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Laser Recrystallized SOI

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Si-on-insulator (SOI) technology has developed rapidly in recent years. Most techniques concentrate on transformation of polycrystalline Si films deposited on dielectric coated (SiO_2 or Si_3N_4) crystalline Si wafers by radiation sources. In this paper, the major recrystallization methods are discussed, with emphasis on laser-irradiated SOI structures. Discussion focuses primarily on crystal growth related phenomena, since a reliable SOI technology must be established to obtain device-worthy crystal quality.

§1. Introduction

In recent years, Si-on-insulator(SOI) has been identified as an alternative to Si-on-sapphire (SOS)[1-4], because it overcomes such drawbacks as substrate cost and poor interface characteristics between the Si and sapphire. The most popular insulators used in this system are dielectric coated (SiO_2 or Si_3N_4) crystalline Si wafers. Poly or amorphous Si films deposited on such insulators are locally melted by irradiation with lasers, electron beams, arc lamps or strip heaters. Most techniques now concentrate on the transformation of poly or amorphous films into large grained or single crystallized ones through the use of such radiation sources.

This paper discusses the major recrystallization methods, with emphasis on laser irradiated SOI structures. In order to develop a reliable SOI technology, growth conditions that produce device-worthy crystal quality must be established. Therefore, this discussion will focus particularly on the crystal growth related phenomena.

§2. Recrystallization Methods

Recrystallized results r[illegible]ed up to now are compared in Table 1. Th[illegible]rences in grain size and single crystal length obt[illegible] are due to the differences in heat flow i[illegible] on the films by the different laser irradiation methods. To date, scanned cw Ar laser is the most widely used to achieve long range seeded crystallization on insulating films. In the following sections, we will discuss in more detail the results obtained using this method.

Table 1 Recrystallization results for deposited poly-Si films on SiO_2 by different types of laser irradiation.

methods \ modes	grain growth size	lateral growth length
stationary pulse	150 nm [5]	3 μm [6]
scanned pulse	5 μm [7]	
scanned cw	20 μm [8]	500 μm [9]

§3. Lateral Seeding Growth

3.1 Effect of seeding

Continuous single crystal film formation on both Si and SiO_2 can be achieved under optimum scanning-speed and laser energy conditions. However, in spite of realizing complete melting of the poly-Si on SiO_2, the poly-Si on Si often does not melt. This is due to a large thermal conductivity mismatch between the Si (seeding region) and the SiO_2 (seeded region). Even in this case, however, seeding from a localized area at the oxide window edge effectively acts on the lateral growth of a deposited film on SiO_2[6,10]. This result is clearly shown in Fig. 1, which was obtained from samples irradiated with lower energy than that used

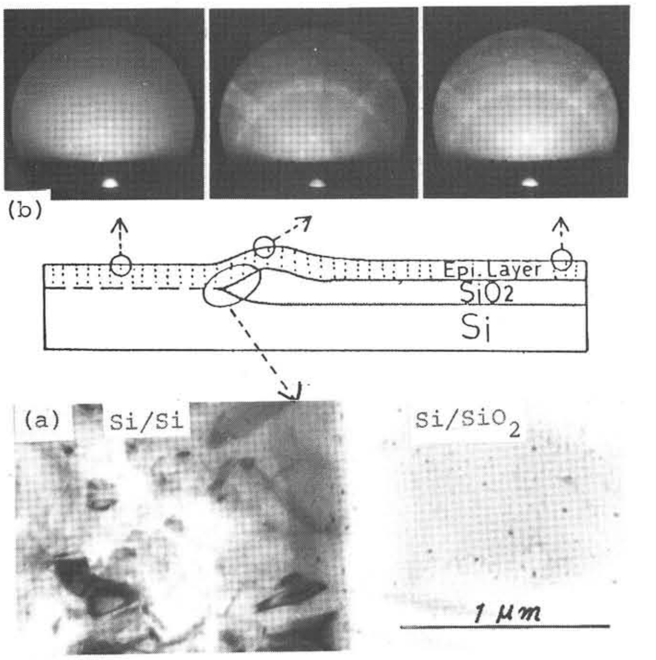

Fig. 1 Seeding effect from a small seeding area. (a) TEM micrograph showing growth differences in laser-irradiated poly-Si between Si and SiO_2. (b) Schematic illustration corresponding to Fig. 1(a) and µ-RHEED observation results.

in the optimum case.

