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Characterization of strain and crystallinity in patterned embedded Silicon Germanium structures

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1. Introduction

Strain engineering has been adopted as a key element for scaling high performance complementary metal-oxide-semiconductor (CMOS) devices. As strain engineering becomes more complex, measurement techniques are needed to reliably characterize not only the strain in the stressor films, but the strain in the active channel-region of the device. Recently, local strain measurements in patterned structure using X-ray diffraction (XRD) technique [1, 2] and Dark Field Holography (DFH) in a transmission electron microscope (TEM) [3-5] were reported.

In this work, we present characterization of the strain in both the epitaxial embedded Silicon Germanium (eSiGe) stressor and the strained Si under a poly-Si gate in specially designed CMOS-like structures using high resolution XRD (HRXRD) and DFH technique. We also study the variation of strain with %Ge and different recess shapes.

2. Experimental

An embedded SiGe (eSiGe) film was grown epitaxially in the recessed Source and Drain regions of a uniform array of transistor-like structures aligned along the <110> direction on a Si (001) wafer using a commercial 300mm reduced pressure chemical vapor deposition (RPCVD) reactor. eSiGe films were grown in recesses with different lengths ([110] direction), but constant widths ([1-10] direction). Two recess shapes were studied, a BOX recess which has {110} side walls and a {001} bottom and a Sigma recess formed with {111} side walls and in the case of the longer recesses, a {001} bottom.

The crystallinity and strain in the eSiGe and Si under the poly-Si gate were evaluated by HRXRD measurement and DFH on a large area measurement pad consisting of a uniform array of the patterned transistor-like structures described above. DFH is a TEM based technique which can determine the relative deformation of a crystalline area at nanometer scale with good sensitivity and large field of view [5].

3. Results and Discussion

Figure 1 shows a 004 ω-2θ scan (black) from a single SiGe layer with 18.8% Ge grown on an unpatterned, large-area pad. The scan has two main diffraction peaks: an intense peak from the Si substrate located at 0 arcsec and a lower intensity peak from the SiGe layer. The positions of these two peaks correspond to the out-of-plane lattice parameter/strain in the layer. The clear thickness fringes around the main SiGe peak indicate a high-quality SiGe layer with good crystallinity [6]. It was confirmed that this layer was fully strained by a (224) relaxation scan. Figure 1 also shows 004 ω-2θ scans from two patterned regions, with 115nm and 230nm gate pitches as shown schematically in the inset. When compared with the SiGe (004) spectrum from the large area pad, it can be seen that the main SiGe (004) peak position has shifted to lower angle. This indicates that the out-of-plane lattice parameter of SiGe in the patterned area is smaller than that in the large area pad, suggesting that the epitaxially grown SiGe on the patterned area is elastically relaxed. No dislocations and stacking faults can be seen in the eSiGe on the patterned areas by plan-view TEM observation confirming elastic relaxation. In addition, a new peak can be observed in the scan of the patterned areas at around -570 arcsec and -690 arcsec for the 115nm and 230nm gate pitches, respectively. This peak comes from strained Si under the gate which has been strained by the adjacent eSiGe regions. For the 230nm gate pitch, the strain value is higher and the intensity of the strained Si peak is lower than that for 115nm gate pitch due to the difference of volume of the SiGe and Si in the patterned region.

XRD Reciprocal Space Maps (RSMs) of the corresponding (224) diffraction for the large and the 115nm gate pitch pads with 18.8% SiGe film are shown in Figs. 2(a) and (b). Compared with unpatterned, large-area pad, a strained Si peak can be seen as an additional feature near the Si substrate peak in the patterned area. Note, that in the (224) RSM, the strained Si peak has shifted along Qx in the positive direction relative to the Si Substrate peak consistent with compressive strain along the [110] direction. On the other hand, the SiGe peak has shifted along Qx in the negative direction relative to the position of a fully-strained SiGe film with 18.8% Ge. Both of these shifts along the in-plane Qx direction are consistent with elastic relaxation of SiGe along the [110] direction and the expected strain transfer from the SiGe stressor to the adjacent Si. Similarly, shifts of SiGe and strained Si peak positions along Qy are also observed. These shifts indicate that the out-of-plane lattice spacing of the SiGe film in the recess is smaller than that of fully strained SiGe and that the out-of plane lattice spacing of strained Si is larger than that of unstrained Si, consistent with the peak shifts detected by the 004 ω-2θ scan (Fig 1).

