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Structure of Crystallized Layers by Laser Annealing of ⟨100⟩ and ⟨111⟩ Self-Implanted Silicon Samples

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Abstract. Channeling effect techniques with a 2.0 MeV He^+ Rutherford backscattering and transmission electron microscopy were used to characterize the crystallized layers after Q-switched ruby laser irradiation of 4000 Å thick amorphous layer on ⟨100⟩ and ⟨111⟩ underlined crystal substrates. At a laser energy density of 2.5 J/cm^2 the crystal layer on the ⟨111⟩ specimen contains a large density of stacking-faults, that on ⟨100⟩ specimen contains a very small amount of screw dislocation lines. High quality single-crystal layers have been obtained after irradiation at 3.5 J/cm^2. From a comparison with the growth rate and defect structure observed in thermally annealed implanted-amorphous layers, we propose that crystal growth by 50 ns pulse laser annealing occurs by melting the amorphous layer.

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Laser annealing has recently been applied to ion implanted Si [1–4]. Electrical measurements show that high doping efficiencies can be obtained [5] although in some cases dopant redistribution occurs [6–8]. The laser-induced transition from amorphous to polycrystalline layers was also demonstrated [9].
Thermal annealing of implanted amorphous silicon shows strong orientation effects [10] and the predominance of twinned regions in ⟨111⟩ samples.
In this work we determined the structure of defects in the crystallized layers by laser irradiation in ⟨100⟩ and ⟨111⟩ oriented substrates. Very low defect density can be obtained in both orientations with an appropriate choice of the Q-switched ruby laser energy density.

Experiment

The samples were prepared from ⟨110⟩ and ⟨111⟩ oriented Si wafers that were implanted at liquid N_2 temperature with ^{28}Si at several energies in the range of 50–200 keV. The thickness of the amorphous layer was about 4000 Å. The ion implantation technique and the silicon ions were used to avoid doping and interface effects. Laser irradiation occurred at room temperature with Q-switched ruby single pulses of 50 ns duration and with energies ranging between 1 and 4 J/cm^2. Channeling effect and backscattering measurements were made with 2.0 MeV He ions. The transmission electron microscope (TEM) was operated at 100 keV. After channeling were made, the samples were thinned for the TEM studies.

Results

The depth analysis of the crystallized layer was investigated by channeling measurements. Typical results are shown in Fig. 1 for both ⟨111⟩ and ⟨100⟩ oriented specimens as a function of the energy density. The aligned spectra for the samples irradiated with 1.5 J/cm^2 coincide with those from the initial amorphous layers (Fig. 1a). These results, indicated an absence of epitaxial growth at the implanted to crystal interface. The aligned spectrum for the ⟨111⟩ sample irradiated at 2.5 J/cm^2 is shown if Fig. 1b. The minimum yield is 12% near the surface and increases to a value of 35% at the implanted to crystal interface. A

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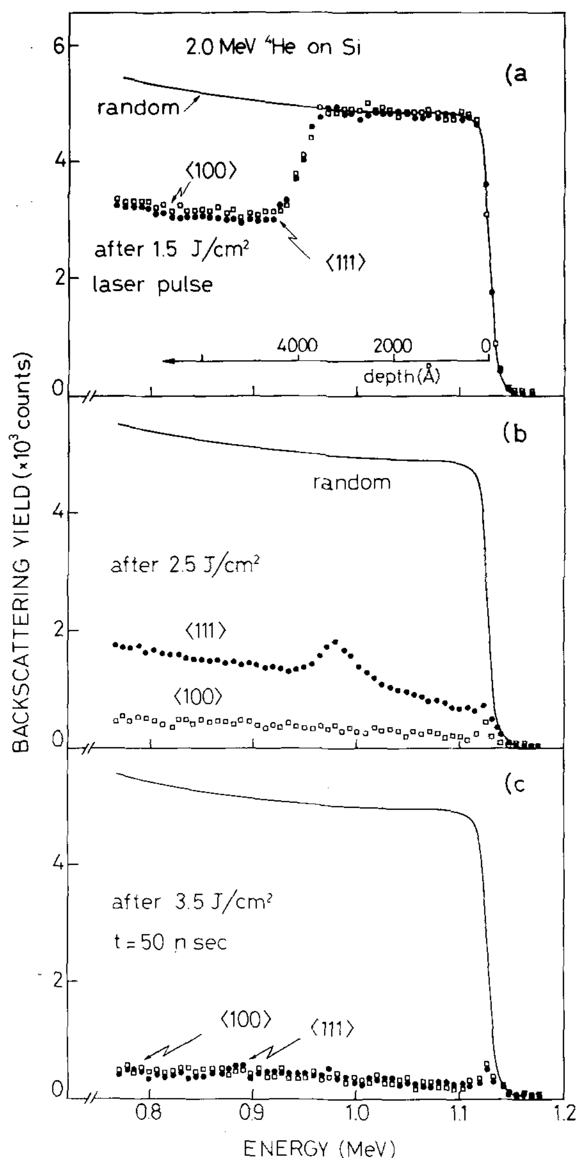

