Epitaxial growth of deposited amorphous layer by laser annealing

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We demonstrate that a single short pulse of laser irradiation of appropriate energy is capable of recrystallizing in open air an amorphous Si layer deposited on a (100) single-crystal substrate into an epitaxial layer. The laser pulse annealing technique is shown to overcome the interfacial oxide obstacle which usually leads to polycrystalline formation in normal thermal annealing.

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It has been recently demonstrated that ion-implanted amorphous layers can be successfully regrown epitaxially on semiconductors by pulse annealing. The required pulses of intense energy are generated by either laser[1–4] or electron-beam radiations.[5] Thermal annealing (in a furnace at ≈one-half of the melting point) of such samples with intrinsically clean interfaces usually also lead to epitaxial regrowth. However, when the crystal—amorphous-layer interface is not free of contaminants as is the case for amorphous layers deposited on single-crystal substrates in a conventional vacuum chamber (10^{-6}—10^{-7} Torr during evaporation), thermal annealing usually leads to polycrystalline, not to epitaxial, growth. To induce epitaxial growth of deposited layers by thermal annealing requires either an interposing metal layer between the amorphous layer and the substrate (solid phase epitaxy)[6] or a clean interface that can be produced by an ultrahigh-vacuum chamber equipped with sputter cleaning and high-temperature annealing (≥ 1000 °C) capabilities.[7] We investigated here the possibility of laser annealing for epitaxial growth of amorphous Si layers deposited on single substrates using conventional vacuum techniques.

Si single-crystal wafers, ⟨100⟩ oriented, were first degreased in organic solvents and were then immersed in a dilute HF solution. The samples were then rinsed in high-purity water and were immediately loaded in an evaporation chamber equipped with ion pumps. Amorphous Si layers 2000—4000 Å thick were evaporated onto the substrates at a rate of ≈40 Å/sec at pressures of $(5-10)\times10^{-7}$ Torr. No high temperature or sputter cleaning of the wafers was applied before the deposition nor were intentional dopants of any kind evaporated.

Samples were then annealed in air with a Q-switched Nd-YAG laser. Two wavelengths of 1.064 and 0.532 μm were used. The pulse was approximately Gaussian in time with a pulse duration of ~20 nsec (FWHM). The beam diameter was about 5 mm (measured from $1/e$ of the maximum intensity). After exposure to single pulses of laser irradiation at various energy densities, the samples were examined by MeV He ion channeling and transmission and scanning electron microscopy.

It was found that a layer of 3800 Å evaporated Si on a ⟨100⟩ Si substrate can be transformed into an epitaxial layer by a single pulse of laser radiation ($\lambda = 1.064$ μm) at delivered peak energy densities of 2.5 and 5 J/cm^2. Figure 1 shows the backscattering spectra for such a sample before and after laser irradiation at 5 J/cm^2. The dotted line denotes the backscattering yield from the as-deposited sample where the analyzing He ion beam (1.5 MeV, beam area ~1 mm^2) is aligned with the ⟨100⟩ direction of the substrate. The amorphous Si layer has a higher backscattering yield than that of the single-crystal substrate. The channeled backscattering yield from the sample after laser anneal (closed circles) is much lower than that of the amorphous Si. The channeled backscattering yield suggests complete epitaxial growth of the amorphous Si layer. The near-surface minimum yield (χ_{min}) is ≈5.9% (as compared to 3.5 to 4% in virgin crystals) and changes slightly as the ion beam scans across the laser beam spot. There is also a higher concentration of scattering centers near the original amorphous/crystalline interface. Examination of the sample surface after annealing by SEM showed that the surface is essentially flat. In some areas the surface showed small ripples, giving the appearance of frozen liquid.

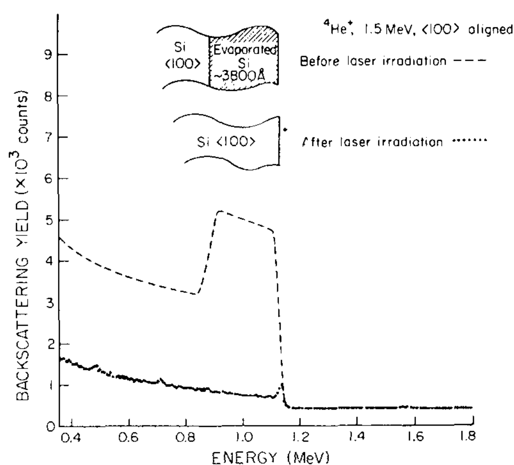

FIG. 1. Backscattering spectra from a sample before and after laser irradiation. The sample consisted of an amorphous Si layer (~3800 Å) evaporated onto a (100) Si wafer. The incident energy of the Nd-YAG laser ($\lambda = 1.064$ μm) was 5 J/cm^2 with a pulse duration of ~20 nsec (FWHM). The analyzing beam (^{4}He$^+$ at 1.5 MeV, beam spot ~1 mm^2) was aligned with the ⟨100⟩ direction of the substrate.

