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Dynamics of Nd:YAG laser annealing of silicon on sapphire

W. Lüthy, K. Affolter, and H. P. Weber
Institute of Applied Physics, CH 3012 Bern, Switzerland

M. E. Roulet
Centre Electronique Horloger SA., CH 2000 Neuchâtel, Switzerland

M. Fallavier, J. P. Thomas, and J. Mackowski
Institut de Physique Nucleaire, F-69621 Villeurbanne, France

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Epitaxial and polycrystalline silicon layers on sapphire have been annealed with Q -switch pulses from a Nd:YAG laser irradiated on the Si surface. Time-resolved optical reflectivity measurements have been performed. The annealing process is shown to be induced by melting and subsequent epitaxial regrowth. The best results were obtained if the whole Si layer was melted, thus allowing the (1 $\bar{1}$ 02) oriented sapphire substrate to act as a seed for recrystallization. In this case commercially available Si-on-sapphire (SOS) wafers with additional Si implantation as well as polycrystalline layers of low-pressure chemical vapor deposited (LPCVD) Si on sapphire could be epitaxially regrown. The same material deposited on amorphous SiO₂ did not show epitaxial regrowth, however an increase in size of randomly orientated grains from 60 nm to 1 μ m could be achieved.

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Thin layers of silicon on sapphire (SOS) are currently used as a basic material for low-power, high-frequency circuitry. Commercial SOS wafers, however, reveal a large number of defects in the region of the Si-sapphire interface because of lattice mismatch between (1 $\bar{1}$ 02) sapphire and (100) Si. The number of defects can be reduced by thermal annealing in a furnace¹ as well as by laser annealing.² In the case of pulse-laser annealing, however, it was not yet known whether melting occurs or not and it was unclear too whether the recrystallization starts from the sapphire substrate or from unmelted Si. In this letter we report on new results which answer these questions in the case of annealing with pulses from a Q -switched Nd:YAG laser irradiated on the Si surface.

Two different experiments were performed in order to detect melting and to clarify the role of the seed. In the first experiment the time-resolved reflectivity of the Si surface at $\lambda = 632.8$ nm was measured simultaneous to the irradiation with a Nd:YAG Q -switch pulse at a fluence of 1–6 J cm⁻². This experiment is based on the fact that molten Si has a metallic reflectivity^{3,4} and therefore a reflectivity rise can be detected if melting occurs. Commercial SOS wafers from Union Carbide with a Si layer thickness of 0.8 μ m were used as target material. To increase the initial absorptivity these samples were implanted with 400-keV Si ions along the $\langle 100 \rangle$ direction with a dose of 10¹⁵ cm⁻² at a dose rate of 10¹¹ s⁻¹ cm⁻². The temperature of the samples during the implantation was not controlled. Annealing of the target material was realized with 30-ns pulses from a Q -switched Nd:YAG laser with approximately a Gaussian beam profile. The experimental setup used for the reflectivity measurements is shown in Fig. 1. The irradiation was performed in ambient air at an incidence of 38°. The irradiated spot on the target was elliptical with diameters at 1/e intensity of 2.8 and 3.5 mm, respectively. The reflectivity of the Si surface was mea-

sured with the aid of 5-mW He-Ne laser beam which was focused to the central part of the Nd:YAG spot irradiated area at an incidence of 7°. The spot size was about 20 μ m. The reflected light with a wavelength of 632.8 nm was detected with an avalanche photodiode (APD). The rise time of the APD was about 20 ns. The light from the laser flashtube and the Nd laser emission (1.06 μ m) was suppressed with a selective filter and a He-Ne interference filter, respectively. The signals from the APD and a fast monitor photodiode (PD) were displayed on a dual beam oscilloscope. The Nd:YAG laser pulse detected by the PD was used as a time reference for the reflectivity measurement. A typical oscilloscope trace obtained in this experiment is shown in Fig. 2. The electrical signal of the APD showed a marked increase during the Nd:YAG laser irradiation. This corresponds to a rise of the Si reflectivity. The high reflectivity lasted for a