Fig. 1. Random and aligned spectra for 2.0 MeV He^+ ions incident on ⟨100⟩ and ⟨111⟩ oriented Si samples implanted at LN_2 and with an amorphous layer 4000 Å thick. The aligned yields are measured after Q-switched ruby laser single pulse of 1.5 J/cm² (a), 2.5 J/cm² (b) and 3.5 J/cm² (c) energy density, respectively

high concentration of defects should be present as residual disorder. At the same energy density the aligned yield of the ⟨100⟩ crystallized layer (Fig. 1b) is comparable with that of an unimplanted Si sample. From the channeling point of view the layer is practically free of defects. For the ⟨111⟩ sample irradiated at 3.5 J/cm² the aligned spectrum (Fig. 1c) coincides with that of an unimplanted ⟨111⟩ Si crystal. No residual disorder has been also detected by channeling at the interface between the crystallized layer and the underlying crystal.

Channeling measurements, although useful for depth analysis, do not provide easily the structure of defects. They are unable, for instance, to distinguish between amorphous and randomly distributed polycrystalline material. The quality of the irradiated layers was then investigated by TEM.

Transmission electron microscopy (TEM) data indicate that the structure of the crystallized layers depends on the energy of the laser pulse and on the sample orientation. For an energy of 1.5 J/cm² on ⟨111⟩ or ⟨100⟩ Si with an amorphous layer of 4000 Å, polycrystalline layers are formed, as shown in Fig. 2a. The average grain size of the crystallites is about 1000 Å. Amorphous layer becomes polycrystalline with no indication of residual amorphous material. At a higher energy of 2.5 J/cm² the ⟨111⟩ crystallized layer is epitaxial but contains a high density of intrinsic stacking-faults, as shown in Fig. 2b. In the ⟨100⟩ instead about 1/3 of the sample contains screw dislocations with an average density of 5×10^4 cm/cm², as shown in Fig. 2c. Other portions of the sample are essentially free of dislocations.

At 3.5 J/cm² no residual disorder remains in the ⟨111⟩ and in the ⟨100⟩ crystallized layers, as shown in Fig. 2d. The micrograph indicates that the crystal is high quality and the diffraction pattern shows Kikuchi lines.

TEM results agree with channeling measurements, compare for instance the micrograph of Fig. 2b with the ⟨111⟩ aligned yield of Fig. 1b after irradiation with a 2.5 J/cm² pulse. The number of faulted planes has been extimated by channeling following the procedure reported in [11], resulting at about six. The faults are of intrinsic type, i.e. missing one of the abc stacking sequence. The average number of the extinction fringes is about 5.5. The fault plane extends from surface to the depth 4100 Å where the original "amorphous to crystal" interface is. The good ⟨100⟩ aligned yield in Fig. 1b is related to the poor perception of channeling to a low dislocation line density.

The results are summarized in the following Table:

Table 1

Energy density [J/cm²]	Sample orientation ⟨100⟩	⟨111⟩
1.5	Polycrystal	
2.5	Single crystal Screw dislocations	Single crystal Stacking-fault
3.5	Single crystal free of defects	

The amorphous to single crystal transition is observed for both orientations above a threshold energy density of about 2.5 J/cm². Amorphous layers on ⟨111⟩ underlined crystals require an energy density of 20–30% higher than that for layers on ⟨100⟩ substrates to crystallize with a low density of extended defects.

