Lateral electron tunnelling spectroscopy in etched GaAs/AlGaAs-based nanostructures

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Abstract. Tunnelling spectroscopy between laterally positioned low-dimensional electron systems is investigated. We demonstrate that a reliable highly transparent tunnelling barrier can be fabricated by means of dynamic ploughing with the tip of an atomic force microscope and wet etching into the surface of a GaAs/AlGaAs heterostructure. This barrier allows to perform a tunnelling spectroscopy with dc bias voltages up to 30 mV. Band edge effects due to tunnel coupling were observed for two-dimensional electron gases (2DEGs) separated by such lateral tunnel barrier. Tunneling spectroscopy of a 2DEG and a laterally adjacent electron waveguide enable to monitor the one-dimensional (1D) density of states. Firstly, a lateral dual electron waveguide with 1D subband spacings of more than 5 meV was implemented showing significant features of 1D mode coupling in tunnelling spectroscopy.

1. Introduction
Using the principle of coherent quantum mechanical tunnelling, an electron waveguide coupler was initially conceived as an electrical analogue to an optical dual-channel directional coupler [1]. The device consists of two electron waveguides (EWGs) that over a certain length come in very close proximity to each other. However, the exploitation of a dual EWG as a logical device relies on the exact coupling characteristics. In particular, the implementation of a suitably thin but high potential barrier enabling the application of finite dc bias voltages of several milli-volts represents a major challenge. The present work is concerned with lateral tunnelling spectroscopy between 2D and 1D low-dimensional electron systems in etched GaAs/AlGaAs nanostructures. Here, we demonstrate the advantage of a new combination of two lithography techniques: The indirect patterning technique based on an atomic force microscope (AFM), and the electron-beam lithography (EBL) with high-resolution negative tone resist. AFM lithography proves to be a reliable technique to produce thin and deep grooves on a semiconductor surface, inducing tunnelling and insulating boundaries in a shallow buried 2DEG of a GaAs/AlGaAs heterostructure [2]. With EBL quantum wires with large 1D-subband spacings can be produced [3]. Three kinds of lateral electron tunnelling devices were successfully fabricated: A 2D-to-2D, a 2D-to-1D and a 1D-to-1D tunnelling device. The manifestation of coupling effects between the electron waveguides are of great interest for the implementation of a quantum directional coupler [1].

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2. Experimental Details

Two Si-doped GaAs/AlGaAs-heterostructures hosting 2DEGs situated 55 nm below the surface were used. The Hall electron densities were $4.4 \times 10^{11}$ cm$^{-2}$ and the electron mobilities were $10$ and $9.4 \times 10^5$ cm$^2$/Vs, respectively, measured at 4.2 K in the dark. Tunnel barriers were prepared by indirect dynamic ploughing with an AFM [4]. For indirect patterning, a standard positive photoresist (Shipley 2510) strongly diluted with thinner (1:40 or 1:50) is deposited with a thickness of 5-7 nm. Using a drive amplitude of the AFM tip much larger than the imaging amplitude the resist can be plastically deformed. This pattern can be transferred into the substrate by subsequent wet-chemical etching [2] with a citric acid solution. Lines etched along the [1-10]-direction give U-shaped grooves in GaAs, whereas a [110] orientation gives V-shaped grooves which was used in this work. Electron wave guides were defined using electron-beam lithography (EBL) with a Leo Gemini 982 (at 2 kV and 0.8 µC/cm$^2$) and Elphy Plus Lithography software. We used the hexaacetate p-methylcalix[6]arene (MC6AOAc) derivative from the negative resist Calixarene which offers a very high lateral resolution [5]. 1 wt.% solution of Calixarene in monochlorbenzene was spun during 30 seconds at 3000 rpm on the sample, followed by a 30 minutes bake at 170°C resulting in a thickness of 25 ±2 nm. After EBL exposure, the resist is developed 30 s in a xylene bath, then stopped by isopropanol (10 s) and baked for 30 min at 110°C under nitrogen atmosphere. The remaining resist frames a high-quality mask for the subsequent wet-chemical etching with citric acid solution. The resist is finally removed in an oxygen plasma (5 min). Ni/AuGe/Ni/Au ohmic contacts were prepared by photolithography, electron-beam evaporation, subsequent lift-off processing and alloying by rapid thermal annealing. Finally, the Schottky Au top gate was fabricated by photolithography, thermal evaporation and lift-off processing.

