Electron Beam Lithography of Silicon-Based SET Structures

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Lateral quantum dots have been fabricated on strained Si/SiGe substrates with a mobility of about 200,000 cm^2/Vs using a split gates geometry, where the gates consist of Pd. The gate structures where realized by e-beam lithography. By applying negative voltages to the gates the underlying 2DEG can be depleted. Similar samples showed fractional quantum Hall effect up to filling factors of 1/3. Furthermore the ν=1/3, 4/7 and 4/9 are observed for the first time in the Si/SiGe system. e-beam lithography was performed with an JEOL 6400. In the 4^{th} quarter of 2003 a LEO Supra 35 FESEM (field emission scanning electron microscope) with a Schottky field emitter (SFE) has been purchased.

Introduction

Lateral quantum dot structures have been of strong interest in the recent years. However, most of this work was done on III-V-compounds (mostly in AlGaAs). Only few papers of silicon based SET (single electron transistor) structures were released so far. Therefore our goal is to realize a SET on a SiGe heterostructure. The main differences between SiGe and AlGaAs are the twofold valley degeneracy and the low Fermi level relative to the ground state, which can lead to pinch-off of devices already at small potential fluctuations.

Experimental

The quantum dot structures are prepared on ion etched Hall bars with alloyed AuSb contacts on Sb modulation-doped SiGe heterostructures with a mobility of about 200,000 cm^2/Vs. Similar samples show fractional QHE down to filling factors of 1/3 at high magnetic fields and 30 mK [1]. Around ν = 1/2 the two flux composite fermion (CF) series of the fractional quantum Hall effect (FQHE) at ν = 2/3, 3/5, 4/7, and at 4/9, 2/5, 1/3 are observed (Fig. 1). The ν = 1/3, 4/7 and 4/9 states are seen for the first time in the Si/SiGe system. This result demonstrates the CF model also applies in the Si/SiGe system. As a remarkable detail of the CF series, the 3/5 state is weaker than the nearby 4/7 state and the 3/7 state is missing. This resembles the observation in the integer quantum Hall regime where ν = 3 is weaker than the ν = 4 state.

The SET gates itself consist of Pd which has, besides Pt, the highest Schottky barrier on n-type silicon. By applying negative voltages to the gates the underlying 2DEG can be depleted and a zero-dimensional constriction is formed – the quantum dot. At low temperatures electrical measurements will show quantization effects caused by localization of electrons.

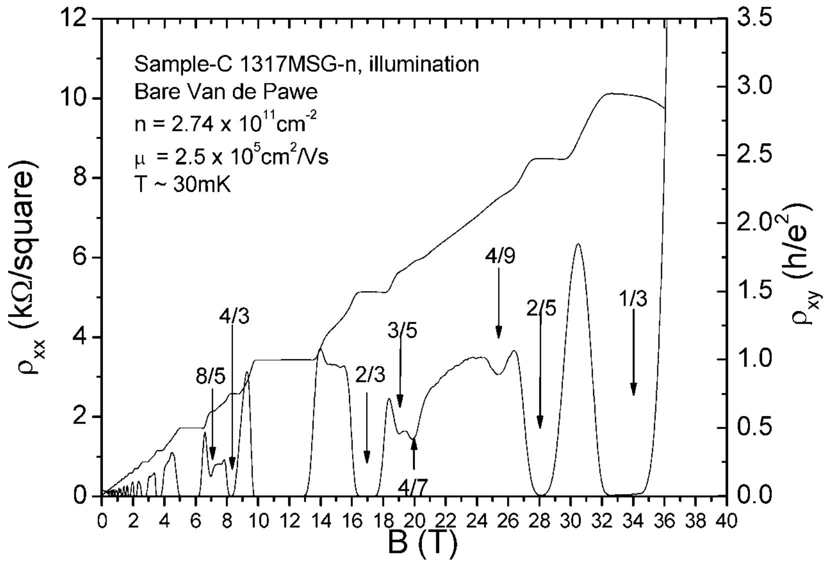

Fig. 1: Diagonal resistivity ρ_{xx} and Hall resistivity ρ_{xy} of the 2DEG measured in Van de Pauw geometry at T = 30 mK [1]. The 2DEG has a carrier density of n = 2.7×10^{11} cm^{-2} and a mobility μ = 250,000cm^2/Vs. Major fractional quantum Hall states are marked by arrows.

