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Compressively strained Ge channel heterostructures grown by RP-CVD for the next generation CMOS devices

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1. Introduction

Due to its superior electronic properties Ge is thought to be one of the major candidates for the p-channel of future CMOS devices. In particular, the room-temperature Ge hole mobility is the highest among elementary and compound semiconductor materials. Additionally, the presence of strain pronouncedly enhances the transport properties of the carriers. Significant progress has recently been reported in enhancing carrier transport in heterostructures that contain a compressively strained Ge channel layer. Mobile holes confined in an optimized compressively strained 20 nm thick Ge channel have been shown to exhibit a very high room-temperature drift mobility of 3100 cm^2/Vs [1]. Those structures were grown by solid-source molecular beam epitaxy (SS-MBE) on a Si(100) substrate via an intermediate relaxed SiGe buffer. Epitaxial growth of such structures by a mass production technique like reduced pressure chemical vapour deposition (RP-CVD) is of great interest; however, the growth mechanism of Ge and SiGe epilayers by RP-CVD is different from by SS-MBE and requires separate research.

In this work, we present compressively strained Ge layers which have been grown by RP-CVD on relaxed reverse linearly graded (RLG) $Si_{0.2}Ge_{0.8}$/Ge/Si(100) virtual substrates (VS), which we developed recently [2]. This relatively thin, high Ge content VS demonstrates good structural properties, i.e. relatively low RMS surface roughness and low threading dislocation density (TDD). It makes this VS an excellent platform to study the growth kinetics and strain relaxation of Ge epilayers.

2. Epitaxial growth of strained Ge channel structures

All the epilayers for this research were grown on 100 mm and/or 200 mm Si(100) substrates in an industrial ASM Epsilon 2000 CVD system, which is a horizontal, cold wall, single wafer, load-lock reactor with a lamp-heated graphite susceptor in a quartz tube. Growth kinetics of the Ge epilayers grown from a common germane (GeH_4) precursor were studied in the low temperature growth region of 350 - 450 ^oC, which is indispensable for suppression of surface roughening and retaining compressive strain in thick epilayers. The process pressure and H_2 carrier gas flow rate were fixed at 20 torr and a few tens of slm, respectively. The schematic design of the Ge channel/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructures is shown in Fig. 1. It consist of a 3 µm RLG fully relaxed $Si_{0.2}Ge_{0.8}$/Si(100) VS and strained Ge channel surface layer. In order to study the strain relaxation of the Ge layers its thickness was varied from a few nanometres up to hundreds nanometres, i.e. below and beyond the critical thickness for a Ge epilayer grown on relaxed $Si_{0.2}Ge_{0.8}$.

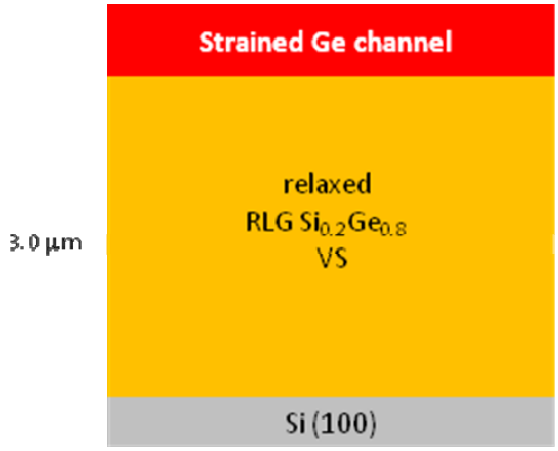

Fig.1 Schematic design of Ge channel/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructure grown by RP-CVD.

3. Results and discussions

The wafers were characterized by high resolution X-ray diffraction, using reciprocal space maps and rocking curves, X-ray reflectivity, cross-sectional transmission electron microscopy (XTEM), atomic force microscopy (AFM) and defect etching, in order to determine thickness of the Ge layer, its surface morphology, state of strain and the density of defects therein.

Fig. 2 shows a typical XTEM image of the surface region of a 30 nm Ge channel/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructure. A very smooth surface of compressively strained Ge surface layer is clearly visible. The heterointerface between the relaxed $Si_{0.2}Ge_{0.8}$ buffer and strained Ge channel layer is abrupt. Both layers are of high crystalline quality and defect free. In fact, the surface of the grown samples exhibits a cross hatch pattern that is common for graded Ge content SiGe VSs. Analysis of relatively large surface regions by AFM shows very low surface roughness of the strained Ge epilayers grown at different temperatures. A typical AFM image is shown in Fig. 3, for which the RMS surface roughness is ~ 2 nm.

For Ge layers grown beyond the critical thickness there is a dramatic rise in surface roughness due to strain relaxation. We found that this critical thickness of the Ge layers strongly depends on the growth temperature and increases as the growth temperature is decreased, as expected.

