BEAM PROCESSING OF SILICON WITH A SCANNING CW Hg LAMP

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ABSTRACT

A scanning arc lamp annealing system has been built using a 3" long mercury arc lamp with an elliptical reflector. The reflector focuses the light into a high intensity narrow line source. Silicon wafers implanted with 100 KeV $^{75}As^{+}$ to $1x10^{15}$ cm^{-2} have been uniformly annealed with a single scan, resulting in complete activation and negligible redistribution of the implanted species. Using a scan rate of 1cm/s, entire 3" wafers have been annealed in less than 10 seconds with this system. The system has also been used to recrystallize thin films of polysilicon deposited on thermally grown silicon dioxide. The recrystallized films contain grains that are typically 0.5-1 mm in width and several centimeters long. Surface texture measurements show the crystallites to be almost entirely (100) in the plane of the film with the orthogonal <100> direction closely paralleling the scan direction. MOSFETs were fabricated in these films with surface mobilities 66% of ones fabricated in single crystal silicon. An epitaxial layer with the same crystallographic features as the recrystallized film was grown on the film itself.

INTRODUCTION

Over the past few years a considerable amount of research has been directed towards developing alternative heat treatment techniques for application to semiconductor processing. The most thoroughly investigated of these has been the use of pulsed and cw laser and electron beams [1]. Work performed using these sources has provided new insights into the mechanisms of thermally induced processes such as solid phase and liquid phase epitaxial growth and thin film recrystallization. In particular, some of the earliest work demonstrated that ion implantation damaged silicon could be annealed with a scanned cw laser such that there was complete electrical activation of the implanted species and virtually no impurity redistribution [2]. In addition, laser recrystallization of fine grain or amorphous films on insulating substrates was found to significantly improve the electronic properties of the film itself [3]. Once these processes were observed and understood, work began to identify alternative beam sources for producing these effects. In this paper we describe the results of using a high pressure Hg arc lamp system for large area annealing of ion implanted crystalline silicon and zone recrystallization of silicon thin films on insulating substrates. We also present data obtained from MOSFETs fabricated in the zone recrystallized film as well as describe the crystallographic features of an epitaxial layer grown on the film itself.

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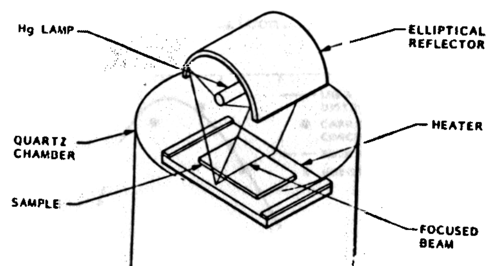
ALING SYSTEM

e have built an arc lamp annealing system which consists of a 3 inch long pressure mercury lamp, an elliptically shaped reflector and a variable l translation hot stage. In previous work xenon and krypton lamps were . We chose to use a mercury lamp primarily for the following two reasons. t, the spectral distribution of this lamp is most heavily weighted in the ange. Consequently, the mean absorption depth for this source is much lower than that for the other lamps.
he second reason the mercury lamp was chosen over the other available s is due to the narrow capillary used for containing the discharge. For ple, a typical 3" krypton lamp has a 5 mm capillary whereas the mercury uses a 2 mm capillary. The tighter confinement results in a narrower ed beam, and thus yields a higher intensity at the sample surface for a n lamp power.
he light from the lamp is focused into a narrow (< 5mm wide) ribbon by a ong reflector with an elliptical cross section. By using this shape of ector to collect and focus the light, we can create an intense linear source and still maintain a reasonable working distance between the le and the lamp. The reflector in our system has major and minor axes 0cm and 8.6 cm respectively. This configuration gives a magnification or of about 3.2 and a working distance of about 26mm between the edge of reflector and the focal plane.
he samples are placed on a heated sample stage, over which the lamp can ranslated at speeds up to 10cm/s. A schematic representation of the arc annealing system is shown in Fig. 1.



1. Schematic representation of scanning cw arc lamp annealing system.

LAMP ANNEALING OF ION IMPLANTED CRYSTALLINE SILICON

rc lamp annealing of ion implanted silicon has several distinct advantages other techniques, in particular laser annealing. First, because the light ncoherent, interference effects which result from the interaction of mono-matic light and the dielectric layers on the semiconductor material are inated. These effects can lead to nonuniform heating of the irradiated rial if not eliminated. Second, the effective processing area for an arc is orders of magnitude greater than that for a laser. For example, an re silicon wafer can be arc lamp annealed in about 10 seconds, whereas a cw r takes several tens of minutes to process the same amount of material. single scan-large area processing also eliminates the periodic nonuni-ities observed in raster scanned laser annealed materials. Finally, an arc is significantly less expensive than a laser and is much more efficient to ate.

