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Precise thickness and strain control during epitaxial growth of strained Ge/SiGe multilayers by industrial class CVD

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1. Introduction

High Ge content, strained Ge/SiGe multilayered heterostructures are attracting increasing research attention due to their potential applications in a variety of photonic, thermoelectric and electronic devices. In such structures the number of nano- or subnano-scale layers can vary from a few up to hundreds, depending on the application. For this reason, thickness control at the monolayer level is essential both to achieve epitaxial growth of such complex heterostructures and to ensure their reproducibility. Epitaxial growth techniques like SS-MBE, GS-MBE or UHV-CVD have been used to grow Si based multilayered heterostructures [1, 2], but generally these techniques do not offer the desired results and cannot be scaled to larger wafers. In particular, for heterostructures containing single or multiple strained Ge layers, growth temperatures have to be kept sufficiently low to retain the strain and limit Ge diffusion and segregation. Meanwhile, for production, the Ge growth rate has to be maintained at a reasonable level and the growth technology has to allow wafer size scaling. By contrast, Reduced Pressure Chemical Vapour Deposition (RP-CVD) satisfies these requirements as a growth technique. At least for epitaxial growth of Si and SiGe materials RP-CVD has been proven to be preferred for mass production of epitaxial wafers. Hence, it is of great interest both for industrial and academic communities to investigate the limits of SiGe epitaxial growth by the RP-CVD technique.

In this work, we demonstrate that RP-CVD epitaxial growth of the desired high Ge content Ge/SiGe multilayers is possible with monolayer thickness and strain control.

2. Epitaxial growth by RP-CVD

The multilayered Ge/$Si_{0.4}Ge_{0.6}$/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructures for this research were grown on 200 mm Si(100) substrates in an industrial ASM Epsilon 2000 RP-CVD system, which is a horizontal, cold wall, single wafer, load-lock reactor with a lamp-heated graphite susceptor in a quartz tube. The heterostructures, shown schematically in Figure 1, consist of a 2.6 μm thick fully relaxed, reverse linearly graded (RLG) $Si_{0.2}Ge_{0.8}$/Ge buffer [3, 4], followed by a number of periods of tensile strained $Si_{0.4}Ge_{0.6}$ barriers and compressive strained Ge QW layers, finalized with a tensile strained $Si_{0.4}Ge_{0.6}$ barrier, and capped with a 200 nm relaxed $Si_{0.2}Ge_{0.8}$ layer and a 2 nm highly tensile strained Si cap layer to protect the structure from in-depth oxidation. The full structure was grown in a single process without any external treatments. The buffer is a strain tuning platform for growth of the subsequent strained balanced multilayers in the active region. Their structural properties such as state of strain, surface morphology and threading dislocation density (TDD) strongly affect the structural properties of the multilayers grown on top. The thicknesses of the Ge QWs and $Si_{0.4}Ge_{0.6}$ barriers were varied from a few nm up to over 10 nm and heterostructures with up to 100 periods were studied. The growth temperature for the multilayers was set to be below 500 °C, to ensure strain was retained in the epilayers and to minimize Ge inter-diffusion and roughening of the heterointerfaces.

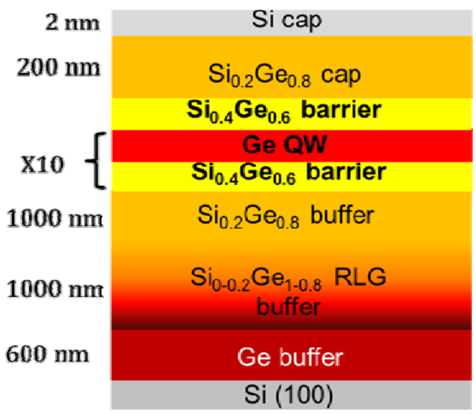

Fig. 1. Schematic design of multilayered Ge/$Si_{0.4}Ge_{0.6}$/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructures.

3. Results and discussion

All the epilayer thicknesses were obtained from direct analysis of XTEM images. A typical XTEM image of the multilayered region of a Ge/$Si_{0.4}Ge_{0.6}$/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructure, designed with 10 periods of 7 nm strained Ge QWs and 5.8 nm strained $Si_{0.4}Ge_{0.6}$ barrier layers is shown in Figure 2. The bottom of the image catches the $Si_{0.2}Ge_{0.8}$ buffer layers. In the middle, darker stripes of the Ge QWs and brighter ones of the $Si_{0.4}Ge_{0.6}$ barrier layers are clearly resolved. The Ge/$Si_{0.4}Ge_{0.6}$ interfaces are seen to be very abrupt, which supports the HR-XRD data, described later. The thicknesses of the Ge QWs and $Si_{0.4}Ge_{0.6}$ barrier layers agree perfectly with the designed values. For samples with these layers thicknesses, there is only a 0.1 nm deviation from the nominal thickness of the $Si_{0.4}Ge_{0.6}$ barrier layers. Analysis of other samples with different thicknesses also demonstrated similar results, with typical deviations from the designed values in the range of 0.1 - 0.5 nm. This means the epilayer thickness has been controlled within a few monolayers! The uncertainty is in fact at a similar level to the experimental error in the TEM measurement.

