Dynamic behavior of mode-locked Nd : YAG laser annealing in ion-implanted Si, GaAs, and GaP

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By measuring the time-dependent optical reflectivity, we have investigated the dynamic behavior of annealing with the 30-psec pulse train of a mode-locked Nd : YAG laser. It was first observed that at narrow ranges of high laser energy density, the reflectivity of implanted Si and GaAs increases slowly to the level consistent with liquid ones, except GaP, and remains at that level for a period less than 200 nsec. As to Si, the mode-locked laser is confirmed to have a weak effect on temperature rise and, therefore, to produce a thin molten layer compared to Q-switched Nd : YAG lasers.

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It is expected that an optimum pulse width should exist for pulsed-laser annealing. This will be mainly determined by linear- or nonlinear-optical-absorption coefficient and electron-hole plasma recombination time which dominate a positive feedback[1] of temperature rise. Therefore, it is very important to investigate the influence of laser pulse width and shape on the dynamic behavior of laser annealing. Some works[2–6] have already been reported for the dynamic measurements of the optical reflectivity. In our previous papers,[3,5] we reported that no flat portion of the reflectivity enhancement was observed in ion-implanted silicon under the irradiation of the pulse train from a mode-locked Nd : YAG laser. However, it was found in the present study that a short flat portion less than 200 nsec can be observed under the irradiation of the mode-locked pulse train with higher laser energy density. In this report, we show some features of laser annealing by the irradiation of the mode-locked pulse train, and compare them with the dynamic behavior by the irradiation of Q-switched Nd : YAG lasers.[2]

The amorphous layers of Si GaAs, and GaP were made by ion implantation at room temperature as follows: For sample 1, 100-kV As^+, $1\times10^{15}/cm^2$ in (100) Si wafers of $\sim 15\ \Omega$ cm p-type C.Z.; for sample 2, 120-kV P^+, $5\times10^{15}/cm^2$ in (111) Si wafers of $\sim 150\ \Omega$ cm p-type F.Z.; for sample 3, 70-kV Te^+, $2\times10^{15}/cm^2$ in (100) GaAs wafer with a carrier concentration of $(0.3–5)\times10^{16}/cm^3$; and for sample 4, 70-kV Te^+, $2\times10^{15}/cm^2$ in (111) GaP wafer. The samples were irradiated in air with the pulse train of the mode-locked Nd : YAG laser which has 30-psec pulse width, 10-nsec time separation between pulses, and a train duration of about 150 nsec. The laser mode was a single transverse mode having a Gaussian profile. The diameter of the laser beam was adjusted to be 1.4 mm at the samples. By varying the gain of three optical amplifiers it was possible to continuously adjust the pulsed-laser energy density from 1.0 to 11 J/cm^2, and the corresponding peak intensity from 3.3 to 37 GW/cm^2.

The dynamic behavior of pulsed-laser annealing was investigated by measuring the time-dependent optical reflectivity of the implanted semiconductor surface at 0.63 μm. The monitor beam of 0.63 μm was carefully focused in the area irradiated by the mode-locked laser. The angle of incidence of the monitor beam was around 16° to the normal axis of the surface. The reflected light was detected by a high-speed PIN diode with a risetime of 3 nsec. A high-speed biplanar photodiode (HTV) was used for the trigger of a 400-MHz dual-beam oscilloscope (Sony Tektronic 7844).

The extent of the amorphization by ion implantation and the crystallization by laser annealing was determined by ion backscattering and channeling (RBS) analysis using 2.0-MeV He^+ ions. Proper laser energies were seen to give recrys-

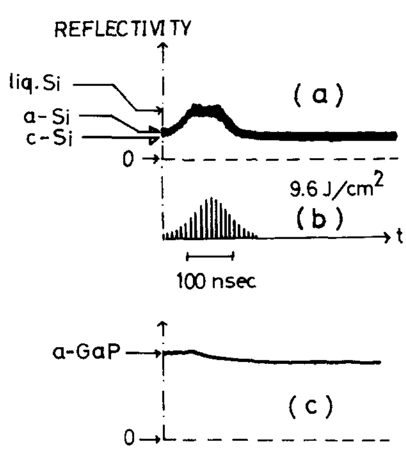

FIG. 1. Typical transient signal (a) of the optical reflectivity at 0.63 μm of Si. Signal (b) indicates the shape of the mode-locked laser which was synchronously observed. The irradiated energy density was 9.6 J/cm^2, and the implanted energy and dose were 100 keV and 1×10^{15} As/cm^2, respectively. Signal (c) indicates a typical transient reflectivity of GaP for irradiation at 4 J/cm^2.

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tallization for all implanted Si and GaAs samples except implanted GaP.

