Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 201-203

Invited

Modulation-Doped High-Mobility Si/SiGe Heterostructures for Device Applications

Ulf König and Friedrich Schäffler

Daimler-Benz Research Center, Wilhelm-Runge Str. 11 D-89081 Ulm, Germany

The rapid progress in the growth of Si/SiGe heterostructures during recent years yielded excitingly high electron and hole low temperature mobilities around 175000 or up to 55000 cm²/Vs, respectively. The material now becomes attractive for devices like heterofieldeffect transistors (SiGe MOD-or MOSFETs). High transconductances were already achieved, e.q. at 300K up to 340 mS/mm for n- and 167 mS/mm for p-type FETs. A review is given on the essential steps in this evolution.

1. INTRODUCTION

In a Si/Si_{1-x}Ge_x heterostructure grown on a Si substrate only the SiGe layers are compressively strained. Nearly a flatband situation is left in the conduction bands, while the total difference between the wide gap Si and the low gap SiGe appears as an offset in the valence band alone ¹). In a Si/Ge heterostructure grown on a strain relaxed SiGe buffer the Si layers experience an in-plane tensile strain. The bandordering now exhibits pronounced offsets in valence and conduction band, with the conduction band minimum located in the wide gap Si (type II ²). Such band alignment can be used either for confining a twodimensional hole or electron gas (2DHG or 2DEG), presuming that the doping is arranged in the neighbouring layers, i.e. p-type in Si or n-type in SiGe (modulation doping).

2. 2DEG, 2DHG STRUCTURES AND PER-FORMANCES

Various types of n- and p- channel Si/SiGe heterostructures were reported. Fig. 1 summarizes some,

which were designed for heterodevices and which have demonstrated record device performances. Among these are MBE grown ^{3,4}) and UHVCVD grown ^{5,6}) layer sequences. 2DEG structures like the first reported by Dämbkes et al. 7) and also later one 8) used relatively thin single step (constant Ge) SiGe buffers. QWs on graded buffers (Ge linearly or stepwise increasing) were recently reported 9 , 10). The graded buffers distinctly reduce the threading dislocations in the active QWs, from up to 10⁹ cm⁻² with single step buffers, by more than three orders of magnitude. Owing to an elevated temperature (around 750 °C) for the buffer growth a dense network of long misfit dislocation segments is formed, which is concomitant with a low density of threading dislocations in the active layers above. A pronounced surface cross hatch pattern appears for buffers with a high Ge content, probably due to strain induced growth inhomogeneities 11). Thin graded buffers (only 100 nm) 5), like one 2DEG structure shown in Fig. 1, are less favorized in comparison to thicker buffers (several µm) 14). Both of the 2DEG structures shown have the modulation doping above the channel. They differ in the total thickness of the



Fig. 1: Electron and hole-gas Si/SiGe heterostructures used for high performance devices



Fig. 2: Composition and doping (SIMS) in an active modulation doped QW, as grown (MBE) and after a rapid thermal treatment.

capping layers, 18 nm or 77 nm, which essentially determines the device operation. A typical composition and doping profile of a modulation doped structure is given in Fig. 2. The as grown sample shows a clear separation of doping and 2DEG-channel. However, elevated temperatures initiate an enhanced doping outdiffusion. Even temperatures around 700 °C will drastically degrade the QW-performance 12,13).

2DHG structures with a SiGe channel grown on a Si substrate or a Si buffer showed disappointing performances with low - RT-mobilities around 150 cm²/Vs. The position of the modulation doping, above the channel like in the first device structure reported by Pearsall, Bean ¹⁴) or below ¹⁵), was found to be less important. A SiGe 2DHG structure without a grown modulation doping, reported by Kesan et al 6) (see Fig. 1), where implants in the substrate act as doping sources, yield field effect mobilities 50% higher than for pure Si control devices, but quantitatively the same low values. An alternative is pure Ge for the hole gas channel, which should provide the highest hole mobility of all commonly employed semiconductors. To overcome the restrictions from the pseudomorphic growth regime, 16) Ge substrates were first used 17). But for a compatibility to Si technology the growth on Si substrates is demanded. A solution is to take profit from the graded Si1-xGex buffer



Fig. 3: Progress of the electron Hall mobilities in QWs, open signs those on single step, dark onses on graded buffers.

concept again 4), however, ending up with very high contents around 70%.

