Time-resolved and space-resolved Si lattice-temperature measurements during cw laser annealing of Si on sapphire

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(Received 12 March 1984; accepted for publication 28 June 1984)

We have developed an optical technique for *in situ* measurement of temporal change and spacial profile of Si lattice temperature during cw laser annealing. This technique utilizes time-dependent optical interference in Si films on insulator. By using a microscope for focusing a laser probe beam to 2.0 μm, time-resolved and space-resolved Si lattice-temperatures were measured below the melting point (1412 °C) on a time scale of 10^{-4}–10^{0} s during cw laser annealing of Si on sapphire.

A new technique for *in situ* measurement of temporal change and spatial profile of Si lattice temperature is strongly needed for fabrication of a better recrystallized Si layer on insulator (SOI) by cw laser annealing. However, no time-resolved Si lattice-temperature measurements have been published for cw laser annealing except in our previous report.[1] The Si lattice temperatures in the steady state were measured only by Raman scattering technique[2] and by using a micro-optical pyrometer.[3] In this letter we report an optical interference technique using a microscope by which time-resolved and space-resolved Si lattice-temperature measurements can be made during cw laser annealing (10^{-4}–10^{0} s) of Si on sapphire (SOS).

This technique[1,4] utilizes time-dependent optical interference[5] induced by small changes in the refractive index n of Si due to variations of the Si lattice temperature during cw laser annealing. This method was developed from the time-resolved measurement that was first used on a shorter time scale[4] from 10^{-9} to 10^{-4} s during pulsed laser annealing. The samples used were (100) Si crystal grown on a sapphire substrate (SOS) by the conventional chemical vapor deposition process. The thickness of each epi-Si layer was in the range 0.3–2.0 μm. The interference effect takes place between the probe beam (0.6328 μm) from the Si surface and that from the Si-sapphire interface. The interference can be sensitively detected by measuring the reflectivity change. The temperature corresponding to the interference maxima and minima of the reflectivity are calculated from the interference conditions and the temperature-dependent Si refractive index $n(T)$.

The interference conditions and $n(T)$ are as follows:

$$2d \cos \theta_t = \frac{(m + 1/2)\lambda}{n(T)} \quad \text{(for maxima)}, \tag{1}$$

$$2d \cos \theta_t = m\lambda / n(T) \quad \text{(for minima)}, \tag{2}$$

$$\sin \theta = n(T) \sin \theta_t, \tag{3}$$

and

$$n(T) = 3.98 + 4.7 \times 10^{-4}\, T\ (^\circ\text{C}), \tag{4}$$

which were described in detail in our previous papers.[1,4]

The experimental method employed for the measurements is as follows.[1] A krypton ion laser (10 W, Kr multilines, TEM_{00}) with wavelengths of 0.647 and 0.676 μm heated the samples and the irradiation time was varied from 9 to 250 ms by a mechanical shutter controlled electrically. The rise and fall times of the irradiation were 0.5 ms. The incident angle of the annealing beam to the SOS samples was $\sim 60°$. A He-Ne laser with the incident angle of $\sim 0°$ was used to probe the changing reflectivity during cw laser annealing. The probe beam was first expanded by a beam expander and was subsequently focused to 2 μm by the objective lens ($\times 20$) of a microscope, which enable us to do space-resolved Si lattice-temperature measurements during annealing. By use of the microscope we can also know which point is monitored by the probe beam and what the sizes of the probe and anneal beam spots are. A Si *p-i-n* photodiode with a rise time of 3 ns was used to monitor the intensity of the reflected probe beam. The time-resolved reflectivity data are memorized on a transient recorder with the fastest sampling time of 100 ns and are subsequently processed or computed by a microcomputer, followed by display in an *X-Y* plotter.

Figure 1 shows typical time-resolved optical reflectivity traces of 2-μm SOS. The irradiation time was 9 ms. The shape of the anneal beam spot was elliptic because the incident angle of the anneal beam was 60°. The dimensions of the elliptic spot were approximately 70 μm in the long axis and 25 μm in the short axis. Reflectivity was measured in the

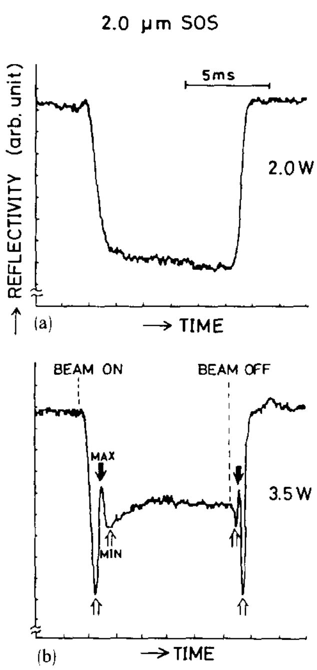

FIG. 1. Typical time-resolved optical reflectivity traces for 2.0-μm SOS during cw laser annealing for (a) 2-W and (b) 3.5-W laser powers, indicating no melting.