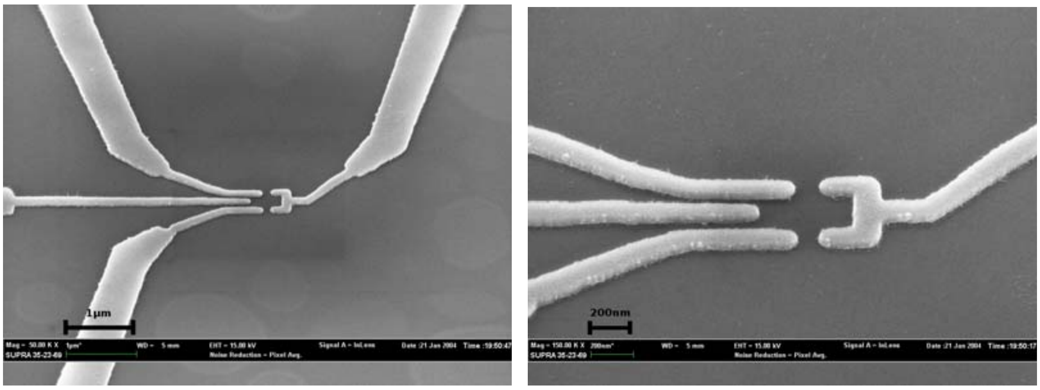

Fig. 2: (a) Electron microscope image of Pd-Schottky gates. (b) The inner part of the gates has a pitch of 175 nm. By depleting the underlying electron gas a lateral quantum dot can be formed

Measurements at 300 mK showed that the electron gas can be depleted by applying negative gate voltages and the conductivity decreases below e^2/h. Further improvements are, however, required to observe quantization and Coulomb blockade effects.

E-beam lithography was performed with a Raith Elphy Plus e-beam lithography system attached to a JEOL 6400 SEM with a thermionic LaB_6 cathode. In the 4^{th} quarter of 2003 a LEO Supra 35 FESEM (field emission scanning electron microscope) with a Schottky field emitter (SFE) has been purchased. In comparison to thermionic emission the SFE has much higher beam brightness and much lower energy spread.

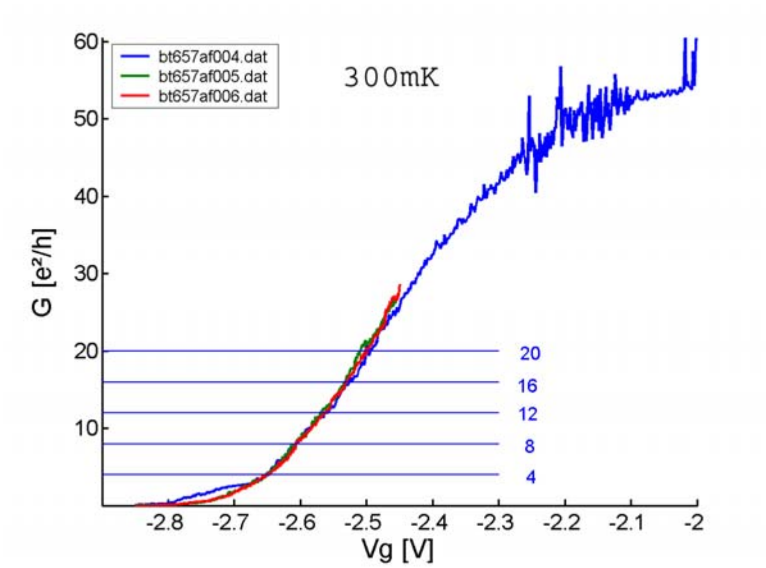

Fig. 3: Measurement of a SET structure at 300mK. The 2DEG gets depleted by an applied negative gate voltage and conductivity decreases below e²/h. However no quantization steps are observed.

