Laser annealing of silicon on sapphire

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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 ω-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.

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Silicon-on-sapphire (SOS) technology is currently used for low-power high-frequency circuitry.[1] 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.[2] 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-Ω cm n-type $\langle 100\rangle$ Si layer was 0.8 μm thick. The sapphire substrate was $\langle 1\bar{1}02\rangle$ orientated. The Si layer then was implanted with a scanned 400-keV Si ion beam at $\langle 100\rangle$ incidence with, possibly, a slight misalignment. During implantation the sample temperature was not controlled. Implantation doses ranged from 0.7×10^{15} to 1×10^{15} cm^{-2} with a dose rate of 10^{11} cm^{-2} s^{-1}. Channeling experiments with 1.5-MeV He$^+$ ions[3,4] showed that partial annealing occurred during implantation because of induced target heating.[5,6] Therefore, relatively little damage was left in the silicon layer.

Implantations have also been performed at random incidence with a dose of 2×10^{15} 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 ($\lambda = 1.06\,\mu$m) operating in the TEM$_{00}$ 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}

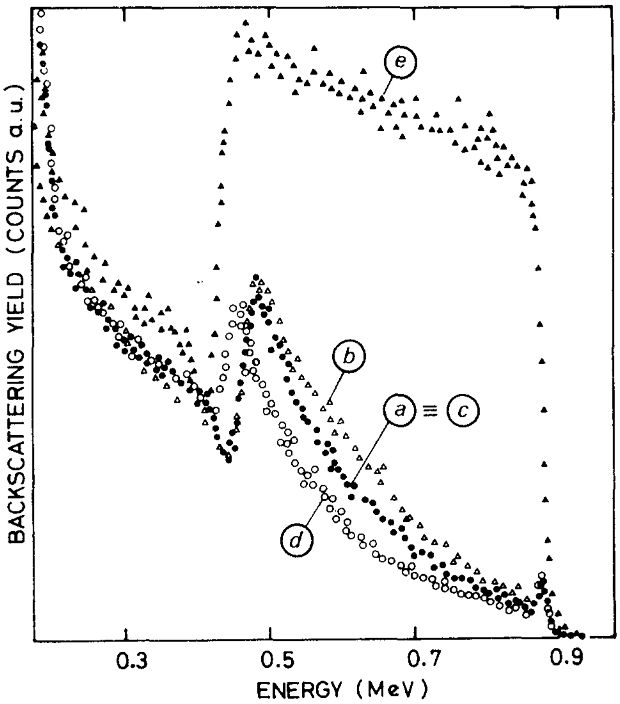

FIG. 1. Random and $\langle 100\rangle$ energy spectra of 1.5-MeV He$^+$ ions scattered at 155° from a 0.8-μm-thick silicon layer on sapphire. Energy-depth conversion ≈ 550 keV/μm: (a) as-grown; (b) 400-keV Si implanted (dose: 1×10^{15} cm^{-2}; dose rate: 10^{11} cm^{-2} s^{-1}; $\langle 100\rangle$ incidence); (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.

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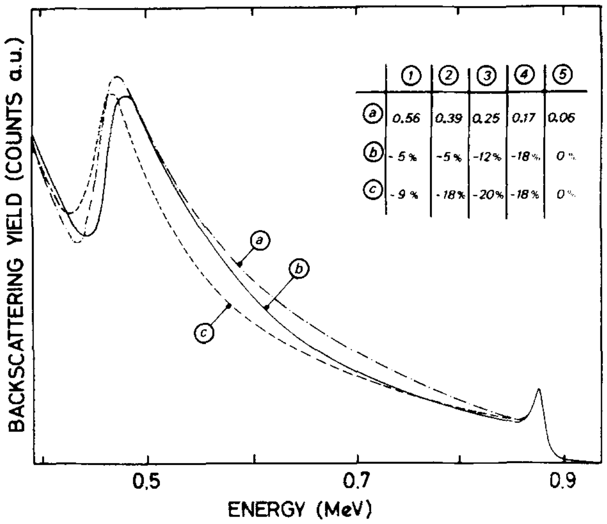

FIG. 2. Energy spectra of 1.5-MeV He$^+$ ions incident in ⟨100⟩ direction and scattered at 155° from a 0.8-μm-thick Si layer on sapphire. The energy-depth conversion is about 550 keV/μm: (a) as-grown; (b) and (c) laser annealed (5 J cm^{-2}; 50 ns) at a sample temperature before irradiation of 20 and 125 °C respectively, after 400-keV Si implantation (dose: 7×10^{14} cm^{-2}; dose rate: 10^{11} cm^{-2} s^{-1}; ⟨100⟩ incidence). The inset shows for (a) the backscattering yield of the virgin sample and for (b) and (c) the deviation of the corresponding spectrum relative to spectrum (a) for various depths measured from the Si-sapphire interface (1: interface, 2: 0.15 μm; 3: 0.30 μm; 4: 0.45 μm; 5: Si surface).

induced a change of color in the irradiated area, the virgin appearance being recovered. In order to obtain a homogeneously annealed area the fluence had to be set within about ± 10%. After irradiation the samples were analyzed by 1.5-MeV He$^+$ channeling along the ⟨100⟩ direction and, some of them, by ω-scan x-ray double diffraction.[7]

We studied the performance of annealing by irradiation from the sapphire side as well as from the silicon side. In the first case, some annealing was observed but found to be insufficient to restore the quality of the as-grown state. This is possibly due to interference effects leading to inhomogeneous heating. These interference effects could not completely be avoided even by immersing the sample into index-matching fluid during irradiation in order to weaken multireflexions in the sapphire substrate. Experimental difficulties were less pronounced if the irradiation was performed from the silicon side. In this case, a homogeneously annealed flat area was found. The result was, however, different for the two types of implantation. In the case of samples implanted at random incidence not even all the implantation damage was annealed. On the other hand, we found for ⟨100⟩ incident implantation that the crystalline quality of the annealed Si layer was improved upon the one of the as-grown material if the sample was kept at 125 °C for irradiation at a fluence of about 5 J cm^{-2}. This is shown in spectrum (d) of Fig. 1. Comparing this curve with the spectrum (a) of Fig. 1 reveals that the annealing effect is more pronounced near the Si-sapphire interface, whereas the surface peak is unchanged. The depth scale has to be referred to the interface and not to the surface because of slight thickness variations in the measured samples.

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 0.7×10^{15} and 1.0×10^{15} cm^{-2} [compare spectrum (d) of Fig. 1 (1.0×10^{15} cm^{-2}) with spectrum (c) of Fig. 2 (0.7×10^{15} cm^{-2})]. Experiments with ω-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.[8] 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 unmelted Si. The role of sample temperature before laser irradiation can be explained by optical absorption mechanisms inherent in Nd : YAG laser annealing of Si.[9] Sample temperature is supposed to be a prominent parameter not only for laser irradiation but also during implantation.[6] It is not yet clear whether the seed for epitaxial regrowth is the sapphire substrate or unmelted 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.

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