Structural characterization of a bonded silicon-on-insulator layer with voids by micro-Raman spectroscopy

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Crystalline quality in a void region of a bonded silicon-on-insulator (SOI) wafer is evaluated by micro-Raman spectroscopy. Downshifting and broadening of the Si optical-phonon peak are observed at the edge of the void, while spectra within the void are little different from those outside the void. Comparison with calculated results based on the theory of the phonon localization shows that both the shift and the broadening are mainly due to structural disorder and not strain. Electrical properties in a void region are also evaluated by a laser-microwave method. The lifetime of excess carriers has its minimum value at the void edge. Those results consistently show that the SOI layer is deformed plastically rather than elastically at the boundary of the void.

I. INTRODUCTION

The silicon-on-insulator (SOI) structure has attracted attention due to applications for high-speed and very large-scale integrated circuits. So far several types of SOI structures have been examined, and among them the SOI structure formed by the wafer bonding method has proven to be most promising.[1,2] The bonding technique provides a high-quality SOI layer and good control of the thickness of the active Si layer. In addition, residual stress in the Si layer is very small compared with the silicon-on-sapphire (SOS) structure; however, the bonded structure sometimes has voids, i.e., poorly bonded regions.[3,4] We may expect that the formation of voids causes stress or defects in the layer, and therefore crystalline quality in the void region is of great interest.

In this article, we report micro-Raman spectra in a void region of a bonded SOI wafer. Raman spectroscopy is a very convenient method of measuring strain and the degree of disorder in semiconductor thin films.[5] Moreover, microscopic characterization can easily be performed by focusing the laser beam through an optical microscope. Thus, the Raman technique is well suited for observing the microscopic distribution of strain and defects within and around a void.

For comparison, we also evaluate the electrical properties in the void region by a noncontact laser-microwave method. In this method, a conductivity change under photoirradiation is detected as a change in reflectivity for 10 GHz microwave.[6,7] The signal is proportional to the excess carrier density and thus is closely related to the lifetime of the excess carriers or the density of defects which act as a recombination center.

In the following section, the sample characterized in this study is described. Results of both the characterizations are given, discussed, and compared in Sec. III.

II. SAMPLE

The fabrication procedure of the SOI sample characterized in this study is as follows. Two n-type (100) silicon wafers were prepared, and one of them was oxidized to form a 1 μm-thick insulator layer. Then, the wafers were bonded and annealed at 1100 °C for 2 h in a dry oxygen ambient. Subsequently, the SOI layer was thinned by polishing one wafer to a thickness of 40 μm. Finally, an $\sim$0.1-μm-thick oxide film was grown on the whole SOI wafer.

Voids in the wafer thus fabricated were revealed by x-ray transmission topography. Figure 1 shows the image of the sample obtained by x-ray topography. In the following, we concentrate our attention on void A in Fig. 1.

III. RESULTS AND DISCUSSION

A. Raman characterization

The micro-Raman experiment was carried out in a backscattering configuration at room temperature using a JASCO NR-1800 Raman spectrometer. The scattered light was dispersed by a triple monochromator and detected by a multichannel photodetector. The spectral resolution is about 5 cm^{-1}, but the accuracy of the determination of the peak frequency is as good as ± 0.02 cm^{-1} owing to the curve-fitting procedure. The 514.5 nm line of an Ar-ion laser was used as the excitation source. The diameter of the focused laser spot is about 1 μm on the sample surface, and the spot was displaced on a straight line which intersects the boundary of void A.

Figure 2 shows the variation of the peak frequency and the peak width of the zone-center optical phonon across the boundary of the void. Appreciable downshifting and broadening are observed at the boundary. On the other hand, the spectra in the inner region of the void are little different from those in the outside region. Moreover, they are almost identical to those observed for a bare unstrained Si wafer. Thus, anomalies are observed only at the boundary of the void in this experiment.

