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Evaluation of anisotropic biaxial stress using an immersion lens by Raman analysis based on the polarization rules

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1. Introduction

The mechanical stress is one of the key parameters to control performance of recent Si LSI [1,2]. The stress can effectively improve the performance by enhancing the carrier mobility if adequately applied with proper orientation and strength, but may also give adverse effects by deteriorating reliability of transistors. Thus, the stress in the device area has to be precisely monitored with high spatial resolution.

The stress tensor in addition to the magnitude of the stress can be evaluated by CBED, NBD, and EBSD, but there is a fear that the stress relaxes during the specimen fabrication. On the other hand, Raman spectroscopy enables us to evaluate the stress nondestructively and with relatively high spatial resolution, although its standard implementation fails to resolve the stress tensor. Generally, the quantity represents a weighted average of stress components which can be interpreted in a variety of ways depending on the stress state.

The goal of this study is to establish a procedure for using Raman spectroscopy to measure an unknown plane-stress state [3-5]. In this study, anisotropic stress in Si induced by SiN film was evaluated by UV-Raman spectroscopy with an immersion lens and high numerical aperture (NA) objective lens.

2. Experimental procedure

SiN film was deposited by microwave plasma-enhanced chemical vapor deposition, and then etched into an 8 × 8 μm^2 square. SiN film stress was approximately - 3.0 GPa (compressive) which was defined by wafer-bowing measurement.

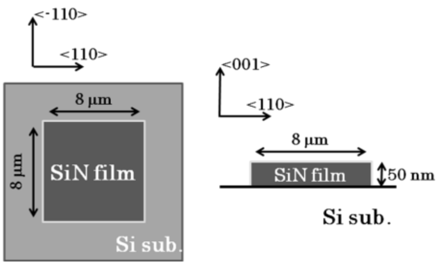

Fig. 1 Sample of 8 × 8 μm² SiN film deposited on Si substrate.

Stress in Si surface of approximately 5 nm induced by SiN film was evaluated by UV-Raman spectroscopy with an Ar ion laser whose wavelength is 364 nm. Standard implementation applied an objective lens with NA of 0.7. High spatial resolution measurement was also performed using an immersion lens (n = 1.33) and objective lens with high NA of 1.2. Figure 2 shows measurements of beam spot size by using Si edge for the conditions of dry and immersion. The Raman intensity profiles were fitted as shown in Fig. 2. The beam spot sizes were estimated to be 0.65 μm for the dry condition and 0.4 μm for the immersion condition, respectively. Moreover, <001> polarized light can be illuminated in Si adding to the conventional <-110> polarized light thank to high aperture angle using the immersion lens and high NA objective lens.

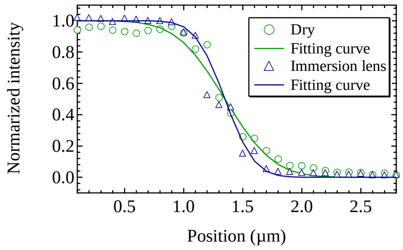

Fig. 2 Raman intensity profiles for conditions of dry and immersion to estimate beam spot size.

3. Technique of anisotropic biaxial stress analysis

Stress was induced by the SiN film locally in Si surface of the sample shown in Fig. 1. Therefore, σ_{zz} in the <001> direction is small. The shear stress τ_{xy} was ignored for simple approximation. As results, the stress tensor σ was reduced to

$$\sigma = \begin{pmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (1),$$

where σ_{xx} and σ_{yy} are parallel to <110> and <-110>. In this study, this anisotropic biaxial stresses σ_{xx} and σ_{yy} were evaluated.

The application of the stress given by eq. (1) removes the cubic symmetry in Si lattice and hence splits the triplet of optical phonons, although they are triply degenerate in the center of the Brillouin zone in a diamond-type material owing to the cubic symmetry of the crystal without stress. The relation between the Raman shifts and stresses are described as follows

$$\Delta\omega_1 = -2.31\sigma_{xx} - 0.37\sigma_{yy} \quad (2a),$$

$$\Delta\omega_2 = -0.37\sigma_{xx} - 2.31\sigma_{yy} \quad (2b),$$

$$\Delta\omega_3 = -1.93\sigma_{xx} - 1.93\sigma_{yy} \quad (2c),$$

where $\Delta\omega_{1,2,3}$ are shifts of the Raman peak from stress-free Si. Raman scattering intensity is indicated by the Raman polarization rules of

$$I = C\sum_j \left| e_i \cdot R_j \cdot e_s \right|^2 \quad (3),$$

where C is constant, e_i and e_s are electrical field of incident and scattered light, respectively, and $R_{1,2,3}$ are Raman tensors. In the case of <-110> polarized light of an Ar ion laser, only $\Delta\omega_3$ is Raman active. On the other hand, in addition to the $\Delta\omega_3$ activated by <-110> polarized light, $\Delta\omega_1$ is also Raman active owing to <001> polarized light using the immersion lens and high NA objective lens.