In the following section, we describe the results of using an arc lamp to anneal ion implanted silicon. We demonstrate that while it has the above advantages over laser annealing, it also provides the benefits of beam annealing over conventional furnace annealing. Specifically it results in high quality, solid phase epitaxial regrowth with complete activation of the implant species and no dopant redistribution.

Annealing experiments were carried out using 2 and 3 inch 1-8 Ω-cm p-type (100) silicon wafers which were implanted with $^{75}As^+$ at 100keV to $1 \times 10^{15} cm^{-2}$. It was found that several combinations of arc lamp power, scan rate and substrate temperature could be used to achieve a wafer temperature sufficient for good annealing, ~ 1000°C. In general, scan rates from 5mm/s to 1cm/s, substrate temperatures of 400°C to 600°C and arc lamp input power of 1kW/inch to 1.5kW/inch gave good results.

Because of the length of the arc lamp, an entire wafer can be annealed in a single scan. Figure 2 is a photograph of a 3" wafer in which the scan was stopped at the center of the wafer. Because of the difference in reflectivities between single crystal and amorphous silicon, the demarcation between the annealed and unannealed regions is readily seen. Transmission electron microscope (TEM) diffraction patterns made from samples taken from the unannealed and annealed regions clearly indicate the amorphous and completely recrystallized nature of the regions, respectively. (The picture is somewhat distorted due to the angle at which the photo was taken.)

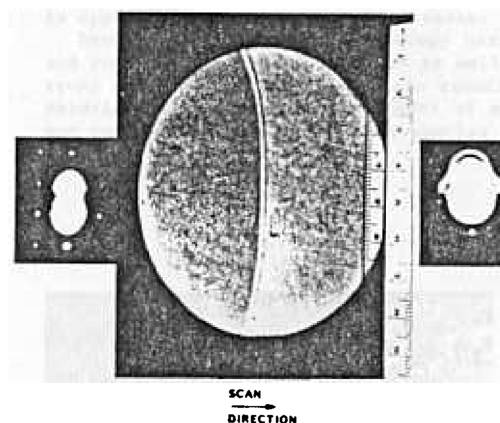
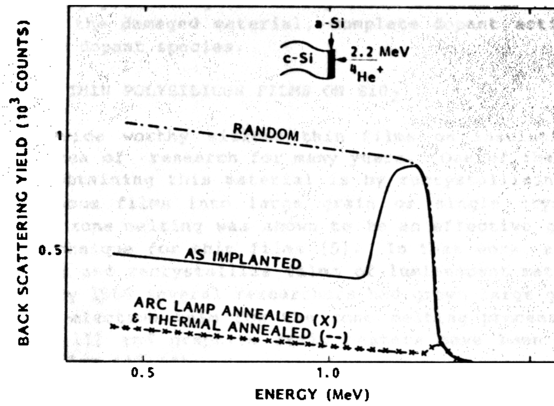


Fig. 2. Photograph of partially annealed silicon wafer, and TEM diffraction patterns from the annealed and unannealed regions.

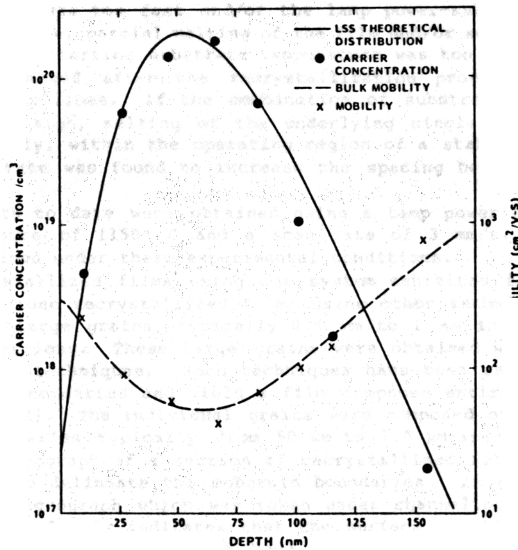
The recrystallized layer was also analyzed by Rutherford Backscattering Spectroscopy (RBS) and directly compared to a sample which was thermally annealed at 850°C for 30 minutes followed by a 10 second 1000°C anneal. Figure 3 shows the backscattering spectra from an as-implanted, arc lamp annealed and thermally annealed sample. As shown, there is no detectable difference between the quality of the regrown material annealed by the scanned arc lamp and the thermally processed sample.