Figure 1(a) shows a typical transient signal of the reflectivity enhancement of ion-implanted Si (sample 1) under irradiation of the mode-locked pulse train at an energy density of 9.6 J/cm^2. The initial level indicates the reflectivity (42%) of amorphous Si at 0.63 μm wavelength. The reflectivity increases slowly with time to the level ($\sim$70%) of reflectivity consistent with liquid silicon[7] and remains at that level for a period of approximately 60 nsec (i.e., a flat portion of the reflectivity enhancement is observed) and then decreases gradually to the final reflectivity level (35%) of crystallized Si before the irradiating mode-locked pulse train finishes. Heating and cooling rates are roughly estimated from the reflectivity rise and fall time to be 3.0×10^{10} and 2.5×10^{10} deg/sec, respectively. It should be noticed that cooling occurs during the irradiation of the mode-locked pulse train, which differs greatly from the behavior under the irradiation of *Q*-switched lasers.[2] This suggests that the 30-psec pulse train has an anomalously weak effect on the growth of the molton Si layer compared to that of the *Q*-switched nanosecond pulse. At an energy density of 7.6 J/cm^2 the reflectivity enhancement was observed but no flat portion was observed for the Si (sample 1), while for the Si (sample 2) implanted with P^+ a flat portion with the duration of 80 nsec was observed at the same energy of 7.6 J/cm^2. The maximum duration of the flat portion was 200 nsec for the Si (sample 1).

Figure 2 shows the reflectivity of an enhancement peak or a flat portion as a function of the laser energy density. The threshold energy for the amorphous-polycrystalline transition is 1.5 and 3.3 J/cm^2 for Si samples 2 and 1, respectively. Above the energy density of 10 J/cm^2, the Si surfaces were

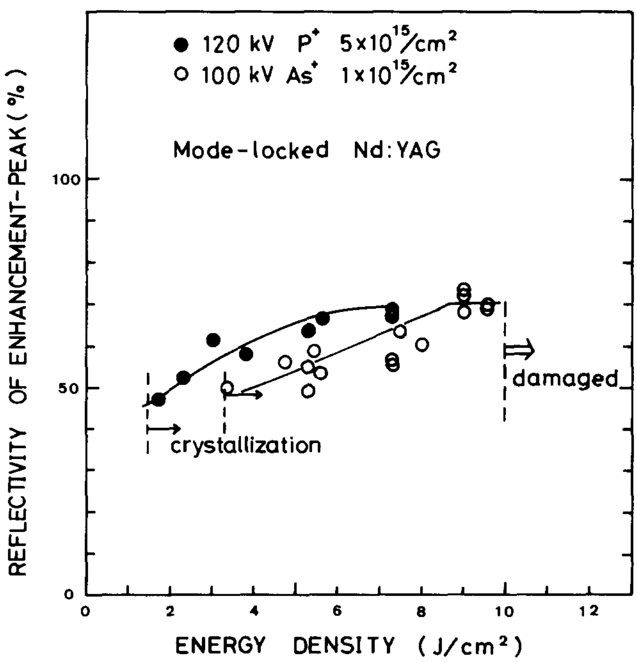

FIG. 2. Reflectivity of the enhancement peak of flat portion as a function of the laser energy density. A difference of the reflectivity between its initial and final levels is observed above the threshold energy at which the crystallization takes place.

visibly damaged. The difference of the laser energy dependence between the two Si samples seems to originate from the difference in the implanted ion species,[8] doses, and/or the thickness of the amorphous layer. The flat portion less than 200 nsec was observed only within very narrow ranges of the energy density, i.e., above the energy of $\sim$7 J/cm^2 for the Si sample 2 and above $\sim$9 J/cm^2 for the Si sample 1. On the other hand, the *Q*-switched laser is known to produce the flat portion of approximately 1 μsec[2,4] with the same energy density (7.6–9.6 J/cm^2). The duration of the flat portion is strongly correlated with the thickness of the molton layer. Auston *et al.* showed that the flat portion of 45 nsec corresponds to a 468-Å thickness of the molten Si layer.[4] Since the maximum duration of the flat portion observed was 200 nsec, the mode-locked pulse train has a much weaker effect on temperature rise and produces a much thinner molten Si layer than the *Q*-switched Nd : YAG laser.

We also performed an irradiation for Si with a single pulse of 30-psec duration selected from the pulse train of the mode locked laser. It was recently stated that using a picosecond Nd : YAG laser, crystalline Si has been made amorphous.[9] However, in this study it was found that the single 30-psec pulse also introduced recrystallization [amorphous to crystalline (a-c) transition] above the laser energy density of 0.9–1.1 J/cm^2 for Si sample 1, which was clarified by time-dependent optical reflectivity measurement and RBS analysis. The maximum duration of the flat portion observed was about 120 nsec. From the reflectivity rise and fall time observed, we estimated the thickness of the molten layer corresponding to the 100-nsec flat portion to be approximately 700 Å.

Although a 30-psec single pulse of the mode-locked laser produces a very high temperature rise compared to a laser pulse of 10-nsec width which has the same energy, after 10 nsec, the temperature will be less in the former case than in the latter. This seems to be due to thermal diffusion during the time separation of 10 nsec between 30-psec pulses, which will weaken the positive feedback[1,5,10,11] of temperature rise. We can estimate the thermal diffusion length to be approximately 6300 Å from $(2D\tau)^{1/2}$, where D is the averaged thermal diffusivity assumed here to be 0.2 cm^2 sec^{-1}, and τ is 10 nsec. This length may be quite larger compared to the penetration depth of 1.06-μm laser beam at very high temperature,[10] which weakens the positive-feedback effect. However, there are also other possibilities: high-density electron-hole plasma produced by a 30-psec pulse with high powers may have a large ambipolar diffusion constant,[12] a reduction in the Auger recombination rate due to the degenerate property of the plasma, or an enhancement of the optical reflectivity.

