p-Modulation Doping on Si Step-Bunching Templates: Anisotropic Transport and Mobility Analysis for an Undulated SiGe-Channel

H. Lichtenberger, T. Berer, D. Gruber, G. Pillwein, G. Brunthaler, F. Schäffler

Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria

In this report first results on p-modulation doped Si/SiGe heterostructures grown on top of a rippled step-bunching Si-buffer are outlined. The short-scale periodic height fluctuations of the Si-buffer (Λ ~ 100 nm) are intended to form well-defined undulations in the SiGe-channel of the remotely p-doped quantum well, giving rise to increased scattering. Thus, an asymmetry in mobility, perpendicular and parallel to the undulations, is expected. This might help to uncouple the different scattering mechanisms, which are conversely discussed as predominant hole-mobility limiting factors for p-modulation doped quantum well structures (p-MODQW), namely alloy scattering and interface-roughness related scattering.

Introduction

Modulation-doped Si/SiGe heterostructures were first realized in 1984 with a SiGe quantum well sandwiched between the Si substrate and an unstrained Si-cap layer. Selective p-type doping in the Si cladding layers leads to an enhanced hole mobility for the established two-dimensional hole gas (2DHG) in the SiGe-channel which is formed according to the valence band offset. Historically later, n-doped structures featuring a two-dimensional electron gas (2DEG) were fabricated. Employing relaxed virtual $Si_{1-x}Ge_x$ substrates, an in-plane tensilely strained Si-channel is formed due to the conduction band offset. Such relaxed SiGe-buffers are nowadays also used in p-type structures with Ge-rich or even pure Ge-channels. Whereas for n-MODQW structures extremely high mobilities reaching values beyond 500 000 $cm^2V^{-1}s^{-1}$ were observed, p-MODQW structures seem to be restricted to hole mobilities around 20 000 $cm^2V^{-1}s^{-1}$ for SiGe-channels, and well below 100 000 $cm^2V^{-1}s^{-1}$ even for pure Ge-channels with a strongly reduced effective hole mass and absent alloy scattering. The origin of the vast difference in low-temperature mobilities is still not clear. Alloy scattering and interface-roughness scattering together with strain fluctuations arising from smeared-out Si/SiGe interfaces coming along with Ge-segregation and interface charges are discussed as the ultimate limitations regarding mobility. However many theoretical treatments are found in literature [1], [2] which usually adjust numerous parameters to fit the experimentally observed low-mobility results for p-modulation-doped structures. Thus, often the predictions for the dominant limiting scattering mechanism are different [3], [4].

Herein, first results on p-modulation doped Si/SiGe heterostructures grown on top of a rippled step-bunching Si-buffer are presented. The short-scale periodic height fluctuations of the Si-buffer (Λ ~ 100 nm) – which were extensively discussed in our preceding work [5] – [7] – are intended to form well-defined undulations in the SiGe-channel of the remotely p-doped quantum well, giving rise to increased scattering. Thus, an asymmetry in mobility, perpendicular and parallel to the undulations, is expected. This is intended to uncouple the different scattering mechanisms, which are conversely discussed as predominant hole-mobility limiting factors for p-modulation doped structures, namely alloy scattering and interface-roughness related scattering.

Earlier experiments in this direction were published by Waltereit et al. [8] for n-modulation doped Si/SiGe heterostructures grown on vicinal Si(001) substrates on top of a compositionally graded strain-relaxed $Si_{0.72}Ge_{0.28}$ buffer. Also, by Neumann et al. [9], [10] anisotropic hole transport measurements on p-modulation doped SiGe channels on step-bunched vicinal Si(113) surfaces were reported. These however were performed on Si(113) which shows strong step-bunching but will hardly become of technical relevance. Our investigations are based on Si(001) substrates with a miscut of 4° which are also used commercially.

