved in the transconductance $dI/dV_g$. This is another way of presenting the same data as in Fig. 6.2 (current) and 6.3 (transconductance). Note that at some frequencies, minima in $dI/dV_g$ indicate more than one AE plateau within the interval $\Delta I = \sigma f$. (b) The actual AE current at the transconductance minima indicated in (a). $P_{RF} = +9.8 \text{ dBm}, T = 1.7 \text{ K}$. 

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6.2 Device HCO103-92-30122-2E

Two separate sets of the AE plateaus within a frequency period of 1.1 MHz were also observed for our other SETSAW devices. Figure 6.6 shows the results obtained for sample (HCO103-92-30122-) 2E in a configuration with two counterpropagating SAW beams. The measurements were performed at $T = 1.2 \text{ K}$ in the $^3\text{He}$ cryostat. An rf power of +13.5 dBm was applied to the driving transducer while the signal applied to the second IDT was attenuated by 8 dB. Prior to those measurements, the phase of the second SAW beam was optimized in order to produce the flattest plateaus in the acoustoelectric current, as described in section 3.8.

Both the current and the transconductance plots of Fig. 6.6 reveal a very clear 1.1 MHz-beating. The AE plateaus can be resolved at all frequencies within this period. Solid and dotted arrows in Fig. 6.6 (b) indicate the SAW frequencies around which one set of the AE plateaus is replaced by another, as discussed for sample (HCO103-92-30122-) 2C. Note another common feature between devices 2C and 2E: broad minima (maxima) observed across the parameter space of the $dI(V_g,f)/dV_g$ characteristics. An example would be a broad transconductance minimum that runs across Fig. 6.3 from $f \approx 2465.8 \text{ MHz}$ and $V_g \approx -200 \text{ mV}$ up to $f \approx 2466.6 \text{ MHz}$ and $V_g \approx -50 \text{ mV}$. Such skew minima (maxima) can be observed over the entire parameter range of Figs. 6.3 and 6.6 (b), for devices 2C and 2E, respectively.

Selected $I(V_g)$ and $dI(V_g)/dV_g$ traces from Fig. 6.6 are plotted in Fig. 6.7 in steps of 0.1 MHz. While varying the SAW frequency, the $I(V_g)$ curves evolve in a similar way as for sample 2C. At $f = 2458.6 \text{ MHz}$, only the first three quantized steps can be resolved in $I(V_g)$ at gate voltages below $V_g < -25 \text{ mV}$. When the frequency is increased, the onset of the acoustoelectric current shifts towards smaller values of the gate voltage. At the same time, the AE plateaus become wider with respect to $V_g$. This trend continues until $f = 2458.8 \text{ MHz}$ (marked with a solid arrow in Fig. 6.6 (b)). Around this frequency, another set of densely spaced AE plateaus appears at the onset of $I(V_g)$. This new set of quantized steps evolves continuously until $f = 2459.5 \text{ MHz}$ (marked with a dotted arrow in Fig. 6.6 (b)). Close to this frequency, the current onset abruptly shifts along the $V_g$-axis towards larger gate voltages.

For some SAW frequencies, quantized steps in the acoustoelectric current can be observed both at the expected multiples of $l = n \Delta f$ and away from those values. In such cases, more than one AE plateau can be defined within a current interval of $\Delta I = \Delta f$. See for example the traces obtained for $f = 2458.8 \text{ MHz}$ or 2459.0 MHz. This is similar behaviour as discussed for sample 2C (Figs. 6.3-6.5).

The evolution of the $I(V_g)$ characteristics in response to the incremented frequency (Figs. 6.4 and 6.6) closely resembles changes observed in $I(V_g)$ when the phase of the second SAW beam is varied (Fig. 3.10). In the latter type of
Figure 6.6: Sample HCO103-92-30122-2E. (a) AE current $I$ and (b) transconductance $dI/dV_g$ with respect to SAW frequency $f$ and gate voltage $V_g$. The measurement was performed in the configuration with two counterpropagating SAW beams. The microwave signal of $P_{RF}=+13.5$ dBm was applied to the driving transducer while the signal applied to the second IDT was attenuated by 8dBm. In (b), dark (light) colour indicates small (large) values of the transconductance. Solid and dotted arrows indicate frequencies around which one set of AE plateaus is replaced by another. $T = 1.2$ K.
experiments, two counterpropagating SAW beams are generated on purpose while the phase shift between them is controlled, as described in section 3.8.

