Preparation of curved two-dimensional electron systems in InGaAs/GaAs-microtubes

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Abstract
We present a preparation method to realise transport measurements on evenly curved two-dimensional electron systems (2DESs). By combining the method of self-rolling strained double layers with a special lithographic procedure we are able to roll-in and contact AlGaAs/GaAs/AlGaAs quantum well structures into tubes or curved lamellas. Applying a magnetic field to such structures results in a strong modulation with changing sign of the magnetic field components perpendicular to the curved 2DES plane. Our preparation method allows transport measurements along or perpendicular to this modulation. We present and discuss our first magneto-transport measurements on such rolled 2DESs.

1. Introduction
Non-planar two-dimensional electron systems (2DESs) in magnetic fields have been the subject of many theoretical [1–3] and experimental works, in recent years. Transport measurements, e.g. on Hall bars containing a tilted facet [4] or on waved 2DESs [5] have been realised using MBE (molecular beam epitaxy) regrowth technology. 2DESs in periodically modulated magnetic fields have also been realised by evaporating and patterning superconducting [6] or ferromagnetic films [7] on top of a heterojunction. However, all the above mentioned systems do not only exhibit a modulation in the perpendicular magnetic field component, but there also exists an intrinsic modulation caused by either strain or surface topography. For example 2DESs at heterointerfaces grown on patterned substrates may be intrinsically modulated by the change of the local crystal orientation in the non-planar interface. Also metal patterns on semiconductor surfaces are known to modulate 2DESs by both strain and surface potentials.

In this paper we present a method to realise evenly curved 2DESs without any change in strain or crystal structure connected to the topographic modulation. Using the method of self-rolling...
strained semiconductor layers by Prinz et al. [8] in combination with a special lithographic procedure developed here we roll very thin AlGaAs/GaAs/AlGaAs quantum well structures into tubes with a predefined radius. Applying a magnetic field $B$ to these structures result in a sinusoidal modulation of the perpendicular magnetic field components between $B$ and $-B$. Depending on the chosen contact geometry it is possible to measure transport along or perpendicular to this magnetic field modulation.

In the following we describe the details of our preparation procedure and demonstrate the existence of 2DESs in our curved structures with first measurements.

2. Preparation

The method of self-rolling strained semiconductor double layers first introduced by Prinz [8–10] enables to build tubes with radii varying between some nanometers and some microns. Here we demonstrate a method to integrate two-dimensional electron systems into the tube walls in order to measure transport of curved high-mobility electron systems. For this purpose two main difficulties have to be mastered. First, the development of thin heterostructures which can be rolled-up into tubes and still contain a high-quality 2DES in the suspended rolled up state. Secondly, the ohmic connection to these rolled-up 2DESs has to be provided.

To design and optimise heterostructures for rolled-up 2DESs we use self-consistent conduction band calculations. Samples are grown in a solid source Riber 32P MBE (molecular beam epitaxy) system. Fig. 1a shows a typical layer sequence together with the conduction band diagram and the free electron density. On top of a In$_{30}$Ga$_{80}$As-layer, where the pseudomorphic strain for the rolling process is stored, we grow an Al$_{33}$Ga$_{67}$As/GaAs-quantum well. Si-delta doping layers are embedded in the Al$_{33}$Ga$_{67}$As barriers on both sides. To characterise the electronic properties of these structures the 2DESs have to be measured in a suspended but flat state. This can be realised by preparing suspended bridges between metal contacts. Fig. 1b shows an example. After defining the bridge by deep mesa etching and evaporating metal contacts the bridge is brought into suspended state by etching away the AlAs sacrificial layer with hydrofluoric acid. Importantly, here the photo resist on top of the bridge is kept to prevent it from rolling-up during the under etching process. At the present state of optimisation our samples exhibit typical electron densities between $4.8 \times 10^{11}$ and $1.0 \times 10^{12}$ cm$^{-2}$ and electron mobilities up to 20 000 cm$^{2}$/Vs at $T = 4.2$ K.

For the preparation of electrical contacts to the rolled-up 2DESs we developed a lithographic method to predetermine the location and length of the forming tubes. This enables us to roll-in metal layers at predefined positions forming contacts. Fig. 2 shows a sketch of the process steps. We start with evaporating and annealing 13 nm of AuGe/Ni/AuGe ($\delta$nm/m/6nm) to build the actual contacts with the 2DES (I). The annealing temperature is 400°C ($\pm 14$). Then a 6 nm thick layer of gold is evaporated to connect the annealed AuGe/Ni/AuGe-contacts with the outside world (II). With this two-step evaporation procedure we are able to realise various geometries, e.g. with current direction perpendicular to the tube axis like shown in Fig. 2b. Furthermore, we exclude bypass currents between the leads. In the next preparation step (III) we define the mesa which will later roll-up into a curved lamella. For the mesa etch process only this area and the gold leads are protected with photo resist. On the rest of the sample we completely etch away the electro-nically active layers and stop just above the AlAs-sacrificial layer leaving some nanometers of the strained InGaAs-layer. This thin InGaAs-layer works as a protection mask during the selective etching process later on. By deep mesa etching we then uncover the AlAs-sacrificial layer along the so called starting edge (IV). In the following selective etching process the AlAs-sacrificial layer is exposed to the hydrofluoric acid only along this

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1 For the calculations we have used the program ‘1D Poisson’ by G. Snider which is provided freely via the internet. See http://www.notre-dame.edu/gsnider.
Fig. 1. (a) Typical MBE-layer sequence, together with the conduction-band diagram and the free electron density for the suspended case. (b) SEM picture of a bridge geometry for the characterization magnetotransport measurements in a suspended but not rolled-up lamella. To prevent the strained bridge from rolling-up photo resist is kept on top during under etching process. The inlay shows a side view of the bridge to demonstrate the suspended character.