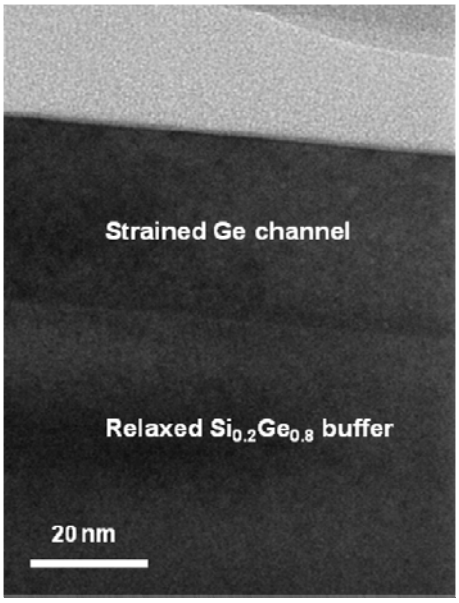

Fig 2. XTEM image of 30 nm Ge channel/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructure.

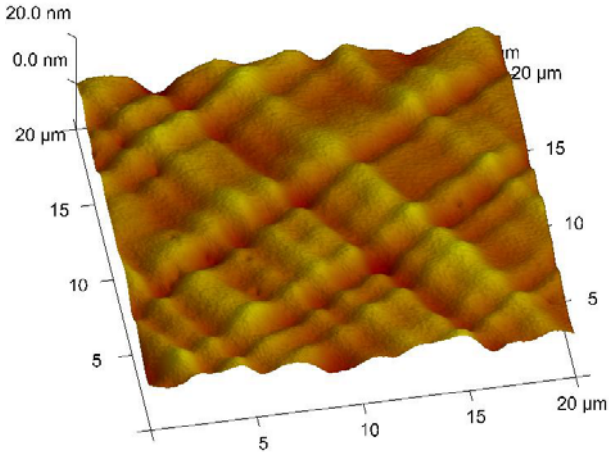

Fig. 3. AFM image of Ge channel/$Si_{0.2}Ge_{0.8}$/Ge/Si(100) heterostructure. RMS surface roughness is ~ 2 nm.

Fig. 4 shows the degree of strain relaxation in the Ge channel as a function of the Ge channel thickness, for growth at 400 °C with the GeH_4 partial pressure set at 10 mtorr. At thicknesses below 120 nm the Ge channel is fully strained. Beyond this strain relaxation occurs and increases markedly as the Ge thickness increases.

Reduction of the substrate temperature from 450 °C to 350 °C demonstrates a pronounced reduction of the Ge growth rate and an increase of the stagnation time on the $Si_{0.2}Ge_{0.8}$ surface before any growth begins. However, a reasonable Ge growth rate of ~ 0.5 $Å s^{-1}$ was achieved even at the lowest temperature of 350 °C. Moreover, reducing the growth temperature did not result in a change from 2D to 3D Ge growth, as confirmed by analyzing the surface morphology of the layers.

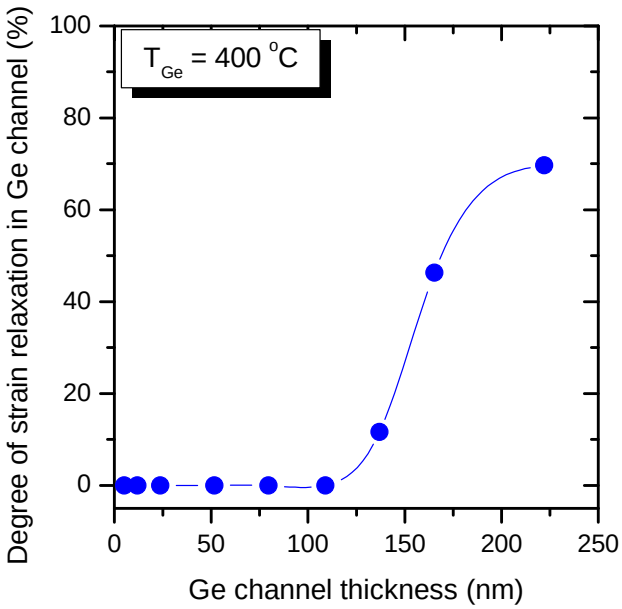

Fig. 4. Degree of strain relaxation in Ge channel as a function of the Ge channel thickness for growth at 400 °C on RLG $Si_{0.2}Ge_{0.8}$/Ge/Si(100) VS.

4. Conclusions

The epitaxial growth by RP-CVD of high quality compressively strained Ge channel heterostructures on Si(100) substrate has been demonstrated. The results show that the maximum thickness of Ge layer that could be grown fully strained depends strongly on the growth temperature and can be tuned by varying this temperature. Fully strained Ge layers with a thickness of more than 100 nm were grown. Very smooth surfaces were obtained for the strained Ge layers, with an RMS surface roughness of around 2 nm. The threading dislocation density was also relatively low, being below $2x10^6$ cm^{-2}. This is similar to values measured on just the relaxed buffers, so no new dislocations are formed in the strained Ge layers. All these excellent properties show a good potential for realizing future high performance p-Ge channel MOSFET on a standard Si(100) substrate for the next generation CMOS devices.

Acknowledgements

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References

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[2] V.A. Shah, A. Dobbie, M. Myronov, D.J.F. Fulgoni, L.J. Nash and D.R. Leadley *Applied Physics Letters* **93,** 192103 (2008).