EVALUATION OF GLOBAL AND LOCAL STRAIN INDUCED FOR CARRIER MOBILITY ENHANCEMENT IN SI SUBSTRATES

In state-of-the-art LSI technologies, strain management in Si is recognized as one of the most important technologies for achieving high-performance operation. This is because carrier mobility can be enhanced by introducing the appropriate strain in the channel region of MOSFETs [1]. Two techniques are proposed for strain introduction. One is “local strain,” in which the strain is introduced only in a desired region during LSI fabrication. The other is “global strain,” which means using a wafer with strained-Si film as a starting material. We consider that quantitative evaluations of amount and uniformity of local and global strains in Si substrates are essential to develop these new techniques. The strain in Si has been characterized by Raman spectroscopy, X-ray diffraction, electron diffraction, and other methods. However, it has been difficult to obtain a detailed profile of the strain in the ultra-thin strained-Si film using traditional evaluation techniques. In this study, we evaluated the local strain induced by SiN deposition on Si substrates and the global strain in so-called strained Si substrates using in-plane X-ray diffraction (XRD) techniques at beamline **BL13XU**.

The structures of the strained Si substrates (global strain) are shown in Fig. 1(a-c). The thickness of the strained-Si film for Bulk substrate was 17.5 nm with 20% Ge concentration in an underlying relaxed SiGe layer (Fig1(a)). SiGe-on-insulator (SGOI) substrate had approximate thickness of 17, 70, and 200 nm for strained-Si, SiGe, and buried oxide (BOX) film, respectively (Fig1(b)). The Ge concentration was also 20%. The Si-on-insulator (SSOI) substrate had a structure with 17 nm strained-Si film directly on the 200 nm BOX layer (Fig1(c)). For the local strain, SiN capping layers with 0 (reference), 20, 40, 60, and 80 nm thicknesses were deposited on Si or SOI (Si-on-insulator) substrates by low-pressure chemical vapor deposition (LP-CVD) for introducing the strain at the Si_3N_4/Si interface. The SOI film thicknesses were 30, 50, and 100 nm. To obtain the depth profile of strain in the near-surface region, we adopted grazing incidence X-ray diffraction using a synchrotron X-ray with approximately 0.1 nm wavelength. If the incident angle the of X-ray to the sample surface is less than the critical angle (0.14°) for total reflection, the X-ray wave field in the sample becomes evanescent and is limited to the top of surface (less than 10 nm) [2]. The X-ray penetration depth varies according to X-ray incident angle. If there is a depth profile of the lattice parameter, the scattering angle of the in-plane diffraction should vary depending on the incident angle.

The result of the in-plane XRD for the Bulk substrate is shown in Fig. 2. The peak position corresponded to $2\theta_\chi$ of the scattering angle, reflecting the lattice distance of the (400) plane perpendicular to the sample surface. Each peak consists of many components, probably reflecting the domain structure in the observation area. However, the peak shape did not change with the change in the incident angle. This indicates that the domain structure was uniform in the depth direction. On the contrary, it is apparent that the peak shifted toward a smaller angle ($2\theta_\chi$) as the X-ray incident angle (ω) increased from 0.12 to 0.15°. This peak shift implies that the lattice distance expanded toward the depth direction. However, different strain depth profiles were observed at different areas in the same substrate. The disordering

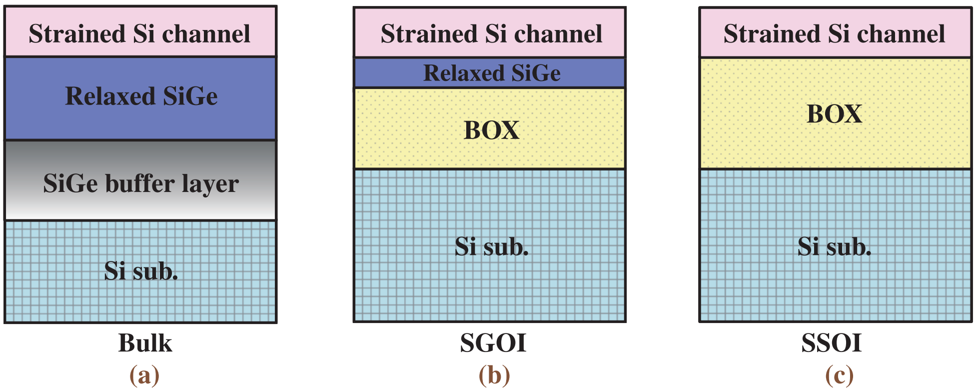

Fig. 1. Structures of strained Si substrates, **(a)** Bulk, **(b)** SGOI, and **(c)** SSOI. The film thickness of each layer in the strained Si substrates is shown.