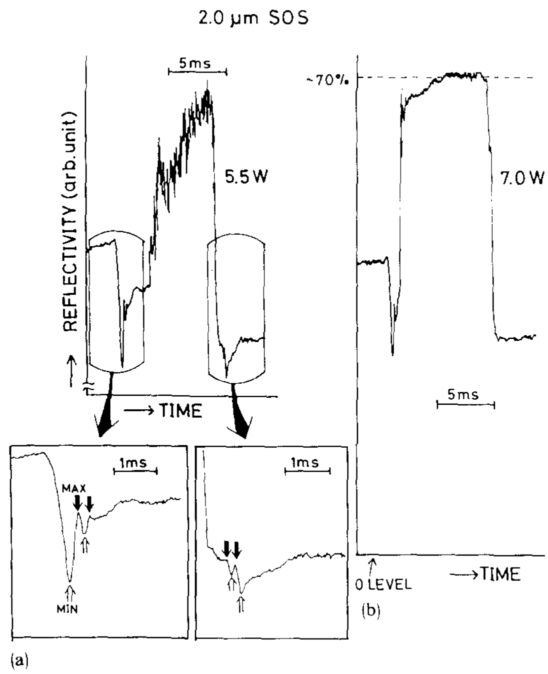

FIG. 2. Typical time-resolved optical reflectivity traces indicating Si melting. In trace (a), two expanded traces are added to show more clearly reflectivity changes around at times when the shutter is opened and closed, respectively.

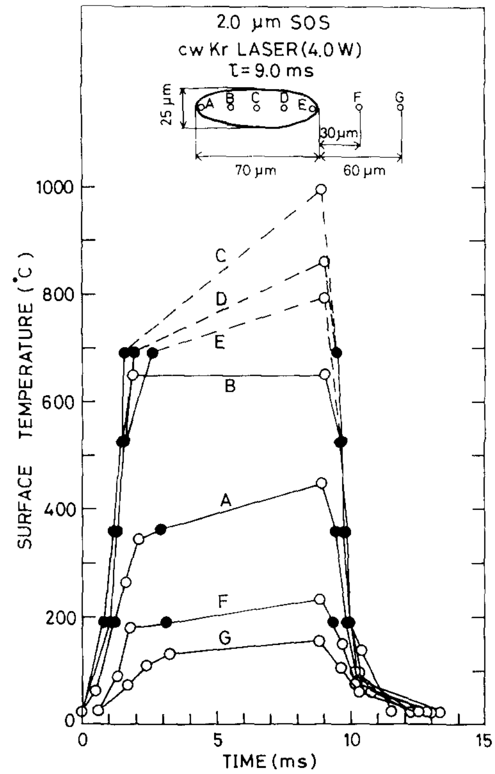

FIG. 4. Time-resolved and space-resolved surface Si lattice temperatures which are obtained from the time-resolved reflectivity traces proved at various points shown in the inset.

center of the anneal spot. The reflectivity changes gradually when the shutter for the annealing beam is opened, as can be seen in Fig. 1(b). Below a power of 2.0 W no interference maxima or minima can be seen [see Fig. 1(a)]. On the other hand, above a laser power of 3.0 W, we can see some minima and maxima, e.g., two minima and one maxima for 3.6-W power, as shown in Fig. 1(b). When the anneal beam is cut off by closing the shutter, the reflectivity begins to change reversely and finally recovers to the initial level.

Above a power of 5.5 W, the reflectivity increases abruptly after the appearance of two interference minima and two maxima, as shown in Fig. 2, indicating the onset of melting of the Si surface layer. Above a power of 6.0 W, the reflectivity reaches to a level of about 70% corresponding to that of a molten Si layer with a thickness more than 200 Å. It can also be seen from Fig. 2(a) that at 5.5 W the interference maxima and minima appear after solidification of molten Si layer. On the other hand, at 7.0 W no interference can be seen after solidification as shown in Fig. 2(b). This suggests that the molten Si layer is unstable without any cap films at higher powers or that the flatness of the Si layer is lost during solidification.

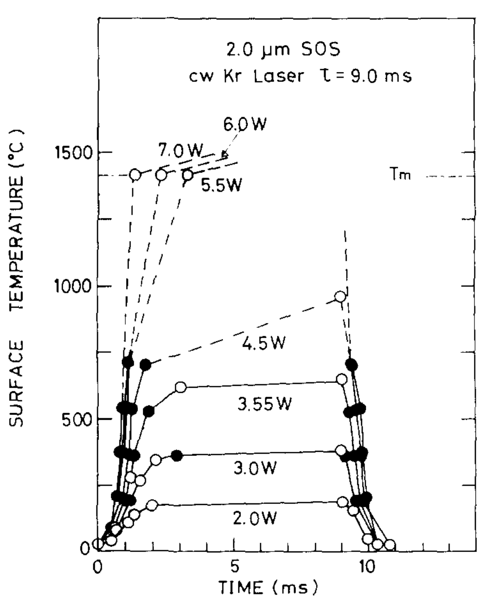

FIG. 3. Time-resolved surface Si lattice temperatures obtained from the data in Figs. 1 and 2, and others.

