An Overview of Laser Crystallisation Processes and Techniques for Low Temperature Polysilicon Technology

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Abstract
In this paper, we describe and review the main techniques which are currently being used or studied, in order to synthesise thin films of device-worthy polycrystalline silicon material (poly-Si) on glass or other non-refractory large area substrates. The problems and limitations of the excimer laser processing are first emphasised and some novel or revisited crystallisation processes with good potential for industrialisation are subsequently presented and discussed.

1- Introduction

The synthesis of device quality polycrystalline silicon material (poly-Si) by laser crystallisation processes has been studied for almost 3 decades [1]. The original aim was to anneal ion implantation damage in silicon, since the thickness of the layers that could be modified by the laser beams were just matched to the damaged depths. However, it was quickly realised that lasers could be used to synthesise silicon-on –insulator structures which exhibit several advantages over the conventional bulk Si material for CMOS circuit fabrication. The first studies on laser recrystallisation (continuous wave) of poly-Si (on quartz substrates), for the purpose of TFT fabrication appeared at the beginning of the eighties [2], while pulsed laser crystallisation of amorphous silicon films (a-Si) was first reported in 1986 [3]. Since then, hundreds of papers have been published on this subject and pulsed excimer laser crystallisation of a-Si is now an industrial process, used to fabricate active matrix displays (with integrated driving circuits) based on liquid crystals (AMLCDs) as well as on organic light emitting materials (AMOLEDs).

In this paper, we shall first present the basic mechanisms of excimer laser crystallisation of a-Si films and emphasise what the present limitations are. We will then review some of the novel (or revisited) laser processes that are being developed, such as sequential lateral solidification (SLS) [4], phase modulated laser crystallisation [5] or continuous wave (CW) crystallisation with a solid state laser, such as a diode pumped YAG laser [6].

2- Pulsed excimer laser crystallisation

In the low temperature polysilicon (LTPS) technology, the basic process is pulsed laser crystallisation of an a-Si precursor film. The latter is generally obtained by PECVD and annealed at ~ 450°C in order to remove most of the hydrogen. Usually, crystallisation is performed with a pulsed excimer laser (pulse duration τ_p ~ few tens of nanoseconds) because in such conditions, the thermal diffusion length ($l = (D\tau_p)^{1/2}$) is of the order of 100 nm (for τ_p = 25 ns) in SiO_2 at high temperature. This means that the substrate (or the buffer layer covering it) is thermally unaffected by the laser-induced heat generation. In the above expression, D is the thermal diffusion coefficient in SiO_2: $D = \kappa/\rho C_p$, where κ, ρ and C_p are respectively the thermal conductivity, the density and the specific heat of the SiO_2 buffer layer that usually encapsulates the glass substrate. Note that at UV wavelengths, the laser energy is absorbed within ~ 10 nm in a-Si.

The mechanism of crystallisation is rather complex [7-10] and depending on the laser energy density, several microstructures and grain size can be obtained for the polysilicon thin film. Figure 1, summarises this situation. Clearly, as the laser energy density increases, the grain size increases up to a maximum value and then abruptly decreases. Of course, as one can intuitively guess, the larger the grain size, the better the carrier mobility and the TFT characteristics. Note however that in order to maintain TFT characteristics uniform, it is desirable to keep the grain size in the 0.5 μm range. In this manner, the number of grain boundaries in the channel of a ~ 3μm long device is statistically almost constant. The other alternative is to use quasi single

crystal Si or grains larger than the TFT size and to localise the grain boundaries at some predetermined positions (which can be achieved by local anti-reflective coating, see below).