Carrier concentration and mobility of the arc lamp annealed material as a function of depth were determined by means of differential sheet resistivity and Hall effect together with an anodic oxidation stripping technique. These



ig. 3. Rutherford backscattering spectra from as-implanted, arc lamp an-
ealed and thermally annealed samples.

esults are shown in Fig. 4, along with the as-implanted profile calculated sing LSS theory and published bulk silicon mobilities for the respective mpurity concentrations. As shown, no measurable dopant redistribution occur-ed during the annealing process and the free carrier mobility in the annealed egion is as good as found in bulk silicon.



'ig. 4. Carrier concentration and mobility versus depth from an arc lamp innealed sample.

To assess the uniformity of the anneal, four point probe sheet resistivity measurements were made on a wafer which was completely annealed in a single scan. The variation across the wafer from side to side and top to bottom (with respect to the scanning beam) showed no significant variation in either direction, indicating a very uniform annealing of the implanted wafer. These data are shown in Fig. 5.

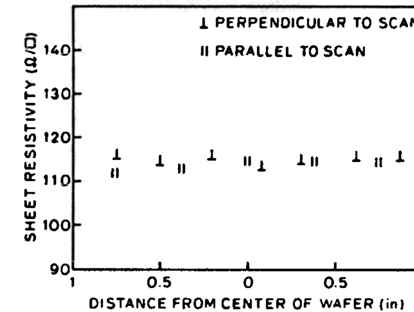


Fig. 5. Sheet resistivity profiles across an arc lamp annealed wafer.

High resolution transmission electron microscopy (TEM) was used to compare the residual dislocation density in arc lamp annealed material to material which was furnace annealed at 1000°C for 1 hour in N_2.

In Fig. 6 we compare the results of a sample which was annealed using 1 kW/ inch lamp power, a scan rate of 7 mm/s and a substrate temperature of 450°C, to one which was thermally annealed. As shown the residual dislocation density is approximately the same in both cases.

Deep level transient spectroscopy has also been performed on these samples and compared to furnace annealed as well as other beam (e.g., laser and elec-tron) annealed samples [4]. These results indicate that the arc lamp annealed material has approximately an order of magnitude lower defect density and does not contain the principle defect species identified in the other beam processed material.

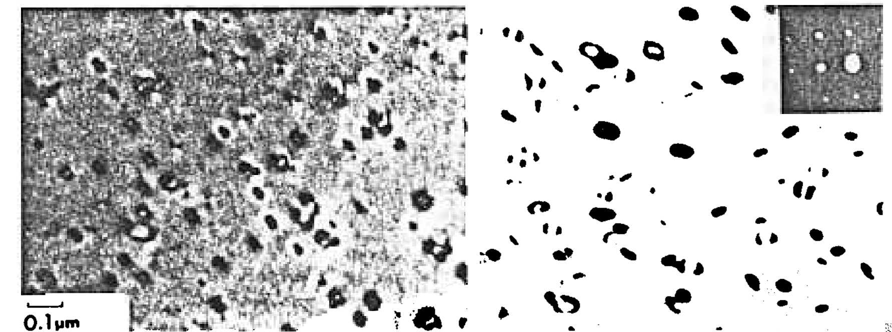


Fig. 6. Bright field TEM micrographs of (a) furnace annealed (1000°C, 1 hr. and (b) arc lamp annealed samples.

In summary, arc lamp processing of ion implanted silicon provides fast, high
lity annealing of the damaged material, complete dopant activation and no
istribution of the dopant species.