Raman spectrum obtained by UV-Raman measurement with the immersion lens was separated into two Raman modes originated in $\Delta\omega_1$ and $\Delta\omega_3$, and then the anisotropic biaxial stresses σ_{xx} and σ_{yy} induced by SiN film could be evaluated.

3 Results and discussion

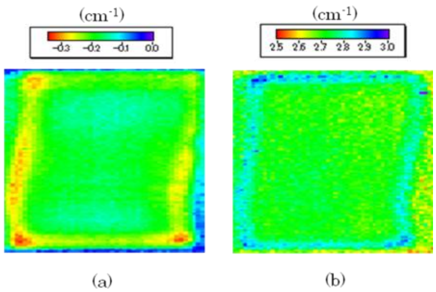

Fig. 3 Raman map of (a) wavenumber shift and (b) FWHM measured with conventional objective lens.

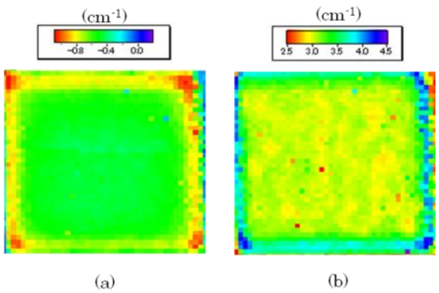

Fig. 4 Raman map of (a) wavenumber shift and (b) FWHM measured with immersion lens.

Raman mapping was performed for the sample shown in Fig. 1. Figures 3(a) and 3(b) show the distributions of wavenumber shifts and full width at half maximums (FWHMs) measured with the conventional objective lens, respectively. The fluctuation of Raman map shown in Fig. 3 was an artifact due to insufficient optical adjustment. The wavenumber shifts were the largest in the corners of the 8 × 8 μm^2 SiN film, and the larger wavenumber shifts were observed at the SiN film edges than in the center. The distribution of FWHM was similar to those of the wavenumber shift as shown in Figs. 3(a) and 3(b).

Figures 4(a) and 4(b) show the distributions of the wavenumber shifts and FWHMs by the UV-Raman measurement with the immersion lens. It was clearly confirmed that the wavenumber shift of 0.99 and FWHM of 3.77 at the corner of the SiN film square in the measurement with the immersion lens were larger than in the measurement with the dry condition (0.28 and 3.11).

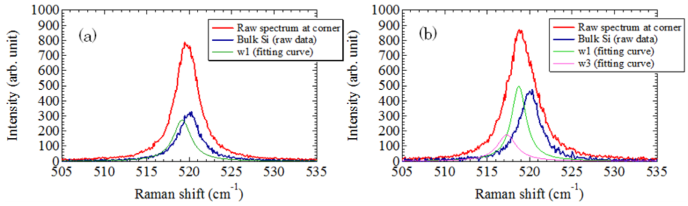

Fig. 5 Raman spectra at corner of SiN square measured with (a) conventional objective lens and (b) immersion lens.

Figures 5(a) and 5(b) show Raman spectra from Si at the corner for dry and immersion conditions. As can be seen in Fig. 5(b), three peaks are identified, which originate in the Raman modes of $\Delta\omega_3$, $\Delta\omega_1$, and stress-free component, respectively. We assume that the Raman mode of $\Delta\omega_3$ appeared owing to the <001> polarized light using the immersion lens.

Finally, the anisotropic biaxial stress σ_{xx} and σ_{yy} were evaluated by separating the Raman spectrum at each position of the Raman map shown in Fig. 4. Figures 6(a) and 6(b) show the distributions of σ_{xx} and σ_{yy}. At the corner and edge of the SiN film square, larger σ_{xx} and σ_{yy} existed than in the center. The difference between σ_{xx} and σ_{yy} may be caused by the asymmetric SiN patterns in the surroundings.

As results, we successfully evaluated the anisotropic biaxial stress using the immersion lens and high NA objective lens by Raman analysis based on the polarization rules.

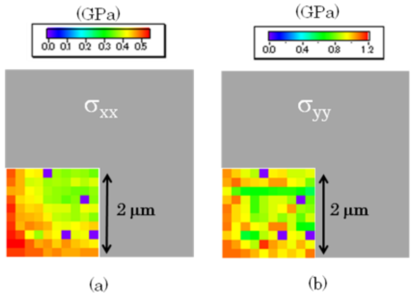

Fig. 6 Distribution of (a) σ_{xx} and (b) σ_{yy} by Raman analysis based on polarization rules.

4. Conclusions

Anisotropic stress in Si induced by an 8 × 8 μm^2 SiN film was evaluated by UV-Raman spectroscopy with an immersion lens and high NA objective lens. In addition to $\Delta\omega_3$ activated by <-110> polarized light, $\Delta\omega_1$ is also Raman active owing to <001> polarized light thanks to high aperture angle using the immersion lens. Raman spectrum was separated into two Raman modes originated in the $\Delta\omega_1$ and $\Delta\omega_3$, and then anisotropic biaxial stresses σ_{xx} and σ_{yy} induced by SiN film square could be evaluated. However, we consider that further investigation is necessary to obtain the identification of $\Delta\omega_3$ activated by <001> polarized light.

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