Enhanced LTPS Manufacturing Equipment employing Excimer Laser Crystallization

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Abstract

For creation of low temperature polycrystalline-silicon (LTPS) the line beam excimer laser annealing (ELA) is a well known and established technique in mass production. With introduction of Sequential Lateral Solidification (SLS) some aspects such as crystalline quality, throughput and flexibility regarding the substrate size could be improved, but for OLED manufacturing still further process development is necessary.

This paper discusses line beam ELA and SLS-techniques that might enable process engineers to make polycrystalline-silicon (poly-Si) films with a high degree of uniformity and quality as required for system on glass (SOG) and active matrix organic light emitting displays (AMOLED). Equipment requirements are discussed and compared to previous standards. SEM-images of process examples are shown in order to demonstrate the viability.

1. Introduction

Ultra Violet (UV) laser treatment of amorphous silicon (a-Si) thin films is the most common approach for manufacturing of low temperature polycrystalline-silicon (LTPS) for active matrix liquid crystal displays (AM-LCD). The a-Si field-effect mobility is limited to app. 1 cm²/Vs [2] whereas polycrystalline-silicon (poly-Si) can have similar qualities as solid silicon with thin film transistors (TFT) mobility of more than 300 cm²/Vs for n-channel and more than 100 cm²/Vs for p-channel [1]. These values are sufficiently high for integrating all driver circuitries within the display panel or even to built system on glass (SOG) displays [3]. Especially displays up to 10'' benefit from the possibility of integrating driver circuitries because it enables very compact and cost effective displays which are required for demanding mobile applications.

Compared to other crystallization methods such as solid-phase crystallization (SPC) excimer laser crystallization provides higher crystallization film quality and requires lower process temperatures [1]. A good overview about recent crystallization techniques can be found in [4].

Laser crystallization itself can be divided into different techniques depending on which laser is used and to which beam shape the a-Si-film is exposed. Regarding the crystallization process after a short time of laser irradiation spontaneous nucleation follows seeded grain growth. If solid silicon is available as seed within the molten area the direction of crystalline grain growth determines the size of the obtained grains. In general lateral crystallization is advantageous compared to vertical one.

Next to poly-Si quality, throughput is most important for production, which is not only influenced by the average power of the applied laser but also by the chosen process. Here we want to present the ability of excimer laser based systems and compare two different processes: line beam excimer laser annealing (ELA) and sequential lateral solidification (SLS).

2. Line Beam ELA Technique

LTPS generation in the Asian display industry is governed by Japan Steel Works (JSW) ELA systems incorporating Lambda Physik 308 nm excimer lasers and line beam optics [5,6]. The annealing process is a nearly-complete-melt process that requires pulses with low energy variation – especially without pulse energies exceeding the complete-melt-threshold. The Lambda Steel 2000 with <1.8 % (σ) pulse energy fluctuation has proven to meet these requirements when emitting 1050 mJ pulses with 300 Hz repetition rate.

The optical system itself projects a narrow line on the substrate that is scanned across the a-Si film. It makes use of the incoherence of excimer laser light that allows sufficient homogenization for the fluence-sensitive process and interacts efficiently with the a-Si film due to its high absorption coefficient of $\alpha = 6 \cdot 10^{-6}$ cm^{-1} at 308 nm. It consists of a flexible arrangement of cylinder-lens-homogenizers and one dimensional projection optics. The shaped laser beam has finally a homogeneity of 2.5 % (2σ) and a ramp profile to allow slowly increasing fluence when scanning the substrate with multiple overlapping of the line-shaped beam. A depth of focus of several hundreds of microns allows easy process control. Modern systems are equipped with alignment tools and process monitoring devices like a beam profiler and on-line pulse energy meters.

The benefits of line beam ELA LTPS are the high homogeneity of morphologic and electronic properties which makes it suitable for SOG [12] and active matrix organic light emitting displays (AMOLED) [13].

2.1 Results of Line Beam Crystallization

The line dimension of 465 mm length and 0.4 mm width results in a crystallization speed of 28 cm^2/s at 300 Hz repetition rate when overlapping 20 pulses per location. The crystallization result is a homogeneous poly-Si film (see Figure 1) with app. 0.3 x 0.3 μm^2 grain size enabling 100 - 150 cm^2/Vs n-channel electron mobility [4].

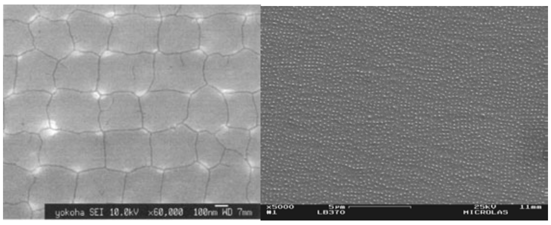

Figure 1: SEM image after Secco etching of line beam crystallized p-Si. Left: High Resolution (Courtesy of JSW). Right: Low Resolution (Lambda Physik).