Similar beating of the acoustoelectric current can be observed in both types of measurements, with a period of either $\Delta f = 1.1\, \text{MHz}$ or $\Delta \phi = 2\pi$. In both cases, two subintervals can be distinguished within those periods. Different sets of plateaus seem to prevail in either of them. Around certain frequencies (phases), one of those sets is abruptly replaced by another.

Close resemblance between the frequency and phase response of the $I(V_g)$ characteristics supports the argument that the 1.1 MHz-oscillations observed in the AE current as a function of frequency are due to the interference between the two counterpropagating SAW beams. Even for the configuration where only one
driving transducer is used, the main SAW beam can be reflected from the second IDT on the opposite side of the QPC. The phase between the main and the reflected beam changes by $2\pi$ when the SAW frequency is varied by 1.1 MHz.

6.3 Common features in the power and frequency response

Similarities can also be pointed out between the frequency and power response of our devices:

On increasing the SAW power, the onset of the \( I(V_g) \) characteristics shifts towards smaller values of the gate voltage, see Figs. 5.3 (a) and 5.5. At low power levels, this onset is still close to the conductance pinch-off, whereas the quantized steps that develop in \( I(V_g) \) are steep and densely spaced with respect to \( V_g \). Only at higher microwave powers, broad AE plateaus start to appear. Finally, at large SAW amplitudes, another set of quantized steps forms in the \( I(V_g) \) characteristics at small gate voltages. Those steps are typically densely spaced with respect to the gate voltage. Refer to chapter 5 for a more detailed description.

Within a certain interval of the SAW frequency, similar behaviour can also be observed for the \( I(V_g) \) characteristics taken at increasing frequencies. For example, follow the changes that occur in Fig. 6.6 (b) within a sub-1.1 MHz range from \( f = 2458.4 \text{ MHz} \) to \( f = 2458.8 \text{ MHz} \). An increase in the SAW frequency within this range results in: 1) a shift of the current onset towards smaller values of the gate voltage; 2) broadening of the lowest plateaus; and finally 3) the appearance of another set of the AE steps that are densely spaced with respect to the gate voltage. Note that such behaviour can be observed within any of the sub-1.1 MHz intervals that are delimited by a dotted and a solid arrow from the bottom and the top, respectively (Fig. 6.3 and 6.6). Qualitatively, those features are similar to those recalled above for the power response.

In the preceding sections, we distinguished two frequency intervals within a period of 1.1 MHz (Figs. 6.3 and 6.6). Presumably independent sets of the AE plateaus seem to appear in either of them. We refer to those frequency ranges by stating whether their lower and upper limit in frequency is indicated by dotted and solid arrow, respectively, or vice versa. On the other hand, to describe the power response characteristics, we use the notation introduced in chapter 5. Three types of AE plateaus are distinguished there (TYPE A, B and C), based on their different behaviour with respect to the gate voltage and rf power (Fig. 5.5). Here, we attempt to merge those two descriptions.

Figure 6.8 shows the transconductance with respect to both the gate voltage and the rf power applied to the SAW transducer. The measurements were performed for device 2C, at four different frequencies. Refer to Fig. 6.3 (taken at \( P_{RF} = +9.8 \text{ dBm} \)) to find out to which sub-1.1 MHz-range those frequencies belong. Note that Fig. 6.8 (c) shows the same data as Fig. 5.4 (b) in chapter 5:
Figure 6.8: Sample HCO103-92-30122-2C. Transconductance $\frac{dI}{dV_g}$ with respect to gate voltage $V_g$ and rf power $P_{RF}$ applied to the SAW transducer. The data in four consecutive panels were measured at the indicated SAW frequencies $f$, $T = 1.7$ K.
Plateaus of TYPE A can be distinguished at large gate voltages $V_g > -100 \text{ mV}$. They are weakly indicated (even in the current derivative) and densely spaced with respect to the gate voltage. On increasing the microwave power, they shift along the $V_g$-axis towards smaller values of the gate voltage. Broad steps of TYPE B start to develop at $P_{RF} > +7 \text{ dBm}$. Finally, at high SAW powers ($P_{RF} > 11 \text{ dBm}$) and low gate voltages ($V_g < -200 \text{ mV}$), another set of plateaus appears (TYPE C) which are densely spaced with respect to $V_g$.