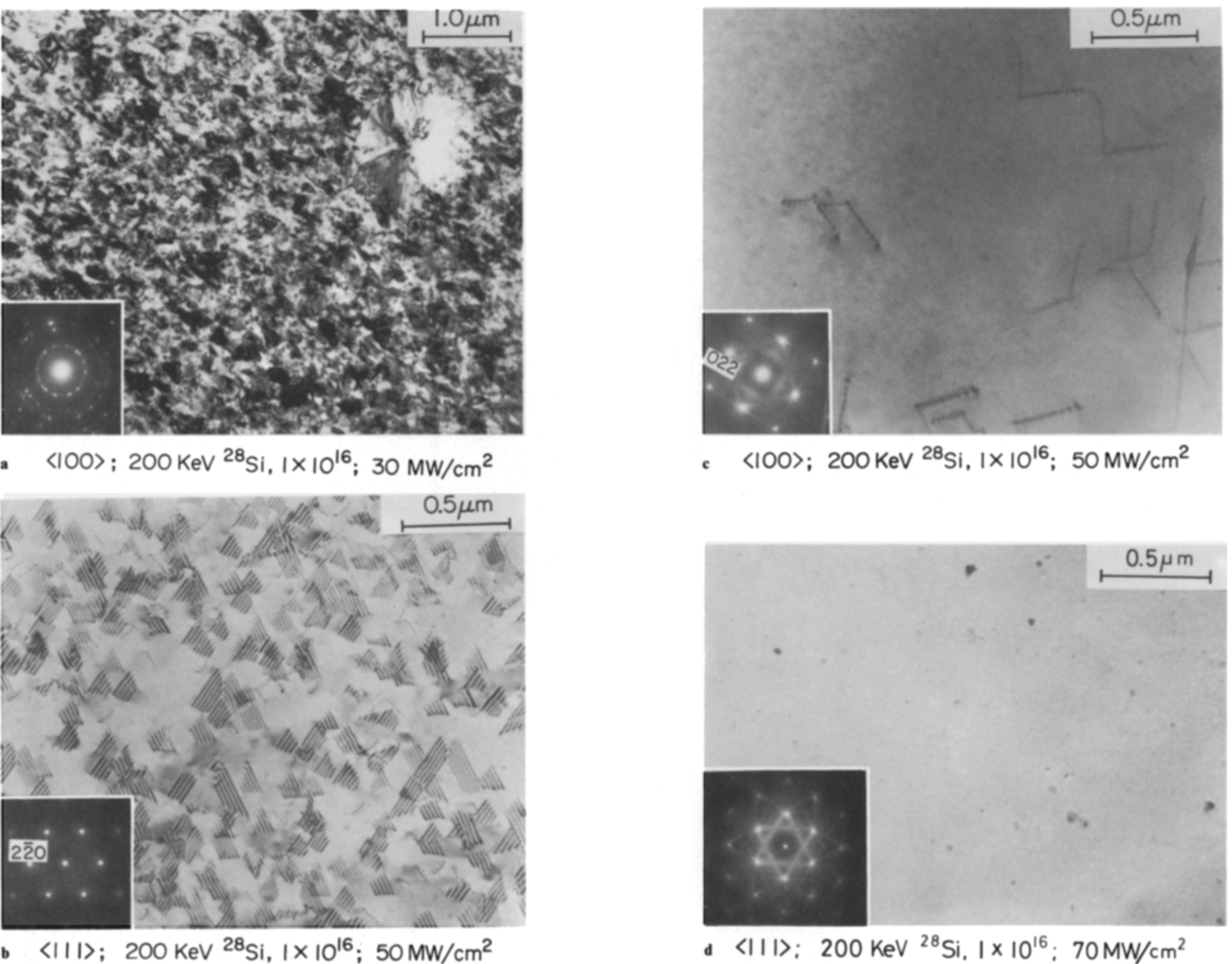

Fig. 2. TEM micrographs and diffraction patterns of a 4000 Å thick amorphous layer on ⟨100⟩ and ⟨111⟩ Si oriented substrates after laser irradiation. (a) polycrystalline grains produced by 1.5 J/cm^2, the diffraction pattern is characterized by rings. (b) ⟨111⟩ crystallized layer with a large density of intrinsic stacking-fault after 2.5 J/cm^2. (c) ⟨100⟩ crystallized layer with screw dislocation lines after 2.5 J/cm^2. (d) single crystal practically free of defects after 3.5 J/cm^2

