PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN 49 (1980) SUPPL. A p. 1303–1306

# DYNAMIC BEHAVIOR OF PICOSECOND PULSED LASER ANNEALING IN ION-IMPLANTED Si

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Implanted, amorphous Si samples have been annealed with the irradiation of a single 30-ps laser pulse at 1.06 μm. The dynamic behavior of the amorphous to crystalline transition has been investigated by means of time-dependent optical reflectivity measurement at 0.63 μm (cw) and 1.06 μm (30-ps pulse). The rise time of the reflectivity enhancement up to 70 % is found to be significantly different between the amorphous and crystalline Si. A model for the origin of the rise time is proposed.

## I. Introduction

Physical mechanism of pulsed laser annealing of ion-implanted, amorphous Si is believed to be explained by thermal melting model [1], although a non-thermal model has also been proposed [2]. Up to now, however, the details of the dynamic behavior prior to melting have not been elucidated [3, 4]. Absorption and relaxation processes in the high power density more than ~100 MW/cm$^2$ are not as well understood as they are at lower power density. It is necessary, therefore, to study dynamics of high density electron-hole (e-h) plasma excited by the pulsed laser with the high power density. Using a single 30-ps laser pulse at 1.06 μm, we have investigated the dynamic behavior of an amorphous to crystalline or polycrystalline (a-c) transition and the e-h plasma by the transient optical reflectivity measurements. The primary motivation for this work was to test a non-thermal effect of ultra-short pulsed-laser annealing. In this note, however, we will propose a thermal model for the 30-ps single pulse annealing.

## 2. Experimental Procedures

Amorphous layers of Si were formed by As or P ion implantation into the [100] Si crystals. The samples were irradiated in air with a single pulse (λ= 1.06 μm) of 30-ps duration selected from the pulse train of a mode-locked Nd:YAG laser [3, 5]. The diameter of the laser beam was adjusted to 0.7~1.5 mm at the Si surface. The experimental method and

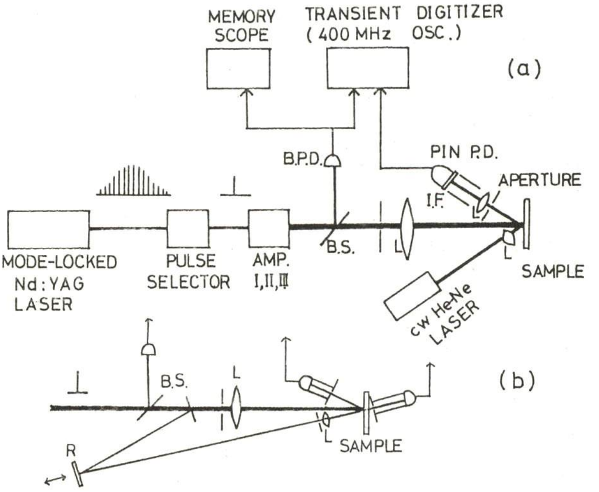


Fig. 1 Block diagram for the transient reflectivity measurements; (a) cw He-Ne probe beam and (b) 30-ps pulse probe beam

system for observing the time-dependent reflectivity at 0.63 μm by using cw He-Ne laser were described in detail in our previous papers [3, 5]. The block diagram for the measuring system is shown in Fig. (1-a). The reflected light was detected by a high speed PIN diode with a rise time of 3 ns. The response time of the measuring system containing the PIN diode was less than 5 ns. As shown in Fig. (1-b), the reflected and transmitted light intensity was also measured by using the 30-ps pulse with a delay time of 0, 9, and 16 ns as a probe beam. The extent of the recrystallization was possibly deduced by the measurement of the position-dependent optical reflectivity at 0.63 μm with a resolution of ~50 μm.

## 3. Results and Discussion

The a-c transition was found to take place between ~1 J/cm$^2$ and ~4 J/cm$^2$, corresponding to the power density of ~30 GW/cm$^2$ and 120 GW/cm$^2$. Reflected light intensity of the 30-ps single pulse increased with the irradiated energy density E and was enhanced when the recrystallization took place. Transmission decreased with E. These are attributed to either the high density e-h plasma excited or direct intraband transitions [6] rather than extremely rapid melting in 30 ps [1] at the surface, since the production rate of e-h is significantly high, i.e., $10^{33}$/cm$^3$·s$^1$. This is also suggested by both the results of the measurements of reflected light intensity of a 30-ps beam with a delay time of 9 ns and 16 ns [7] and the time-dependent reflectivity measurement mentioned next.

