Extended Abstracts of the 15th Conference on Solid State Devices and Materials, Tokyo, 1983, pp. 39-42

Invited

Characterization of Laser Recrystallized SOI

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A Raman microprobe technique has been applied to the characterization of laser annealed polycrystalline silicon films on insulating substrates. The crystalline perfection and residual strain in the annealed films are evaluated by Raman parameters such as the Raman intensity, bandwidth, peak frequency and polarization properties. The observation has revealed that the crystallinity can be characterized with a spatial resolution of <1μm. The structural perfection of lateral seeding epitaxial films has also been examined by the measurements of Raman intensity profile under different polarization configurations.

§1. Introduction

The penetration depth of visible laser light in silicon ranges from 0.1 to 1 μm. Since ion implantation and laser annealing take place within the optical penetration depth, Raman scattering which probes the sample within the optical skin depth provides a sensitive tool for characterizing the ion implanted and laser annealed layers in silicon. An important advantage of Raman scattering is its ability to study samples in a non-destructive way.

Raman microprobe techniques have been successfully applied in a wide variety of fields in the last decade. However, it has not been used extensively in the semiconductor field. More recently, the Raman microprobe technique has been applied to the characterization of small areas of recrystallized polycrystalline silicon films on insulator (PSOI) and polycrystalline silicon films directly deposited on crystalline silicon (PSOSI). These observations[1),2)] have revealed that the crystallinity can be charaterized with a spatial resolution of <1 μm.

A significant amount of interest has been shown in laser recrystallization of polycrystalline silicon films on insulators. Thin crystalline films of large area are required for the fablication of three-dimensional integrated circuits. Laterally seeded regrowth of PSOI is one of the promising ways to enlarge the grain size of silicon films. The silicon films attached onto substrate materials have inevitably boundaries of large area. Hence the physical properties of laser annealed polysilicon films are affected considerably by the boundaries. The boundaries usually induce strain, defects and grain boundaries during the recrystallization, which can be characterized by the Raman microprobe measurements.

This report will be mainly concerned with characterization of laser annealed PSOI by the Raman microprobe technique. In §2 the Raman microprobe apparatus is described. The results of the measurement of PSOI are briefly reviewed in §3. The emphasis is placed on the regrowth process and residual strain in the annealed films. The results on PSOI are compared with those of PSOSI. The characterization of laterally seeded growth of PSOI is also reported in §4.

§2. Raman microprobe

The basic instrument combines a conventional optical microscope, double monochromator as an optical filter with a very low stray light level and a detector system. A block diagram of the instrument is shown in Fig.1. A microprobe objective lens focusses the laser beam on a sample surface. The same lens collects the scattered light in a wide solid angle and sends it to the monochromator. The general principle of operation of Raman microprobe does not differ appreciably

from the observation of specimens with a conventional optical microscope followed by recording of the spectrum with a Raman spectrometer.

The diameter of the focal spot remains finite due to diffraction and can be determined from the numerical aperture of the objective lens. This diffraction limited spot size on a sample surface is given by

$$D = 1.22\ \lambda_0\ /\ NA$$

where λ_0 is the wavelength of laser light and NA is the numerical aperture of the objective lens. The objective lens with a numerical aperture as large as 0.9 is commercially availble. For the 4880 Å line of an Ar laser and an objective lens

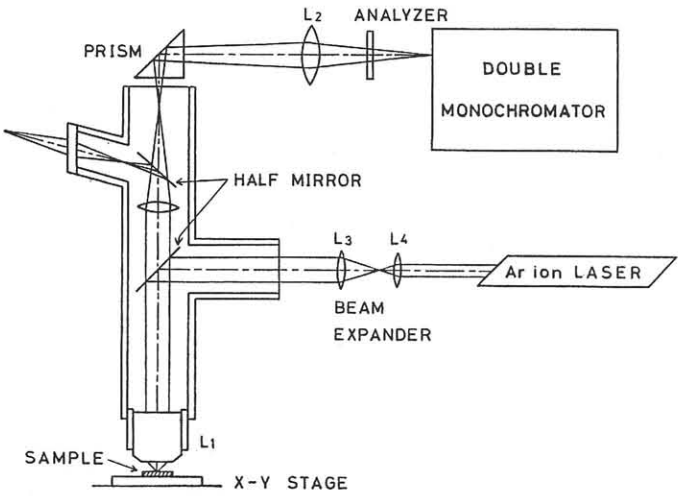

Fig.1 Schematic diagram of Raman microprobe apparatus.

