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Measuring the Temperature of a Quartz Substrate during and after the Pulsed Laser-Induced Crystallization of a-Si:H

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Transient thermometry measurements were used to study the heat diffusion in the near-surface region of a quartz substrate when hydrogenated amorphous silicon deposited on the substrate was melted and crystallized by irradiation with a pulsed XeCl excimer laser. The use of a thin platinum layer as a temperature sensing layer made it possible to measure the rapid heat diffusion from the silicon film on the top to the underlying substrate. The substrate was heated to no more than 170°C at 800 nm below the silicon film during and after the crystallization process.

KEYWORDS: transient thermometry measurement, transient conductance measurement, time resolved optical reflectivity measurement

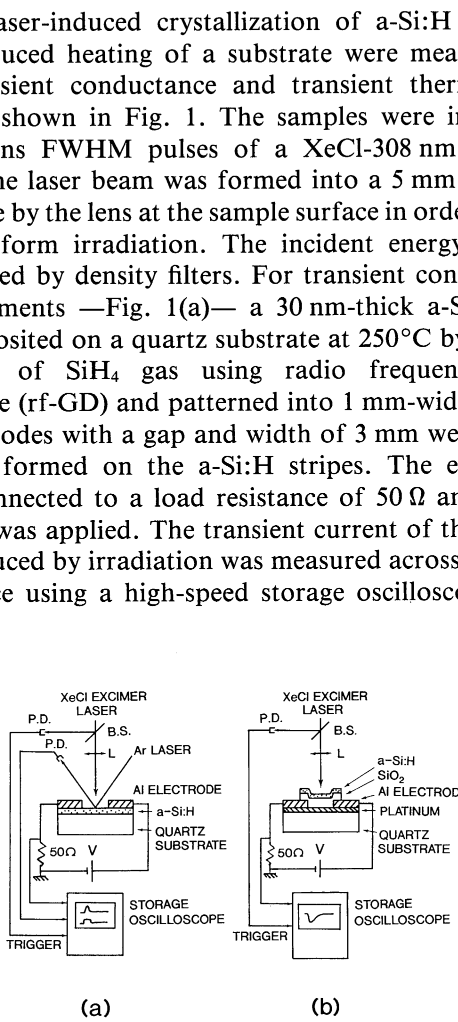
§1. Introduction

Pulsed laser annealing is an attractive technique for fabricating three-dimensional stacked silicon devices and devices on a glass substrate, because a shallow p-n junction and crystalline silicon layer can be fabricated using this technique without heating the underlying region to a high temperature.[1-5] We have reported the fabrication of polycrystalline silicon thin film transistors (poly-Si TFT's) with a high effective electron mobility using a XeCl excimer laser annealing to crystallize hydrogenated amorphous silicon (a-Si:H).[6,7] If it is known how high the temperature in the substrate is in the laser-annealing process, a low cost glass can be used as a substrate. For measuring the temperature of the silicon surface during and after a pulsed laser annealing, several techniques have been reported, which include the time-of-flight method of measurement of the velocity of thermally evaporated silicon atoms,[8] the time-resolved X-ray measurement of lattice strain,[9] the time-dependent optical interference method,[10] the time-resolved thermal radiation of silicon[11] and the time-resolved measurement of the Raman-Stokes and anti-Stokes lines.[12] Although the temperature at the silicon surface was sensitively monitored with these techniques, the heat diffusion from the silicon film to the substrate cannot be measured. Thompson recently reported on transient thermometry to measure the rapid temperature change of germanium film in the range of 600 to 1000 K during crystallization after pulsed-laser-induced melting.[13] He used a silicon film as a temperature-sensing layer and determined the temperature change from the resistivity change of the silicon film caused by laser heating. Thompson's method, however, has a problem; it is difficult to measure the rapid temperature change below 600 K because silicon film has a very high resistivity at low temperature.

The present paper reports the measurement of the heat diffusion from the silicon film to the near-surface region of the substrate during and after laser-induced crystallization of a-Si:H film using transient thermometry. In order to measure the temperature change from room temperature to several hundred degrees centigrade, a thin platinum film was used as the temperature-sensing layer because the resistivity of platinum has an almost linear temperature dependence in a wide range including room temperature.

§2. Experimental

The laser-induced crystallization of a-Si:H and the laser-induced heating of a substrate were measured by the transient conductance and transient thermometry systems shown in Fig. 1. The samples were irradiated with 30 ns FWHM pulses of a XeCl-308 nm excimer laser. The laser beam was formed into a 5 mm × 10 mm rectangle by the lens at the sample surface in order to provide uniform irradiation. The incident energy density was varied by density filters. For transient conductance measurements —Fig. 1(a)— a 30 nm-thick a-Si:H film was deposited on a quartz substrate at 250°C by decomposition of SiH_4 gas using radio frequency glow discharge (rf-GD) and patterned into 1 mm-wide stripes. Al electrodes with a gap and width of 3 mm were subsequently formed on the a-Si:H stripes. The electrodes were connected to a load resistance of 50 Ω and a bias voltage was applied. The transient current of the a-Si:H film induced by irradiation was measured across the load resistance using a high-speed storage oscilloscope. The



(a) (b)

Fig. 1. Schematic diagram of sample and measurement apparatus for transient conductance (a) and transient thermometry (b) L, lens; B.S., beam splitter; P.D. photodiode.

melting threshold energy of a-Si:H was determined by measuring the time-resolved optical reflectivity using an Ar-514.5 nm laser beam as a probe light. The reflectivity increase[14] associated with surface melting was detected using a high-speed photodiode.

