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RECRYSTALLIZATION OF Si ON INSULATING SUBSTRATES BY USING INCOHERENT LIGHT SOURCES

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Résumé:
Cet article passe en revue les différents résultats obtenus dans la réalisation de films minces de Silicium déposés sur un substrat isolant et recristallisés à l'aide de faisceaux de radiations incohérentes. Ces systèmes de recuits utilisent soit des rubans de graphite chauffés, soit des lampes à halogène ou à arc. Dans tous les cas, on obtient de grandes surfaces monocristallines de silicium orientées <100>. Les études actuelles portent sur l'élimination ou la localisation volontaire des défauts résiduels (sous-joints de grains, précipités).

Abstract:
This paper reviews the main results obtained to date in the recrystallization of thin Silicon On Insulator films by means of incoherent light sources. Different sources such as graphite heaters, halogen tungsten filament lamps and mercury arc lamps have been investigated. Large area monocrystalline <100> Si films have been obtained using these various means. The defects remaining in the films are discussed, i.e. grain and/or subgrain boundaries, precipitates and strain. Electrical measurements are also reported. Current research is devoted first to the design of appropriate set-ups and shaping of the energy beams and, second, to film patterning in an aim to reject grain boundaries out of the active areas of devices.

INTRODUCTION
Crystalline films of Si on insulating substrates (SOI) are of great interest for numerous applications. They are of special interest in the field of VLSI circuitry which demands high-performance single-crystal films on insulating substrates.

In this paper, we will focus on the more recent developments in research in this field of application. As compared to bulk silicon VLSI, SOI material is expected to lead to an increase in both the speed of MOS transistors and the density of integration in circuits. The speed of MOSFETs is mainly affected by parasitic capacitances resulting from interconnections on field oxides whereas higher density is hindered by the necessity of isolating transistors from one another. Silicon-on-sapphire (SOS) first seemed a means of overcoming these drawbacks, owing to its insulating features /1/. Nevertheless, it has not had the expected commercial development, because of the high cost of sapphire substrate and indeed the poor Si/insulator interface. As a result of lattice mismatch and a difference in thermal
expansion coefficients, SOS devices characteristically have low mobilities and high leakage currents. Replacing the poor Si/sapphire interface by the long-used and studied Si/SiO₂ interface should provide an adequate substrate if defect-free single-crystal Si films can be grown on SiO₂. A wide variety of techniques have therefore been investigated /2-5/. These can be divided into two groups: first, those involving crystallization in a solid phase; second, those in which silicon is recrystallized from the melt. Melting is obtained via heating a deposited polysilicon film with an energy-beam (electrons or photons). After a review of the main techniques currently being investigated, we will present the results and problems encountered in zone-melting recrystallization of Si on insulating substrates by using incoherent light from lamp- or carbon strip-heaters.

I. SOI FROM THE SOLID PHASE

Most industrial laboratories working on LSIs would like to be able to obtain device-worthy SOI in a way as compatible as possible with their usual semiconductor processes. They have, accordingly, investigated different techniques for processing wafers without going through the liquid phase. Moreover, the solid phase seems more promising for 3-D integration of circuits, thanks to reduced thermal stress and a low temperature more compatible with the other processing steps.

1. The Epitaxial Lateral Overgrowth (ELO) technique /6/ utilizes a classical CVD process for growing silicon by epitaxy through openings etched in the SiO₂ layer of an oxidized silicon wafer. A silicon film is deposited at 1000-1150°C in a series of growth steps, each one being followed by an etching step (in a mixture of HCl and H₂) to prevent the random nucleation occurring at the edges of the openings and on the SiO₂ surface. The silicon epilayer grows up through the channel openings and then proceeds to expand laterally over the SiO₂ mask.

2. It is also possible to obtain a buried oxide layer by Implantation of Oxygen into a Si-wafer (SIMOX) /7,8/. This dielectric isolation provides an abrupt Si/SiO₂ interface. Subsequent thermal annealing will improve the Si/SiO₂ interface quality. So far, this technique has been limited by the time required for processing industrial wafers and the need for high flux implanters.