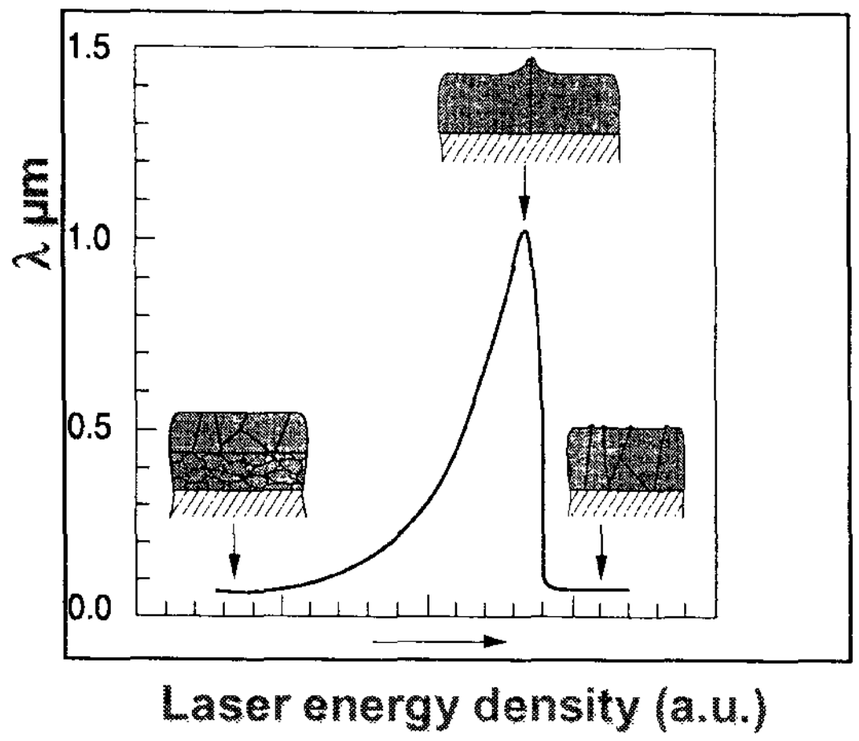

Figure 1: Polysilicon grain size (λ, expressed in µm) as a function of laser energy density (arbitrary units).

When crystallisation over large areas is concerned (e.g., 0.9 m x 0.7 m glass substrates for the most recent situation), the laser is scanned, with its beam shaped to a line (the most recent laser systems exhibit line beams 365 mm long) and with an energy profile thoroughly homogenised and usually "top-hat". Multi-shot irradiations are used (10 to 20 shots or even more), because the grains tend to grow larger and exhibit a better size homogeneity after several melt and re-growth sessions.

The maximum in the grain size (occurring at a laser energy density E_{SLG}) corresponds to a particular situation, usually referred to as the super lateral growth (SLG) mode, where molten silicon just reaches the interface with the substrate [9]. For laser energy densities below E_{SLG}, the silicon film is only partially melted. When a-Si films are crystallised at the SLG energy density, TFTs with field effect mobility values as high as 350 and 150 cm^2/Vs can be obtained for n- and p-type devices respectively (with a substrate temperature of ~ 350°C) [11]. However, the laser energy density must be kept within a ~ ±1% window (peak-to-peak) in order to maintain the SLG conditions upon scanning over large areas [12]. Figure 2 shows how this energy window can be measured. A ramp-type energy profile is used instead of the flat "top-hat" one for the laser beam. If the slope of the ramp and the average energy density are correctly adjusted, the energy density region around the maximum of the curve of fig.1 can be investigated in one shot. As shown on fig.2, a sharp optical contrast appears for the region of the crystallised film corresponding to the SLG energy. Thus, if the slope of the energy ramp is known, the measure of the width of the SLG region directly yields the SLG energy window [12]. Here, we find ΔE_{SLG} = 10 mJ/cm^2 for a pulse energy of 420 mJ/cm^2. Note from the strong contrast (on the right hand side of the bottom micrograph of fig. 2) that the transition from SLG-type grains to very small grains is very abrupt as qualitatively indicated by the curve of fig. 1.