The data of Fig. 6.8 (c) was acquired at a fixed frequency of $f = 2469.2 \text{ MHz}$. At $P_{RF} = +9.8 \text{ dBm}$, two broad minima of TYPE B are revealed in the transconductance scan performed along the gate-voltage axis $dI(V_g)/dV_g$. Those minima correspond to the first two quantized steps ($n \leq 2$) in the AE current. Similar $dI(V_g)/dV_g$ trace, taken at the same parameter settings of $P_{RF} = +9.8 \text{ dBm}$ and $f = 2469.2 \text{ MHz}$, can also be found in the frequency response plot of Fig. 6.3. It appears within the sub-1.1 MHz interval delimited by a dotted and a solid arrow at $f \approx 2469.0 \text{ MHz}$ and $f \approx 2469.4 \text{ MHz}$, respectively.

Broad plateaus that appear within this frequency range could, thus, be referred as those of TYPE B. On increasing the SAW frequency, they become wider with respect to $V_g$ (Fig. 6.3). At the same time, the current onset shifts towards smaller values of the gate voltage. At a certain frequency (solid arrow in Fig. 6.3), broad plateaus in $I(V_g)$ are replaced by densely spaced current steps, thus, marking the lower limit of the second frequency interval that can be distinguished within a period of 1.1 MHz. The replacement of the broad AE plateaus by densely-spaced steps, which occurs at small gate voltages, resembles the formation of plateaus of TYPE C in the power response experiments of chapter 5. When the SAW frequency is further increased, the current onset shifts back towards larger values of $V_g$. At the same time, the AE plateaus can become broader with respect to the gate voltage.

Figures 6.8 (a), (b) and (d) show the results of the power response measurements, performed at fixed frequencies from this second type of sub-1.1 MHz range. In the following we concentrate on Fig. 6.8 (b). At the power level of $P_{RF} = +9.8 \text{ dBm}$, the lowest plateaus resemble broad steps of TYPE B. However, one could still speculate that those are current steps of TYPE C that evolved in response to the change in frequency. Figure 6.8 (b) would then suggest that some modifications are necessary in the way we describe plateaus of different types. The main emphasis should be placed on the fact that those are separate sets of quantized steps which have distinctively different response to the SAW frequency and power.

6.4 Change in the period of frequency modulation

The frequency response characteristics of our devices (Figs. 6.2-6.6) were highly reproducible during the same cool-down of the device. When the
Figure 6.9: Transconductance $\frac{dI}{dV_g}$ with respect to SAW frequency $f$ and gate voltage $V_g$ for samples: (a)-(b) HCO103-92-30122-2C and (c) HCO103-92-30122-2E. Note the change in the period of frequency modulation from 1.1 MHz (a) to 2.2 MHz (b)-(c). The microwave power applied to the SAW transducer was: (a) +9.8 dBm, (b) +10.8 dBm, and (c) +12.8 dBm. $T = 1.7$ K.
investigated sample was thermally cycled to room temperature and cooled down again, the new results differed from those obtained with the same parameter settings in previous cool-downs. In most cases, they remained, however, qualitatively similar to those in Figs. 6.2-6.7. Nonetheless, this was not always the case. On few occasions, notable departures from patterns of Figs. 6.2-6.7 were observed, as demonstrated in Fig. 6.9.