?YSTALLIZATION OF THIN POLYSILICON FILMS ON SiO_2

Fabrication of device worthy silicon thin films on insulating substrates
been an active area of research for many years. One of the most success-
approaches for obtaining this material is by recrystallizing as-deposited
e grain or amorphous films into large grain or single crystal material.
Over 30 years ago zone melting was shown to be an effective grain enlarging
rystallization technique for thin films [5]. In that work, a platinum wire
used to zone melt and recrystallize films of luminescent material on insu-
ing substrates. By 1966 several researchers had grown large grain germanium
n films using an electron beam for the zone melting process [6-9]. More
ently, lasers [10,11] and graphite strip heaters have been used for zone
ting of silicon films [12-14].
In this section we show that a scanned, high pressure mercury lamp can be
d for zone melting and recrystallization of silicon thin films on insulating
strates.
The samples used for these experiments were thermally oxidized single crys-
silicon wafers upon which polycrystalline silicon films had been deposited
ng low pressure chemical vapor deposition (LPCVD). The thermal oxide was
m thick and the deposited silicon film was 600 nm thick. Finally, the
ms were encapsulated with 1 μm-2 μm of CVD SiO_2.
Three parameters controlling the zone melting process were investigated;
lamp power, starting substrate temperature and zone scan rate. Although a
iety of combinations of these parameters could be used to achieve a molten
e in the deposited film, the following general observations were made.
If the scan rate was too fast and/or the lamp power-substrate temperature
bination was too low, partial melting of the film and/or severe agglomeration
ld occur. If the starting substrate temperature was too low, the substrate
ld be highly damaged after the recrystallization process, exhibiting a
ge number of slip lines. If the combination of substrate temperature and
p power was too high, melting of the underlying single crystal substrate
ld occur. Finally, within the operating region of a stable molten zone, an
rease in scan rate was found to increase the spacing between the subgrain
ndaries.
Our best results to date were obtained using a lamp power of 1 kW/inch, a
strate temperature of 1150° C and a scan rate of 3 mm/s. The following
ults were obtained under these experimental conditions.
The zone recrystallized films using our system exhibited features similar
those found in zone recrystallized films using other techniques. The film
isisted of very large grains, typically 0.5 mm to 1 mm in width and up to
eral centimeters long. These large grains were obtained without using any
entional seeding techniques. Such techniques have been shown to eliminate
ge angle grain boundaries and yield a film composed entirely of low angle
in boundaries [12]. The individual grains were composed of many subgrains,
h subgrain boundaries typically from 50 μm to 100 μm apart. Figure 7 is
optical photomicrograph of a section of recrystallized film which has been
co [15] etched to delineate the subgrain boundaries. In Fig. 8 we show a
nning electron micrograph which was taken under channeling contrast condi-
ns. This figure clearly indicates that the surface normals of the regions
arated by the subgrain boundaries have slightly different orientations.
Because of the large grain size in the recrystallized films, conventional
stallographic techniques for evaluating the structure of the films are very
e consuming and complex. This is because the incident beam, i.e., electron

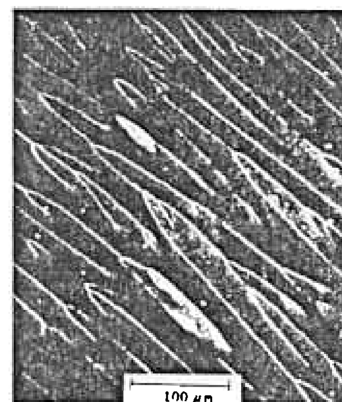


Fig. 7. Photomicrograph of zone re-recrystallized film which has been Secco etched to delineate the sub-grain boundaries.

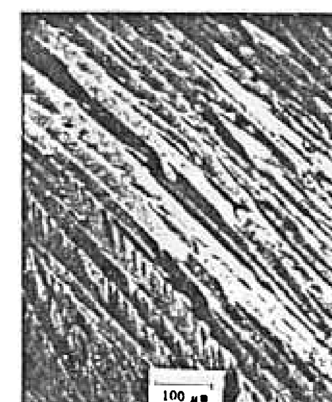


Fig. 8. Scanning electron micrograph of zone recrystallized film taken under channeling contrast conditions.

or X-ray, is smaller than or on the order of the average grain size of the material. Consequently the data obtained from a single diffraction pattern is representative of at most a few grains. Thus in order to obtain any statistically meaningful information about the crystallographic composition of the film, many patterns over a large area of the film must be taken and analyzed.

Geis et al. have described a technique for observing the orientation and size of large grains in zone recrystallized films by using an anisotropic etch in combination with a square array of etch pits [16]. We have used this approach to evaluate our zone recrystallized film. Using conventional photolithographic techniques, round holes on 50 μm centers were fabricated in the SiO_2 encapsulant after the underlying material was zone recrystallized. The samples were then immersed in a 50% by weight solution of KOH in DI H_2O at 80° C for 6 - 8 minutes. This solution preferentially etches in the <110> direction [22]. Consequently the symmetry and alignment of the etch pits can be related to the crystallographic nature and in-plane orientation of the grains being etched.

