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Characterization of Strain in Si for High Performance MOSFETs

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1. Introduction

Strain management by using silicon-nitride (SiN) film as a stressor in LSI fabrication process is recognized as one of the most important technologies to achieve high performance MOSFETs due to enhancements in both electron and hole mobilities. It has been confirmed that the device operation with local strain induced by SiN film could be improved, while it has not been done enough to evaluate the strain quantitatively. The mechanism of strain introduction into Si-substrate with SiN film was not evaluated sufficiently either. In this study, we characterized the strain induced by SiN film for high performance MOSFETs by using high resolution UV-micro-Raman spectroscopy with a quasi-line shape excitation source.

2. Experiment

(001) Si-substrates with SiN film patterned into Line (SiN film)/Space (bare-Si) along a [110] direction were prepared. SiN film was deposited by the microwave CVD using Si_2H_6/NH_3 and Si_2H_6/N_2 gas mixtures for SiN films with tensile (1GPa) and compressive (3GPa) internal stress, respectively. Line/Space pattern of SiN film was then formed by means of dry-etching in $CH_4/CHF_3/Ar/O_2$ mixture gases.

The strains in the samples were measured by newly developed UV-Raman spectroscopy. There are two measure features in the Raman system. One is, considering the shallow channel region, an Ar ion laser (λ = 364 nm) was selected as an excitation source whose penetration depth is approximately 5 nm into the Si-substrate. Resonant effect using this particular wave length helped us to obtain strong signal with short measurement time in spite of the evaluated volume was very small. Another is, for high spatial resolution applicable to the finite device evaluation, a combination of a quasi-line shape excitation source and a two dimensional charge coupled device (2D CCD) detector was used. We have achieved a spatial resolution of 200 nm with the system. The energy resolution was also excellent (0.02 cm^{-1}). Detailed explanations on the UV-Raman system have been described elsewhere [1].

3. Results and discussion

First of all, we studied the effect of SiN film deposition with various thicknesses on Si substrates before patterning. As is shown in Fig. 1, unpatterned SiN film induced only small strain in the Si surface although the induced strain increased with film thickness. The strain was clearly too small to improve device performance. We assume this might be because there was no space to relieve strain in the same sample. We therefore evaluated strain line-profile in the Si substrate after SiN film patterning into Line/Space pattern to study strain introduction and relaxation mechanism simultaneously.

Fig. 2 shows the strain distribution in Si-substrate with an isolated SiN line. As can been seen, we have succeeded in detecting the strain induced by 300 nm SiN line. Moreover, the induced strains were much larger than those in Si surface with unpatterned SiN film. Because the strain induced by the patterned SiN should not be biaxial and possibly asymmetric, we could not convert the Raman shift into strain value. However, the Raman shift was two order magnitudes larger than those from unpatterned SiN sample. In Fig. 2, the high wavenumber shift implying compressive strain introduction was induced by SiN with tensile internal stress, and the low wavenumber shift was vice versa. Furthermore, the ranges of wavenumber shift were proportional to the internal stress of SiN film.

Fig. 3 shows the strain distribution in Si-substrate after patterning SiN film into Line/Space. Similarly to the result in the isolated SiN line, the tensile strain induced by SiN film with compressive stress was about three times larger than the compressive strain induced by SiN with tensile stress. In this measurement, moreover, large wavenumber shifts existed at the pattern edges of SiN film. Fig. 4 shows the result of comparison between Raman measurement using UV-laser (λ = 364 nm) and green-laser (λ = 532 nm) as an excitation source. As can been seen, the large wavenumber shifts at the SiN pattern edges were not identified by using green laser, that is, the strains at pattern edges were concentrated at SiN/Si interface. Strain shift toward inverse direction was also observed in the space area of high compressive stress SiN pattern. This inverse strain might be a reaction of the high strain at the pattern edge.

To verify the mechanism of this inverse strain introduction at the SiN space, we observed strain line profiles in different space widths of patterned tensile SiN film. Fig. 5 shows the result; here the space widths were 2, 1 and 0.3 μm. By reducing the space width from 2 to 1 μm, the inverse strain also appeared in the SiN pattern with tensile stress as well as SiN with compressive stress. Closer distance between two pattern edge strain enhancements might bring the inverse strain more effectively as a result of their reaction. In the modern high performance LSI technology, SiN film is used for nMOSFETs. We believe the inverse strain observed in this study is the origin of the device performance improvement. Because, the SiN film was a kind of Line/Space in the real MOSFET, and the channel area should correspond to the space. This is also consistent with the experimental fact that the tensile strain enhances the electron mobility. The mechanism for the pMOSFET should be opposite to the discussion above.