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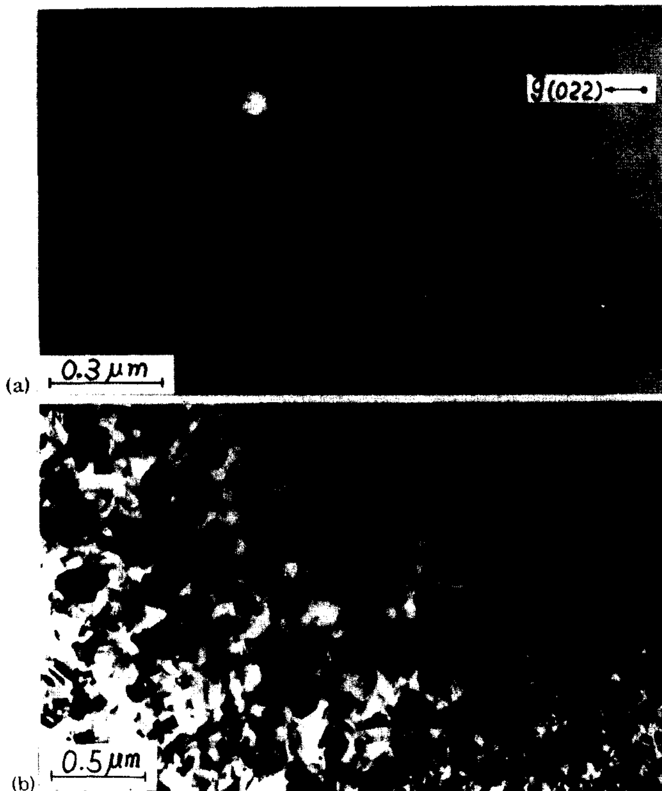

FIG. 2. Transmission electron micrographs of a similar sample as shown in Fig. 1, but irradiated with energy of 2.5 J/cm^2. (a) The central area of irradiated spot shows a single crystal with a few dislocations. The dislocation extends to the depth of five (220) extinction fringes (5× 757 Å). This is equivalent to the original amorphous Si thickness. (b) The area near the edge of irradiated spot shows polycrystals. The grain size decreases as the laser incident energy drops near the edge of the beam spot, i.e., left to right in the micrograph.

Transmission electron microscopy investigation indicated that the epitaxial layer obtained at 5 J/cm^2 is essentially free of planar defects and showed the presence of dislocations in some areas. At a delivered energy of 2.5 J/cm^2, we found that the rippled surface area is much less than that for the sample irradiated at 5 J/cm^2. Transmission electron microscopy on this sample shows epitaxial growth of the amorphous layer in the vicinity of the center of the laser beam spot with a few dislocations apparently emitting from the original Si(a)/Si(xtal) interface [Fig. 2(a)]. As the region of observation moves away from center to the edge of the laser beam spot where the incident energy of the laser drops, TEM studies showed a transition of epitaxial growth to polycrystals and that the grains become smaller near the edge area of the laser beam spot [Fig. 2(b)]. From this observation, it is apparent that a certain energy density is required to induce epitaxial growth. It thus seems feasible to grow layers larger than the laser beam spot by sequential exposure of adjacent areas. This conclusion is in agreement with laser annealing results obtained from epitaxial growth of ion-implanted layers.[8-10] It is interesting to note that laser irradiations with $\lambda = 0.532$ μm and a maximum delivered energy density of 0.76 J/cm^2 only induced polycrystalline formation and not epitaxial growth.

In summary, we have demonstrated that a single pulse of laser irradiation of sufficient energy is capable of recrystallizing a deposited amorphous Si layer (~4000 Å) into an epitaxial layer. The deposited was carried out in a conventional dry pumping chamber ($\sim 10^{-6}-10^{-7}$ Torr) without the use of sputter cleaning and/or high-temperature decomposition of the substrate surface. Normal thermal annealing of such a deposited layer will lead to polycrystalline formation due to the presence of native oxide and/or other contaminants near the amorphous/crystalline interface. We speculate that the short energy pulse produces sufficient undercooling near the Si(a)/Si(xtal) interface that homogeneous nucleation of epitaxial Si is the primary process of recrystallization and overshadows heterogeneous nucleation of Si crystallites of random orientations at impurity nucleation sites.

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