The improved buffer qualitiy led to a dramatic increase of 2DEG mobilities 18-20). The best values reported were between 170 000 and 180 000 cm²/Vs 21,22). That is about an order of magnitude above the mobilities obtained with single step buffers (see Fig. 3). 2, 23,24). Also the low temperature hole gas mobilities experienced an outstanding development, from around 800 cm²/Vs before ¹⁵) to about 15 000 cm²/Vs with a graded buffer 4). Very recently a new landmark was set by AT & T with 55 000 cm²/Vs 25 for p-type structures. Moreover, RT-mobilities close to 2000 cm²/Vs were found in n-MODFET samples, which exceed the values of commercial Si-MOSFETs by a factor of two. For a wide range of doping the RT values in 2DEG-structures are about four-times higher than the bulk mobilities of Si and SiGe.

3. HETERO FIELD EFFECT TRANSISTORS

The excellent Si/SiGe electron and hole gas samples can be exploited for hetero field effect transistors, called SiGe MODFETs or SiGe MOSFETs . After the very early demonstration (1985) of n- and p- channel. MODFETs 7, 14) the development stagnated for several years. Since mid 1990 Si/SiGe hetero-FETs gain new interest. Most of the devices had relatively simple Mesa-like layouts. For source and drain alloyed contacts were used, if the channel was close (< 20 nm) to the top surface 5). Deep channels have to be contacted by means of implanted zones 3). Different gate versions were investigated. For n-MODFETs mainly Schottky gates were applied, either deposited on the cap Si layer of the structure 5) or recessed 3) in a groove close to the 2DEG, and very special undercut gates 15). For hole gas FETs MOS gates were favorized, nonselfaligned 27) or even very advanced selfaligned versions, reported by an IBM group 6), taking profit of well established Si-MOS technologies.

The DC performance of Si/Ge MODFETs and SiGe MOSFETs is well studied. The performance is already comparable to standard data of more experienced



Fig. 4: IV-curves (77K) of an n-channel and a p-channel MODFET

GaAs/GaAlAs HEMTs. Fig. 4 presents own record IVcurves of n- and p- MODFETs 3, 4). At least at 77K the IV-curves are nearly ideal, free of loops and with a good saturation. RT curves usually suffer from an uncomplete pinch off, due to a remaining parasitic channel in the substrate or buffer layer. Furthermore Schottky-gated MODFETs indicate leakage. Just this is the motivation for MOS gates. But the deposition of proper gate oxides on Si/SiGe heterostructures is not trivial owing to a high temperature treatment usually required, which can degrade the temperature sensitive QWs.

High external transconductances g_{me} could be achieved, for n-MODFETs 340 and 670 mS/mm at RT or 77K by our group ³), for p- MOD or MOS-FETs 167 mS/mm at RT by IBM ⁶) or 295 mS/mm at 77K by DB ⁴). Intrinsic transconductanes g_{mi} , which eliminate the source resistance R_s are even higher, around 400 and 800 mS/mm. Fig. 6 reviews transconductances of p-channel FETs with MOS and Schottky gates. SiGe ⁶, 15) and most pronounced Ge ⁴) channel-hetero FETs are superior to conventional, pure Si control devices ⁶). Moreover, the theoretically expected increase of the transconductance with decreasing gate length is found.