The TEM micrograph of Fig. 1(a) shows the result of producing a continuous sheet of Si film on SiO_2, in contrast to the fine grained structure of poly-Si on Si. The corresponding schematic illustration for Fig. 1(a) and the µ-RHEED (microscopic reflection high-energy electron diffraction) observation results are shown in Fig. 1(b). The µ-RHEED technique makes analysis of a very small area of 0.1 µm[11] possible using a field emission electron source with a probe beam focus of 0.1 µm. As clearly shown in Fig. 1(b), the diffraction patterns obtained for both Si/SiO_2 areas and the Si/window vicinity are the same ones. Detailed analysis of these patterns identified a substrate orientation of (100) 4° off the axis. These results clearly indicate that seeding from the substrate is essential for forming single crystal Si over the SiO_2.

Now let us look at the effect of seeding on macroscopic lateral growth. Figure 2 shows optical micrographs obtained by a one-line scan from the seed areas to the SiO_2 areas. As shown in the figure, single crystallized areas with almost regular triangles are observed on the Si/SiO_2 regions close to the seeds, regardless of beam diameter,

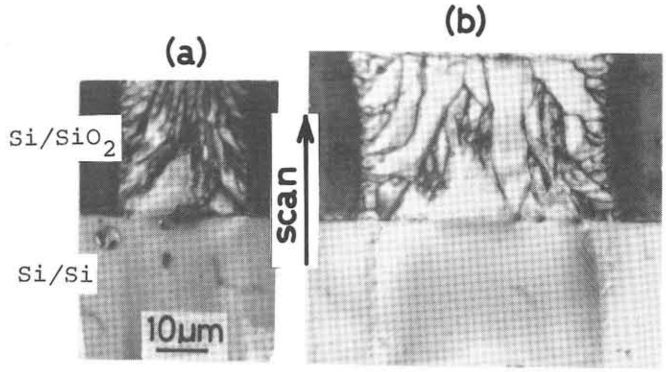

Fig. 2 Optical micrograph of a laser-irradiated sample scanned from seed to seeded area. (a) beam width: 20 µm (b) beam width: 50 µm.

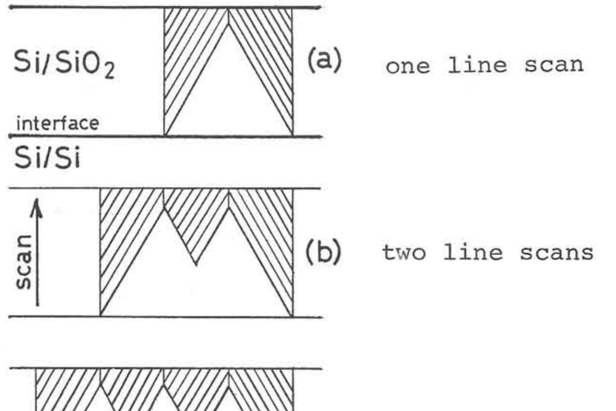

Fig. 3 Schematic illustration of recrystallization patterns of Si films on SiO_2 obtained by repeated scanning of Fig. 2. Beam overlapping: 50%.

although chevron structures are formed on other Si/SiO_2 areas. Therefore, if we repeat this scanning with 50% beam overlapping, this triangle area also acts as a seed for the following recrystallization process. As a result, schematic illustration can be drawn for the state of crystallization on the Si/SiO_2, as shown in Fig. 3. Thus, in the case of irradiation by normal Gaussian beam, the effect of seeding can be expected to produce lateral epitaxial films without grain boundary formation within the beam diameter distance extending from the boundary between the Si/Si and Si/SiO_2.

3.2 Residual defects

Si layers on SiO_2 Common defects remaining in recrystallized Si films on SiO_2 are dislocatons, grain boundaries (dislocation coalescence), twins and elongated stacking faults. Of these defects, dislocations are the most common and important ones. This is because they become degradation sources in devices made in the SOI film, and dislocation clusters result in formation of grain boundaries.

The dislocation formation mechanism has been discussed by Pinizzotto et al[12]. They propose a 9% volume expansion occuring during the Si transition from liquid to solid as the main cause of dislocation generation in SOI films. Also, in the laser irradiation process, the liquid phase is very short (- msec) and the substrate temperature is rather cool (- 400°C). Accordingly, these factors induce large lateral strains in the solidified material. This stress build-up produces dislocations and eventually, high-density dislocation coalescence. As a matter of a fact, although longitudinal strains exist in the material, the stress gradient is considered to become maximum at a position deeper than the deposited film thickness($\geq$1 μm), as discussed in the next section. Therefore, this vertical strain is not the primary cause of dislocation generation in the films considered here.

Stability of the interface between recrystallized Si and SiO_2 should be studied from the view point of bond matching through the interface. Biegelsen[4] noted that Si(100) planes easily bond with SiO_2, resulting in minimum bonding energy. However, in solid phase epitaxially grown SOI films, high density dislocation generation, which may be considered to be induced by mismatch stress at the interface, has been observed[13, 14]. More detail analysis of the bonding arrangement at the interface between Si and SiO_2 is necessary using both theoretical models and experiments.