Typical signal traces of the time-dependent reflectivity are shown in Fig. (2-a) and (b), (c) and (d), and (f) and (g) for crystalline Si, 100-keV As, 5 x $10^{15}$/cm$^2$ and 100-keV P, 5 x $10^{15}$/cm$^2$ implanted Si, respectively. Figure (2-e) indicates an intense 30-ps single pulse monitored by the PIN diode, which shows an abrupt rise time of at most 5 ns. It is clearly found that the rise time more than 5 ns is not instrumentally determined. $\tau_r$, $\tau_f$, $\tau$, $R_a$, $R_\ell$ and $R_c$ are denominated in the Fig. (2-f), indicating the rise time, fall time and duration of the flat-top portion of the enhanced reflectivity, and the reflectivities of amorphous Si, of the flat-top portion and of recrystallized or crystalline Si, respectively [3]. It can be seen that $\tau_r$ of crystalline Si is much shorter than those of implanted, amorphous Si. The fact that there exists the rise time $\tau_r$ clearly demonstrates that the enhanced reflectivity is not attributed to the high density e-h plasma and that the e-h plasma decays considerably during times less than about 3 ns.

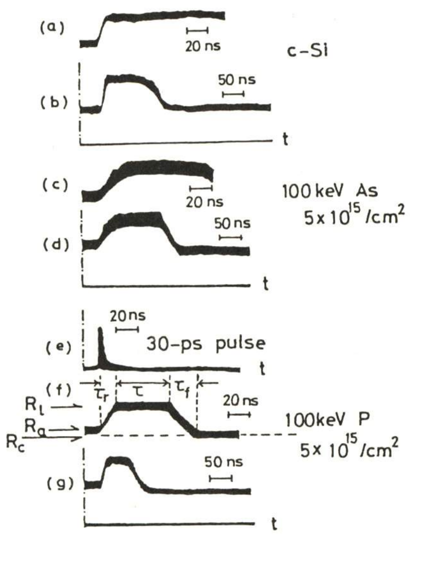


Fig. 2 Typical transient signal traces of the reflectivity at 0.63 μm after the 30-ps pulse

The maximum value of $\tau$ observed was 110 ns. The times $\tau_r$ and $\tau_f$, and the reflectivities $R_\ell$ and $R_c$ were measured as functions of the duration $\tau$, as indicated in Figs. (3) and (4). $\tau_r$ and $\tau_f$ is extremely sensitive to the surface condition such as a slight contamination [3, 4]. For 100-keV As, 5 x $10^{15}$/cm$^2$ implanted Si, the rise time $\tau_r$ increases from ~10 ns to ~30 ns as $\tau$ increases up to 110 ns. It can be seen that $R_c$ becomes around 35 %, corresponding to the reflectivity of crystalline Si. On the other hand, for crystalline Si, $\tau_r$ observed shows a constant value less than 10 ns over the $\tau$ range of 0~110 ns. The high dispersion of $\tau_f$ seems to be caused by the surface condition. It should be stressed that

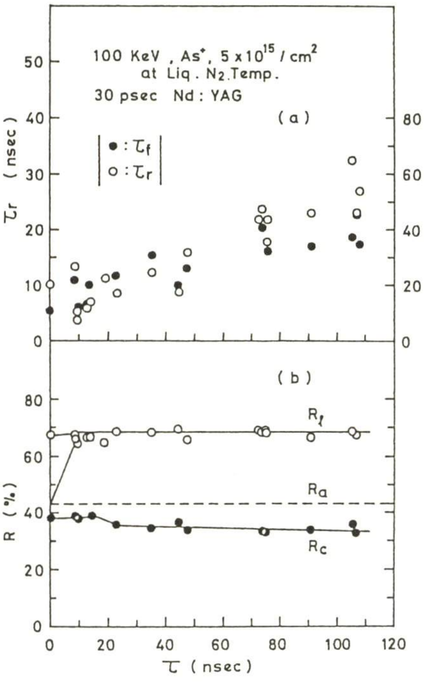


Fig. 3 (a) Reflectivity-rise time $\tau_r$ and -fall time $\tau_f$, and (b) $R_c$ and $R_\ell$ as functions of the duration $\tau$ for the amorphous Si