with NA of 0.8, the expected value of D is 0.74 μm. The measured spot size was nearly equal to the calculated value. The length equal to the axial focal tolerance is given by

$$L \sim \lambda_0\ /\ (NA)^2$$

Samples were placed on an X-Y stage which is moved by differential micrometers or piezoelectric positioning elements. With a piezoelectric element, the translation can be controlled with a precision of 0.05 μm.

The quanties obtained from Raman scattering measurements are intensity, bandwidth, bandshape and polarization properties. All of these quantities provide the information about the crystallinity of the laser annealed Si:

(1) The degree of disorder and density of defects are estimated from the band width and the intensity.

(2) The presence of residual strain is demonstrated by the bandshape and the shift of the Raman frequency with respect to the single crystal value.

(3) The crystallographic orientation and the size of regrown grains are determined by the polarization measurements.

(4) The depth profile of the crystallinity is obtained by the excitation wavelength dependence of the Raman spectra.

§3. Raman measurements of laser annealed SOI

The crystallinity of laser annealed-amorphized PSOI (APSOI) depends strongly upon the annealing condition. Figure 2 shows a typical example of cw laser annealed APSOI, which is compared with pulse laser annealed APSOI and Si on sapphire (SOS). The Raman band in APSOI shifts toward the low frequency side with respect to the value of single crystal silicon, whereas the Raman band in SOS shows up-shift owning to the presence of compressional stress in the film. The Raman band in pulsed laser annealed APSOI is broad and shifts downward by an amount as much as 10 cm^{-1}. This result is consistent with the result of Tsu and Jha,[3] who attribute the down-shifted Raman peak to the transformation of the layer from amorphous state into partially annealed polycrystalline state under tensile stress.

We have measured the Raman intensity and bandwidth together with the mobility and sheet resistivity for laser annealed APSOI as a function of the annealing laser power. The mobility increases and the bandwidth decreases as the anneal-

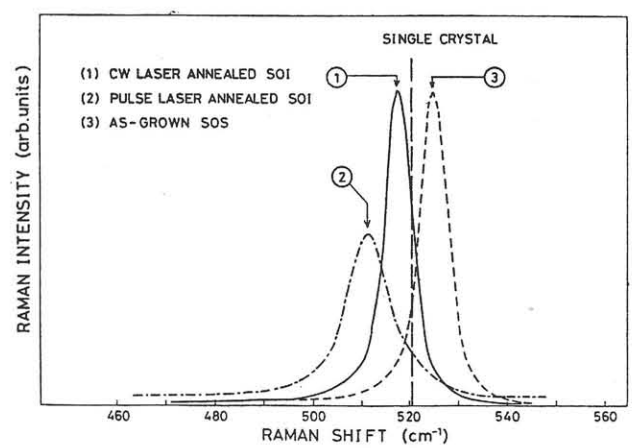

Fig.2 Raman spectra of cw-laser annealed SOI, pulse laser annealed SOI and as grown SOS.

ing power is increased, indicating more complete recovery of the crystallinity at higher laser power. In Fig.3 the integrated intensity and the width of the Raman band are plotted as a function of the mobility. The variation of these Raman parameters with mobility suggests that Raman intensity and bandwidth can be used as a measure of the crystallinity in laser annealed APSOI.