For transient thermometry measurements —Fig. 1(b)— thin Pt stripes with a thickness of 30 nm and a width of 0.2 mm were evaporated on a quartz substrate in order to measure the temperature change without perturbing the heat diffusion in the substrate. Al electrodes with a gap and width of 3 mm were subsequently formed on the Pt stripes. SiO_2 and 30 nm-thick a-Si:H films were subsequently deposited using rf-GD at 250°C in a 5 mm × 5 mm area on the cap of the Al electrodes including the end of the electrodes. The electrodes were connected to a load resistance of 50 Ω and a bias voltage was applied. The resistivity change in the Pt layer was measured across the load resistance using a high-speed storage oscilloscope when the top a-Si:H layer was irradiated. For determination of the temperature change from the transient resistivity data of the Pt layer, the sample was placed in a furnace and the temperature dependence of resistivity in the Pt layer was measured in the range of 30 to 300°C.

§3. Results and Discussion

The a-Si:H film was melted by irradiation at an energy density greater than 130 mJ/cm^2. The transient conductance associated with molten silicon increased as the laser energy density was increased from 140 to 210 mJ/cm^2, as is shown in Fig. 2. The a-Si:H film was completely crystallized by the irradiation at 210 mJ/cm^2, when the surface melted for 80 ns. The silicon surface was very smooth. Transmission electron micrography (TEM) revealed that the grain size is distributed between 10 and 60 nm. Moreover, Fourier transform spectroscopy (FTIR) revealed that hydrogen concentration in the film was decreased from 10 atomic percent to as low as 0.2 atomic percent by the laser-induced crystallization.[7] Investigation of the effect of the residual amount of hydrogen atoms on the electrical properties of the poly-Si film is continuing.

Figure 3 shows the temperature change in the Pt layer, which was overlaid with 200 nm-thick SiO_2 and 30 nm-thick a-Si:H films when the sample was irradiated at an energy density between 120 and 210 mJ/cm^2. These temperature-change data were obtained from the transient-resistivity data using the temperature dependence of resistivity for the Pt layer, which was experimentally obtained by

$$T=2.5\times 10^{7}(r-2.6\times 10^{-5})\quad (^{\circ}\mathrm{C}) \qquad (1)$$

where r is resistivity in Ω·cm. The transient thermometry accuracy was ±15°C. When the irradiation started, the temperature increased and reached a maximum at 100 ns, for each irradiation. The maximum temperature increased from 200 to 380°C as energy density was increased from 120 to 210 mJ/cm^2. The rapid heating of the substrate from room temperature to 380°C was measured by transient thermometry using the Pt layer.

Figure 4 shows the dependence of temperature change on the thickness of the intermediate SiO_2 layer during irradiation at an energy density of 180 mJ/cm^2. The thickness of SiO_2 was 200, 400, 600 and 800 nm. The top a-Si:H layer was 30 nm thick. As the thickness of the SiO_2 layer increased, the temperature increased more slowly and the maximum temperature decreased, as can be seen in Fig. 4. For every sample, the temperature in

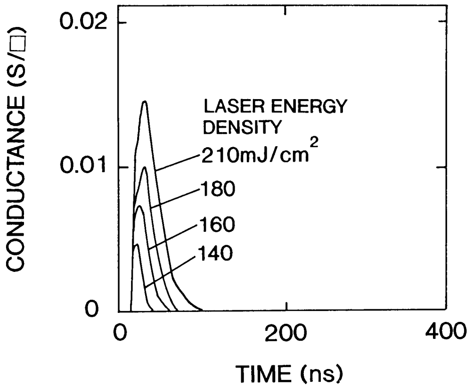


Fig. 2. Evolution of transient conductance of 30 nm-thick a-Si:H as laser energy density was increased from 140 to 210 mJ/cm^2. Melting threshold energy was 130 mJ/cm^2.

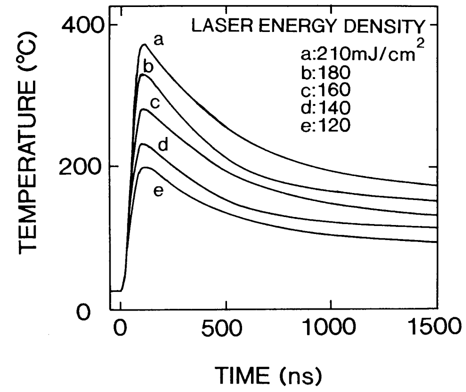


Fig. 3. Measured temperature in the Pt layer as a function of time for laser energy densities between 120 and 210 mJ/cm^2. The Pt layer was overlaid with 200 nm-thick SiO_2 and 30 nm-thick a-Si:H.