Figure 3 shows typical 004 ω-2θ scans for Ge: 18.8% with BOX type recesses and Ge: 19.0% and 26.0% with Sigma type recesses which have 115nm gate pitch. The (004) peaks observed to the left of the Si substrate peak consist of two components coming from strained Si and strain-relaxed SiGe. The positions of these peaks are plotted against the Ge concentration (as measured on the unpatterned, large-area pad) in Fig. 4 (a) and (b). A fairly good linear correlation with Ge concentration was found for both the strained Si peak position and the strain-relaxed SiGe peak position. The difference for the strain-relaxed SiGe peak positions between the BOX type and the Sigma type is small or even negligible. On the other hand, compared to the BOX type recess, the strained Si peak positions of the Sigma type recess are significantly more negative (higher strain) at a given Ge concentration. This indicates that the Sigma type recess is more effective at transferring strain to the Si. This enhanced effectiveness can be attributed to an increased volume ratio of SiGe to Si in the Sigma type recess or to the closer proximity (the “tip” of the Sigma shape extends under the gate, bringing it closer to the active region of the device).

For comparison with the HRXRD results, deformation along the [110] direction was measured using DFH. Figure 5 shows two dimensional maps of the deformation along [110], relative to the unstrained Si in the deeper substrate region. Figure 6 shows the average [110] strain value measured by the DFH in the Si region located between eSiGe regions plotted against the HRXRD strained Si peak position. The correlation between these two measurement techniques is good which indicates that the strain in the channel region can be nondestructively measured by XRD in both BOX and Sigma recesses.

We investigated the impact of thermal annealing (Rapid Thermal Annealing and Millisecond Annealing) in the conventional CMOS process flow on the crystallinity of the strained SiGe/Si structures with different pitch patterns on four samples with varying SiGe thickness and 26% Ge concentration with a sigma type recess. Four samples include one as-grown sample and three annealed samples A, B and C, with Sample A having the thinnest eSiGe and sample C having the thickest eSiGe. The XRD scans on 115nm and 230nm gate pitches are shown in Fig. 7 (a) and (b) respectively, and plan view TEM images are shown in Fig. 8. There is no change in the positions of the strained Si and the relaxed SiGe peaks in the XRD pattern between the annealed sample A and the as-deposited film for the 115nm pitch. No defects are seen in the plan view TEM (Fig. 8). On the other hand, for samples B and C with thicker SiGe the intensity of the strained Si and relaxed SiGe peaks are reduced by defect introduction (Fig. 8). Note that the dislocations are confirmed only along the [110] direction which contributes to strain relaxation of the SiGe along the [1-10] direction, indicating there is no need to introduce dislocations along [1-10] direction because the strain along [110] of the SiGe is already relaxed elastically. As shown in Fig. 7 (b), the strained Si peaks on the 230nm pitch disappear after annealing even on sample A, indicating the the larger SiGe volume is more susceptible to dislocation formation and complete strain relaxation compared to the 115nm pitch structure(Fig. 8).

4. Conclusions

It was found that the strains in strained Si and SiGe regions can be detected as distinct peaks by XRD on a regular array structures. Peak positions varied with Ge composition, recess shape and pitch as predicted by simple elastic models [7]. Both XRD and DFH results shows that a) higher Ge concentration leads to more strain and b) a Sigma recess is more effective in transferring strain compared with Box recess. We have also demonstrated the capability of XRD to detect defects in patterned strained Si and SiGe structures.

5. Acknowledgements

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6. References

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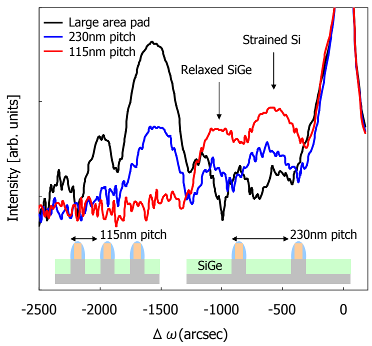

Fig.1. (004) ω-2θ spectra from a SiGe layer with 18.8% Ge grown on unpatterned large area pad and patterned regions with 115nm and 230nm gate pitches as shown schematically in the inset.

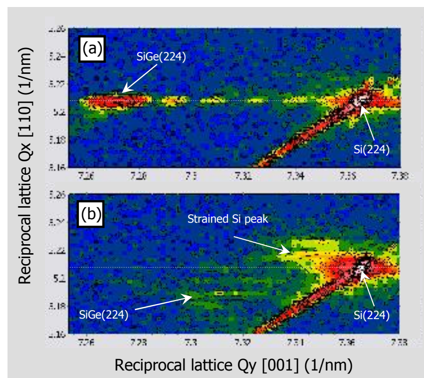

Fig.2. Reciprocal Space Maps around the Si(224), SiGe(224) diffraction spots of a SiGe layer with 18.8% Ge grown on (a) large area and (b) patterned region with 115nm gate pitch.

