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Three-Dimensional Visualization Technique for Crystal Defects in High Performance CMOS Devices with Embedded SiGe-Source/Drain

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1. Introduction

Stress induced technology with embedded SiGe-S/D for performance enhancement in pMOSFETs has been reported [1]. However, performance degradations with channel stress relaxation and/or junction leakage current increase due to undesirable crystal defects are sometime observed [2]. To resolve these problems, it is essential to perform a detailed analysis to reveal crystal defect formation and the growth mechanism. For analyzing crystal defects, transmission electron microscope (TEM) analysis is one of the most powerful techniques. However, conventional TEM observations bring only two-dimensional information. It is insufficient to investigate the crystal defects for understanding the formation mechanism of crystal defects. By using electron tomography, it is possible to analyze a three-dimensional structure in a nanometer-sized area [3-4]. Recently, LAADF-STEM technique has been proposed for strain imaging [5-6]. This technique is also expected to be a powerful tool for the visualization of crystal defects.

In this study, to analyze the three-dimensional structure of crystal defects, we propose a three-dimensional visualization technique, which is combined electron tomography and LAADF-STEM technique. Furthermore, a detailed investigation of crystal defects in high-performance CMOS devices with embedded SiGe-S/D was performed using this proposed TEM technique. Consequently, we discuss the potential of this new analysis technique for performance improvement of a highly reliable CMOS device.

2. Experiment

For sample preparation, strained pMOSFETs based on epitaxial growth of SiGe in recessed S/D on Si (100) substrate are manufactured using 32 nm node process flow (Fig. 1). To analyze the crystal defects in CMOS devices, we performed new advanced TEM technique combining electron tomography and LAADF-STEM techniques.

3. Results and Discussion

Fig. 2 shows Ion - Ioff characteristics of pMOSFETs with embedded SiGe-S/D. Sample A and sample B were manufactured with different process conditions. It is clear that the Ion current of sample B is degraded compared to that of sample A. Fig. 3 shows the cross sectional TEM images of pMOSFETs of each sample. There is no crystal defect in sample A as shown in Fig. 3 (a). On the other hand, crystal defects are observed in sample B as shown in Fig. 3 (b). Fig. 4 shows the results of channel strain measurements by using Nano-Beam Diffraction (NBD) technique. We confirmed that crystal defects influence device performance degradation due to strain relaxation. Fig. 5 shows high-angle annular dark field (HAADF)-STEM image and LAADF-STEM image of sample B. Crystal defects are clearly observed in LAADF-STEM image compared to the HAADF-STEM image. Fig. 6 shows the three-dimensional reconstructed images focusing on the crystal defects in pMOSFET by using the combined technique of LAADF-STEM with electron tomography. Fig. 7 shows the observation directions for each reconstructed images of Fig. 6 (a) to (c). Despite observing defect A by using conventional TEM analysis, we cannot observe defect B clearly (Fig. 3 and Fig. 5). In Fig. 6, we can clearly observe defect A and defect B in three-dimensional images and how they are intersected with each other. By using this analysis technique, it is possible to visualize a three-dimensional structure of the crystal defects. Fig. 8 shows sliced image parallel to the (111) plane at cross section A in Fig. 6 (b). We can confirm that the defect A is growing on the (111) plane from the edge of the SiGe/Si interface and defect B from different edge of the SiGe/Si interface is pinned by defect A in <110> direction (Fig. 9). As the result, we revealed that the origin of each defects is on the edge of the SiGe/Si interface and they are growing along different (111) planes. This three-dimensional detailed analysis for crystal defects in advanced MOSFETs is powerful technique to develop electrical performance improvement.

4. Conclusions

We performed a detailed analysis of the crystal defects in pMOSFETs with embedded SiGe-S/D, which causes current degradation due to the stress relaxation, by using new advanced TEM technique combined electron tomography and LAADF-STEM technique. This is the only technique for evaluating the three-dimensional structure of crystal defects in advanced CMOS devices. By performing three-dimensional analysis, we can understand the mechanisms of generation, growth, slip, multiplication and interaction of crystal defects. This technique is sure to contribute to a highly reliable process development without the crystal defect issue.