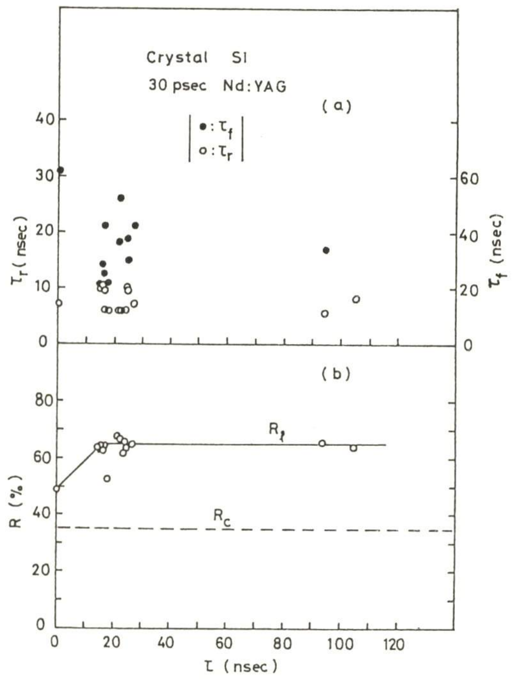


Fig. 4 (a) Reflectivity-rise time $\tau_r$ and -fall time $\tau_f$, and (b) $R_\ell$ as functions of $\tau$ for the crystalline Si

the rise time $\tau_r$ shows the $\tau$-dependence and structure-dependence.

The relaxation time $\tau_{e\text{-}h}$ of the high density e-h plasma can be estimated to be between 10 ps and 1 ns. If $\tau_{e\text{-}h}$ is less than 10 psec, the melting process must be in the same way as the nanosecond pulse annealing [4] and, therefore, the melt-front velocity above the sound velocity in solid Si is needed in order not to be damaged by boiling. There exists a maximum velocity of melt-front so low compared with the sound velocity, due to a limitation of thermal diffusion in liquid Si. If $\tau_{e\text{-}h}$ is more than 1 ns, the plasma diffuses into solid over several μm, indicating no molten layer. This situation corresponds to the non-thermal model [2], which is inconsistent with the $\tau$-dependence and structure-dependence of the rise time $\tau_r$.

The question is, what is the origin of the rise time $\tau_r$. A model is proposed here. For picosecond pulsed annealing of amorphous Si, a molten layer appears first not at the surface but at an inner region where the e-h plasma density Ne-h is $10^{19}\sim10^{21}/cm^3$. The rise time $\tau_r$ is attributed to the time requred for the inner molten layer to extend to the surface due to thermal diffusion and heating up within the surface solid layer.

According to Yoffa [8], the energy relaxation time from the hot, dense plasma to the lattice is proportional to $N_{e\text{-}h}{}^2$ above $N_{e\text{-}h}$ of $2\sim4 \times 10^{21}cm^{-3}$, due to the screening of electron-phonon interaction. This is different from the $N_{e\text{-}h}$ dependence of the conventional Auger recombination [1]. Since a 30-ps single pulse used has a high e-h production rate of $\sim10^{33}/cm^3\cdot s$, $N_{e\text{-}h}$ above $1 \times 10^{21}/cm^3$ might be realized through non-linear absorption processes and relaxation processes such as carrier-carrier scattering and Auger recombination, although a maximum value of $N_{e-h}$ is limited by the number of electron state density which is possible to interact with irradiated photons. If it is the case, the e-h plasma with $N_{e-h}$ of $10^{19}$ - $10^{21}/cm^3$ will first relax to transfer the energy to the lattice and, therefore, first produce a molten layer there. The molten layer may rapidly grow due to the diffusion of the e-h plasma [8] with $N_{e-h}$ above 1 x $10^{21}/cm^3$ in the surface solid layer toward the inner molten layer. When the plasma dissapears by the recombination, the thickness of the molten layer must be more than 1000 Å in order not to be damaged by boiling. The hot, inner molten layer cools due to thermal diffusion, but the surface solid layer is heated up, followed by the movement of the inner molten layer toward the surface. If the thickness of the surface solid layer is 1000 Å - 1 µm, the melt-front velocity toward the surface is estimated to be 10 - 100 m/s for the rise time $\tau_r$ of 10 ns, which agrees well with the calculated value of the maximum melt-front velocity [9]. According to this model, the rise time $\tau_r$ increases with the increase of irradiated energy density E (or the duration $\tau$) and the absorption coefficient because they enhance the e-h plasma density $N_{e-h}$ and, therefore, make the region with $N_{e-h}$ of $10^{19}$ - $10^{21}/cm^3$, i.e. the inner molten layer, deeper into Si.

In summary, the experimental results of the 30-ps single pulse annealing of implanted Si are inconsistent with the non-thermal model [2] and is qualitatively well explained by our thermal model mentioned above. As to Si, the 30-ps single pulse produces finally the molten layer even if the non-thermal annealing takes place in time less than several ns. However, we still think that the experimental test of the non-thermal effect is needed for compound semiconductors.

The authors would like to thank Y. Segawa for the help on the mode-locked Nd:YAG laser operation.

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