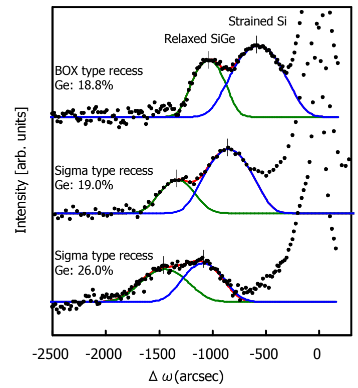

Fig.3. (004) ω-2θ spectra from BOX type and Sigma type recessed structures with different Ge concentrations with 115nm gate pitch.

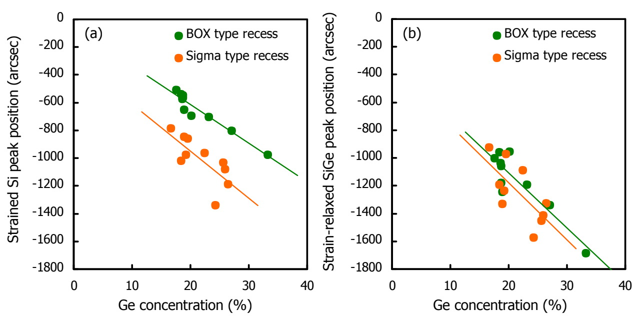

Fig.4. Ge concentration dependency of peak position of (a) strained Si and (b) strain-relaxed SiGe measured in BOX type and Sigma type recessed structures with 115nm pitch.

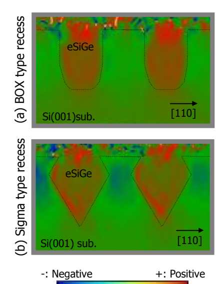

Fig.5. Two dimensional deformation maps. Relative deformation along [110] direction of the area measured compared to the unstrained Si region with (a) BOX type recess and (b) Sigma type recess.

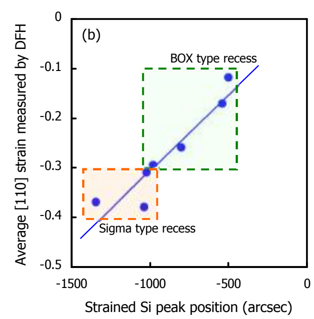

Fig.6. Average [110] strain value measured by DFH against strained Si peak position in patterned region with 115nm gate pitch.

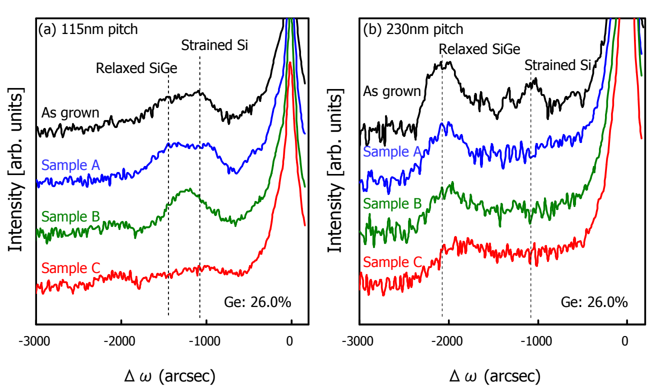

Fig.7. (004) ω-2θ spectra from Sigma type recessed structures with (a) 115nm and (b) 230nm gate pitch for as grown sample and after annealing samples (sample A, B and C). For the 115nm pitch, the strained Si and relaxed SiGe peaks of sample A are unchanged even after annealing. No defects are seen for this sample in Plan View TEM images.

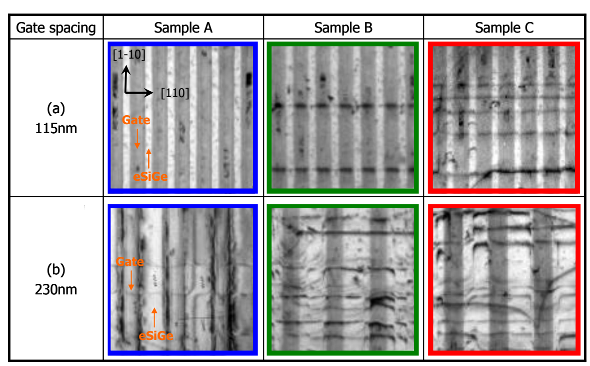

Fig.8. Plan view TEM images of Sigma type recessed structures with (a) 115nm and (b) 230nm gate pitch for after annealing samples (sample A, B and C).