The most apparent difference is the change in the period of the frequency modulation from around 1.1 MHz to about 2.2 MHz. This suggests an enhanced role of a direct pick-up of the irradiated microwave signal (section 3.8). The observed structure of the AE transitions is indeed very complex. At present, we cannot provide a generalized description of those results, as it was presented in the preceding sections for the 1.1 MHz oscillations. Note, however, that the data of Fig. 6.9 also indicates different sets of the transition lines (transconductance maxima).

6.5 Summary and conclusion

The frequency response measurements presented in this chapter reveal a complicated pattern of the AE transitions. Their most apparent feature is the 1.1 MHz beating of the acoustoelectric current. This immediately recalls the interference patterns due to the standing wave. In fact, we demonstrate that the results obtained while varying the SAW frequency closely resemble those when the phase is controlled between two counterpropagating SAW beams. The period of 1.1 MHz corresponds to a phase shift of $2\pi$.

Several new experimental observations, presented here, should be emphasized. Quantized steps can be observed in the AE-current-versus-gate voltage characteristics at all frequencies from the 1.1 MHz period. This is in contrast to previous reports by Shilton et al. They observed quantized steps only off the maxima of the oscillations, on their high-frequency side. Later results by Cunningham et al. indicated that the AE plateaus can also form at other frequencies within the modulation period. However, no full description of the observed structure was provided.

In our measurements, quantized steps are revealed at any frequency within the 1.1 MHz range. We demonstrate that two subintervals can be distinguished within this period where different sets of AE plateaus seem to prevail close to the current onset. At certain frequencies, one set of quantized steps is replaced by another. In some cases, they can simultaneously appear in the $I(V_g)$ traces, as if they were superposed. When such a situation occurs, quantized steps can be resolved in the AE current both at the expected multiples of $nef$ and away from those values. In other words, more than one AE plateau can appear within a current interval of $\Delta I = ef$. Those two sets of plateaus seem to be independent
from each other. They respond in a different way to the SAW frequency and power.

The occurrence of two independent types of AE plateaus is, at present, not well understood. A possible scenario could be the branching of electron flux which occurs at the entrance to the QPC. This could affect the way the moving quantum dots are populated with electrons. Such branching behaviour was recently demonstrated by Topinka et al.\textsuperscript{134-136} In their experiments, a negatively charged STM tip was scanned above the 2DEG while probing the conductance of the nearby QPC. Spatially resolved images of the electron flow in the 2DEG were, thus, acquired, indicating current strands at the entrance and exit to the point contact. This was attributed to focusing of the electron trajectories by a large ensemble of small (~10% $\varepsilon_f$) ripples in the background potential caused by impurities or donors. In the SETSAW experiments, such branching of the electron flux could affect how the moving quantum dots are populated with electrons. Quantized acoustoelectric current could be obtained for each of those discrete trajectories, explaining different sets of AE plateaus observed in our measurements.

Close to the pinched-off QPC, the screening of the impurity potentials is reduced. Hence, the size of those potential fluctuations (~50 mV) could be much larger than in the 2DEG.\textsuperscript{127,128} This could lead to the formation of separate pathways through the constriction. Note that the change in the SAW frequency (phase) results in a shift of the nodes and antinodes of the standing wave. Therefore, the amplitude of the SAW modulation is affected at a particular position with respect to the center of the QPC. At certain frequencies (phases), different SAW channels could, thus, be opened/suppressed, leading to different sets of quantized steps in the acoustoelectric current. Both mechanisms suggested here are speculative. Further study is required to understand the exact physical origin of the observed AE transitions.
Chapter 7

Conclusions

This thesis has presented new experimental results concerning the SAW-driven single-electron transport through shallow-etched quantum point contacts. The electrostatic potential associated with the SAW can drag electrons across the potential barrier of a closed QPC defined in a GaAs heterostructure. In the regime beyond the conductance pinch-off, the resultant acoustoelectric current exhibits quantized steps in units of $\frac{e\nu}{2}$, where $e$ is the electron charge and $\nu$ the SAW frequency. The current quantization can be observed as a function of the gate and bias voltage, the SAW power and frequency. In the course of this project, the effects of variations in either of those parameters have been investigated in detail. Here, we summarize the main results.