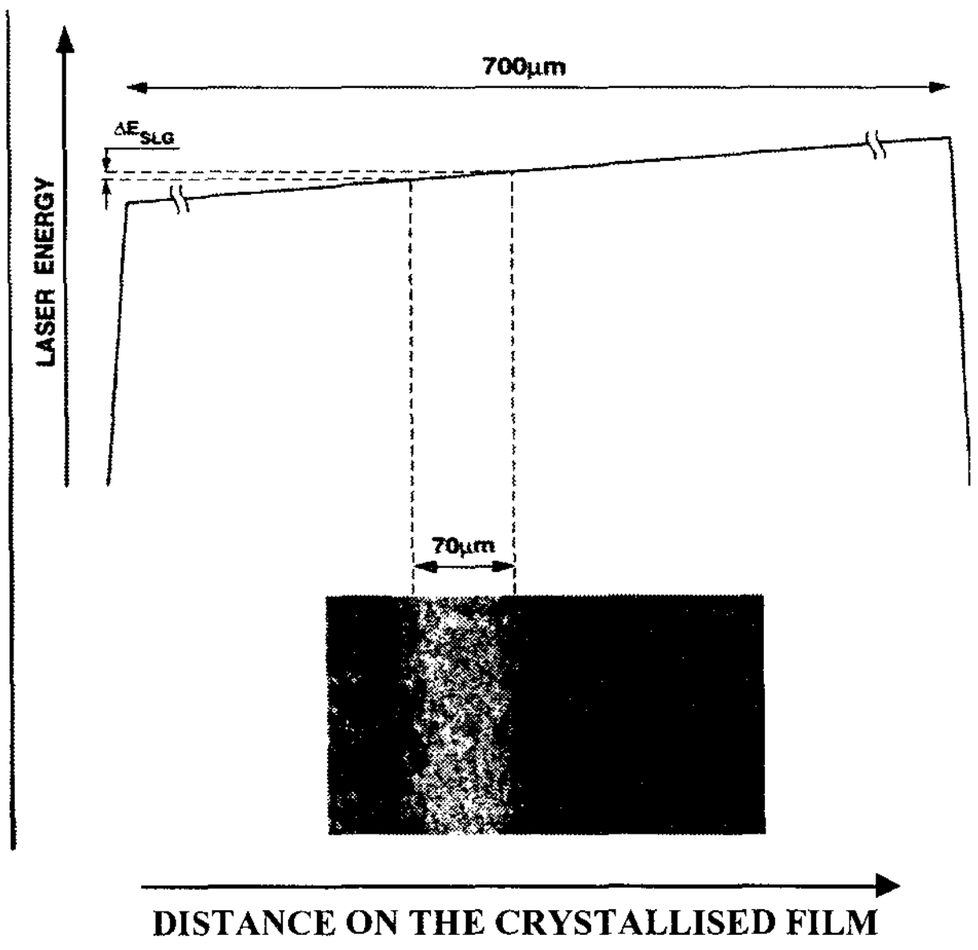

Figure 2: Measurement of the process window for SLG crystallisation. The top part of the figure shows the ramp-shaped energy profile of the laser beam. The bottom part of the figure shows a top view optical micrograph (taken in the region around the SLG energy density) of the film after crystallisation. Note the sharp optical contrast in the SLG region.

However, the most recent excimer lasers developed for polysilicon crystallisation exhibit peak-to-peak energy fluctuations higher than ± 1%. Consequently, in order to avoid falling on the right-hand side of the peak of fig. 1 (where the grain size is very small, thus yielding poor TFT characteristics) display manufacturers compromise on the grain size (and TFT characteristics), keeping the laser energy

density well below E_{SLG}. The corresponding TFT field effect mobility values are of course relatively low (typically < 200 and < 100 cm^2/Vs respectively for n- and p-type devices) compared to the values that can, in principle, be reached [11].

Another drawback of the excimer laser crystallisation process is the grain structure in the regions of beam overlapping (as the beam is scanned). This is related to the energy fall-off region at the leading edge of the beam, a region of several tens of microns, where the energy goes from the plateau "top-hat" energy value, E_P, ($E_P < E_{SLG}$, as explained above) to zero. In this region, because of the energy gradient, the polysilicon microstructure and grain size evolve continuously according to a portion ($0 \leq E \leq E_P$) of the curve of fig.1. When the beam is moved one step forward and the energetically-flat part of the laser spot (the plateau) is shone over the former region, the already existing microstructure is retained, because the melt front does not reach the interface with the substrate (remember that $E_P < E_{SLG}$).