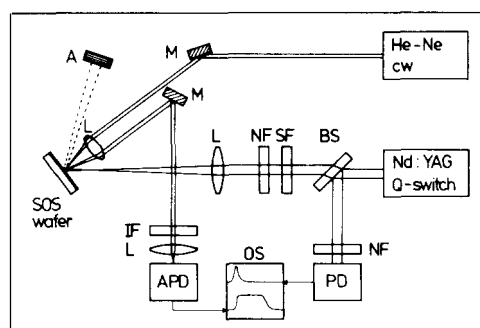


FIG. 1. Experimental setup for the reflectivity measurements. BS = beam split, SF = selective filter, NF = neutral filter, L = lens, A = absorber, M = mirror, IF = interference filter (0.63 μ m), APD = avalanche photodiode, PD = fast photodiode, and OS = oscilloscope.

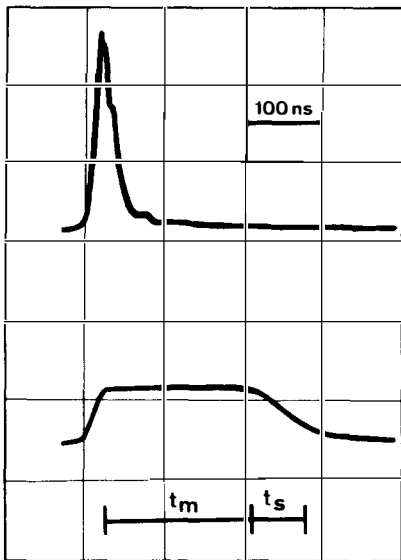


FIG. 2. Typical result of a reflectivity measurement. Upper trace: Signal from the monitor photodiode (PD) showing the temporal shape of the annealing pulse. Lower trace: Signal from the avalanche photodiode (APD) showing the time-resolved reflectivity of the Si surface at $\lambda = 632.8$ nm for a fluence of the annealing pulse of 4.8 J cm^{-2} . t_m is the duration of the melt and t_s is the duration of the decay of enhanced reflectivity.

time interval t_m of several hundred ns, far longer than the Nd : YAG laser pulse. This time interval depended on the fluence of the annealing pulse. This behavior proves that the surface of the sample was molten by the laser pulse. After the period t_m the APD signal did not fall abruptly, but within a time interval t_s of about 65 ns (at approximately 5 J cm^{-2} laser fluence) to a value corresponding to the reflectivity of the resolidified Si. The time interval t_s has been explained by Auston *et al.*^{5,6} as the time which is necessary for the recrystallization front to move through a surface layer of 17 nm corresponding to one skin depth. Therefore the velocity of recrystallization near the surface can be calculated to be about 0.3 m s^{-1} . This velocity is lower than the values determined on bulk Si.⁵⁻⁷ This behavior can be explained qualitatively by assuming that the heat flow through the Si-sapphire interface and through bulk sapphire is less effective than in bulk Si. The duration t_m of the melt one skin depth below the surface as a function of laser fluence is shown in Fig. 3. The measured values of t_m are rather randomly distributed, showing, however, a melting threshold of about 2 J cm^{-2} with a rising tendency of about $80 \text{ ns solidus J cm}^{-2}$. The dashed line gives a least-square linear approach to the measured values. Their high dispersion is not caused by a lack of experimental precision but rather by the annealing with $1.06\text{-}\mu\text{m}$ laser light without preheating as in Ref. 2, which leads to interference effects and thermal runaway phenomena.^{8,9} This assumption is supported by the inhomogeneously annealed spots that resulted.

The value of t_m corresponding to optimum annealing conditions was estimated as follows: The annealed samples reveal a change in color from dark brown to light yellow.

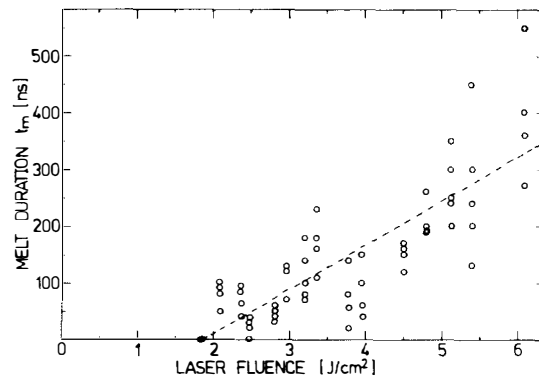


FIG. 3. Melt duration t_m near the Si surface as a function of the fluence of the Nd : YAG laser annealing pulse. Dashed line: linear approach to the measured values.