7.1 Summary of results

The current-versus-gate voltage characteristics of our devices have proven to be very robust to the action of a dc bias. The application of large (few 100 mV) bias voltages to the source contact of the QPC does not affect the shape of the $I(V_g)$ staircases. They only shift along the gate-voltage axis as if they were displaced parallel to each other. As a consequence, quantized AE current can also be observed as a function of the bias voltage, at a fixed value of $V_g$. This is true as long as the tunnelling contribution is negligible in the total current.

We have also studied the transitional regime where the acoustoelectric and the tunnelling current simultaneously counterflow through the same narrow constriction of the QPC. Since their response to the gate and bias voltage is distinctively different, we can separate them from each other. We demonstrated the quantization of the AE current at up to ten times larger tunnelling counterflow.
In this regime, the magnitude of the AE current was strongly suppressed for two of our devices, and unaffected for the third. The suppression did not seem to result from the electrostatic interaction between the two currents.

We have investigated as well the effect of variations in the SAW power. The AE current quantization can be observed over a broad range of microwave powers applied to the SAW transducer, both in $I(V_g)$ and $I(\mathcal{P}_{RF})$. At very low values of the SAW amplitude, the onset of the $I(V_g)$ characteristics is close to the conductance pinch-off. In this range, the total current is still dominated by the voltage-driven contribution (due to the burden voltage of the measurement instrument or a small bias applied on purpose). However, some anomalies can be observed which, on increasing the SAW power, smoothly evolve into plateaus at $n\varepsilon_f$. In the quantized regime, our experiments reveal rather a complicated pattern of the AE transitions. In particular, the transconductance plots $dI(V_g,\mathcal{P}_{RF})/dV_g$ reveal crossings between the transition lines (maxima in $dI/dV_g$) separating the AE plateaus (minima in $dI/dV_g$). At very high SAW amplitudes, we demonstrate for the first time the $I(V_g)$ characteristics where the lowest quantized steps are only weakly indicated in the steeply rising current, while the higher plateaus are still broad and flat.

The frequency response experiments revealed pronounced oscillations in the AE current with a period of $\Delta f = 1.1$ MHz. We attribute it to the interference between two counterpropagating SAW beams that meet at the point contact. The second SAW beam results from the reflections of the main beam from the transducer on the other side of the QPC. It can also be generated on purpose by applying an rf excitations to this second IDT. The period of 1.1 MHz corresponds to the phase shift of $2\pi$. Quantized steps can be observed in the $I(V_g)$ traces taken at any frequency within this modulation period. However, we demonstrate that two subintervals can be distinguished there where different sets of AE plateaus seem to prevail at the current onset. At certain frequencies, one set replaces another. However, under some conditions, both of them can be simultaneously resolved in the $I(V_g)$ traces. In such case, more than one plateau can form within the current interval of $\Delta I = \varepsilon_f$.

7.2 Concluding remarks

In the course of this project, we have investigated in detail the quantized acoustoelectric effect for eight devices. Some of them exhibited up to 20 plateaus at the expected multiples of $n\varepsilon_f$. Moreover, we were able to demonstrate quantized steps in $I(V_g)$ with a gradient of around 150 ppm/mV, i.e. surpassing the best precision of the AE current quantization reported before. However, this would be an understatement to report about the above results without mentioning the tremendous problems with acquiring the working SETSAW devices. The optimization of the processing procedures, performed during this study, greatly
improved the yield of samples with fully functional transducers and QPCs. Nevertheless, this was not a guarantee of success in finding the quantized steps in the AE current. A large number of devices did not show current quantization although their transmittance and conductance characteristics were very similar to those obtained for the samples presented in this study. The low yield of working SETSAW devices could result from the presence of random potentials in the vicinity of the point contacts. We indeed observed the disorder-related features in a number of experiments, as reported throughout the thesis. Still, the presence of the impurity or donor-induced potentials could be considered as leading to either the suppression or enhancement of the current quantization, depending on their exact configuration. It would be of considerable interest if the effects of those potentials could be taken into account in the theoretical studies on the quantized AE transport.
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