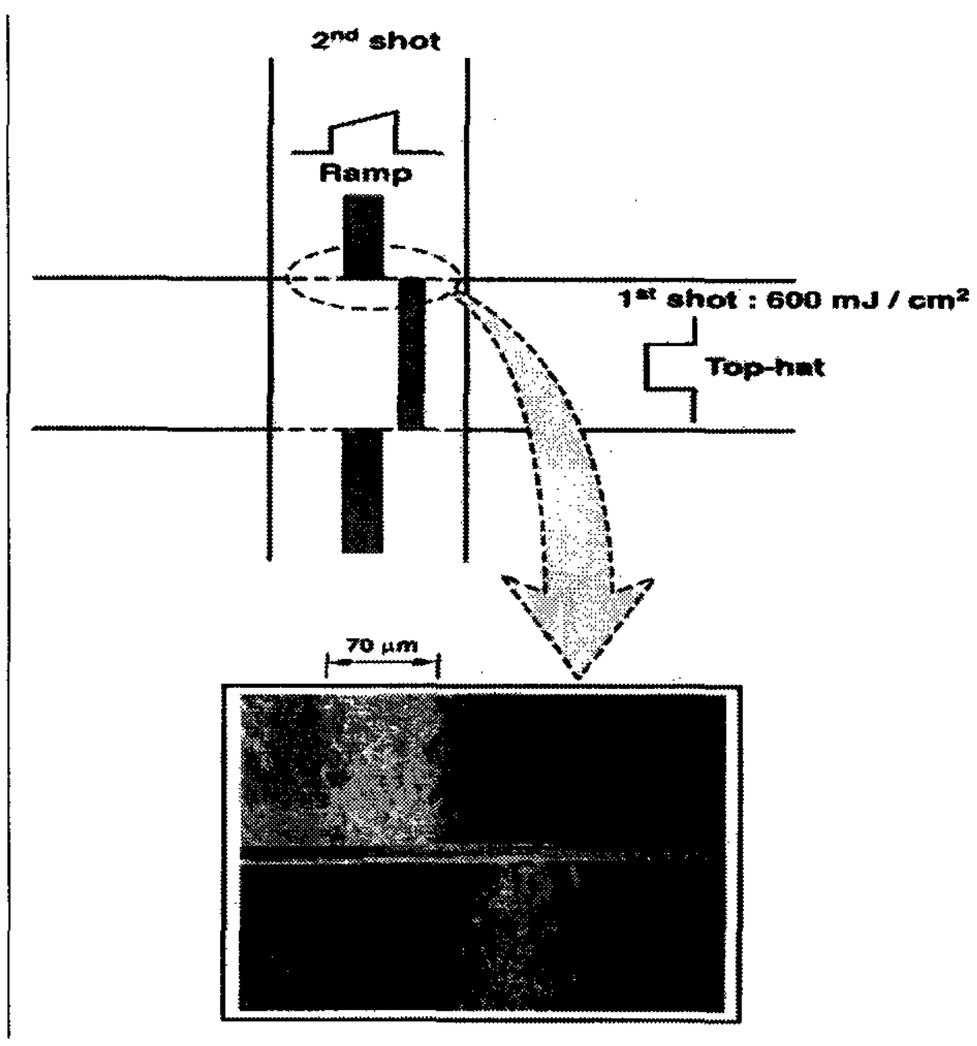

Figure 3: Experiment with crossed laser irradiations of an a-Si film showing that SLG-type polysilicon can be recovered from fine grain material (see text). The top drawing shows the two perpendicular laser impacts on the a-Si film and the bottom picture is a top view micrograph of the intersection region.

In other words, there is only partial re-melting of the polysilicon material followed by liquid phase epitaxy, which is seeded on the un-melted part of the grains. Hence, a periodic marking corresponding to the repetition step of the beam is observed on the laser-crystallised plates, whose width corresponds to the width of the energy gradient region at the leading edge of the beam.

This problem can be sorted out by the use of a non uniform energy profile (ie different from top-hat), for example a ramp profile as that shown on fig. 2. To understand why, we first refer to figure 3. Here, we have used crossed laser irradiations to produce various microstructures in the crystallised film. This is schematically shown on the top part of fig. 3. The a-Si film was first irradiated with a top hat energy profile, at an energy density of ~ 600 mJ/cm^2, leading very small grain poly-Si material (horizontal region on the top of fig. 3). The film was then irradiated with a second shot, perpendicular to the first one, but this time with a ramp energy profile. A non uniform poly-Si microstructure is therefore obtained in the region corresponding to this second irradiation. This microstructure was analysed (by optical and electron microscopy), particularly in the frontier region between the first and second shots (see fig. 3). The typical contrast corresponding to the SLG-type grains appears in the middle of the ramp-irradiated region, when the precursor was pure a-Si. However, the same kind of contrast is observed in the region where the precursor was very small grain material synthesised with the first 600 mJ/cm^2 shot. Scanning electron microscope observations confirm this finding, as large grains are obtained in this region. Clearly, due to a similar SLG-type mechanism (in which most of the film is completely melted and only some surviving seeds or grains at the interface act as re-growth centres), small grain poly-Si can be reverted to large grain material. Also note on fig. 3 that the SLG-type region originating from small grain poly-Si material is shifted towards higher energy densities, compared to that originating from a-Si. This confirms that the heat capacity and melting temperature of a-Si are lower than those of crystalline Si.