3. An electrochemical technique also seems promising for obtaining Si islands on SiO₂. By anodically etching silicon in a hydrofluoric acid (HF) electrolyte, one gets a porous silicon (FIPOS) /9,10/. Subsequent oxidation, properly carried out, results in a complete dielectric isolation of predetermined monocrystalline silicon regions. The size of the islands can be controlled by a difference in the anodization and oxidation rates between differently doped materials.

II. RECRYSTALLIZATION FROM THE MELT

A large amount of work has been devoted to this means of crystallization because of its similarity with the zone-melting technique widely used in growing and zone-refining single-crystal silicon ribbons /11/. However, as Hurle has said /12/: "The growth of good quality single crystals from the melt is still an art as well as a science ".

Since Gat et al. /13/ showed that a scanned cw laser beam could significantly increase the grain size of polysilicon through local melting of the film, beam crystallization of SOI from the melt has been the subject of numerous investigations. Fig. 1 shows the range of time durations accessible with the presently available energy beams. They correspond to different molten state durations related to the dwelling time of the scanned beams. One can notice that they differ by many orders of magnitude from lasers to lamp-heaters, leading to large differences in quenching rates. The influence of both the diffusion of impurities and the temperature gradients will therefore be far different from one technique to another.

Fig. 1: schematic showing the range of dwelling times accessible with different heat sources.

Pulsed beams have been used to grow grains of silicon on low cost transparent substrates owing to a rapid quenching which prevents heat from being transferred to the underlying substrate. The fast scanning (≥m/s) of a cw laser has also been used in this type of application /14/. However, because of the poor electrical quality of the resulting material, namely low mobility resulting from the high density of grain boundaries, these techniques have not been applied to the growth of suitable material for VLSI. cw laser- and electron-beams scanned at a moderate speed (∼10 cm/s) are therefore today competing with cw lamp- or graphite strip-heater-systems for the production of high quality single crystal films.

The coherent nature of the energy beams has not proved to be an absolute necessity for achieving local zone-melting. The advantage to using coherent radiation is that it becomes possible to adjust the energy to fit the absorptivity of the material being treated, in order to melt it down to a desired thickness, without significantly affecting the surrounding or underlying material. This technique therefore shows potential for eventual multilayered structures in 3-D integrated circuit applications. In cases where the underlying layers or substrates support being heated up (∼1400°C), the sample will be preheated, thereby increasing the absorption coefficient and broadening the absorption spectrum. Whatever the heat source used, the silicon film is molten within a narrow zone or band which is scanned across the sample.

Temperature gradients following the moving molten zone bring about growth of silicon grains at the liquid-solid interface after a competition between random nuclei. If the beam is circular, and if the growth rate along the interface is constant, grains propagate at right angles to the interface, resulting in
the famous "chevron-like" structure /13/. Consequently, beam shaping to produce a concave trailing edge will result in grains growing outward towards the scanned line boundaries /15/.

Problems arise when the melting of a zone occurs in a continuous film: the local change in density associated with melting induces surface-tension gradients and mass-transport, resulting in a rippling of the thin film surface /16/. Moreover, liquid silicon does not wet SiO2 well. It therefore tends to agglomerate into droplets when the surface tensions are too great for instance when the molten zone becomes overly wide. Kamins /17/ has shown that in the case of a scanned cw laser where the dwelling time is on the order of 1 msec., a 60 Å Si3N4 layer on top of the poly-silicon is sufficient to maintain satisfactory smoothness of the recrystallized film. In the case of incoherent radiations, the dwelling time is on the order of 1 sec. and the molten zone is fairly broad; a more substantial cap layer is therefore required. It has been shown /18/ that a 1-2 μm thick SiO2 encapsulant layer is necessary for achieving surface flatness and sometimes a 300 Å thick Si3N4 layer on top of that provides better wetting of liquid silicon on the underlying SiO2 /19/. Fig. 2 (upper left) shows the final multilayered structure commonly used to recrystallize the poly-Si films.