Figure 9 is a photomicrograph of a recrystallized film which has been preferentially etched in the manner described above. The first feature to note is that the etch pits are square, indicating a <100> surface texture of the film. We have also observed hexagonally shaped etch pits in some of our films which indicates a <111> texture. However, this texture was found only in some very localized areas and on just a few samples. All the material we have recrystallized has exhibited predominantly a <100> texture.

The second feature to notice is that the etch pit diagonals closely parallel the zone scan direction, indicating a <100> texture in the growth direction. Also shown in Fig. 9 is a grain boundary as evidenced by the misalignment of the etch pits on either side.

DEFECTS IN ZONE RECRYSTALLIZED FILM

The principal defects we have observed in the zone recrystallized film and/or substrates are: (1) slip and warpage, (2) substrate melt through, (3) protrusions, (4) voids and (5) agglomeration or dewetting.

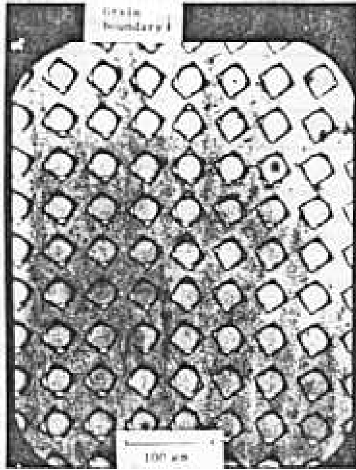


Fig. 9. Photomicrograph of zone recrystallized film illustrating misalignment of etch pits due to the presence of a grain boundary.

Slip and warpage damage to the single crystal silicon substrate are a result f the large thermal stresses the substrate sees during the processing. In eneral, higher substrate temperatures and very uniform substrate heating reduce r eliminate these problems.

When the molten zone (or an area of it) becomes too hot, melting of the rystalline substrate beneath it can occur. Under these conditions the thermal xide can rupture resulting in a large 'melt through' pit, where the surface ilm and substrate have fused together. This is shown in Fig. 10(d).

If the film to be recrystallized contains impurities, they can segregate to ne sub-boundaries during the solidification process. This segregation will epress the melting tmeperature of the film in that region. Consequently, it ill solidify after the zone front has passed that region and the neighboring ilm has solidified. Since silicon has a positive expansion coefficient upon olidification, these small molten areas which are constrained by the surrounding solid silicon must expand upward, resulting in small protrusions at the urface of the film. Figure 10(b) illustrates this case. Note how the protruions all lie along the low angle grain boundaries. In general, clean material, educed scan speeds and steep thermal gradients will prevent this defect.

We have also observed small areas in the zone recrystallized film where the ilm has thinned out and exposed the underlying thermal oxide. These 'voids' are elieved to be a result of some local contamination at the interface between the xide and the deposited film. Figure 10(c) is a photomicrograph of this defect.

The last defect, agglomeration and dewetting is a gross feature which genrally renders the film useless. This is the case when the film balls up or athers into separate unattached regions, as shown in Fig. 10(a). The driving orce for this reaction is the minimizing of free energy by reducing the surface o volume ratio of the film. The encapsulation layer is intended to minimize r eliminate this effect. Some investigators have found that two layer encapulants (18) are more effective than the single layer SiO_2. We have observed, owever, that some deposited films are less prone to agglomeration than others nd can be relatively insensitive to the encapsulant. In either case, this roblem is perhaps the most demanding and the solution must be understood and niversally reproducible if this process is to become a useful technique.