Now, if the leading edge of the ramp energy profile is adjusted at a high energy density, corresponding to complete re-melting of the energy fall-off non uniform region at the leading edge of the beam, very small grains can be obtained at the leading edge (instead of grains with various microstructures), which can be reverted to large grains when the laser

beam with the ramp profile is moved one step forward. Note that the trailing edge of the beam does not modify the microstructure, since only partial melting occurs there (because of the ramp) and re-growth is seeded on the bottom, unmelted part of the grains. A similar effect has already been reported with a semi Gaussian beam energy profile [13] instead of a ramp.

Although the ramp profile cannot compensate the pulse to pulse fluctuations, the resulting microstructure of the film after scanning is much more uniform than when a top hat beam is used. This is evidenced on figure 4 below, which shows TFT characteristics taken from poly-Si films crystallised with a top hat or a ramp energy profile.

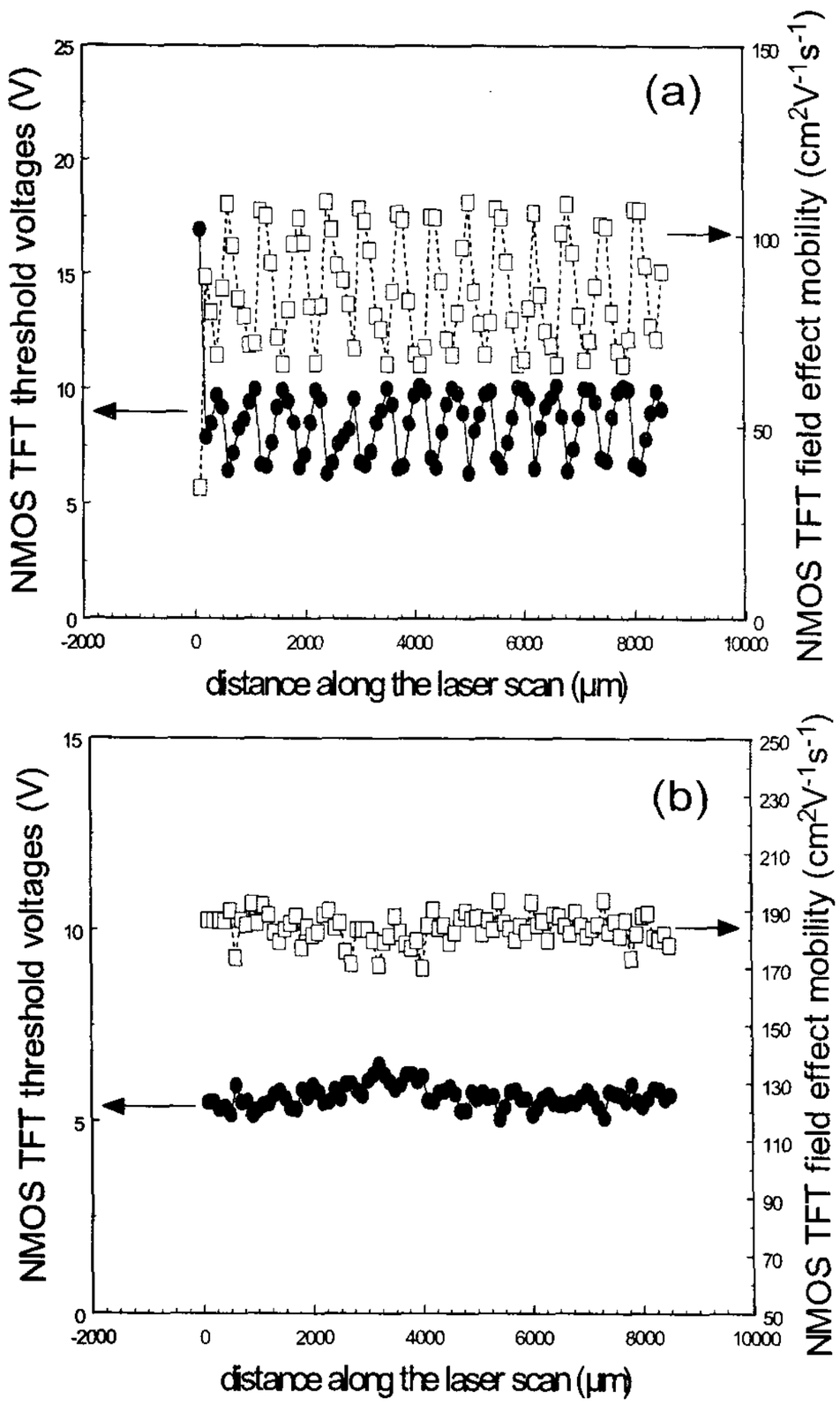

Figure 4: TFT characteristics after scanned excimer crystallisation. (a): top hat energy profile. (b): ramp energy profile.

3- Improvements of the pulsed laser crystallisation process.