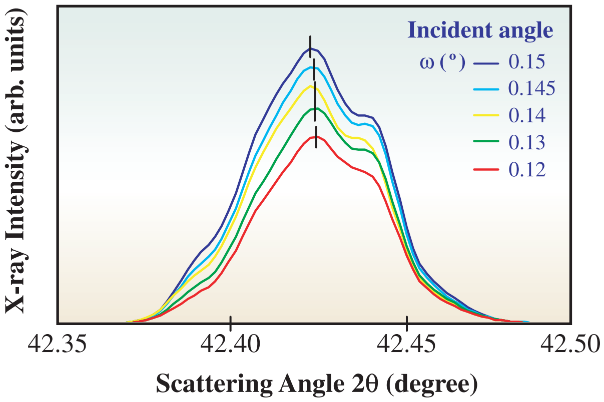

Fig. 2. Results of in-plane XRD of Bulk strained Si substrate with changing incident X-ray angle.

of strain depth profiles could come from the crystalline defects. We consider that it is necessary to measure the strain precisely in the channel depth of MOSFETs and to design the device parameters based on the measurement, since the largest lattice deformation 0.012% toward depth, and disordering of strain depth profiles were observed, as described above.

As for the sample of local strain, the peak positions of the X-ray diffraction profiles for the Si substrate with Si_3N_4 cap of 80 nm thickness are shown in Fig. 3. The diffraction angle shifted toward the smaller angle with decreasing X-ray incident angle (decreasing X-ray penetration depth). Therefore, we concluded that the local strain was concentrated at the Si_3N_4/Si interface. We also evaluated the strain by UV-Raman spectroscopy [3]. There is a strong correlation in observed strains between UV-Raman spectroscopy and in-plane XRD. However, these are not matched each other. We consider that was because the penetration depth of the XRD measurement with synchrotron radiation was set to be shallower than that of the UV-Raman spectroscopy measurement.

Table 1. Summary of Δd/d and FWHM for each substrate with local or global strain.

Strain	Δd/d (%)	FWHM (°)
Local strain	0.014	0.004
Global strain	0.81	0.04
Cz-Si	——	0.004

Table 1 summarizes the Δd/d (%) and full-width-at-half-maximum (FHWM) for each substrate. The FWHM of the strained Si substrate (global strain) was larger than that of the Si substrate with Si_3N_4 cap of 80 nm thickness (local strain), which was almost the same as that of Cz-Si. Strained Si substrates (global strain) had a large strain of approximately 0.81% (tensile). However, the strain of SiN-capped Si (local strain) was only 0.014% (compressive). Therefore, we can conclude that the Si substrates with local strain had good crystal quality with very small strain, while the strained Si substrates such as Bulk, SGOI and SSOI had a large strain, but the crystal qualities were very poor.

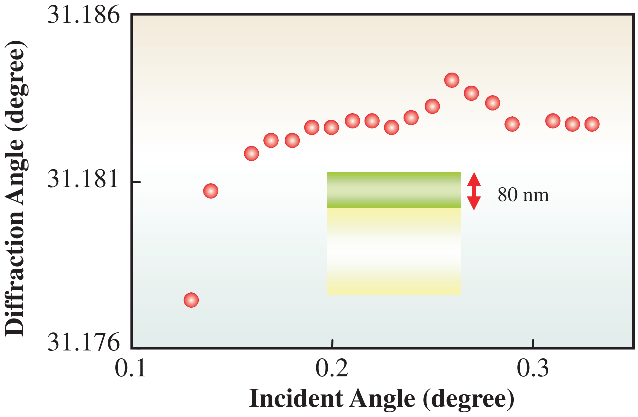

Fig. 3. Depth strain profile of local strain at Si_3N_4 interface by (440) in-plane XRD.

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