3. Lateral tunnelling spectroscopy

The electrical measurements were performed at 4.2 K with a lock-in amplifier. The differential conductance $g_D=\frac{dI_D}{dV_D}$ describes the variation of the ac drain current $I_D$ with the ac drain voltage $V_{D,ac}$ (40-100 µV, 433 Hz) and was measured as a function of the dc top gate voltage $V_G$. A dc drain voltage $V_D$ (up to ±30 mV) as applied across the tunnel barrier for the tunnelling spectroscopy (tunnel spectrum) and along the EWGs for transport spectroscopy of the 1D subband spectra.
3.1.1. 2D-2D tunneling

The characteristic of the differential drain conductance $g_D$ across the barrier also denoted as tunnelling conductance was measured as a function of the bias drain voltage $V_D$ as shown in Fig. 2. $g_D$ generally increases with increasing top gate voltage $V_G$ and it drops with larger increasing dc drain voltages which is attributed to the heating of charge carriers in an electric field. For the drain bias interval $|V_D| \leq \pm 25$ mV, the behaviour of the tunnelling conductance strongly depends on the applied top gate voltage $V_G$. The basic behaviour of the curves is symmetric with respect to zero bias. However, due to the measuring assembly, the increase of the negative drain voltage $V_D$ acts like an increase of the effective gate voltage $V_G\text{eff}$ along the transistor channel leading to an increase of $g_D$. When the barrier width $W$ is of about the Fermi wavelength $\lambda_F \sim W$, the wavefunctions of both 2DEGs, which penetrate into the barrier, overlap each other and tunnelling can occur. For small gate voltages $V_G \leq 330$ mV and at zero drain bias voltage the tunnelling conductance is zero. An increase of source-drain bias voltage $|V_D|$ induces a reduction of the effective barrier height such as $\Delta \phi = \frac{1}{2}e\Delta V_D$ and the transmission probability is increased. The tunnelling probability also increases as the top gate voltage $V_G$ gets larger. For large $V_G \geq 430$ mV, minima appear in $g_D$ nearly symmetric for positive and negative $V_D$. The minima in $g_D$ reflect Fermi-edge effects due to the tunnelling process across the barrier [6,7]. For small $V_D$ the tunnelling probability remains nearly constant, in turn the $I(V)$-curve should be linear and $g_D$ should show a quasi-plateau near $V_D=0$. In Fig. 2 this quasi-plateau is not horizontal because of the asymmetric contact geometry. Further, the drain bias gap between the minima is not constant with increasing gate voltage because of the increasing influence of the series resistance. With larger $V_D$, the barrier disappears and the 2DEG properties dominate the conductance characteristics. As the drain voltage interval between the two drops of the conductance is directly proportional to the Fermi energy of the 2DEG, $e\Delta V_D = 2E_F$, we can determine the density of the 2D electron sheet from $n_S = E_F m^*/(\hbar^2)$. 

**Figure 2.** 2D-to-2D tunnelling device: Differential drain conductance $g_D$ at 4.2 K measured as a function of: (I) the top gate voltage $V_G$, (a) and (b) of the 2DEGs each side of the potential barrier, (c) across the potential barrier, (II) of the dc drain voltage $V_D$ across the barrier (dotted line: calculated transconductance $d g_D/dV_D$) and (III) (a) of the $V_D$ bias at gate voltages $V_G$ ranging from 290 to 590 mV with 20 mV interval.
For a top gate voltage of 520 mV, the 2D electron density of \( n_S = 3.38 \times 10^{11} \text{ cm}^{-2} \) compares well with \( 3.7 \times 10^{11} \text{ cm}^{-2} \) as extracted from Shubnikov-de Haas measurements on the heterostructure without a top-gate. Critical in the tunnel spectroscopy is the very high sensitivity of the tunnel barrier to the gate voltage and to the drain voltage. As \(|V_D|\) increases the effective height of the barrier is reduced. The differential conductance rises because of the dramatic increase of the transmission probability leading to a V-shaped tunnelling conductance characteristic.