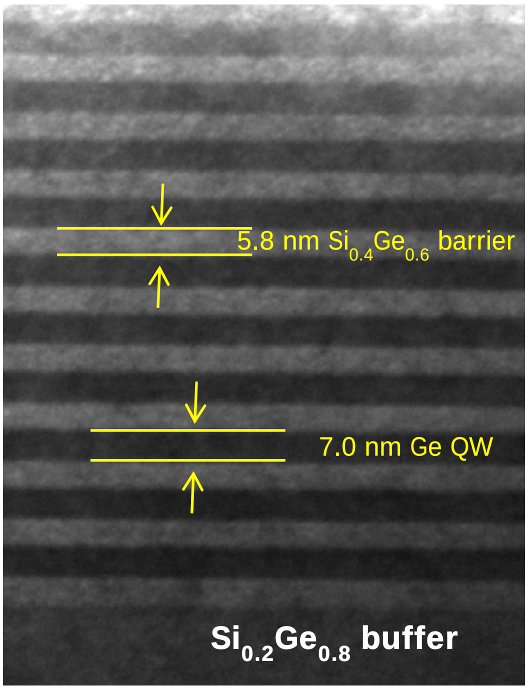

Fig. 2. Typical XTEM image of multilayered $Ge/Si_{0.4}Ge_{0.6}/Si_{0.2}Ge_{0.8}/Ge/Si(100)$ heterostructure with 10 periods of 7 nm strained Ge QW and 5.8 nm strained $Si_{0.4}Ge_{0.6}$ barrier layers.

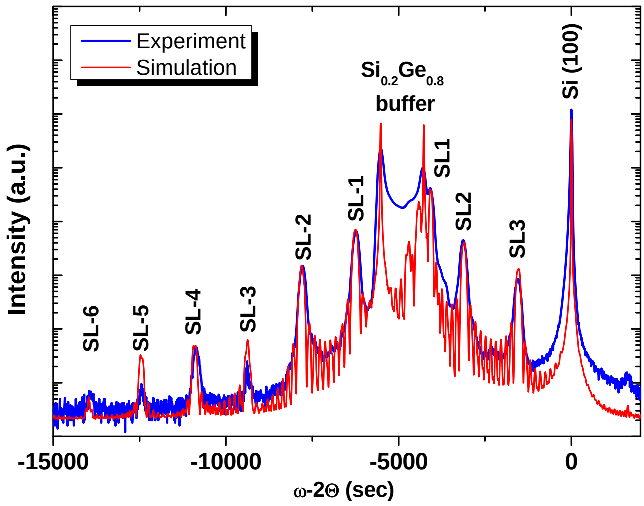

Fig. 2. HR-XRD (004) rocking curves of multilayered $Ge/Si_{0.4}Ge_{0.6}/Si_{0.2}Ge_{0.8}/Ge/Si(100)$ heterostructure with 10 periods of 7 nm strained Ge QW and 5.8 nm strained $Si_{0.4}Ge_{0.6}$ barrier layers.

The state of strain and Ge composition in each layer of these multilayered heterostructures were obtained from HR-XRD, by measuring and analyzing symmetrical and asymmetrical reciprocal space maps (RSMs). The Ge QW and $Si_{0.4}Ge_{0.6}$ barrier layers were found to be fully strained and their thicknesses are reproduced over 10 and 100 periods of the structure. Further confirmation of this comes from the HR-XRD symmetric (004) rocking curves shown in Figure 3, which are a cross-section of the symmetric RSM at $Q_x = 0$. The measured experimental data matches the simulation very well and contains around 10 clearly resolved and very sharp peaks arising from the periodicity and reproducibility of the Ge QW and $Si_{0.4}Ge_{0.6}$ barrier layers. These sharp peaks also indicate the desired abruptness of the $Ge/Si_{0.4}Ge_{0.6}$ interfaces. Any non-periodicity or smearing of the interfaces would have resulted in broadening of the peaks, a reduction of their intensities and the disappearance of weaker peaks, but we clearly do not see this.

Both the XTEM and HR-XRD results agree and confirm the excellent structural properties of the samples grown and the reproducibility of layer thicknesses, not just within one sample but also from wafer to wafer.

4. Conclusions

In conclusion, an RP-CVD epitaxial process to grow strain-balanced $Ge/Si_{0.4}Ge_{0.6}$ multilayers on 200 mm diameter Si(100) substrates, via an intermediate relaxed $Si_{0.2}Ge_{0.8}/Ge$ buffer has been reported. The thickness of the compressively strained Ge and tensile strained $Si_{0.4}Ge_{0.6}$ epilayers were varied from a few nm to over 10 nm and the number of periods was also varied. The results obtained indicate that, with proper selection of the epitaxial growth conditions, strained balanced multilayered heterostructures can be produced with a precisely defined $Si_{0.4}Ge_{0.6}$ alloy content and control of the strained epilayer thicknesses to within a few monolayers. Heterostructures with up to 100 periods of strained $Ge/Si_{0.4}Ge_{0.6}$ epilayers have been produced, with additional features appearing in the HR-XRD from the periodicity that demonstrate the reproducibility of layer thickness throughout the stack. These excellent results open up possibilities for epitaxial growth by industrial class CVD of very complicated high Ge content SiGe heterostructures, with precise layer thickness and strain control and superior reproducibility of materials from wafer to wafer.

Acknowledgements

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