It is clear from the previous paragraph that pulsed laser crystallisation is a complicated process, difficult to master, particularly in a factory environment. Moreover, even if large grains can be obtained in a reproducible manner, the problem is to manage the number of grain boundaries under each TFT gate, in order to get low variations of threshold voltage, leakage current and mobility values. For the above reasons, several techniques have appeared over the past few years, aiming at increasing the grain size, particularly by controlling the lateral growth of the grains.

First of all, we must examine the critical distance of concern in lateral growth from a seed, when the substrate is not intentionally heated (T_S ~ 300 K) and no particular care is taken to reduce thermal leakage.

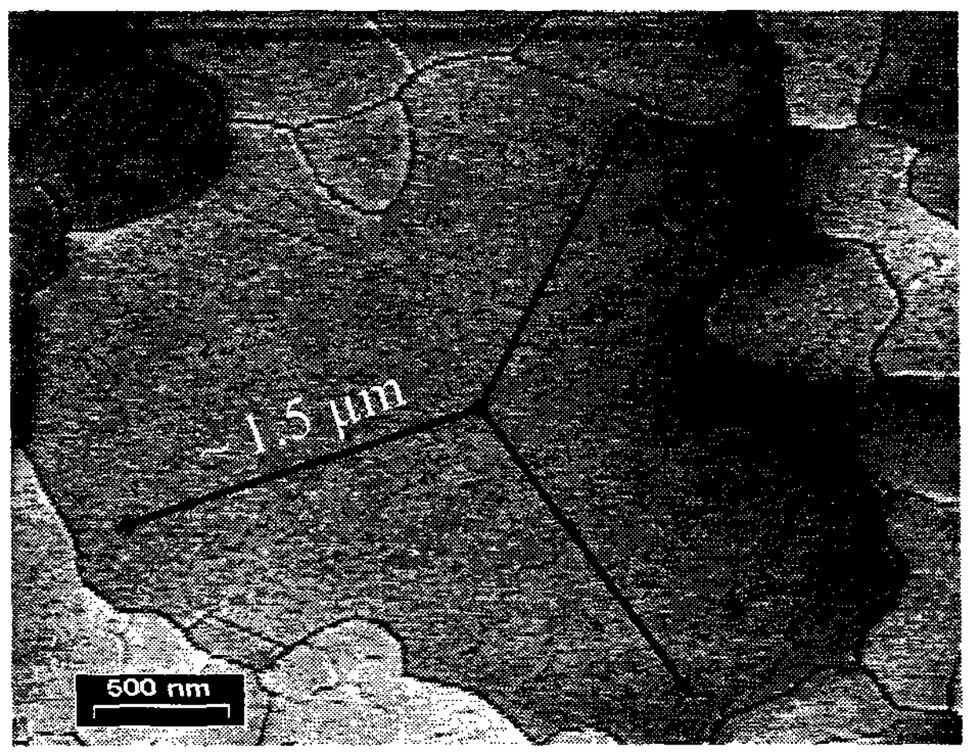

Figure 5: SEM micrograph showing the dimensions of a large SLG-type grain. Note the small grains at the periphery.

This is analysed on figure 5, where a typical lateral growth distance of ~ 1.5 µm can be measured, assuming that the original seed was located at the centre of the large grain. Small grains, originating from homogeneous nucleation can be observed at the periphery of the large grain. This means that (in spite of the latent heat of crystallisation which is rejected in the liquid), a large undercooling of the melt around the laterally growing grain exists, which triggers homogeneous nucleation, thus halting lateral growth. Consequently, unless the substrate temperature is raised or the thermal leak reduced (so as to decrease

undercooling), the maximum lateral growth distance for a grain is about 1.5 to 2µm.