3.1.2. 2D-1D tunnelling

Fig. 3 shows measurements of the 2D-to-1D tunnelling device. The drain conductance of the 2D channel (contacts 1-2) exhibits a two-step characteristic arising from the barrier height controlled by the gate voltage. The first saturation at about 2 mS reflects the series resistance \( R_S \approx 500 \Omega \) of the reservoirs and the alloyed contacts. At \( V_G \approx 450 \text{ mV} \), the barrier is completely removed, and the effective width of the 2D channel increases strongly. This reduces the saturation range to about 320 \( \Omega \). The conductance measured across the barrier (contacts 1-3) corresponds to a gradual increase from \( V_G \approx 300 \text{ mV} \) to a saturation value determined by the series resistance \( R_S \approx 350 \Omega \) of the common reservoirs. The electron wavefunction “leaks” out of the 1D waveguide channel through the tunnel barrier into the adjacent 2D electron bath and vice versa. Tunnelling spectroscopy was performed by measuring the two-terminal drain conductance \( g_D \) (across contacts 1-3) as a function of the drain voltage \( V_D \). A modulation voltage \( V_D = 400 \mu \text{V} \) was imposed upon the 2DEG (contact 1), and the ac current \( I_D \) is monitored by lock-in technique on contact 3. Figure 3 shows a series of tunnelling spectra for a top-gate-voltage interval \( 120 \text{ mV} \leq V_G \leq 310 \text{ mV} \). A positive bias voltage refers to that applied at the 2DEG (contact 1). The gradual increase of the conductance with increasing gate voltage indicates the dependence of the barrier transmission with \( V_G \) as observed in 2D-2D tunnelling. Each curve exhibits oscillations superimposed on a slowly varying background: With increasing \(|V_D|\) the effective barrier height is diminished, increasing the tunneling transmission and thereby the total conductance. For \(|V_D| > 25 \text{ mV} \), these oscillations are averaged out. Oscillations in the tunnelling conductance directly reflect the density of states of the 1D subband system in the waveguide and can be discussed by the semiclassical model of Eugster and del Alamo et al. [7]. Momentum conservation along the
waveguide (x-direction) requires that \( k_{x,2D} = k_{x,1D} \) is fulfilled in the event of 2D-to-1D tunnelling and vice versa. However, in the model [7] a square-shaped barrier is regarded. In our experiment the effective barrier height depends on the applied drain voltage \( V_D \) leading to the V-shaped background of the tunnelling conductance characteristic. A peak in the tunnelling conductance arises if the electrochemical potential of the 2DEG is in resonance with the edge of a 1D subband because the density of states is highest near the bottom of the 1D subband. As the 1D-DOS diminishes with increasing energy, the conductance decreases. From the oscillation period we estimate an average 1D subband separation of \( \Delta E_{1,2} = 4.0 \pm 0.5 \text{ meV} \) which agrees well with that obtained from transport spectroscopy (not shown here). However, because of the layout design of the device under investigation tunnelling spectroscopy of the lowest 1D subbands is not possible. First, the top-gate covers the whole device and hinders the influence of the in-plane gates. This does not give independent control of the tunnel barrier height and the electron density in the 1D waveguide. Second, the etch depth of the nanostructure, thereby the strength of the 1D confinement is limited by the subsequent AFM lithography step. This could be overcome by decreasing the width of the EWG.

3.1.3. 1D-1D tunnelling

Figure 4 shows the differential drain conductance \( g_D \) as a function of the topgate voltage \( V_G \) at \( T = 4.2 \text{ K} \) measured (a) along the wide waveguide (contacts 3-4), (b) along the narrow waveguide (contacts 1-2) and (c) across the potential barrier (contacts 1-3). In (a) and (b), the solid curves represent the conductance corrected for the series resistance: \( R_{SW} = 900 \text{ \Omega} \) (wide EWG), \( R_{SN} = 750 \text{ \Omega} \) (narrow EWG); the dotted curves are as measured. (II) Sketch of the potential landscape of a 1D-to-1D tunnelling device at a finite \( V_G \) and \( V_D = 0 \). (III) (a) \( g_D \) at \( T = 4.2 \text{ K} \) across the barrier (contacts 1-3 on Fig. 38) as a function of the applied dc voltage \( V_D \) for \( 598 \lesssim V_G \lesssim 658 \text{ mV} \), with 10 mV interval. (b) Grey-scale plot of the numerically derived tunneling transconductance \( d g_D / d V_D \) as a function of \( V_D \) bias and \( V_G \). The dotted lines mark the corresponding measurements on (a).

