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TIME-RESOLVED CONDUCTIVITY AND REFLECTIVITY DURING LASER ANNEALING OF SEMICONDUCTORS

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Transient conductivity and reflectivity have been measured during pulsed-laser annealing in silicon on sapphire. It was found that, in the laser power range where the reflectivity suddenly increased, the conductivity was saturated but its value did not reach to that of ordinary molten Si. The increase in conductivity did not last as long as the reflectivity did. Nonthermal processes are suggested to play an important role in the pulsed laser annealing, rather than normal thermal melting.

I. Introduction

There has been a heated controversy on the mechanism of pulsed laser annealing of amorphous ion-implanted silicon; one is a strictly thermal melting and recrystallization model[1-4] and other is a plasma annealing model[5,6].

The most important question whether the surface layer melts, gets hot without melting or is warmed only moderately depends on the rates at which energy is transferred from the electrons and holes created by the laser to the lattice as heat.

In order to find the answer, it is experimentally the best method to take time-resolved measurements of some physical quantities during the laser annealing. In several laboratories a significant increase in the reflectivity of the surface has been observed[7-10]. Auston et al.[8] have suggested that the reflectivity increase is due to melting of the Si surface since the value was consistent with liquid Si, while Van Vechten et al.[5] have argued that the reflectivity increase is due to the presence of a dense electron-hole plasma since it occurred near the peaks of the light pulses. Conclusive experimental evidence in putting the end to the heated controversy has not yet been presented to our knowledge. In this paper, we report time-resolved measurements of the conductivity and reflectivity during pulsed laser annealing in silicon on sapphire (SOS), which confirm that the surface layers do not thermally melt since the conductivity does not reach to that of ordinary molten Si. This conclusive result has been also supported by Raman scattering measurements made to estimate the residual stresses in the laser-annealed SOS.

II. Experimental

The wafers used in the present experiments were 0.6-μm-thick single crystal silicon layers deposited on $(1\bar{1}02)$-oriented single crystal sapphires. The silicon layers were n-type and their conductivity was 10 to 100/Ωcm. One part of wafers was implanted with 100 keV arsenic ions at a dose of $10^{15}/cm^2$. The samples were formed as a shape shown in Fig.(1), and the electrodes were alloyed with Au:Sb to make ohmic contacts.

Figure (1) shows the experimental arrangement for measuring the transient conductivity and reflectivity. A pulsed dye laser was used to generate the annealing pulses at a wavelength of about 590 nm. The dye used was Rhodamine 6G. The pulse width was about 300 nsec. The laser beam was monitored with a high speed PIN photodiode and an oscilloscope with total response times of 15 nsec, passed through beam attenuators and then was roughly focussed by a lens onto the sample mounted on a rotatable x-y-z movable sample holder. The beam diameter was large enough to bridge a distance of two potential electrodes. The sample was biased through two current electrodes by a constant voltage source. In order to obtain the transient conductivity, the differential voltage between two potential electrodes was measured by a storage oscilloscope with response time of 3.5 nsec. The total response time including stray capacities was less than 15 nsec.

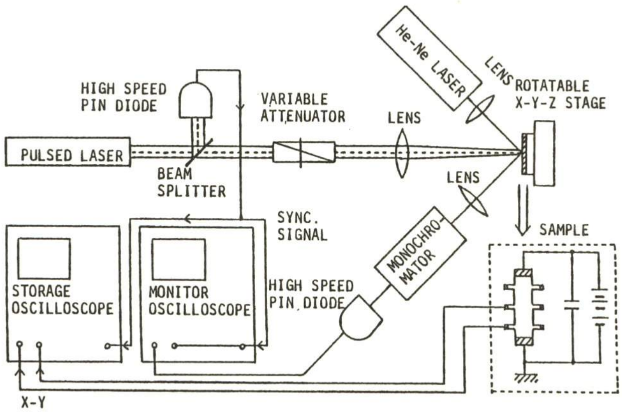

Fig.(1) Experimental arrangement for measuring transient conductivity and reflectivity

A continuous 0.63-μm He-Ne laser was used to measure the optical reflectivity of the sample surface during the annealing. The beam was focussed to a diameter of approximately 0.2 mm and was aligned with the center of the annealing beam at the crystal surface. The angle of incidence of the 0.63-μm beam was 45° to the surface normal. A high speed PIN photodiode was used to detect the reflected beam with rise time of approximately 3 nsec. Accurate timing was ensured by synchronously triggering both oscilloscopes with the signal from the annealing laser beam.

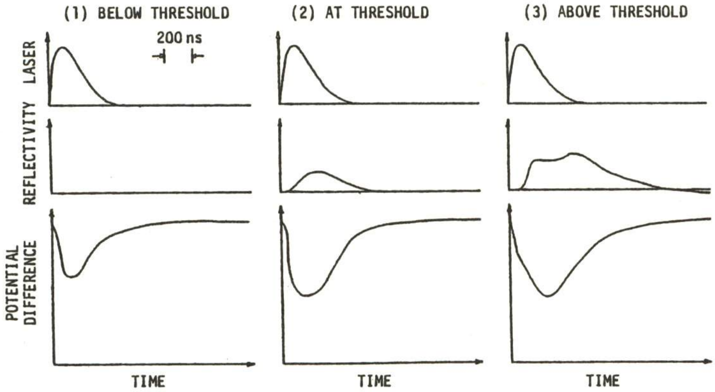

Fig.(2) Oscilloscope traces of annealing laser pulses, reflectivities and potential differences between two electrodes