The appropriate power range for maintaining the flatness is found to be very narrow; i.e., from 5.5 to 6.2 W, for 9-ms cw laser annealing of 2-μm SOS at room temperature.

On a relatively longer time scale such as cw laser annealing, the temperature gradient within a thin Si layer is very small in the longitudinal direction. Therefore, temperatures obtained by this measurement are thought to indicate the surface temperatures. Closed circles in Fig. 3 show the surface temperatures which are obtained from the interference maxima and minima. Open circles in Fig. 3 were obtained from other points not at the interference maxima and minima by calculating on the assumption that the surface temperatures are proportional to the variations of the reflectivity between a maximum and a neighbor minimum. This result indicates that, under the conditions of anneal beam spot and powers used here, cooling is more rapid than heating and that it takes more than 2 ms for the Si lattice temperature of the 2.0 μm SOS to reach a steady state.

Furthermore, we measured time-resolved optical reflectivity for SOS samples with various Si thicknesses of 1.5, 1.0, 0.6, and 0.3 μm. It was found from the results that, as the thickness decreases, higher temperatures can be measured more accurately because of clearer interference at higher temperatures.

Figure 4 shows the time-resolved and space-resolved surface temperatures. They were also obtained from the time-resolved reflectivity traces which were measured at various points indicated by the letters A,B,..., etc. (see the inset of Fig. 4). No melting occurs at any of the probed points during annealing at a power of 4.0 W. It can be seen that the temperature changes very gradually at points F and G which are not directly irradiated with the anneal beam. The difference of the temperature change between points A and E is attributed to the inhomogeneous intensity of the anneal beam along the long axis of the elliptic spot because of the oblique irradiation of Kr multilines laser. Thus, this interference technique using a fine probe beam with a diameter of 2 μm enable us to do time-resolved and space-resolved Si lattice-temperature measurements on SOS samples during cw laser annealing.

In conclusion, we have developed time-resolved and space-resolved Si lattice-temperature measurements during cw laser annealing, by utilizing time-dependent optical interference. Using a microscope for focusing a probe beam, we can perform time-resolved and space-resolved Si lattice-temperature measurements on SOS with a spatial resolution of 2 μm. By developing further this technique it would be possible to determine the temporal temperature gradient, thermal stress, or liquid zone stability, in very small Si islands during beam recrystallization of SOI.

We are greatly indebted to M. Muroi and H. Kamijo for assistance with the experiment. This work was supported in part by both the 1983 Grant-in-Aid for Scientific Research from the Ministry of Education of Japan and the 1982 Grant-in-Aid for Project Research from the University of Tsukuba.

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cw operation of an AlGaInP double heterostructure laser diode at 77 K grown by atmospheric metalorganic chemical vapor deposition

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(Received 4 June 1984; accepted for publication 2 July 1984)

Continuous wave operation of an $Al_{0.21}Ga_{0.31}In_{0.48}P/Ga_{0.52}In_{0.48}P/Al_{0.21}Ga_{0.31}In_{0.48}P$ double heterostructure (DH) laser diode was achieved for the first time at 77 K. The device was made from a DH wafer grown by atmospheric metalorganic chemical vapor deposition using triethyl metals and phosphine as source materials. At 77 K, the lasing wavelength was 0.653 μm and the threshold current was 55 mA for a diode with a nitride-insulated, 8-μm-wide and 250-μm-long stripe geometry.

AlGaInP in a double heterostructure (DH) on a GaAs substrate has potential applications in lasers with the shortest wavelength emission (down to about 0.58 μm at room temperature) of any III-V semiconductor alloy with complete lattice matching to a binary compound.[1] Metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) are both promising technologies for growing this material.

Asahi *et al.* first reported on the MBE growth of AlGaInP visible laser diodes operating at 0.66–0.68 μm under a pulsed condition at room temperature, but the 26-kA/cm^2 threshold current density of their lasers was high.[2]

Recently, Hino *et al.* also achieved room-temperature pulsed operation of AlGaInP DH laser diodes grown by low pressure MOCVD. The threshold current density reported was 26 kA/cm[2,3] which is the same value as that of MBE.

In this letter, we report on the first achieved cw operation of the AlGaInP DH laser at liquid nitrogen temperature. The epitaxial layers were grown by conventional atmospheric MOCVD.

The MOCVD growth of AlGaInP was carried out in a cold-wall horizontal reactor at atmospheric pressure. The growth temperature was 600 °C. The source materials used were triethyl-aluminum, triethyl-gallium, triethyl-indium, and phosphine. Hydrogen selenide and dimethyl-zinc were used as dopants for the *n*-type and *p*-type layers, respectively. Pd diffused H_2 was used as the carrier gas. The substrate was a (100) oriented Si-doped GaAs wafer.

The organometals and hydrides were introduced separately into the reactor until they were mixed just in front of a susceptor to suppress the parasitic gas phase reaction.[4] A high carrier gas flow rate of about 6 *l*/min was used to obtain