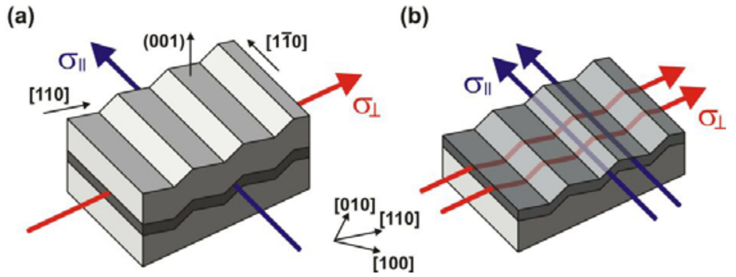

Fig. 1: Schematic drawings of a conventional p-SiGe modulation-doped structure with front-side doping. The conduction takes place at the upper interface of the SiGe-channel. The modulation of the channel yields expected differences in conductivity for measurements parallel ($\sigma_{||}$) and perpendicular ($\sigma_{\perp}$) to the ripple structure.

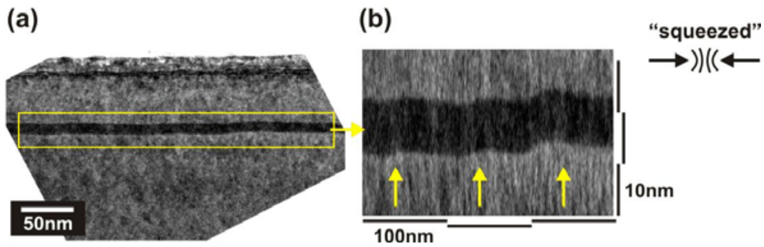

Fig. 2: (a) XTEM image of the $Si_{0.75}Ge_{0.25}$ channel of a miscut sample. The yellow box serves as guide to the eye to help resolving the periodic modulations (Λ ~ 100 nm) of the $Si_{0.75}Ge_{0.25}$ channel grown on top of the step-bunching template. (b) Representation of the same image squeezed together in lateral direction to emphasize the modulation of step-bunching for the SiGe-channel. The yellow arrows indicate the minima of the undulations with ~100 nm periodicity.

Experimental Procedure

The modulation-doped quantum well structures (MODQW) grown on a step-bunching template enable surface-roughness-dependent measurements on one and the same sample (Fig. 1) which makes the experiment and interpretation less sensitive to other growth-process- or sample processing-induced artifacts: Especially background impurity scattering is known to be hard to control and thus giving unpredictable results.

Low-temperature epitaxial growth in our solid source SiGe-MBE system is used to prepare the Si step-bunching buffer and to define a conformal 10 nm thick $Si_{0.75}Ge_{0.25}$-channel by suppressing strain-driven thickness fluctuations, which are known to occur already at moderately elevated temperatures. Cross-section transmission electron microscopy (XTEM) reveals the intended periodic modulation of the buried SiGe-channel (Fig. 2) with rather sharp interfaces.