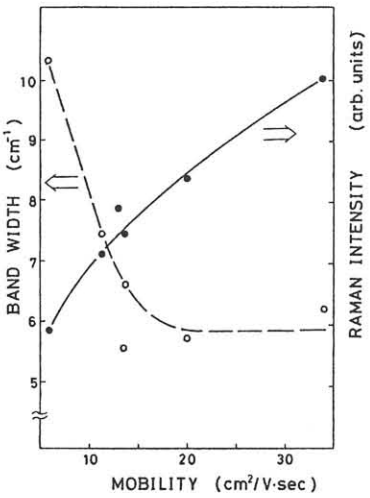

Fig.3 The Raman intensity and bandwidth are plotted as a function the mobility for laser annealed APSOI.

The intensity of the annealing laser beam of the specimens varies always along the radial direction. This causes non-uniform recovery of crystallinity in the annealed zone. Such non-uniformity has been studied by the Raman microprobe. Figure 4 shows Raman intensity distribution for APSOI which was annealed using a scanning Ar laser beam with a focused spot size of about 20 μm. The annealing power varied from 3 to 5.5 W in 0.5 W steps at a 50 cm/s scan rate and only a single scan was made. The Raman intensity was measured by moving the position of the probe laser spot across the laser annealed stripe. For laser power less than 5.0 W the intensity does not change appreciably in the central region of the annealed stripe.

For laser power higher than 5 W, a large random variation of the Raman intensity is observed in the central region of the stripe. In order to see the origin of the random intensity profile, Raman polarization measurments were made. Reflectance has also been measured along with the Raman measurements using the same apparatus. Large variations of the reflectance were found which is due to surface irregularities. In some regions the Raman intensities for two polarizations change in different ways. The behavior arises

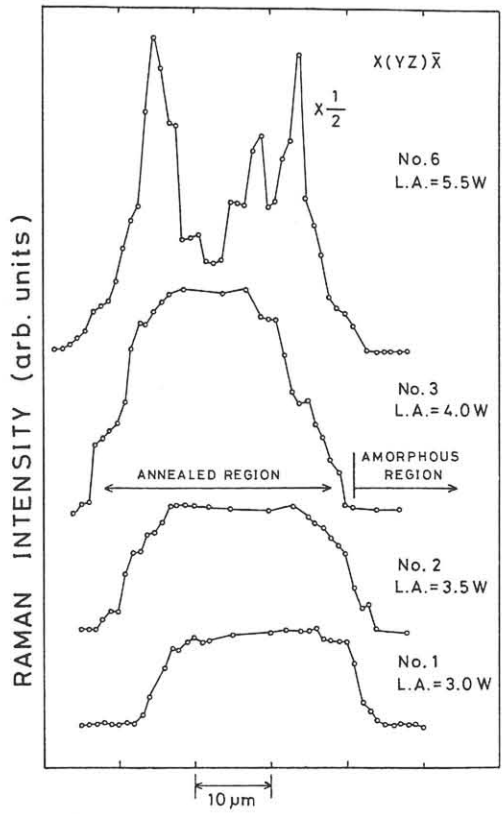

Fig.4 Typical Raman intensity profiles for APSOI samples annealed at different powers. The Raman intensity is measured by moving the position of the laser spot across the annealed stripe.

from the presence of grains with different orientations. The grain size estimated from the intensity profile is 2~5 μm.

The Raman frequencies of laser annealed APSOI are plotted as a function of the annealing power in Fig.5. We plot also the Raman frequencies of laser annealed APSOSI for comparison. The frequency values for APSOSI annealed below 5.0 W are nearly the same as that of the laser annealed APSOI, while above 5.5 W the frequency of laser annealed APSOSI shows upshift. Above 5.5 W the whole polysilicon layers in APSOSI are completely melted and regrowth starts from the crystalline substrate. Figure 4 indicates that for this liquid phase regrowth, less stress is induced than for other growth processes at low power levels.