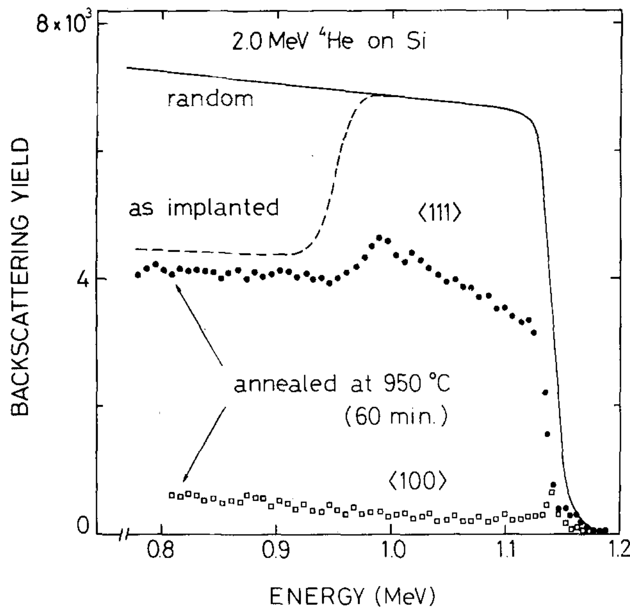

Fig. 3. Random and aligned spectra for 2.0 MeV He^+ ions incident on an as-implanted Si sample. The aligned yields refer to the implanted ⟨111⟩ and ⟨100⟩ substrates after thermal annealing at 950° C for 1 h

Thermal annealing of the implanted layer results in different defects structures for ⟨100⟩ and ⟨111⟩ samples. The ⟨111⟩ implanted specimens annealed directly to 950° C contain 30–40% of twinned regions. Similarly annealed ⟨100⟩ samples are relatively free of defects. Figure 3 shows the aligned spectra from such samples. The high dechanneling rate in the ⟨111⟩ sample has been correlated with the high twin concentration. The aligned yield for the ⟨100⟩ sample coincides with that from an unimplanted specimen. Experimental investigation has shown that the twinned structures in these ⟨111⟩ samples cannot be removed by thermal cycles [12]. These results indicate that there is a difference for amorphous layers on ⟨111⟩ Si between thermal annealing and pulsed laser annealing where twins are not observed.

In thermal annealing the crystallization of the amorphous layer is epitaxial, it is initiated at the amorphous to crystal interface with an activation energy of 2.30 eV [13]. The maximum growth rate in the solid state (i.e. at 1400° C) is about 2×10^7 Å/s. However in pulsed laser annealing, the sample is at "high" temperatures for times of about 10^{-7} s. To grow a 4000 Å thick amorphous layer in 10^{-7} s would require a growth rate of 4×10^{10} Å/s, a value which is orders of magnitude higher than the maximum rate in the solid state.

A simple estimate of the average temperature in a 4000 Å thick amorphous layer irradiated at 2.5 J/cm² in 50 ns indicates that the layer will reach the melting point and change from the solid to the liquid state. This estimate is based on the following numerical values: 53% reflectance [14], absorption given by $\exp(-\alpha x)$ with $\alpha = 6 \times 10^3\,\mathrm{cm}^{-1}$ [15], heat capacity $= 0.89$ J/gK and heat of fusion equal to 1.42×10^3 J/g. These values give 0.25 J required to melt the 4000 Å layer with 10% of the energy absorbed in this layer. Since liquid Si is metallic in bonding, we can use Turnbull's [16] estimate of 10^{12} Å/s for the growth rate of a supercooled metallic liquid in contact with a solid. This growth rate would be sufficient to account for the regrowth of the amorphous layer.

Therefore we believe that the appropriate description of the observed single crystal regrowth of the laser-annealed amorphous layer should be based on a liquid-solid system similar to the concept of quasi-melting advanced by Khaibullin et al. [5]. This concept would also explain the absence of twins in our laser annealed ⟨111⟩ samples since interface instabilities are minimized [17] in a liquid-solid reaction. At lower power densities the amorphous to crystal interface does not become liquid and polycrystalline rather than epitaxial growth occurs.

In conclusion, the results indicate that laser annealing can be used to crystallize relatively thick amorphous layers of Si. By appropriate choice of laser energy, an epitaxial layer with low defect density can be obtained from the implanted amorphous layer. Problems arising in the thermal growth of amorphous layer on ⟨111⟩ underlying crystal can be solved by laser annealing.

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