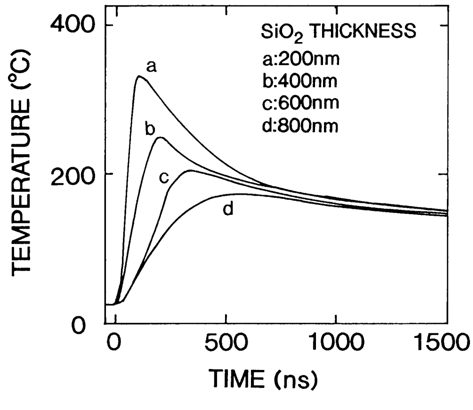


Fig. 4. Measured temperature in the Pt layer as a function of time at laser energy densities of 180 mJ/cm^2 for thickness of intermediate SiO_2 layer between 200 and 800 nm. The top a-Si:H was 30 nm thick.

the Pt layer at 800 ns was close to 170°C. This shows that the silicon layer was rapidly cooled to about 170°C 800 ns after the melt followed by solidification seen in Fig. 2. The region under the 200 nm-thick SiO_2 layer was heated to no more than 400°C, as can be seen in Fig. 4. This shows that a poly-Si film can be fabricated on a nonrefractory material such as aluminum if an intermediate SiO_2 layer thicker than 200 nm is formed. Furthermore, the Pt layer was heated to no more than 170°C at 800 nm under the top silicon layer. This means that even plastic can be used as a substrate.

In order to explain the results of Fig. 4, the heat diffusion was calculated using a simple unidimensional model.[15] Heat was assumed to be generated at the surface of the semi-infinite SiO_2 substrate and heat diffusion in the silicon layer was ignored, because a-Si:H and crystalline Si films have a large optical absorption coefficient of $1\times10^6\ \mathrm{cm}^{-1}$ at 308 nm[16] and have a thermal diffusion coefficient much larger than that of SiO_2.[17] If the thermal diffusion coefficient of SiO_2 is assumed to be independent of temperature, the time t at which the temperature is maximum is related to a depth X by

$$\frac{1}{t_M}\int_0^{t_M} (D/4\pi(t-t_m))^{1/2}\exp(-X^2/4D(t-t_m))\,\mathrm{d}t_m - \frac{1}{(2\tau-t_M)}\int_{t_M}^{2\tau}(D/4\pi(t-t_m))^{1/2} \times \exp(-X^2/4D(t-t_m))\,\mathrm{d}t_m=0, \qquad (2)$$

where D is the thermal diffusion coefficient, and the laser pulse is assumed to have a triangular shape with a peak intensity at the time, t_M, of 15 ns and the pulse width τ of 30 ns in full-width-half-maximum. Figure 5 shows the dependence of the time at the maximum temperature on depth. The time at the maximum temperature increases with increasing depth. Experimental data were close to the calculated data with diffusion coefficients between 0.004 and 0.006 cm^2/s, which agreed well with the conventional values of Goldsmith *et al.*[17] Figure 5 shows that the transient thermometry measurements of the thin Pt layer accurately gauge the rapid heat diffusion in the substrate.

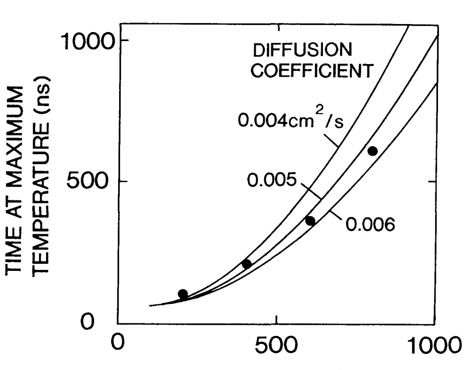


Fig. 5. Calculated and experimental time at which temperature reached the maximum as a function of thickness of SiO_2. Solid lines are calculated and solid circles are experimental data obtained from Fig. 4.

§4. Conclusions

The rapid heating of the near-surface region in a quartz substrate was investigated using transient thermometry. The use of a platinum thin layer as a temperature-sensing layer made it possible to measure the temperature change in the substrate in a range from room temperature to 400°C with an accuracy of ±15°C. The 30 nm-thick a-Si:H film was completely crystallized by the irradiation at 210 $\mathrm{mJ/cm}^2$, when the surface melted for 80 ns and then cooled to about 170°C after 800 ns. The substrate was heated to no more than 170°C at 800 nm below the top silcon layer. This result shows that polycrystalline devices can be fabricated by excimer laser annealing on a substrate such as plastic.

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