Suppose now that the laser beam is shaped to a ~ 1.5 to 2 µm-wide line and scanned with a repetition step of 1.5 µm. Then the grains can be grown laterally over large distances, since epitaxial lateral growth can be seeded repeatedly on the already crystallised film, after each step of the laser beam. This is the basis of the so-called sequential lateral solidification (SLS) process developed by James Im and co-workers at Columbia University [4] (see also the corresponding paper in this session). However, the practical realisation of this concept is not so easy (particularly in terms of throughput), since the elementary scanning step of the laser beam has to be of the order of ~ 1.5 µm only and, as far as the width of the beam is concerned, any dimension over ~ 1.5 µm is wasted. Actually, assuming that 800 mJ pulses can be delivered by the laser on the substrate (taking into account the losses induced by the various lenses) and assuming that an energy density of 600 mJ/cm^2 is necessary to fully melt the a-Si film, a 2 µm-wide beam should be ~ 67 m long if practically none of the beam energy was to be wasted. Of course this is unrealistic and the beam has to be folded or shaped to reasonable spot dimensions. This is achieved by shining the laser through a mask consisting of parallel stripe openings. Although part of the energy is still lost (a minimum of 50% when the width of the stripes equals their repetition step), the process is still competitive if one remembers that in the "standard" excimer crystallisation process, the film is re-melted at least 10 times, which means that at least 90% of the energy is lost. Last but not least, in order to obtain ~ 1.5 µm parallel beamlets on the substrate, a projection system is needed after the mask, just like in a stepper machine used for fine photolithography.

The poly-Si films obtained by SLS exhibit a low surface roughness, in contrast with those obtained by direct laser crystallisation. This is an obvious advantage, as far as TFT reliability is concerned. Also, the process energy window is much larger, since the only requirement is now to completely melt the precursor. Hence, the pulse-to-pulse fluctuations of the laser are no longer a problem. Mobility values of respectively ~ 350 and 140 cm^2/Vs for n- and p-type devices can be obtained from SLS-crystallised poly-Si (without substrate heating) when the transport occurs parallel to the grain boundaries [14]. When the transport occurs perpendicular to the grain boundaries, the mobility values drop to ~ 160 and 80 cm^2/Vs.

A somewhat simpler SLS-type technique (at least from the equipment point of view), using a mask deposited on the substrate and a two-step laser crystallisation process has been proposed by the group of G. Fortunato in Rome [15].

Another way of increasing lateral growth is by inducing a lateral temperature gradient in the molten Si film. This can be engineered by controlling the heat flow after melting [16], or by phase modulation of the incident laser light [5]. Controlling the heat flow in the melt by structuring the substrate (or the various deposited films) adds-up to the complexity of the TFT process. Display manufacturers tend to prefer "full sheet" methods, where no preliminary processing steps are necessary. The same remark holds for the "location-controlled" synthesis of large grains by a micro Czokralski process, although the later seems to yield poly-Si films with interesting characteristics [17, 18].