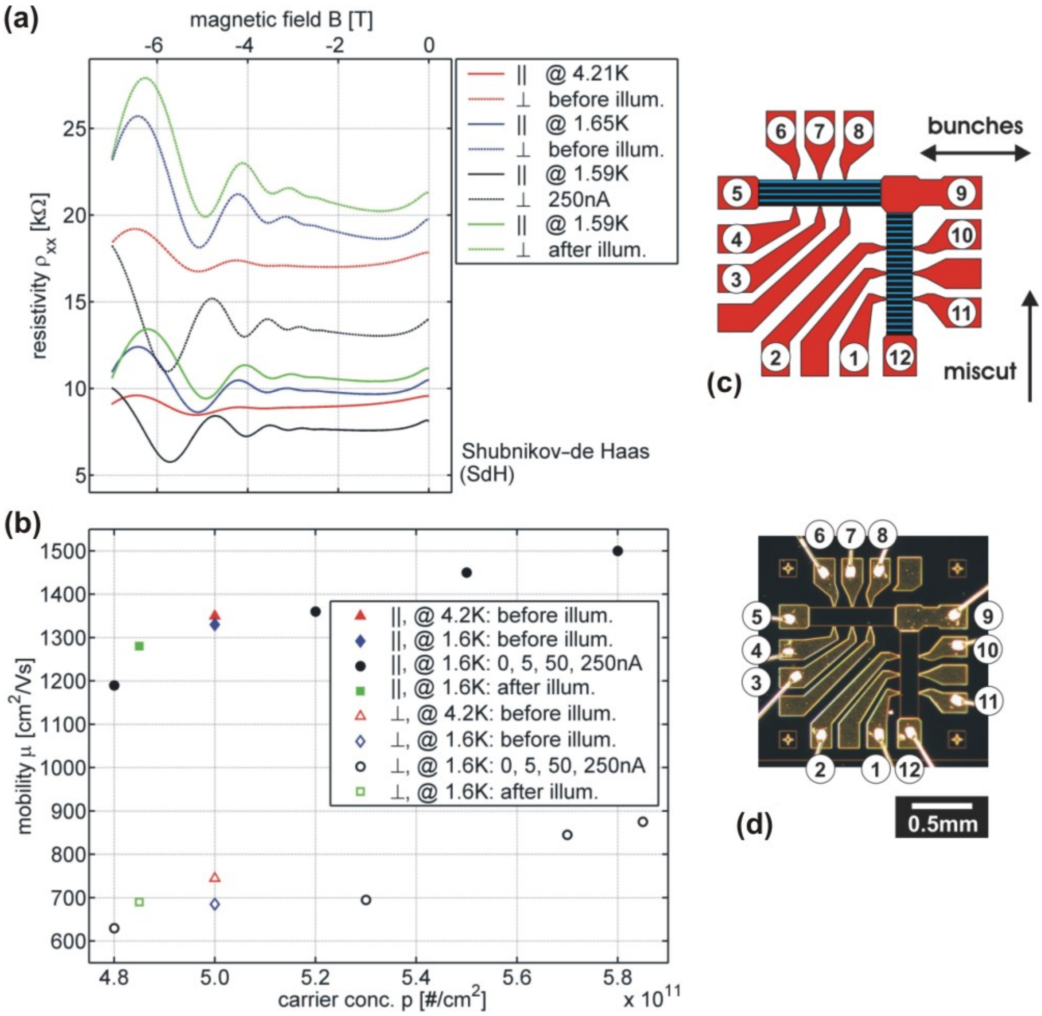

Fig. 3: (a) Plots of the longitudinal resistivity ρ_{xx} for the Hall-bars parallel (solid curves) and perpendicular (dashed curves) to the periodic modulations in the SiGe-channel due to step-bunching. (b) Evaluated data from (a) summarized in a plot showing mobility μ versus carrier concentration p_s. The data clearly prove a lower carrier mobility perpendicular to the ripples due to increased scattering. (c) Schematics of metal contact pads (red color) and etched Hall-bars (blue color). The line pattern indicates the elongation direction of step-bunching. Thus, the upper branch of the Hall-bar is used to measure the conductivity parallel to the bunches ($\sigma_{||}$), and the lower branch perpendicular to the ripple structure ($\sigma_{\perp}$). (d) Photograph of a processed Hall-bar, mounted and bonded onto a sample carrier.

The electrical characterization is performed in a ^{4}He-immersion cryostat with adjustable temperatures down to 1.6 K and magnetic fields up to B = 7 T. Magneto-transport measurements on a special two-branch Hall-bar geometry (Fig. 3(c) – (d)) are applied to extract important parameters from Shubnikov-de Haas oscillations in the longitudinal resistivity ρ_{xx}. These are the carrier concentration p_s, the mobility parallel ($\mu_{||}$) and perpendicular ($\mu_{\perp}$) to the undulations in the SiGe-channel.

Results and Discussion

Although still at the beginning, the first measurements confirm a significant resistivity anisotropy with a decreased low-temperature mobility across the undulations by nearly a factor of two (Fig. 3). Such a remarkable effect was beyond expectations for the technologically relevant Si(001) surface.

The reported results, combined with additional modeling are expected to provide a new approach toward settling the long-lasting dispute on the limiting scattering mechanisms of the hole mobility in p-MODQW structures.

Summary

First results on p-modulation doped Si/SiGe heterostructures grown on top of a rippled step-bunching Si-buffer are reported. The short-scale periodic height fluctuations of the Si-buffer (Λ ~ 100 nm) are used to form well-defined undulations in the SiGe-channel of the remotely p-doped quantum well, giving rise to increased scattering. In fact, an asymmetry in mobility perpendicular and parallel to the undulations was found. This way the different scattering mechanisms might be uncoupled, to finally identify the predominant hole-mobility limiting factor for p-modulation doped structures.

Acknowledgements

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