Further reduction of the space width resulted in the lost of inverse strain at the space again. We believe this is due to the limitation of the Raman spatial resolution. Indeed, we observed increase of FWHM or sometimes double peaks in this condition as is shown in Fig. 6. One of the double peak may represent the strain in the space. However, we need to be more careful because this is possibly because of an appearance of forbidden Raman peaks originated in TO phonons as well as allowed LO phonon due to an asymmetry strain-field at the pattern edges [2]. This can be a cause of the multiple peaks, and make a strain analysis more complicated. We have confirmed, so far, the appearance of Raman peak under the forbidden polarization configuration.

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References

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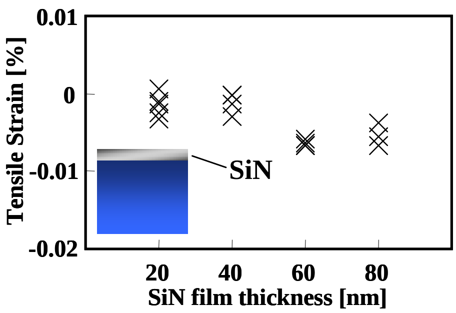

Fig. 1 Strain at SiN film/Si interface before patterning.

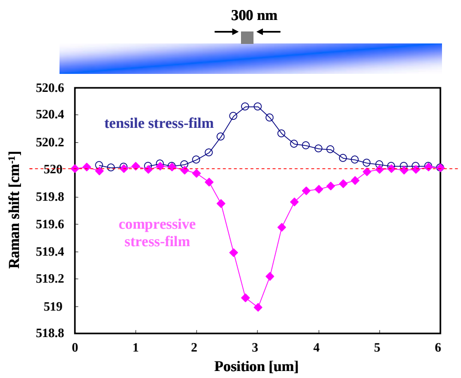

Fig. 2 Strain line-profile in Si-substrate with an isolated SiN line (300 nm).

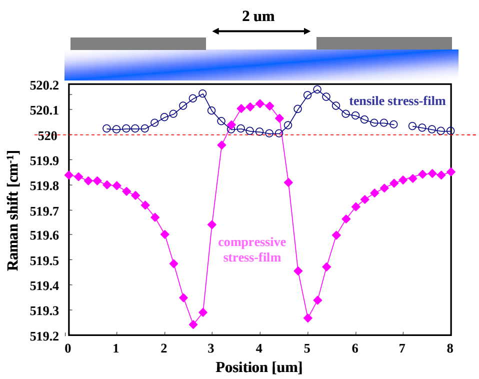

Fig. 3 Strain line profile in Si-substrate after patterning SiN film into Line/Space (2 um) pattern.

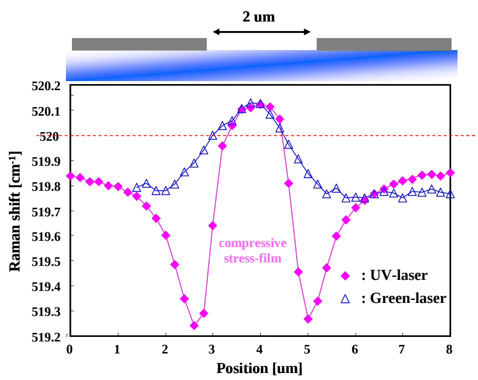

Fig. 4 Strain enhancements at SiN pattern edge measured by UV and visible laser excitation source.

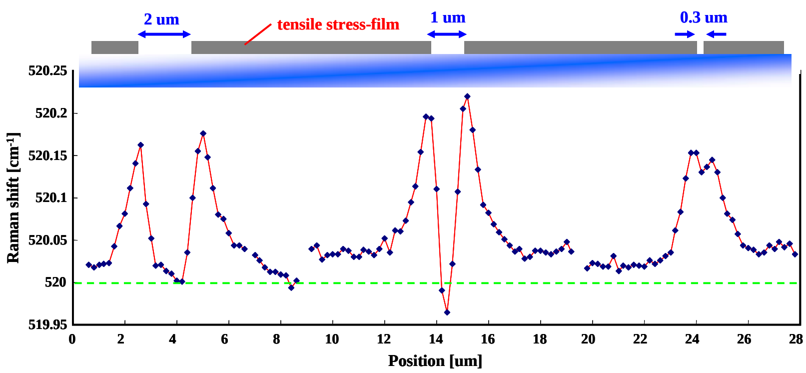

Fig. 5 Dependence of strain distribution on space (bare-Si) width, 2 um, 1 um and 0.3 um.

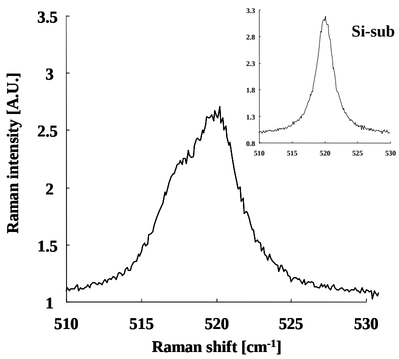

Fig. 6 Raman spectrum obtained from the SiN pattern edge.