Fig. 2. (a) Sketch of the preparation procedure: After evaporating and annealing a first metal layer (I) as the actual contact to the 2DES we evaporate a second metal layer for the leads (II). In (III) the mesa that will later roll into a tube is defined. By deep-mesa etching we then define the starting edge from where the rolling begins (IV). In the last step we release the rolling mesa from the substrate by etching away the AlAs-sacrificial layer with HF. As a result we get a contacted curved lamella (V). By varying the length $L$ of the mesa in comparison with the tube circumference $U$ we can tune the number of revolutions $N$ ($N = L/U$). (b) Contact geometry for transport measurements along the curvature of the tube. (c) Lithographic method to integrate coils into contact geometry.
starting edge and therefore the mesa begins rolling from here. The other edges of the mesa are protected by the above-mentioned thin InGaAs layer. However, the connection between the mesa and the protection layers tears along fracture lines on all sides of the mesa during the roll-up process. As a result we get a freestanding tube attached to the crystal surface by the metal layer contacts only (V). By choosing the adequate length of the mesa \( L \) in comparison with the tube circumference \( U \) we can predetermine the number \( N \) of revolutions the lamella carries out \( (N = L/U) \). For \( L = U \) we get a tube with exactly one revolution, for \( L < U \) we get a fraction of one revolution, respectively. Note that the duration of the selective under-etching process does not determine the number of revolutions anymore. Taking advantage of the fact that the crystal strongly prefers the \( \langle 100 \rangle \) rolling direction it is also possible to roll up coils \[8\]. Fig. 2c shows a method how these coils can be integrated into a contact geometry. The orientation angle between mesa and rolling direction determines the coil spacing.

3. Measurements

As a demonstration of our preparation method Fig. 3 shows two rolled-up lamellas: lamella 1 with 14\% of a complete tube, i.e. \( N = 0.14 \), and lamella 2 with \( N = 0.60 \). Both were prepared from the same initial heterostructure. The bending radius of the lamellas is 8 µm which is close to the value expected for the tube wall thickness and composition by the model of Tsui and Clyne \[11\]. Figs. 3b and 3d show transport measurements in four point geometry performed in a standard Helium cryostat at \( T = 4.2 \) K with \( B = 7 \) T maximum magnetic field. An effective AC-current value of 10 nA is fed through contacts 1 and 4. The magneto resistance is determined by measuring the voltage between contacts 2 and 3 using standard lock-in technique.

Lamella 1 exhibits clear Shubnikov de Haas oscillations with magnetic field oriented quasi-perpendicular relative to the lamella surface (1). Applying the magnetic field quasi-parallel to lamella 1 (2) results in less pronounced oscillations. In contrast to this lamella 2 exhibits weak SdH-oscillations for all applied angles (Fig. 3d).

This difference in magneto resistance can be explained by the fact that the perpendicular component of the magnetic field is strongly modulated only for lamella 2. Since lamella 1 forms only a small fraction of a complete tube \( (N = 0.14) \) it can be considered as an almost flat stripe with quasi-constant perpendicular magnetic field components. In fact, in lamella 1 we see a behaviour similar to flat 2DESs in tilted fields. This observation proves the existence of 2DESs in our samples. In lamella 2 the SdH-oscillations wash out because of the superposition of oscillations belonging to different filling factors over the curved 2DES. This indicates that the current distributes over regions of the tube with different filling factors. Interestingly, the oscillations in lamella 2 are superimposed on a smooth magneto-resistance with slope depending on the angle of the magnetic field vector. We note that the slope in general is not symmetric with respect to field inversion. However, for the symmetric field orientation (1) we observe a slope symmetric in magnetic field. Though lamella 1 shows magneto-resistance similar to a flat stripe regarding the amplitude of the SdH-oscillations, the phase dependence on the angle deviates from a flat stripe. Those features will be discussed in more detail in a forthcoming publication.

4. Conclusions

In conclusion we prepared evenly curved two-dimensional electron systems in InGaAs/GaAs-microtubes. Four-point magneto-transport measurements along and perpendicular to the curvature are possible. As an example we present four-point measurements of two lamellas with different fractions of a complete tube. First results of the magneto-transport measurements demonstrate the presence of a curved 2DES in the lamellas with a magneto-resistance behaviour that depends on the fraction \( N \) of a full turn.
Fig. 3. (a) SEM picture of lamella 1: $N = 0.14$, i.e. 14% of a full turn. The curvature radius is 8 μm. The white arrows point at the suspended curved lamella between the rolled-up metal contacts. (b) Magneto-transport measurements at $T = 4.2$ K with field orientations indicated in the insert. Two orientations (1) and (2) for the field vector are depicted. (c) SEM picture of lamella 2: $N = 0.60$. (d) Magneto-resistance measurements of lamella 2. Curves for different magnetic vector orientations are offset by a constant value for visibility.

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References