References

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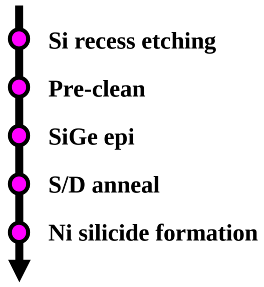


Fig.1 Process flow of CMOS device with embedded SiGe-S/D.

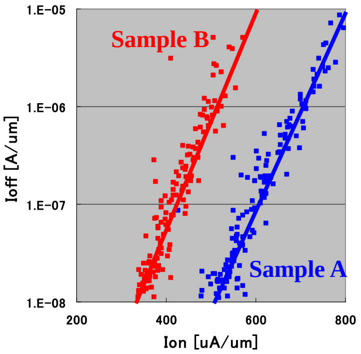
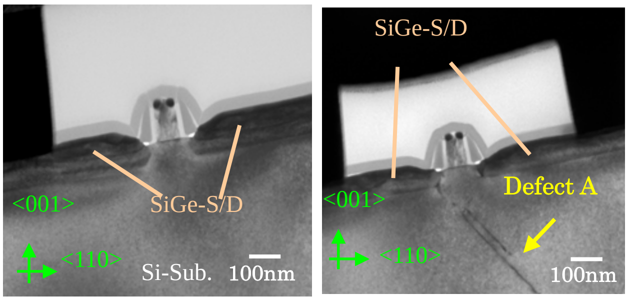
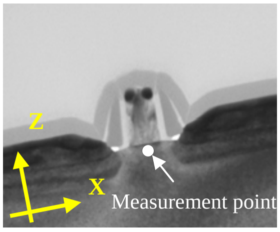


Fig.2 Ion-Ioff characteristics of PMOS transistors with embedded SiGe-S/D.



(a) Sample A (b) Sample B

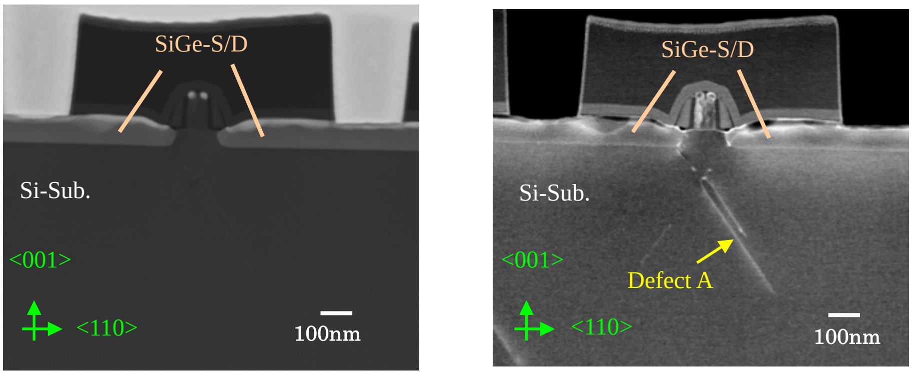
Fig. 3 Cross sectional TEM images of PMOS transistors.