A shift in the Raman peak is caused by (1) strain or stress and (2) phonon localization due to disorder. In the present case, factor (2) is dominant. The reason is as follows:

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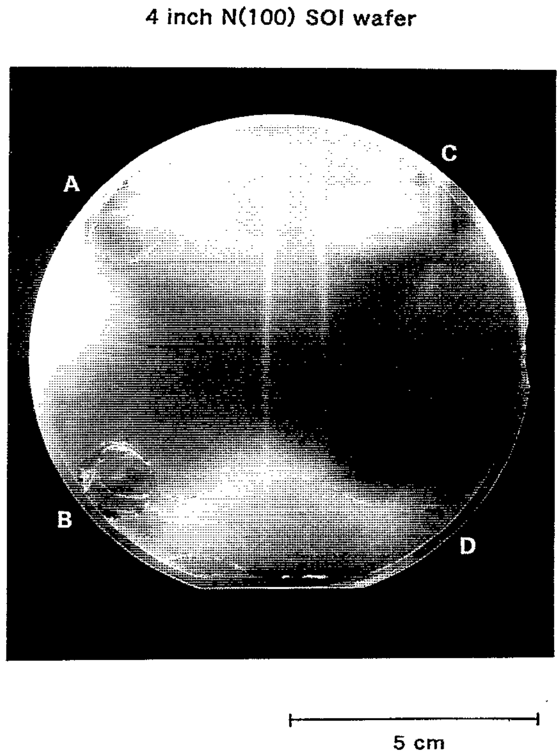

FIG. 1. X-ray transmission topography of the SOI sample.

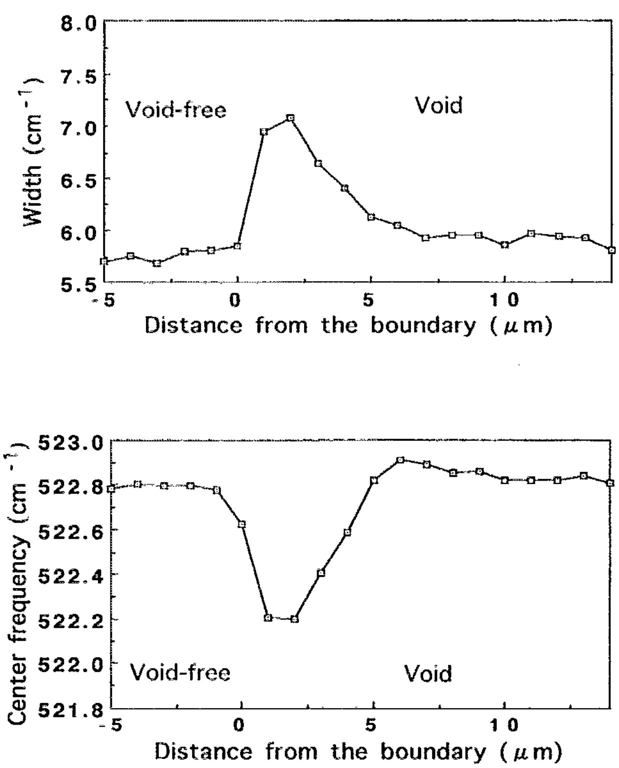

FIG. 2. Variation of the Raman frequency and the full width at half-maximum of the peak near the boundary of void A.

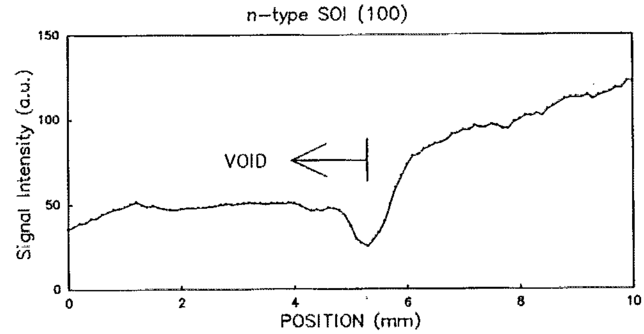

FIG. 3. Variation of the LBIC intensity across the boundary of void A.

It is known that the shift due to disorder is always negative and accompanied with a broadening. As can be seen from Fig. 2, the observed shift is negative and is obviously correlated with the broadening. The relation between the negative shift due to disorder and the broadening has been theoretically calculated by Richter, Wang, and Ley for Si.[8] According to their results, the frequency is downshifted by 0.65 cm^{-1} because of the disorder when the width is increased by 1 cm^{-1}. In the results Fig. 2, the shift is -0.6 cm^{-1} and the increase in the width is 1.2 cm^{-1} at the boundary. Thus, the relation between the shift and the broadening coincides almost completely with that calculated considering disorder. This shows that the shift and the broadening are both caused mainly by disorder.