III. Results and Discussion

Figure (2) shows typical oscilloscope traces of annealing laser pulses, reflectivities and potential differences between the electrodes measured in implanted SOS. We have obtained similar results in unimplanted SOS. These waveforms have a number of distinguishing features which constitute a characteristic signature for laser annealing. A significant increase in the reflectivity was observed at a threshold, as found by Auston et al.[8]. However, as the pulse energy was increased above the threshold, the increased value was not always flat although the duration became longer. It should be noted that the reflectivity increase occurred near the peak of the laser pulse at the threshold. If the reflectivity increase were due to the presence of a molten layer, or due to any process that simply involved heating the surface layer to a high temperature, then this increase would have occurred well down the tailing edge of the pulse at the threshold energy.

The potential difference between the electrodes, connecting with the conductivity, reflected almost the shape of the annealing pulse sufficiently under the threshold. As the pulse energy was increased, it lasted longer than the annealing pulse. It should be noted that the potential difference did not saturate while reflectivity was increasing. If there existed a molten layer, the potential difference would have reached to zero and then saturated during the existence of the molten layer.

The transient conductivity has been calculated from the measured potential difference between the electrodes with the assumption that the laser light is homogeneously absorbed in the silicon layer. Although this assumption does not always lead to the correct value it can give the order of the magnitude. The results measured in unimplanted and implanted SOS are shown in Figs.(3a) and (3b), respectively, where the allow indicates the beginning of the reflectivity increase. As the laser energy was increased, the transient conductivity increase experienced the two-step saturation. It should be noted that the second saturation occurred at the beginning of the reflectivity increase. The saturated conductivities in implanted and unimplanted SOS were of 40/Ωcm and 150/Ωcm, respectively, which were extremely smaller than the ordinary molten silicon of 1.2×10^4 /Ωcm[11] and were compared with the conductivity of 70/Ωcm at 1200 K in the intrinsic range of Si[13]. It is therefore concluded that the silicon layer does not melt but it seems to be annealed by plasma.

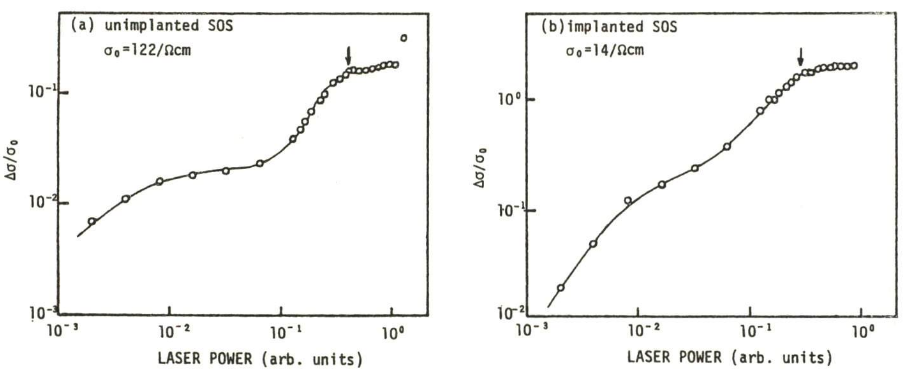

Fig.(3) Conductivity changes by laser irradiation in (a) unimplanted and (b) implanted SOS

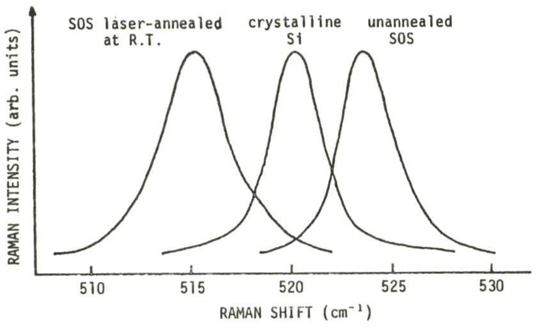

Fig.(4) Typical Raman spectra of crystalline Si, unannealed SOS and laser-annealed SOS

In order to characterize the annealed SOS and to confirm this conclusion, Raman scattering measurements have been made. The typical Raman signal from the optic mode in the annealed SOS is shown in Fig.(4), together with those measured in single crystalline silicon and unannealed SOS. It was found that the Raman signal in the unannealed SOS was shifted upward by about 3 cm^{-1} compared with that in the single crystalline Si, while the Raman signal in the laser-annealed SOS was shifted downward by about 5 cm^{-1}. The upward shift could be explained with the contractive stress produced by the thermal expansion difference between the silicon layer and the sapphire substrate when SOS were deposited at about 1000°C and then cooled down to the room temperature. If the silicon layer melted and the sapphire substrate warmed in some degree during the laser annealing, then the tensile stress would be expected to shift the Raman signal downward by about 3 cm^{-1} in maximum. However, this simple thermal melting model could not explain the downward shift of 5 cm^{-1} measured in the laser-annealed SOS. It may be therefore suggested that a mechanism is needed to produce such a tensile stress during the laser-annealing.

IV. Concluding Remarks

All experimental results obtained here confirm the importance of nonthermal processes rather than the normal thermal melting process in the pulsed laser annealing. Further investigations on dynamics of electron (and hole) system are needed to dissolve veils on the pulsed laser annealing.

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