Si layers on Si Severe dislocations are also generated in laser-epitaxially grown Si layers on Si substrates. Kamins et al.[15] and Minagawa et al.[16] have pointed out that slip dislocations parallel to the wafer surface are generated several microns beneath the substrate surface. Figure 4 is a cross section TEM micrograph showing depth distribution of dislocations in the sample. From dislocation contrast analysis, the deep lying <110> dislocations were found out to be of 60° type with a/2 <110> Burgers vectors. This result strongly suggests that the dislocations were introduced by slipping due to the large vertical thermal stress. The vertical thermal gradient induced by cw scanned

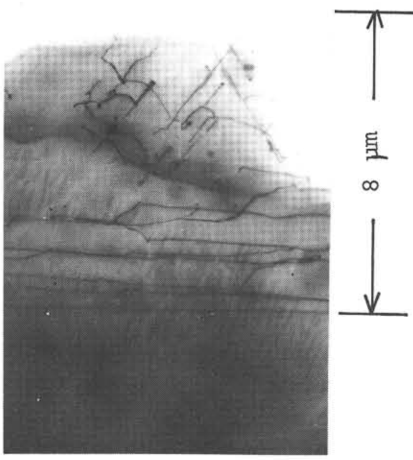

Fig. 4 Cross section TEM micrograph showing depth distribution of dislocations.

laser melting is considered to be the largest several microns from the surface, as suggested by this result.

Such dislocation generation can be controlled if we use Si epitaxial growth on Si substrates by thermal decomposition of SiH_4. In this case, since the laser power is much less than for completely melting poly-Si films deposited on both Si and SiO_2, we can expect thermal gradient reduction to be associated with the laser melting process. That is, deep-lying dislocation generation can be controlled.

§4. Growth Control

Many methods of obtaining larger SOI regions without boundary formation have been proposed. In this section, we briefly discuss some of them.

4.1 Beam shaping

If films uniformly deposited on SiO_2 are irradiated with a Gaussian laser beam having a circular melt zone, grain growth is usually observed in the scan direction. This growth phenomenon is caused by the boundary propagation perpendicular to the moving soli-liquid interface with the scanned beam. In this case, first nucleation of grains occurs at the side edges (cooler than the center) of the molten zone. This effect can be eliminated if irradiation is carried out using a laser beam having a concave trailing edge. This was first suggested by Biegelsen et al.[2] Additionally, control of temperature gradient obtained by beam shaping into a half-circle[17], a slit[18] and a doughnut[19] has also been proposed. Larger grain sizes with the preferred orientation and improved smooth surfaces have been obtained in these experiments.

4.2 Beam scanning

There are two types of lateral seeding. One is scanning parallel to the interface between the Si/Si and Si/SiO_2 (traverse seeding[20]). The other is scanning perpendicular to the interface (longitudinal seeding[20]). Transverse seeding yields a larger SOI area than longitudinal seeding does. This can be explained as follows: In the circular laser spot transverse scanning has a larger isothermal radius in the scan direction than longitudinal scanning due to elongation of the molten zone in the scan direction. Therefore, lateral seeding crystal growth normal to the solid-liquid interface is favored more in transverse seeding. Celler et al.[9] obtained SOI areas as large as 50 x 500 μm using a combination of transverse scanning and modified seed structure. Rapid scanning of a circular beam in an oscillatory fashion in the direction of growth has also been successfully applied to obtain larger SOI areas[9].

4.3 Sample structure

The laser melting process often induces such problems in recrystallized Si films on SiO_2 as random cracking, thermal detachment and mass flow, due mainly to the difference thermal expansion coefficients of Si and SiO_2. In order to eliminate this effect, patterning the deposited films into islands and dielectric film encapsulation on the films have been discussed[2-4]. These are also intended to produce wider optimum irradiation conditions by controlling the optical power absorbed in the sample[21, 22]

§5. Conclusion

CW visible laser adaption is one of the best choices, at the present time, to obtain crystalline Si on dielectric film-deposited substrates having previously diffused junctions. A number of sophisticated devices have been successfully made in SOI structures formed by this laser irradiation technique. However, there remain many problems to solve. Among them is the crystal growth phenomenon that accompanies the localized melting process. Particularly, control of defect formation and enlargement of the SOI area are current problems. Moreover, SOI structure application for stacked device fabrication requires low-temperature processing to reduce interference between mutual devices. In this scheme, we should clarify the limits of application for laser-assisted lateral epitaxial process melting characteristic.

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