This change is due to an enhanced optical transmittance in the visible part of the spectrum and allows a rough estimate of annealing performance. The ratio T_a/T_i of transmittance of an annealed (T_a) and an as-implanted (T_i) sample is found to be highest at a wavelength in the region of 430 nm. Correlating the change in color with the duration of melt shows that the best conditions for laser annealing are obtained with pulses that are sufficient to melt the surface for about 250 ns. Melting longer than 300 ns leads to visible damage, whereas at a duration below about 150 ns, the annealed spot reveals only a partial change in color, interpreted as only partial annealing.

In a second series of experiments, the role of the seed was studied. Since Q -switched Nd : YAG laser annealing of SOS involves melting, there are different possibilities for the epitaxial regrowth: does the recrystallization start from the sapphire substrate or from unmolten Si? To answer this question the following experiment was performed: low-pressure chemical-vapor-deposited (LPCVD) polycrystalline Si

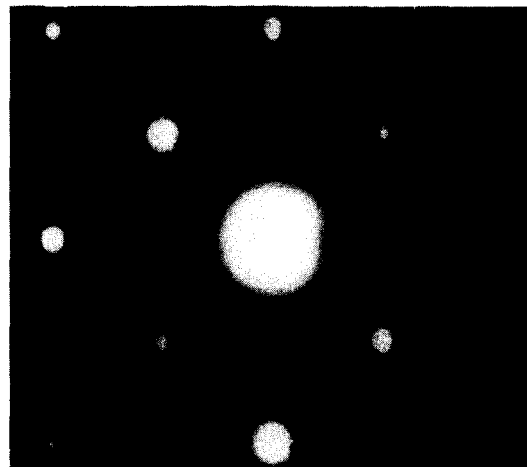


FIG. 4. Electron diffraction pattern of a LPCVD Si layer on sapphire after laser annealing with a 30-ns pulse from the Q -switched Nd : YAG laser at a fluence of 3 J cm^{-2} and after removing the sapphire substrate.

on sapphire with a Si layer thickness of $0.3\ \mu\text{m}$ and a Si grain size typically 50–60 nm was irradiated with pulses of the Nd : YAG Q-switch laser. The irradiated sample was prepared for TEM analysis by locally removing the sapphire substrate (the backside of the sapphire wafer was polished and subsequently ion milled until only the Si layer remained). Electron micrographs of the Si layer as well as electron diffraction patterns have been recorded with a TEM at 100 keV. Figure 4 shows the electron diffraction pattern of a spot annealed at a laser fluence of $3\ \text{J cm}^{-2}$. The pattern reveals an epitaxially regrown layer of (100) orientation over an area of approximately $1\ \text{mm}^2$, corresponding to the central part of the laser beam spot which was 2.2 mm in diameter at $1/e$ intensity. From this experiment we infer that the laser fluence was high enough for completely melting the Si layer and that the sapphire substrate acted as a seed for the recrystallization. This assumption is strongly supported by the fact that in corresponding experiments performed with LPCVD Si layers on an amorphous SiO_2 substrate, no single crystal could be grown at any laser fluence used in the experiments. In this case, however, annealing resulted in an enhancement of grain size from originally about 60 nm up to $1\ \mu\text{m}$.

In conclusion we have shown that laser annealing of SOS with Q-switch pulses from a Nd : YAG laser applied to the Si side involves melting of the Si surface. Therefore the recrystallization starts from the underlying unmelted material. We speculate that for best annealing performance it is therefore necessary to melt the Si layer completely because of the high number of defects in the vicinity of the Si-sapphire interface. In the case of complete melting, the sapphire

substrate can act as a seed for epitaxial regrowth. Moreover we have demonstrated that polycrystalline layers of LPCVD Si on (1 $\bar{1}$ 02) oriented sapphire can be transformed into a single-crystalline Si layer over a dimension of 1 mm by laser annealing.

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