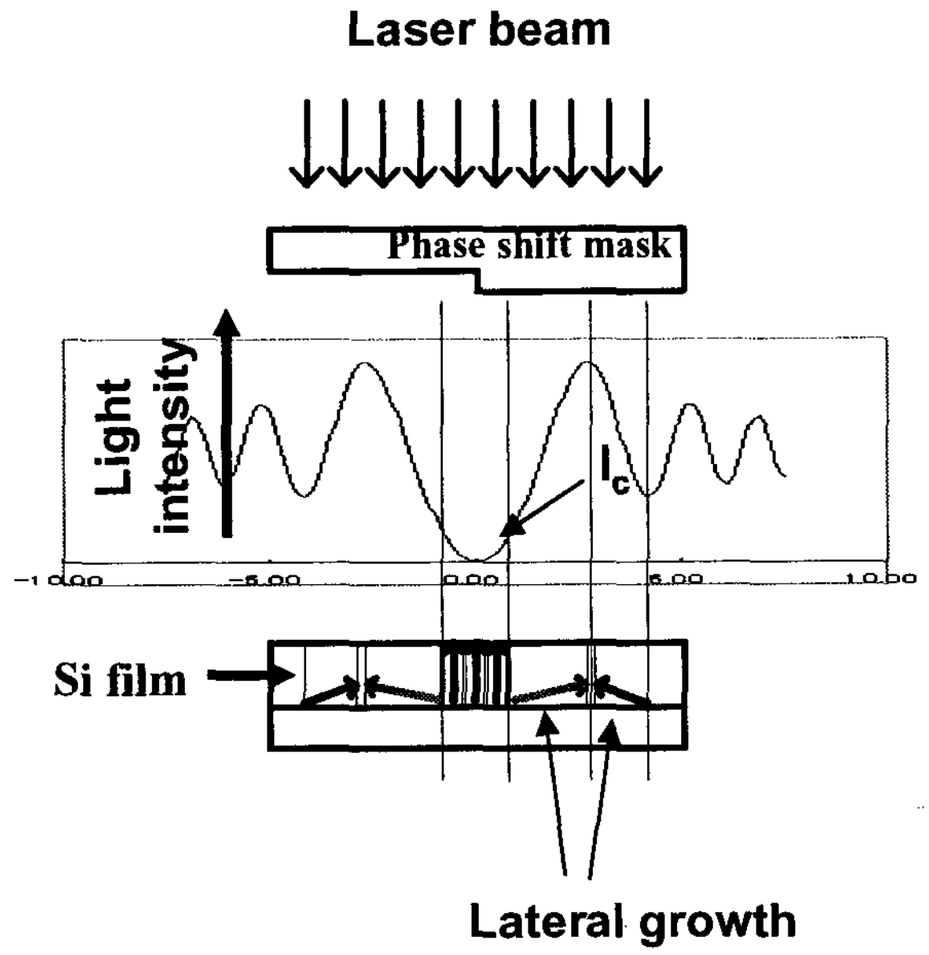

Figure 6: Principle of the phase modulated laser crystallisation method (after refs. 5 & 19). I_C is the critical energy at which the film is fully molten.

In the phase modulated laser crystallisation method developed by the group of Masakiyo Matsumura, first at TIT and now at ALTEDEC [5, 19], a phase shift mask creates a non-uniform light intensity profile on the sample. As a consequence, a temperature gradient is locally created, that locally gives rise to lateral motion of the solid-liquid interface. The situation is summarised on figure 6

above [5, 19]. Large grains, with a lateral extension of ~ 3 to 4 μm can be obtained in the two regions on either side of the of the energy minimum.

4- Continuous-wave laser crystallisation.

CW laser crystallisation (or recrystallisation) has been intensively studied at the beginning of the eighties [20] and is now being revisited using 2ω (λ = 532 nm) diode-pumped solid state lasers [6]. The thermal budget of this technique is not favourable, because the dwell time of the beam (τ_d) is in the 10 μs range, even for high scanning speeds of ~ 200 cm/s. τ_d is much higher than the equivalent pulse duration of an excimer laser and is likely to induce a significant temperature rise in the underlying substrate, because the thermal diffusion length $(D\tau_d)^{1/2}$ becomes important.

The poly-Si grains after laser crystallisation are very elongated, typically 3 μm wide and 20 μm long and the grain boundaries are parallel to the scan direction [6]. The precise orientation of the grain boundaries and the grain size critically depends on the shape of the liquid solid interface [20]. In particular, the use of a convex interface (toward the liquid) favours the formation of grains with larger widths.

As indicated above (§ 2), the grain boundaries can be located by the use of anti-reflective coatings [21].

Mobility values for TFTs can reach 560 and 200 cm^2/Vs for n- and p-type devices respectively. These values are obtained for low scanning speed (20 cm/s) and for transport parallel to the grain boundaries. Here again, lower values are obtained when transport occurs perpendicular to the grain boundaries (~ 290 cm^2/Vs for n-type devices). This technique is very attractive, but as quoted above, the thermal budget is not in favour of glass or other non-refractory substrates. Also, the absorption depth of the green radiation in a-Si is larger that that of UV which is another drawback.

5- Conclusion.

Although pulsed laser crystallisation of a-Si is an industrial process, it is not yet widely used, because it is complicated, difficult to master and still plagued with problems, such as grain size non-uniformity, surface roughness etc… However, because the process is very attractive (the ultimate aim being to synthesise single crystal Si on glass) lots of efforts and creativity are being devoted to improving it. There is no doubt that a universal laser crystallisation technique will appear within the next few years.

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