![Diagram](image)

**III. INCOHERENT RADIATION SYSTEMS**

Since zone melting was first described /20/, numerous heating techniques, such as resistance and inductive heaters, have been experimented with, in order to achieve zone melting. Their development for the growth of single-crystal germanium or silicon ribbons has been extensive. In 1963, Maserjian /21/ used a scanned electron-beam to recrystallize a Ge-film on an insulating substrate. Recently, Fan et al. /22/ have applied the same basic technique to the crystallization of thin films of SOI. The configuration of their system is shown in Fig. 3. The sample is placed on a stationary graphite sheet with the poly-Si film facing up. The sheet is resistively heated up to 1100-1300°C and preheats the sample. The additional amount of energy necessary to melt the poly-Si film in a narrow zone is provided by a movable graphite heater (1 mm wide) positionned above the sample.
We have applied the same principle but used halogen lamps instead of graphite heaters /24/. They offer several advantages. The first is that the heaters are not in close contact with the samples which eliminates the risk of contamination. It allows a reduction in volume of the processing chamber and more freedom with the ambient atmosphere, since the samples only are placed in it. Moreover, given the optical nature of the energy beam, the spot can be handled with optical devices and thus any desired shape can be easily induced in the molten zone (see Fig. 2). Fig. 4 shows the configuration described in Ref. 25, that we have used to recrystallize SOI. For thermal insulation, the sample is placed horizontally on three ceramic pins. We have used 150 W halogen lamps having their filament at one focus of a built-in ellipsoidal reflector. Their emission is in the range of the solar spectrum, with a peak around 0.8 µm. One lamp preheats the sample up to 1000°C from below and another lamp is focused on the upper face of the sample causing melting of the Si-film.

![Fig. 3: Schematic diagram of the graphite strip-heater oven used at MIT for zone-melting recrystallization of Si-films on SiO2.](image1)

![Fig. 4: Schematic configuration of our lamp-heater. We have used 150 W halogen lamps. Either the lamps or the sample are scanned.](image2)
on a 6*4 mm elliptical spot. By partial masking of the beam, we get the convex-to-the-liquid molten zone shape (see Fig. 3). Because of the low power available in our experiment, we were not able to recrystallize over entire 4-in. wafers. We have therefore used only 6-10 mm wide strips cut out of 4-in. wafers. By moving the upper lamp at 0.7 mm/sec., we have grown single-crystal <100> Si films. Another incoherent radiation study has been published /26/ which uses the beam of a short Hg arc-lamp (instead of a halogen lamp) focused on the sample by means of an elliptical reflector. In this case, the sample is preheated from the back by a silicon carbide coated graphite heater. Lam et al. /27/ have shown that SiC coatings on graphite heaters are necessary to avoid precipitation of SiC in the sample after recrystallization.

IV. CHARACTERIZATION OF RECRYSTALLIZED FILMS

As already mentioned and to be noted first is the (100) texture generally observed. We have obtained single crystal areas 6 cm long and 4-5 mm wide with a <100> direction normal to the surface of the film and a <100> axis parallel to the scan direction /28/. The in-plane misorientation over the sample is generally less than 1 degree except along the edges of the recrystallized line where random nucleation leads to the formation of short "chevrons". Fig.5 is an optical micrograph of the beginning of the recrystallized line in our samples after removal of the cap layers and Secco /29/ decoration of the defects. The lines observed are made up of subgrain boundaries which consist of dislocation arrays generated to accommodate two low angle misoriented crystalline regions /28/. One can see in Fig. 5 that after a competition in the transition region, the subgrains grow wider (right part of the photograph) and then tend to an equilibrium width of about 100 - 200 μm in the speed range used (1-0.7 mm/s). It is worth noting that we did not find any crystalline defects inside the subgrains.
themselves (no twins nor stacking faults). Precipitates can be found along the subgrain boundaries, resulting from segregation of impurities. We have published /30/ extensive crystalline characterization of these films and given some explanations as to the origin of these remaining defects which we believe have to be related to a cellular growth /12,31/.