SiGe Hetero FETs operating in depletion and / or enhancement mode were realized. The latter, normally-off one, suffer from leakage of the forward biased gate, but offer low power dissipation. The layer design, i.e. the gate to channel distance d_{GC} and the doping level determine the operation mode. In general, a thick (> 25 nm) total layer above the channel yield depletion. But it was possible to adjust both operation modes in a given layer structure 15). The gate to channel distance has to be varied by gate recess. The devices can operate over a wide gate-bias range. On the other hand, comparing n-MODFETs from different labs, IBM 5) and DB 3) (see Fig. 6) one finds both modes, inspite of roughly the same $d_{GC} \approx 13-18$ nm. Here the different carrier densities, 2.5 $\cdot 10^{12}$ cm⁻² in the depletion mode device and only 1.1 \cdot 10^{12} cm⁻² in the enhancement mode became effective. Furthermore in the IBM depletion device the doping is spread more to the surface, due to an already mentioned UHVCVD growth artefact, which demands negative bias to deplete. It is interesting that roughly the same



Fig. 5: Effect of the Ge-content in the channel of p-FETs, (ref. 4, 6, 15). The transconductance grows with smaller gate lengths L_{G} .



Fig. 6: Different operation modes of the record n-MODFETs reported 3,4), in the cases adjusted by the doping.

maximum transconductances were obtained, though the gate lengths differ, 0.25 μ m in the IBM or 1.4 μ m in the DB device.

4. PERSPECTIVES

SiGe MODFETs have the potential to high frequency operation. One can estimate for small gates \approx 0,15 µm around 150 GHz, taking profit from a velocity overshoot, expected in Si, too. Apart from this, Si/Ge offers an exclusive property superior to any other semiconductor system. This concerns complementary MODFETs (CMOD), a serial combination of n-Si and p-Ge-channel QW-FETs. A lot of work is necessary for a suitable SiGe-hetero FET technology.

5. **REFERENCES**

- 1) C.G. Van der Walle, Phys. Rev. <u>34</u> (1986), 5621
- G. Abstreiter et al., P.R.L. 54 (1985), 2441
- 3) U. König et al., Electr. Lett. <u>28</u> (1992), 160
- 4) U. König, F. Schäffler, IEEE EDL 14 (1993), 205
- 5) K. Ismail et al., IEEE EDL 13 (1992), 229
- 6) V.P. Kesan et al., IEDM (1991), 25
- 7) H. Dämbkes et al., IEEE Trans ED 33 (1986), 633
- 8) U. König et al., Electr. Lett. 27 (1991), 1405
- 9) E.A. Fitzgerald, Appl. Phys. Lett. 59 (1991), 811
- 10) F.K. Le Goues, Phys. Rev. Lett. 66 (1991), 2903
- 11) J.W. Hsu et al, Appl. Phys. Lett. 61 (1992), 1293
- 12) F. Schäffler, H. Jorke, A.P.L. 58 (1991), 397
- 13) U. König et al., IEEE EDL 14 (1993), 97
- 14) T.P. Pearshall, J.C. Bean, IEEE EDL 7 (1986), 308
- 15) U. König, F. Schäffler, Electr. Lett. 29 (1993), 486
- 16) P. People, J.C. Bean, A.P.L. 49 (1986), 229
- 17) E. Murakami et al., IEEE EDL 12 (1991), 71
- 18) K. Ismail et al., Appl. Phys. Lett. 58 (1991), 2117
- 19) Y.J. Mii et al., Appl. Phys. Lett. 59 (1991), 1611
- 20) S.F. Nelson et al., EMC (1993), P10
- 21) F. Schäffler et al., Sem. Sci. Tec. 7, (1992), 260
- 22) D. Monroe, MRS (1992), p.D 4.9
- 23) H.-J. Herzog et al T.S., Films <u>184</u> (1990), 237
- 24) G. Schuberth et al., A.P.L <u>59</u>, (1991), 3318
- 25) D.J. Gravesteijn et al., JCG 111, (1991), 916
- Y.H. Xie et al., EMC (1993) P4
- 27) J. Chang, Microel. Eng. 15 (1991), 19