Figure 4. (I) Differential drain conductance \( g_D \) as a function of the topgate voltage \( V_G \) at \( T = 4.2 \text{ K} \) measured (a) along the wide waveguide (contacts 3-4), (b) along the narrow waveguide (contacts 1-2) and (c) across the potential barrier (contacts 1-3). In (a) and (b), the solid curves represent the conductance corrected for the series resistance: \( R_{SW} = 900 \text{ \Omega} \) (wide EWG), \( R_{SN} = 750 \text{ \Omega} \) (narrow EWG); the dotted curves are as measured. (II) Sketch of the potential landscape of a 1D-to-1D tunnelling device at a finite \( V_G \) and \( V_D = 0 \). (III) (a) \( g_D \) at \( T = 4.2 \text{ K} \) across the barrier (contacts 1-3 on Fig. 38) as a function of the applied dc voltage \( V_D \) for \( 598 \lesssim V_G \lesssim 658 \text{ mV} \), with 10 mV interval. (b) Grey-scale plot of the numerically derived tunneling transconductance \( d g_D / d V_D \) as a function of \( V_D \) bias and \( V_G \). The dotted lines mark the corresponding measurements on (a).
meV (narrow EWG) and $\Delta E_{1,2}=8.7$ meV±0.5 meV (wide EWG). Fig. 3 pictures a series of measured tunnelling conductance spectra for several top-gate voltages. For different cooling cycles the results are concordant. The positive bias refers to the potential at the right wire, contact 3. Sweeping the drain voltage corresponds to displacing 1D energy subband ladder of one wire relative to the other. For topgate voltages $V_G$ of 595 mV and above, the tunnelling spectra exhibit oscillations similar to the ones observed in the 2D-to-1D tunnelling spectroscopy. Here, they map the 1D density of states by a resonantly enhanced tunnelling current for degenerate 1D subbands. Again, the asymmetry of the background with respect to $V_D = 0$ is due to the measuring assembly. As previously described, $V_G$ influences the tunnelling transmission as detected in the conductance magnitude. Finally, two kinds of oscillations are observed: For the smaller gate voltages, the tunnelling oscillations go in pairs and, with increasing $V_G$, they merge to an oscillation with a larger magnitude and with and twice the period. This is shown in the grey-scale plot of the transconductance (Fig. 4) in which a full tunnelling oscillation is represented by the association of a dark stripe (ascending $g_D$) and a bright stripe (descending $g_D$). Two assumptions are considered: (i) only the top-most partially occupied subband contributes significantly [8], and (ii) when 1D subband edges come into resonance the electron wave functions couple leading to a splitting of the subband degeneracy into antisymmetric and symmetric states, has recently been demonstrated on vertically stacked tunnel-coupled EWGs [9]. A splitting of $\Delta E=2.2±0.5$ meV is measured coinciding well with the observations of anticrossings from transport spectroscopy (not shown here [8]). As $V_G$ is made more positive, the tunnelling barrier is reduced. The anticrossings disappear and the two tunnelling oscillations corresponding to the antisymmetric and symmetric coupling states merge and the resulting pattern directly translates the 1D density of states of the biased waveguide. The measured spacing $\Delta E_{N,N+1}=5.5±0.5$ meV agrees with the spacings between the subbands of higher energy of the waveguide as determined by transport spectroscopy.

4. Summary and Outlook
The AFM lithography with subsequent wet-chemical etching allows to fabricate a groove of desired depth-to-width aspect ratio in the surface of a semiconductor for lateral tunnelling devices. By combining it with EBL lateral tunnelling in electron waveguide devices of large subband spacings (~10 meV) can be achieved. Our results are promising for future investigations on lateral tunnelling also with respect to other material systems. Implementation via top-down fabrication is relatively easy compared to cleaved-edge-overgrowth [10] or flip-chip techniques [11]. Future developments might include distinct fingergates and sidegates for an independent control of the barrier height and EWG electron densities. Opportunities of lateral tunnelling in the single-mode regime exist for a quantum directional coupler, investigation of the 0.7-conductance anomaly, and spin-filtering applications.

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5. References
[1] del Alamo J A, Eugster C G 1992 Appl. Phys. Lett. 56, p 78
[2] Klehn B, Kunze U 1999 J Appl. Phys. Lett. 85, p 3897; ibid 1998 Superlatt. Microst. 23, p. 441
[3] Apetrii G, Fischer S F, Kunze U, Reuter D, Wieck A D 2002 Sem. Sci. Techn. 17, p 735
[4] Knop M, Richter M, Maßmann R, Wieser U, Kunze U, Reuter D, Riedesel C, Wieck A D 2005 Sem. Sci. Techn. 20, p 814
[5] Fujita J, Ohnishi Y, Ochiai Y, Namura E, Matsui N 1996 J Vac.. Sci. Techn. 14, p 4272
[6] Eugster C G, del Alamo J A, Melloch M R, Rooks M J, 1993 Phys. Rev. B. 48, p 15057
[7] Eugster C G, del Alamo J A, Melloch M R, Rooks M J, 1994 Appl. Phys. Lett. 64, p 3157
[8] The full experimental details and transport spectroscopy will be given elsewhere.
[9] Fischer S F, Apetrii G, Kunze U, Schuh D, Abstreiter G, 2006 Nature Physics 2, p 91
[10] Auslaender OM, Yacoboy A, de Piciotto R, Baldwin KW, Pfeiffer LN, West KW, 2002 Science 308, p88
[11] Bielejec E, Reno JL, Lyo SK, Lilly MP, 2008 Solid State Comm. 147, p 79