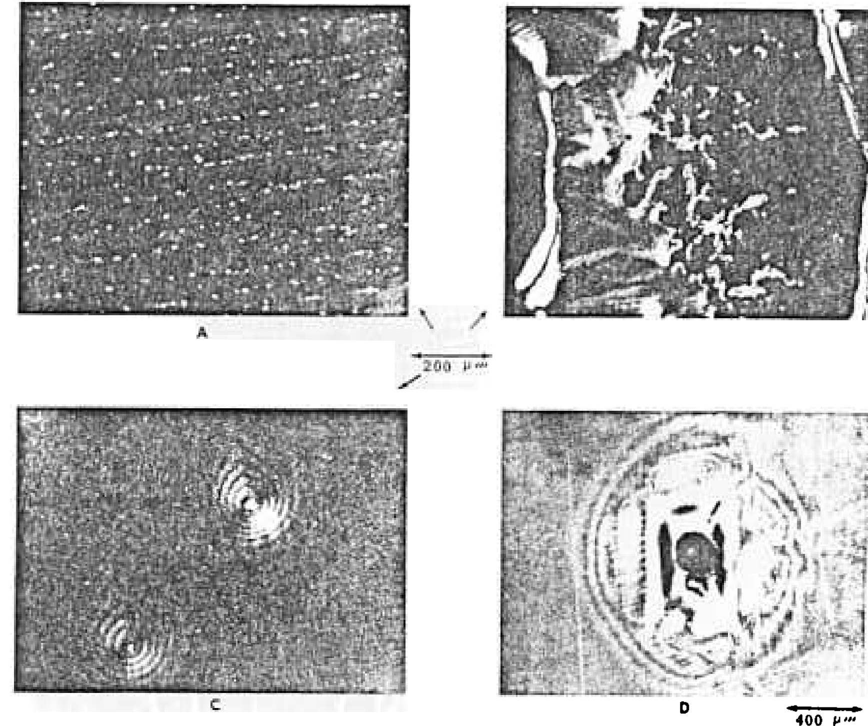


Fig. 10. Defects in zone recrystallized films (a) agglomeration, (b) protrusions, (c) voids, and (d) substrate melt through.

MOSFETS IN ZONE RECRYSTALLIZED FILM

In order to investigate the electronic properties of the zone recrystallized films, n-channel metal-oxide-semiconductor field-effect-transistors were fabricated using an aluminum gate process. The transistors had channel lengths of 10 µm, 20 µm and 50 µm with all channel widths being 200 µm. The transistors were fabricated such that there were channels running both parallel and perpendicular to the low angle grain boundaries. In this way the effect of the low angle boundary orientation on the channel mobility could be assessed. Channel implants of 1.5×10^{11} cm^{-2} boron and phosphorus were used for the enhancement and depletion mode devices, respectively. The implants were thermally annealed under such conditions as to insure a uniform dopant distribution through the film thickness, yielding a net impurity concentration of 2×10^{15} cm^{-3}. The gate oxide thickness was 1000 Å and all devices were isolated by an island etch.

A circular bulk resistor pattern was also included to evaluate bulk properties of the film. Resistivity data obtained from these devices indicate that there was complete activation of the phosphorus implant and single crystal bulk mobilities in the film. Surface mobility data were obtained by analyzing transistor IV characteristics from a curve tracer. In Table I we summarize the surface mobility data obtained from the MOSFETs. As shown, the average

ıBLE I

ımmary of N-channel MOSFET surface mobilities (cm^2/V-S)

'hannel Length + Direction	Enhancement	Depletion	Single Crystal Control Enhancement
0 µm parallel	436	334	537
0 µm perpendicular	418	399	
		432	573
	382	415	
0 µm parallel	345	332	591
0 µm perpendicular	335	357	

nclusions: no sub-boundary orientation effects on surface mobility.

rface mobilities for the enhancement and depletion mode devices in the zone crystallized film ranged from 335 cm^2/V-s to 436 cm^2/V-s. No systematic riation due to low angle grain boundary orientation or channel length was served. Included in Table I are the surface mobilities of enhancement mode vices simultaneously fabricated in single crystal material. The average bility for these devices is 567 cm^2/V-s. Thus the transistors fabricated the recrystallized film had surface mobilities approximately 66% of those bricated in single crystal material.

'ITAXIAL LAYERS ON ZONE RECRYSTALLIZED FILM

Although 0.5 µm silicon films can be used for MOSFET devices, thicker lms are desirable for bipolar applications. In light of this need, a 14 µm itaxial layer was grown on a 0.5 µm zone recrystallized film. The sample eparation and zone recrystallization were performed as described in the evious section. After processing, the 2 µm SiO_2 encapsulation layer was moved from the sample. The sample was then cleaned and placed in a standard nventional epitaxial reactor.

It was found that the epitaxial layer replicated and enhanced the surface atures of the zone recrystallized film. In particular, the low angle grain undaries were clearly evident in the topography of the epitaxial layer. gure 11 is a Nomarski photomicrograph of the surface of the film illustrating ese features. Diffraction patterns of epitaxial layers grown on as-deposited well as zone recrystallized material were taken using a Read camera. These tterns, shown in Fig. 12, clearly indicate that while the layer grown on the -deposited film is fine grained with no preferred orientation, the layer own on the recrystallized film is large grained and highly oriented. In der to evaluate the macroscopic crystallographic features of the epitaxial yer, the preferential etch pit method previously described was used. These sults are presented in Fig. 13. As shown, there are no facets in the etch ts formed in the layer grown on the as-deposited film. However the etch pit ttern in the layer grown on the recrystallized film clearly indicates a 00) film orientation. The photomicrograph shown in the lower portion of g. 13 was taken using light scattered off the sample surface. All the etch ts within a single grain will have their facets aligned. This alignment wever will vary from grain to grain. Thus this technique can be used to