Two unique features of the column design enhance the resolution limit of the microscope: the beam booster and the cross-over-free column. The beam booster always maintains a high energy throughout the column, regardless of the electron energy selected by the operator. After passing the scanning system the beam is decelerated to the chosen energy. Because of the high beam energy throughout the column the beam is well protected against stray magnetic fields, even when operated at low voltages. Also the column has been designed to eliminate cross-overs in the beam path. Cross-overs lead to Coulomb interactions between beam electrons and hence reduce brightness and resolution.

The combination of cross-over-free beam path and high beam energy leads to high resolution, even at low operating voltages. This is extremely important, as with low beam energy the charging of non-conducting materials (e.g. PMMA e-beam photo resist – see Fig. 4) can be minimized.

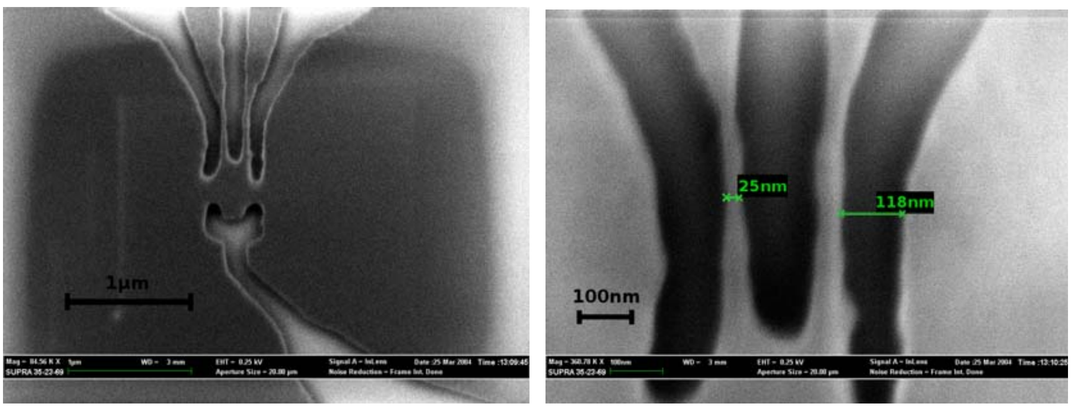

Fig. 4: (a) Electron microscope image of an exposed and developed photo resist (100nm thick PMMA) at 0.25kV acceleration voltage, preventing charging effects. (b) Detail of the SET structure. The areas of removed resist have a width of about 120nm, the PMMA stripe between two fingers is about 25nm thick.

Another interesting feature of the microscope is the in-lens detector. Besides the usual backscatter detector (for backscattered electrons (BE)) and the Everhart-Thornley detector (for mostly secondary electrons (SE)), an in-lens detector is located above the objective lens. Low-energy secondary electrons are intercepted by the weak electrical field at the sample surface and accelerated to a high energy by the field of the electrostatic lens. The electrons are then focused on the in-lens detector. With the in-lens detector one gets only information of the SE and not a mixture of SE and BE (due to generation of secondary electron at the chamber walls by impact of backscattered electrons) as with the Everhart-Thornley detector.

Conclusion

Lateral quantum dots were fabricated on strained Si/SiGe substrates with a mobility of about 200,000 cm^2/Vs using a split gates geometry. The gate structures where realized by e-beam lithography. First measurements at 300 mK showed that the electron gas can be depleted by applying negative gate voltages and the conductivity decreases below e^2/h. However further improvements are required to observe quantization and Coulomb blockade effects.

Similar samples showed fractional quantum Hall effect up to filling factors of 1/3. The ν = 1/3, 4/7 and 4/9 are observed for the first time in the Si/SiGe system. This result demonstrates the CF model also applies in the Si/SiGe system.

The e-beam lithography was performed with a JEOL 6400 up to now. A new LEO Supra 35 FESEM has been purchased and brought to operation conditions.

Acknowledgements

This work was financially supported by FWF (P16223-N08)

References

[1] K. Lai, W. Pan, D.C. Tsui, S. Lyon, M. Mühlberger and F. Schäffler: *“The Two-flux Composite Fermion Series of Fractional Quantum Hall States in Strained Si”*, submitted to PRL