Fast Growth Method for the Fabrication of Modulation Doped Si/SiGe Field Effect Transistors

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The fabrication of SiGe-based n- and p-type MODFET structures requires the growth of strained Si or SiGe quantum wells on top of relaxed SiGe buffer layers. In order to achieve a sufficiently low threading dislocation density in the active layers, the concept of SiGe buffers with gradually increasing Ge content was developed. A disadvantage of these buffers is the time required for their fabrication, mostly by MBE or UHV-CVD. We present a novel, fast technique based on DC-plasma enhanced CVD which offers growth rates 10 – 50 times bigger than those obtained with MBE or UHV-CVD. The investigations of graded SiGe buffers by x-ray diffraction, atomic force microscopy and secondary ion mass spectroscopy reveal structural properties comparable to MBE or UHV-CVD grown material.

1. Introduction

SiGe-based MODFET structures have demonstrated device performances superior to conventional Si-based MOSFETs in the field of high-frequency applications. In order to achieve the desired electronic structure, i.e. to tailor the band gaps and band alignment, Si and SiGe channels have to be grown pseudomorphically on top of relaxed SiGe layers. In a tensely strained Si channel on top of relaxed SiGe, the sixfold degeneracy of the Δ-minima of the conduction band is removed. Two of these (Δ_2-minima along growth direction) are lowered in energy and form the quantum well for electrons. As growth is usually performed on the (001) surface, the effective mass of the electrons relevant for the in-plane movement is then the small transverse mass (m_t = 0.19 m_0 for unstrained Si), which is favorable for fast device applications. However, misfit dislocations, which are required for the plastic relaxation of SiGe, are accompanied by threading segments which intersect the active layers and decrease the device performance. It has become a main aim of growth optimization to reduce the threading dislocation densities [1]. The most widely used technique is the growth of SiGe buffers, where the Ge content is graded from zero up to the final concentration of typically 20 – 30 %, followed by a constant composition buffer and the active layers (see Fig.1) [5]. The whole buffer stack has a typical thickness of several µm, and hence the time required with conventionally applied techniques such as MBE or UHV-CVD is considerably large, since the growth rates are typically in the order of Angstrom per second.

A novel growth technique developed at the ETH Zurich in cooperation with Balzers is the so-called “Low Energy DC Plasma Enhanced CVD” (LEPECVD) [2]. With this method growth rates higher than 50 Ås^{-1} have been demonstrated. We have investigated the structural quality of LEPECVD grown samples by means of x-ray diffraction (XRD), atomic force microscopy (AFM) and secondary ion mass spectroscopy (SIMS). It turned out that the sample quality is comparable to material grown by conventional techniques.

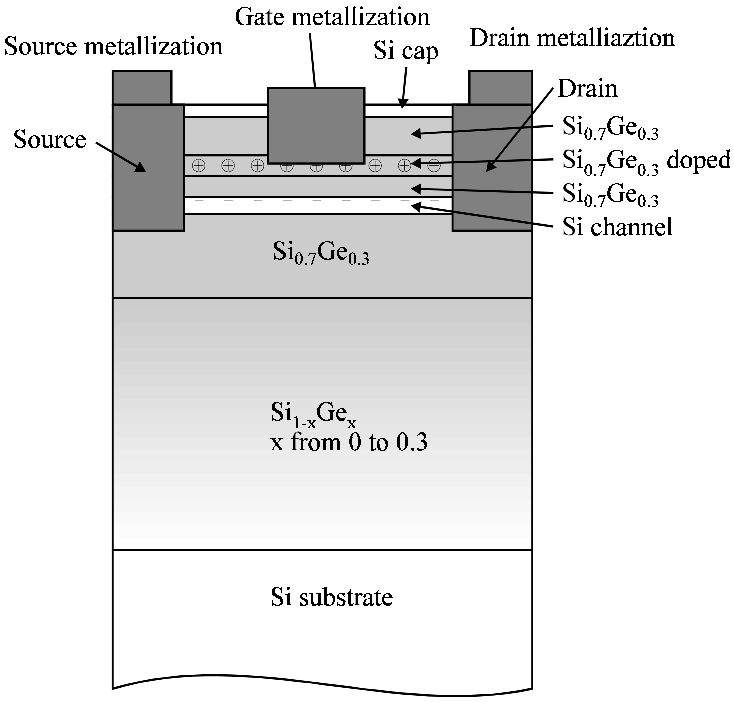

Fig. 1: Scheme of a n-type MODFET grown on a graded SiGe buffer. The layer thicknesses are not on scale, in reality the active layers are much thinner.

