Laser annealing of silicon on sapphire

M. E. Roulet and P. Schwob

Centre Electronique Horloger, a) CH 2000 Neuchatel, Switzerland

K. Affolter, W. Lüthy, and M. von Allmen

Institute of Applied Physics, a) University of Bern, CH 3012 Bern, Switzerland

M. Follavier, J. M. Mackowski, M. A. Nicolet, b) and J. P. Thomas

Institut de Physique Nucléaire et IN2P3, F 69621 Villeurbanne, France

(Received 5 December 1978; accepted for publication 6 February 1979)

Silicon-implanted silicon-on-sapphire wafers have been annealed by 50-ns pulses from a Q-switched Nd:YAG laser. The samples have been analyzed by channeling and by omega scan x-ray double diffraction. After irradiation with pulses of a fluence of about 5 J cm⁻² the crystalline quality of the silicon layer is found to be better than in the as-grown state.

PACS numbers: 61.80.Jh, 81.40.Ef, 79.20.Ds, 68.55. + b

Silicon-on-sapphire (SOS) technology is currently used for low-power high-frequency circuitry. For applications it is important to obtain electrical properties in the epitaxial Si layer comparable to those of bulk silicon with the benefit of an insulating substrate. Specific problems, however, appear, resulting from the heteroepitaxy. Lattice and expansion coefficient mismatches and strains between Si and sapphire lead to an unsufficient crystal quality of the Si layer especially near the interface. These problems cannot be overcome with chemical vapor deposition technique used for SOS fabrication. In order to improve device performance, annealing of the native crystal defects has to be studied. In this paper we report on experiments of laser annealing of SOS.

In our experiments we used commercial SOS wafers from Union Carbide. The 50-μm cm n-type (100) Si layer was 0.8 μm thick. The sapphire substrate was (1102) orientated. The Si layer then was implanted with a scanned 400-keV Si ion beam at (100) incidence with, possibly, a slight misalignment. During implantation the sample temperature was not controlled. Implantation doses ranged from 0.7 × 10¹⁷ to 1 × 10¹⁸ cm⁻² with a dose rate of 10¹⁶ cm⁻² s⁻¹. Channeling experiments with 1.5-MeV He⁺ ions showed that partial annealing occurred during implantation because of induced target heating. Therefore, relatively little damage was left in the silicon layer.

Implantations have also been performed at random incidence with a dose of 2 × 10¹⁸ cm⁻² but at dose rates smaller by a factor of 3. In this case the channeling spectrum showed a buried amorphous layer close to the Si-sapphire interface. In the channeling process the scattering yield was about 90% at the interface and 45% at the surface with respect to the yield at random incidence. Both types of implantation changed the color of the silicon layers from light brown-yellow (typical for a virgin sample) to dark brown-grey.

Annealing was performed using 50-ns pulses from a Q-switched Nd:YAG laser (λ = 1.06 μm) operating in the TEM₀ᵣ mode. The beam was focused to a diameter of 0.3 cm. The samples were mounted on a temperature-controlled heat finger and kept in air. A single laser pulse of a few J cm⁻²

![Graph](image)

**FIG. 1.** Random and (100) energy spectra of 1.5-MeV He⁺ ions scattered at 15° from a 0.8-μm-thick silicon layer on sapphire. Energy-depth conversion: (a) as-grown; (b) 400-keV Si implanted; (c) annealed in a furnace (550°C for 2 h in Ar); (d) laser annealed (5 J cm⁻²; 50 ns; sample temperature before irradiation = 125°C); (e) random.
The spectra in Fig. 2 show annealing efficiencies for different sample temperatures before laser irradiation. The inset gives the decrease of the channeling yield relative to the one of the virgin sample at different depths calculated from the spectra. Channeling stopping power has been roughly approximated by the one for random orientation. No significant difference could be found between the spectra of annealed samples for implantation doses of $0.7 \times 10^{17}$ and $1.0 \times 10^{19}$ cm$^{-2}$ [compare spectrum (d) of Fig. 1 ($1.0 \times 10^{14}$ cm$^{-2}$) with spectrum (c) of Fig. 2 ($0.7 \times 10^{14}$ cm$^{-2}$)]. Experiments with $\omega$-scan x-ray double diffraction on laser annealed samples showed a doubling of the peak reflectivity relative to the value before annealing. The half-width (FWHM) of the diffraction curve was approximately constant and the wings were slightly attenuated. We interpret these results as due to an enhancement of lattice order, giving more coherence in diffraction. As-grown samples gave much the same curves as implanted samples without laser annealing corresponding to the relatively weak modification of the channeling spectrum (cf. Fig. 1). For comparison with laser annealing, implanted samples were thermally annealed for 2 h at 550 °C in Ar atmosphere. Implantation defects were found to be reduced but only the quality of the as-grown state had been reached.

Our experiments show that laser annealing of SOS does not require total amorphization. An important step of our sample preparation is, however, a Si implantation that produces optical absorption centers without heavily damaging the crystallographic structure, for with unimplanted SOS we did not observe any noticeable change in the channeling spectrum after laser treatment.

There are two possible mechanisms for laser annealing: (a) solid phase and (b) liquid phase epitaxial regrowth. Solid phase regrowth is a relatively slow process and seems inconsistent with the transient nature of the short laser pulse. In our case of laser annealing, we rather take into consideration partial or total melting of the silicon layer, the seed being either sapphire or unmelting Si. The role of sample temperature before laser irradiation can be explained by optical absorption mechanisms inherent in Nd : YAG laser annealing of Si. Sample temperature is supposed to be a prominent parameter not only for laser irradiation but also during implantation. It is not yet clear whether the seed for epitaxial regrowth is the sapphire substrate or unmelting Si. Further experiments to clarify this question are in progress.

In conclusion, we have shown that the crystalline quality of SOS can be improved upon the as-grown state by laser annealing. It has turned out that implantation with partial amorphization is necessary to establish optimum conditions for laser treatment. Sample temperature during the implantation as well as before annealing has been found to be an important parameter.

The authors would like to thank Dr. H. Luginbühl of CEH for the ion implantation, L. Simmen, R. Kirsch, and the Atomic Collision Group of the IPN, Lyon, for technical assistance, and Dr. G. Rolland of LETI, Grenoble, for the x-ray double diffraction measurements. One of the authors (M.E.R.) is grateful to Professor W.G. Spitzer of the Univer-
sity of Southern California for helpful discussions on optical properties of implanted silicon. The authors from IAP, Bern, are grateful to Professor H.P. Weber for his stimulating interest in this work.