Therefore, the present results indicate the some type of defects exist at the boundary of the void. On the other hand, the defect density in the inner region of the void is much smaller than that at the boundary. In addition, strain in and near the void is not appreciable.

Although the type of the disorder cannot be identified from the Raman spectra, we speculate that the dominant defects are dislocations which are introduced to relax the strain during the high-temperature annealing; the Si layer at the void boundary would be deformed plastically, not elastically, and therefore have a large density of dislocations and null strain.

B. Laser-microwave characterization

Recently, Usami *et al.* demonstrated that electrical properties of SOI wafers can be characterized successfully by a noncontact laser-beam-induced conductivity (LBIC) measurement based on a laser-microwave method.[7] In this experiment, the sample is irradiated with a focused He-Ne laser beam, and the reflectivity change for 10 GHz microwave is detected in the steady state. The LBIC signal intensity thus detected is proportional to the excess carrier concentration and thus decreases with the concentration of recombination centers. By moving the laser beam on the sample surface, we can measure spatial variation of the LBIC intensity.

Figure 3 shows profile of the LBIC intensity across the boundary of void A in the present sample. As shown in this figure, the LBIC intensity has its minimum value at the boundary of the void. This indicates that a large number of defects (recombination centers) exists at the void boundary, and thus is consistent with the Raman results described above. However, the LBIC intensity in the inner region of the void is slightly smaller than that outside the void, although an increase in the defect density within the void is not observed in the Raman experiments. This is due to the fact that while the lifetime of carriers is greatly affected even by a small number of recombination centers, the Raman spectrum is not very sensitive to point defects. According to the calculation results in Ref. 8, the peak width increases by 1 cm^{-1} when each phonon is confined in a region about 5 nm in diameter. The diameter of 5 nm corresponds to a defect density of the order of 10^{19} cm^{-3}, if we consider it as the average distance between defects. Thus, the broadening of the Raman peak becomes appreciable only in a region with a defect density as large as 10^{19} cm^{-3}, and therefore, the defects within the void are not revealed by the present Raman experiments.

The downshifting and the broadening of the Raman peak are appreciable in a region about 5 μm in width, but the decrease of the LBIC intensity is observed in a much wider area. This is because of a large laser-beam diameter (100 μm) and diffusion of photoexcited carriers in the LBIC measurement. Since the carrier diffusion length in Si is usually of the order of 100 μm, the spatial resolution of the present LBIC measurement will be about 200 μm.

IV. CONCLUSION

We have measured Raman spectra in the void region of a bonded SOI wafer. Downshifting and broadening of the Si optical-phonon peak are observed at the boundary of the void. We attribute them to structural disorder and not strain. These results show that the SOI layer is deformed plastically at the boundary of the void. Consistent results have been obtained by the LBIC measurement based on a laser-microwave method.

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[1] J. B. Lasky, Appl. Phys. Lett. **48**, 78 (1986).
[2] W. P. Maszara, G. Goetz, A. Caviglia, and J. B. McKitterick, J. Appl. Phys. **64**, 4943 (1988).
[3] W. P. Maszara, J. Electrochem. Soc. **138**, 341 (1991).
[4] K. Mitani, V. Lehmann, R. Stengel, D. Feijoo, U. M. Gösele, and H. Z. Massoud, Jpn. J. Appl. Phys. **30**, 615 (1991).
[5] See, for example, T. Nishioka, Y. Shinoda, and Y. Ohmachi, J. Appl. Phys. **57**, 276 (1985).
[6] A. Usami, in Proceedings of the International Conference on Microelectronic Test Structures, 1991, Vol. 4, p. 1.
[7] A. Usami, H. Fujiwara, N. Yamada, K. Matsuki, T. Takeuchi, and T. Wada, IEICE Trans. Electron. **E75-C**, 595 (1992).
[8] H. Richter, A. P. Wang, and L. Ley, Solid State Commun. **39**, 625 (1981).