The residual stress in laser annealed SOI can be relaxed by thermal annealing.[4] In Fig.6 the peak frequency is shown for several combinations of laser- and subsequent thermal-annealing conditions. The thermal annealing causes the

frequency shift toward the high frequency side, while the samples annealed only with a laser have a peak at 517 cm^{-1}. The peak frequencies of the

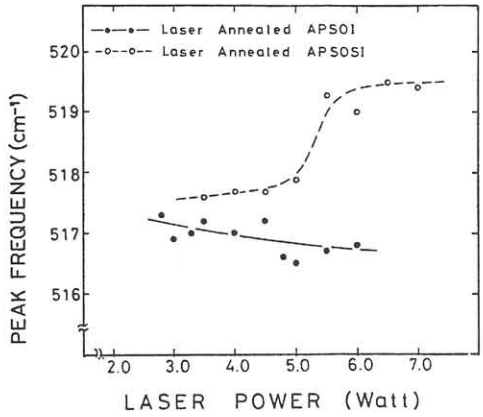

Fig.5 Raman frequencies are plotted as a function of the annealing laser power of APSOI and APSOSI.

sample subsequently thermally annealed more closely approach the frequency of single crystal Si (521 cm^{-1}) when the sample is annealed at low laser power. This result suggests that the combination of the laser annealing at low power and the thermal annealing at relatively elevated temperature is more useful in reducting the strain.

§4. Characterization of SOI regrown by lateral epitaxy

Laser annealed PSOI usually consists of small grains. Several attempts have been made so far to obtain single crystalline films of large area on insulators. Lateral seeding regrowth is one of the powerful ways to obtain single crystalline films of large area. Lateral seeding epitaxial films have been characterized by the Raman microprobe technique. The Raman intensity profile along the scanning direction of the annealing cw laser has been measured on lateral seeding regrown PSOI for two scattering configurations (Fig.7).

In the $X(YZ)\bar{X}$ configuration the polarization vector of the incident light which is perpendicular to that of the scattered light is take to be parallel to the <100> direction of the crystal substrate. Hence, the scattering from the annealed layer is allowed for this configuration, if the crystallographic orientation of the annealed layer is the same as that of the substrate. As shown in Fig.7, the intensity in the (YZ) configuration

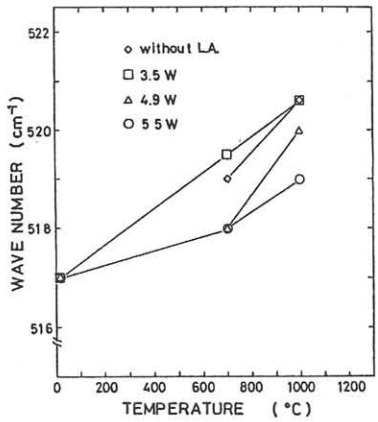

Fig.6 The peak frequencies of the Raman band for APSOI's which are laser annealed and subsequently thermally annealed at different temperature.

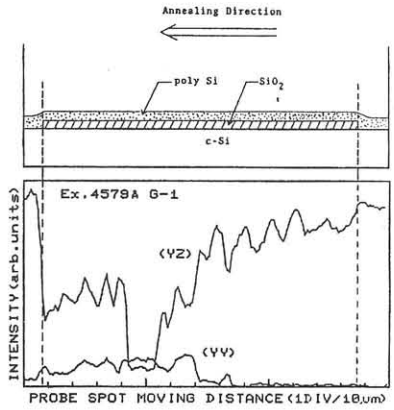

Fig.7 Raman intensity profile of a lateral seeding regrown films along the scanning direction of the annealing laser.

decreases gradually as the probe laser spot leaves away from the region in which the polysilicon layer is deposited directly on Si substrate and the nucleation starts, whereas the intensity in the (YY) configuration increases. It is found that the Raman frequency decreases slightly away from the starting point. These results indicate that crystallinity in annealed films becomes worse and crystallites with different orientations are created as the distance from the starting point increases.

In summary, the crystallinity of the laser annealed polysilicon films on insulators are well characterized by the Raman microprobe technique. More detailed study will make it possible to understand the mechanism for regrowth and also the creation of stress in annealed silicon films.

References

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