In addition to both the Si samples, we obtained similar results for the implanted GaAs, but a quite different one for the implanted GaP. GaP showed no significant reflectivity enhancement at 0.63 μm and a very fast a-c transition, as shown in Fig. 1(c). This will be published elsewhere. Before we compared the dynamic behaviors of the a-c transition in implanted Si, GaAs, and GaP, we observed the damaged process by the irradiation at strongest laser energy density.

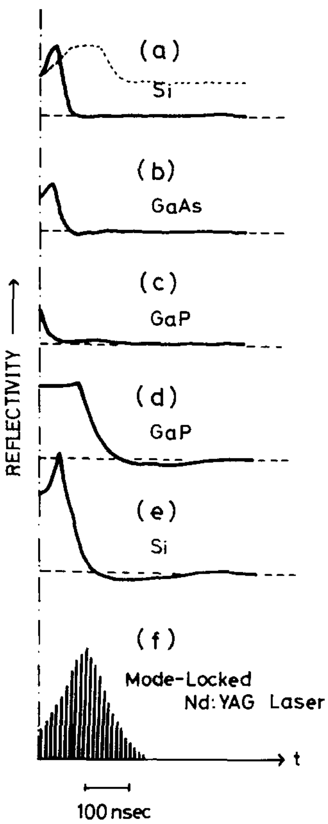

FIG. 3. Typical transient signals (a–e) of the damaged process by the pulse train irradiation of the mode-locked laser. A transient signal corresponding to the crystallization at 9 J/cm^2 is also shown for comparison by the dotted line in Fig. 3(a). Signal (f) indicates a typical shape of the mode-locked laser.

The effect of surface damage was an irreversible reflectivity decrease. The transient signals of the damaged processes are shown in Figs. 3(a)–3(c) for irradiation at ~ 20 J/cm^2, and in Figs. 3(d) and 3(e) for irradiation at the lower energies of 8.6 and 11 J/cm^2, respectively. As to the implanted Si and GaAs, an initially abrupt increase of the reflectivity was observed, followed by a rapid decrease to approximately zero. On the other hand, the implanted GaP showed no increase of the reflectivity before the rapid decrease.

In conclusion, we observed a short flat portion of less than 200 nsec of the reflectivity enhancement under the irradiation of the pulse train of the mode-locked Nd : YAG laser at 7–10 J/cm^2 for Si. It was confirmed that the mode-locked laser has a weaker effect on temperature rise and therefore produces a thinner molten layer than the Q-switched laser. No significant reflectivity enhancement was observed in ion-implanted GaP in either the process of amorphous to crystalline transition or surface damaging, which differs from observations made on Si and GaAs.

[1]K. Murakami, E. Ikawa, K. Gamo, S. Namba, and Y. Akasaka, Appl. Phys. Lett. **35**, 413 (1979).
[2]D.H. Auston, C.M. Sarko, T.N.C. Venkatesan, R.E. Slusher, and J.A. Golovchenko, Appl. Phys. Lett. **33**, 437 (1978).
[3]K. Murakami, M. Kawabe, K. Gamo, S. Namba, and Y. Aoyagi, Phys. Lett. A **70**, 332 (1979).
[4]D.H. Auston, J.A. Golovchenko, A.L. Simons, R.E. Slusher, P.R. Smith, C.M. Surko, and T.N.C. Venkatesan, in *AIP Conf. Proc. of Laser-Solid Interactions*, edited by S.D. Ferris, H.J. Leamy, and J.M. Poate (AIP, Boston, 1978), p. 11.
[5]K. Murakami, K. Gamo, S. Namba, M. Kawabe, Y. Aoyagi, and Y. Akasaka, in Ref. 4.
[6]Y.S. Liu and K.L. Wang., Appl. Phys. Lett. **34**, 33 (1979).
[7]K.M. Shvarev, B.A. Baum, and P.V. Gel'd, Sov. Phys. Solid State **16**, 2111 (1975).
[8]K. Murakami, E. Ikawa, K. Gamo, and S. Namba (unpublished).
[9]R. Tsu, R.T. Hodgson, T.Y. Tan, and J.E. Baglin, Phys. Rev. Lett. **42**, 1356 (1979).
[10]M. von Allmen, W. Luthy, J.P. Thomas, M. Fallavier, J.M. Mackovski, R. Kirsch, M.A. Nicolet, and M.E. Rovlet, Appl. Phys. Lett. **34**, 82 (1979).
[11]T.N.C. Venkatesan, J.A. Golovchenko, J.M. Poate, P. Cowan, and G.K. Celler, Appl. Phys. Lett. **33**, 429 (1978).
[12]D.H. Auston and C.V. Shank, Phys. Rev. Lett. **32**, 1120 (1974).