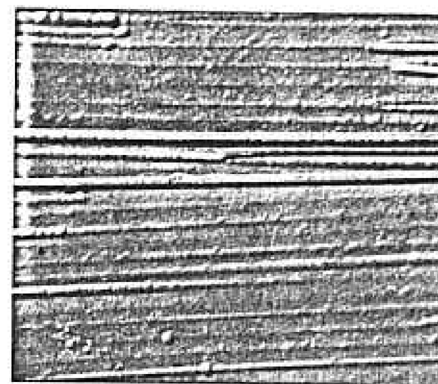
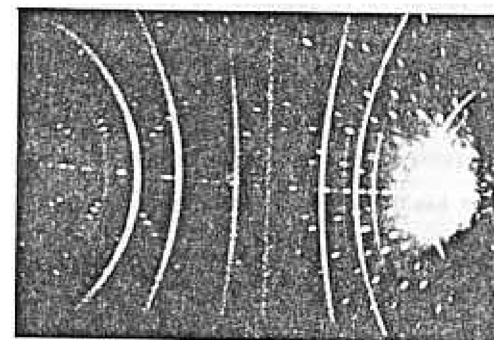


Fig. 11. Nomarski photomicrograp of surface of epitaxial layer grow on zone recrystallized film.



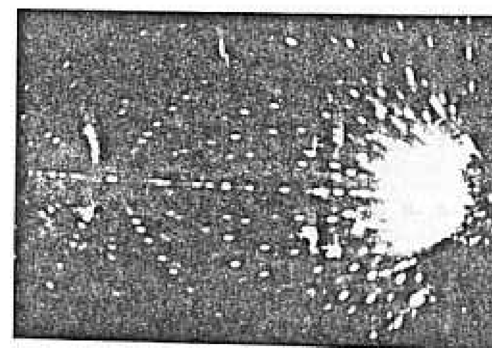
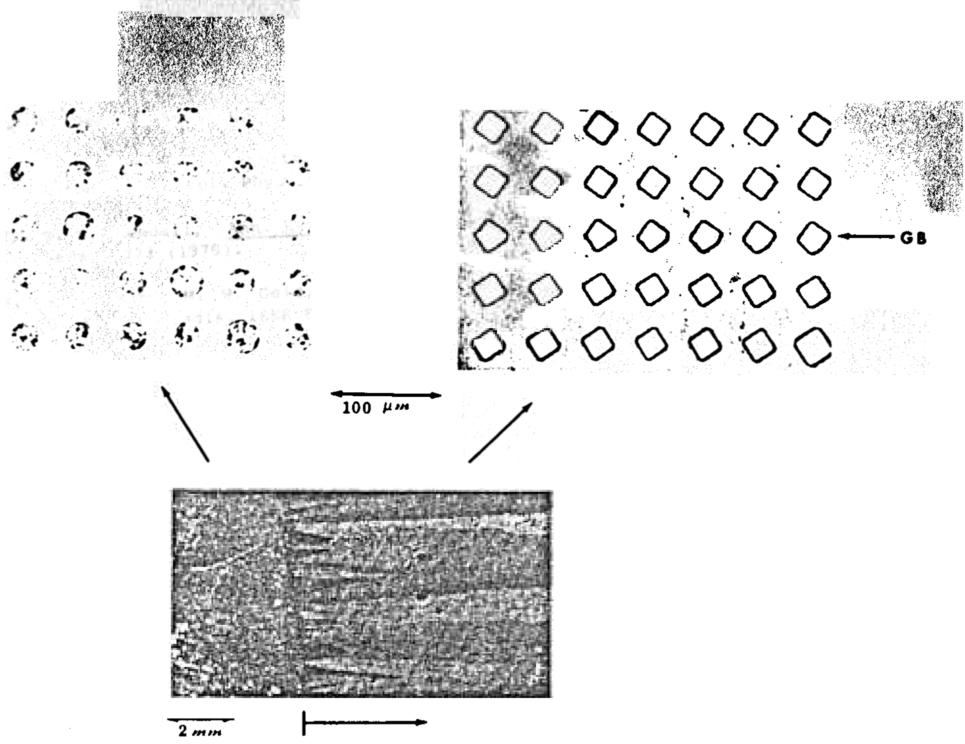


Fig. 12. READ camera diffraction patterns from (a) epi on as-deposited film, (b) epi on zone recrystallized film.