2. Experimental

The samples have been grown at the ETH Zurich on (001) oriented Si wafers. HF dipped wafers were loaded into the growth chamber via a load-lock. After outgasing and cleaning in an H-plasma, 100 nm Si buffers were grown at 600 °C, followed by the SiGe buffer layers grown at temperatures between 500 – 600 °C and at rates between 10 – 50 Ås^{-1}, typically. In contrast to conventional CVD techniques, in LEPECVD an intense low-energy plasma (arc discharge voltages of 20 – 30 V DC) is used to decompose the reactive gases SiH_4 and GeH_4 and to enhance the hydrogen desorption on the surface. The energy of the ions impinging on the substrate can be controlled by the substrate bias and usually lies in the region below 10 eV. Details on the method and sample growth can be found elsewhere [2], [3].

XRD reciprocal space maps have been recorded using a triple-axis setup with primary beam divergence and analyzer resolution of 12 arcsec, respectively. From maps around the symmetrical (004) and asymmetrical (224) reciprocal lattice points (see Fig. 2) the strain in the samples could be determined as a function of the Ge content [4].

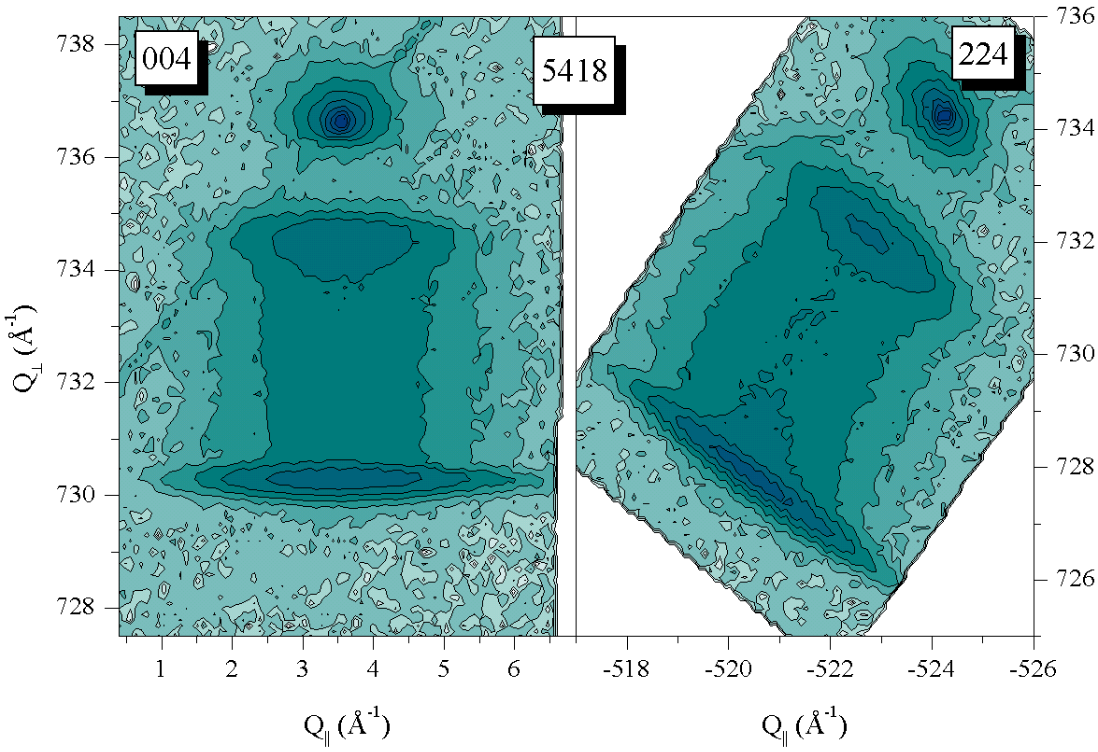

Fig. 2: Reciprocal space maps around the (004) and (224) reciprocal lattice points for LEPECVD grown sample 5418.