	Sample A	Sample B
ε xx (Horizontal)	−0.57%	−0.21%
ε zz (Vertical)	+0.77%	+0.37%

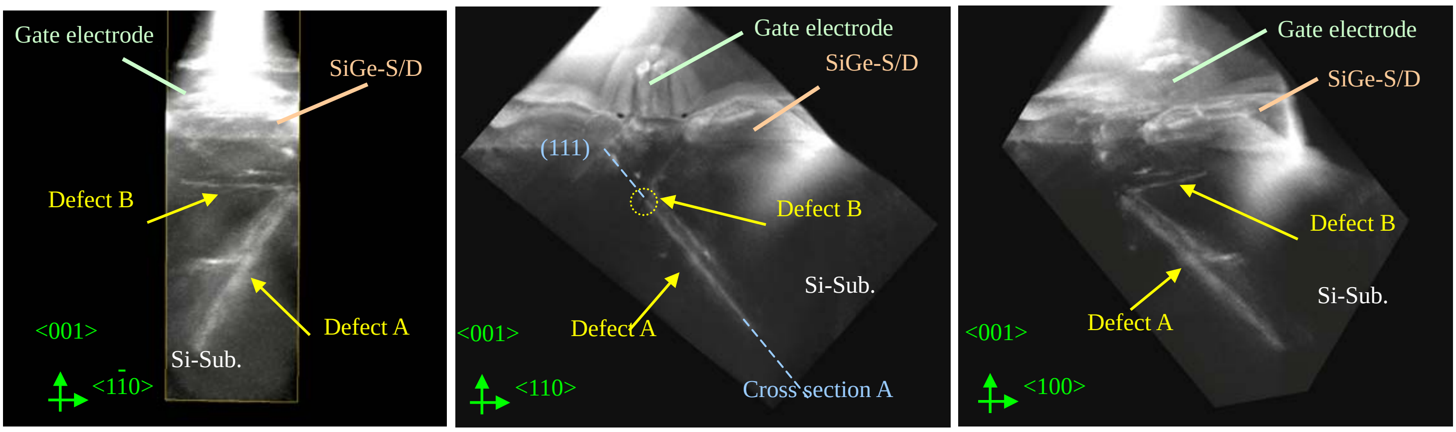
Tensile strain and compressive strain are represented by + and -, respectively.

Fig. 4 Results of strain analysis using NBD measurements.



(a)HAADF-STEM image (b) LAADF-STEM image

Fig. 5 Cross-sectional ADF-STEM images of PMOS transistor of sample B.



(a) Parallel to gate electrode (b) Cross section of gate electrode (c) Rotated 45 degrees from Fig. 6 (b)

Fig. 6 Three-dimensional reconstructed images.

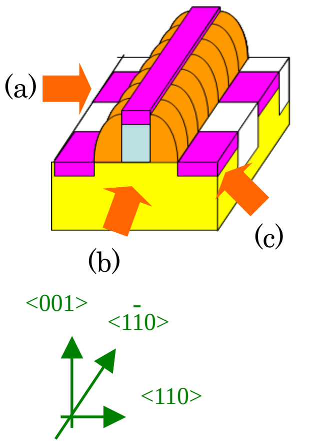


Fig. 7 Schematic diagram of MOSFET.

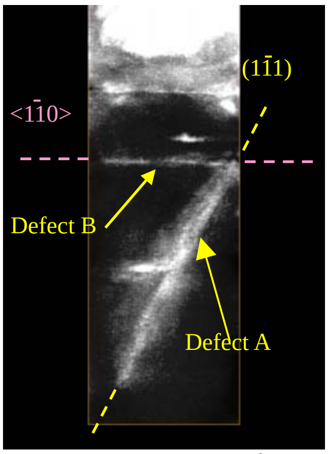


Fig. 8 Sliced image of the cross section A in Fig. 6 (b).

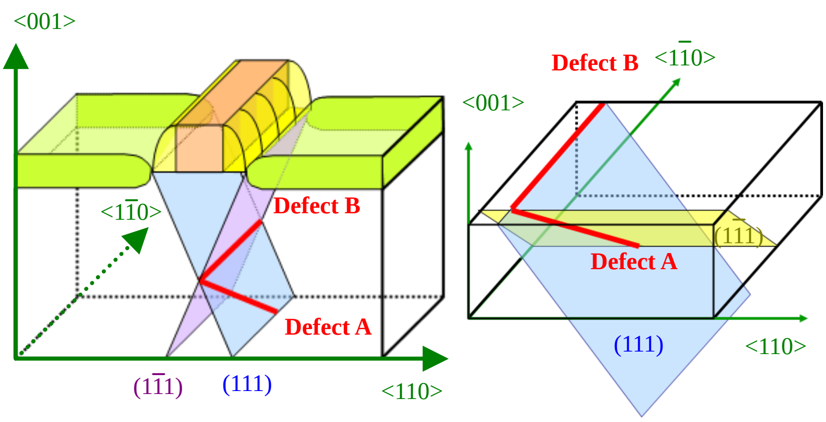


Fig. 9 Schematic diagram of crystal defects.