13. Etch pits and scattered light photo of epi on zone recrystallized n.

ineate and observe the grains in the film. As shown, the grains in the taxial layer tend to be 0.5 mm to 1 mm in width, as was observed in the zone rystallized films.

In summary, an epitaxial layer which replicates the surface and crystal-raphic features of a zone recrystallized thin film substrate have been grown. < in progress includes evaluating the electronic properties of these epi-ial layers.

ʼARY

Ve have built a scanning Hg arc lamp system which can be used for thermal cessing of semiconductor materials. The Hg lamp was chosen over other ilable high intensity sources due principally to its large near UV spectral tent which results in better optical coupling with the silicon being cessed. The scanning Hg arc lamp system was used to anneal ion implanted icon and to zone recrystallize silicon thin films on insulating substrates. annealing experiments have demonstrated that Hg lamp irradiation can produce igh quality diffusionless anneal in less than 15 seconds. The recrystalli-ion experiments have demonstrated that large grain, highly oriented thin ms of silicon on amorphous substrates can be produced using this system.

The recrystallized film had a (100) in plane orientation and exhibited a <100: texture in the direction of the zone scan. Enhancement and depletion mod MOSFETs were fabricated in the zone recrystallized film. The electron surfac mobilities were greater than 60% of those measured in devices fabricated i single crystal silicon, demonstrating that the electronic properties of th film are suitable for device applications. Finally, a 14 μm epitaxial laye was grown on a zone recrystallized film. This layer contained the sam crystallographic features as the zone recrystallized film used as a substrat and has potential for bipolar device applications.

ACKNOWLEDGMENTS

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ZONE-MELTING RECRYSTALLIZATION OF SEMICONDUCTOR FILMS

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ABSTRACT

The use of zone melting recrystallization (ZMR) to prepare large-grain (and in some cases single-crystal) semiconductor films is reviewed, with emphasis on recent work on Si on SiO_2. Encapsulants are generally required to minimize contamination and decomposition, induce a crystalline texture, improve surface morphology and prevent agglomeration. In the case of Si, the solid-liquid interface is faceted, which gives rise to subboundaries. These can be entrained by laterally modulating the temperature through the use of an optical absorber on top of the encapsulant. Control of thermal gradients and in-plane crystallographic orientation are important for reliable entrainment.

Preparation of high-quality semiconductor films on insulating substrates has been the subject of numerous investigations. One of the more promising techniques for producing such films is zone-melting recrystallization (ZMR) which is accomplished by scanning a molten zone through the semiconductor film. The resulting film usually consists of large grains with a specific crystallographic texture, and has electrical properties approaching those of bulk single crystal material. In this article we review briefly the development of ZMR and discuss its application to Si on SiO_2.

The concept of ZMR was first discussed by Leitz[1] as a possible method for obtaining single-crystal films of ZnS. Mitchell[2] et al. used a zone melting technique to produce single-crystal films of AgCl and AgBr. Later, ZMR was used to produce crystalline films of Ge, InSb and, in recent years, Si on SiO_2. Various methods have been used to produce the molten zone. For relatively low-melting-temperature materials, such as AgCl, AgBr and certain organics, a small hot plate, which was moved with respect to the substrate, was sufficient. Materials with higher melting temperatures, such as Si and Ge, require higher power densities, which can be obtained with electron or laser beams. If the substrate is heated to near the melting temperature of the semiconductor by some auxiliary means, a resistively heated wire or carbon rod, or a focused lamp, can be used to supply the additional heat necessary to melt a narrow zone in the semiconductor.[15-18]

Most investigators have found it necessary to use an encapsulant layer on top of the film to be recrystallized by zone melting. These encapsulants serve the obvious purposes of minimizing contamination and decomposition of the film during ZMR. However, they also induce a crystalline texture, improve the surface morphology of the film, and reduce or prevent agglomeration. For example, an SiO_2 encapsulant was found necessary to obtain a (100) texture in ZMR of Si films on SiO_2.[9] As shown in Fig. 1, the surface morphology of a Si film improves with the SiO_2 encapsulant thickness.[19] In the case of ZMR of InSb, the natural oxide, In_2O_3, was used as an encapsulant.[6]

Often, a molten semiconductor will not wet a substrate and will "bead up" or agglomerate during ZMR. Maserjian[4] found that agglomeration could be avoided by keeping the molten zone very narrow, a few 100 µm wide. However, such narrow molten zones usually require highly focused energy sources such as

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