Asymmetrical maps have been recorded in different (110) azimuths to detect a possible anisotropy of strain relaxation, but no such effect has been observed. Combining the XRD results with the SIMS profiles of the depth-distribution of the Ge content, finally the strain as function of depth below the sample surface has been determined. Figure 3b shows a typical SIMS profile. From the combination of this profile with the strain data from the XRD maps, finally the strain as a function of depth can be determined (Fig. 3b).

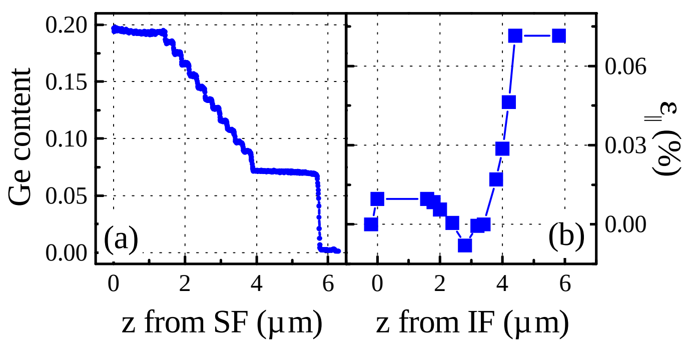

Fig. 3: (a) SIMS profile of the Ge content of sample 5418 as a function of depth below the sample surface. The graded region is grown as a sequence of small steps in the Ge content, which is clearly resolved by the SIMS. (b) Strain distribution of sample 5418 as a function of thickness above the interface between Si buffer and SiGe graded buffer.

As intended, the strain is virtually zero in the lower part of the graded buffer, and increases linearly in its upper part [5]. The constant composition part of the SiGe buffer as well as the active layers have been grown pseudomorphically on top of the graded buffer. Figure 4 shows an AFM image of the surface of a LEPECVD grown buffer layer. The typical “cross-hatch” pattern connected with the extended misfit dislocations within the graded part of the buffer is clearly visible.

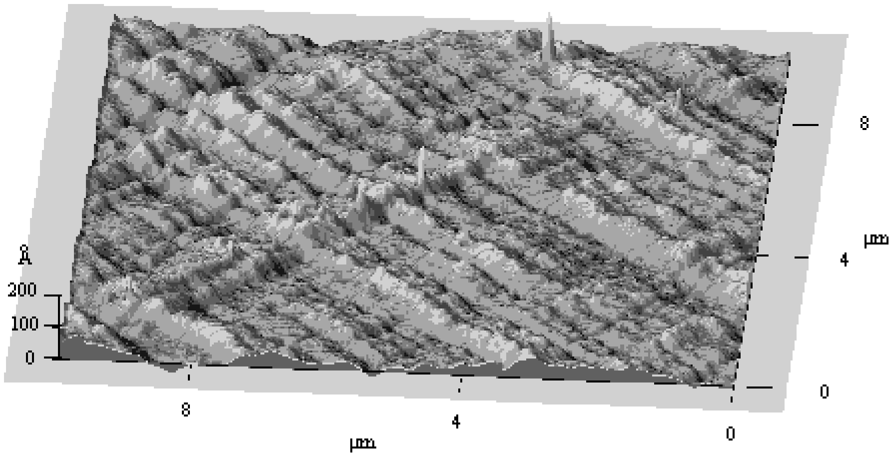

Fig. 4: AFM image of LEPECVD grown sample 5441. The typical cross-hatch pattern connected with the misfit dislocations along {110} directions in the graded buffer is clearly visible.

3. Conclusion

The comparison of these results with measurements on comparable samples grown by MBE shows that the structural quality of LEPECVD grown material is quite comparable to samples grown by conventional techniques. The FWHM along ω-direction in the reciprocal space maps is only slightly larger than in MBE grown samples. The surface roughness of the samples is typically 20 – 30Å (r.m.s. value), also comparable to MBE grown material. Thus LEPECVD seems to be a promising method for the fast growth of SiGe buffer layers for high-speed device applications on an industrial scale.

Acknowledgements

We are grateful to Christian Spallek, GeMeTec, for the SIMS analyses. This project was supported by the European Community (ESPRIT LOCO) and the Swiss Priority Program in Micro & Nano System Technology (MINAST).

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