We still do not understand, however, why the Si-film is recrystallized in a (100) texture. There is no "memory effect" with respect to the original (100) substrate. Geis et al. /32/ have reported the recrystallization of poly-silicon over Si02 in which parallel openings were provided down to a (111) oriented Si wafer. As soon as the melt coming from the unseeded region and solidifying in a (100) texture came in contact with the (111) seeded growth, the latter was occluded and a (100) texture remained. It has been advanced /33/ that the encapsulant layer plays an important role in the orientation of the film, because of minimized interfacial free energy between Si and Si02 for the (100) planes. The MIT group /34/, who has recrystallized large samples, have also observed a (100) texture but the in-plane <100>-axis was sometimes more than 20 degrees off from the scan direction. This large-angle misorientation cannot be accommodated by the generation of dislocations but results in the formation of grains separated by grain boundaries about 1 mm apart. As grain boundaries are detrimental to electronic devices, researchers have tried to avoid them. As they arise from local large-angle misorientations, it has been tried to ensure a (100)-orientation by seeding the growing crystal film from a (100) single-crystal. This is achieved by etching openings in the insulating layer before deposition of the poly-silicon film such that the latter comes into contact with the original (100) Si-substrate. By positioning the sample such that the zone-melting starts in the seed area, epitaxy will proceed first vertically and then expand laterally as the molten zone advances /22/. Another way of obtaining a single orientation in recrystallization of thin Si films consists in a growth using a planar "neck" /35/ patterned into the deposited poly-Si film. The thermal profile induced inside the constriction will force the grain- or even the subgrain-boundaries outward towards the edges of the molten line, in a way similar to the beam-shaping already described.

V. ELECTRICAL MEASUREMENTS IN RECRYSTALLIZED SO1 FILMS

Some preliminary electrical measurements have been done on our lamp-recrystallized samples. DLTS spectra and C-V curves of MOS capacitors /36/ show the high quality of the material: 1.E11 traps/cm3 and 1.E10 interface states/cm2.eV at the upper interface. The MOS capacitors are 300 µm in diameter, i.e. larger than the subgrain boundary spacings. Some transistors have been made, showing mobilities as high as 650 cm2/V.s, which is on the order of the surface mobility in n-channel transistors made in bulk Si. This doping level is attributed to phosporous present in the LPCVD reactor used for the deposition of our encapsulating Si02 layer. Many laboratories have published measurements on devices made for the study of the respective electrical influence of grain- and subgrain-boundaries. The selective annealing technique, developed by Colinge et al. /37/ in our laboratory with a cw Ar+ laser provides a good way of studying the influence of grain boundaries. This technique uses the antireflecting property of Si3N4 stripes on poly-Si to induce
Fig. 6: Optical micrograph showing the localization of grain boundaries by selective annealing. In this case a cw Ar+ laser is used and the power is increasing from right to left when the laser beam is scanned.

a periodic variation in the crystallization front. When the thickness of the nitride is adapted to the wavelength of the coherent radiation used, the regions absorbing the most energy are the last to freeze, thus localizing the defects and grain boundaries as shown in Fig.6. This localization makes it possible to study the influence of a grain boundary on the behaviour of a MOSFET. More detailed results have been presented at this Conference by Colinge et al. /38/. They show that when a grain boundary is perpendicular to the channel of a transistor, the threshold voltage is increased by the potential barrier induced by the trapping of carriers at the boundary. On the contrary, when the grain boundary is parallel to the channel, a high leakage current flows through the transistor /39/. Tsaur et al. /40/ have analyzed the effects of subgrain boundaries on the majority carrier transport in MOSFETs and on test circuits such as ring oscillators /41/. They have shown that the mobilities and delay times respectively are not significantly affected by the presence of subgrain boundaries either parallel or perpendicular to the channels of the transistors used. The influence of subgrain boundaries on the aging of the devices has not yet been studied. Subgrain boundaries do, however, seem to cause the formation of shallow grooves in subsequent epitaxial growth of Si layers on the recrystallized films /42/. This could affect the fabrication of bipolar transistors.

CONCLUSIONS

Microzone-melting has proved to be a satisfactory means of recrystallizing thin films of silicon deposited on an insulating amorphous substrate. Incoherent radiations can be used both for preheating the samples and local melting of the thin film. Most of the results published so far have been obtained on samples that are relatively small (in comparison to industrial wafers), and some important problems have to be solved before this
technique can be applied to industrial IC processing. If it seems possible to avoid or localize the grain boundaries, it will be more difficult to get rid of the subgrain boundaries which may affect further epitaxial growth necessary for making bipolar transistors.

Another problem to be solved is the mechanical behaviour of the wafers under thermal stress, namely warpage and slip lines. This point is becoming more and more critical as the era of submicronic technology approaches.

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