3. SLS process

As known from literature [7],[8],[9] lateral crystallization produces larger grains than vertical crystallization seeded by solid silicon at the Si-substrate-interface due to nearly-complete-melt (line beam ELA). The required sharp transitions can be generated by a high resolution mask-projection. If the opaque-transparent pattern is adding seeded crystallites to grains generated by the previous pulse the process is called sequential lateral solidification (SLS) [10]. The Lambda Physik optics system *MicroLas* as shown in Figure 2 makes it possible to employ this SLS process to produce high quality poly-Si films on substrates with theoretically unlimited size.

In contrast to the established line beam technique SLS systems are still under evaluation for mass production. In addition to larger grain sizes other advantages concerning throughput, panel size capability and flexibility are already obvious:

Mainly due to the fact that with a lower amount of pulses each location on the substrate can be completely crystallized, the throughput with 315 W SLS systems can be higher than with comparable line beam systems. Considering e.g. substrates with 1.2 x 1.3 m^2 size the number of irradiated panels per hour would be twice as high as in the case of 315 W line beam irradiation.

Due to the high resolution imaging technique and high precision air bearing stages image fields can be positioned subsequently until the complete substrate is irradiated. Thus the substrate size is not limited to the beam size and the whole substrate is uniformly LTPS-coated.

Finally mask projection is a very flexible way to allow the user to vary the crystallization process just by changing the mask pattern. Repeated line patterns, chevron lines or dot patterns are just examples for processes engineers can imagine.

Presently the standard configuration of SLS-systems achieves also 2.5 % (2σ) beam homogeneity in the mask plane as result of cylinder lens homogenizers. The mask projection itself is done with a sophisticated projection lens that allows a micron-scaled resolution with a numerical aperture of 0.1 or 0.13. The resulting image field might have a size of 15 x 2 mm^2 or 30 x 1 mm^2 respectively and can be used for crystallization within less than 50 µm depth of focus. Therefore, an advanced process control is necessary.

A pulse duration extender (PDE) is used to smoothen the temporal pulse shape (see Figure 3) and thus increase the crystallization length dramatically due to lower thermal gradients in the silicon film. The PDE is set up externally to the laser and allows up to 8 times pulse extension while transmitting app. 80 %. The pulse duration can be adjusted in order to optimize the process.

Figure 2: Lambda Physik *MicroLas* optics module for SLS

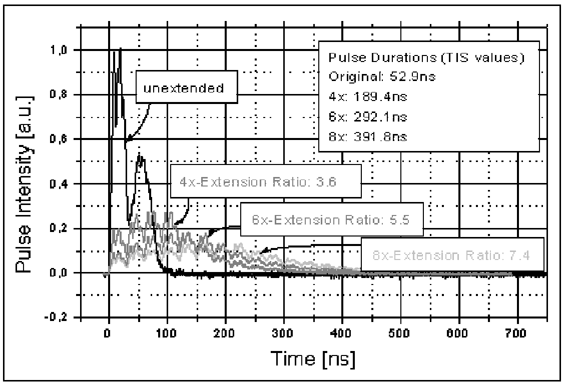

Figure 3: Pulse Shape after passing the Pulse Duration Extender

3.1 Results of SLS Crystallization

Current SLS-systems with Ø18 mm or Ø30 mm image fields reach a crystallization speed of 45 cm²/s at 300 Hz repetition rate with the two-shot-process, which is 60 % higher than with line beam technique. The grains have up to 3.5 µm in length so that the field-effect mobility in the direction of the crystals' long axis can be twice as high as for the smaller grained line beam material. Laboratory investigations found field-effect mobility of 462 cm²/Vs for electrons [7].

The major challenge of SLS-projection systems sets up for high power transmission while maintaining the high resolution imaging character. The high laser power should not have any impact on the optical elements. In particular the projection lens might warm up and change its performance so that temperature stabilization is required. Recently in addition to that a new patented method was introduced by Lambda Physik which changes projection-component positions actively so that focus and demagnification can be kept constant. This Dynamic Focus Control (DFC) in addition to a projection lens that is capable of transmitting more than 100 W of power enables the setup to be suitable for industrialized LTPS-mass production.

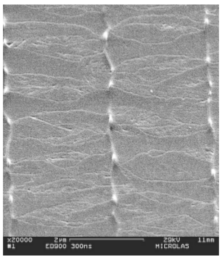

Figure 4: SEM image after Secco etching of SLS crystallized p-Si (Lambda Physik)

4. System Throughput

Excimer laser based production systems have proven to be capable to achieve maximum crystallization rates of 45 cm²/s, whereas green (YAG2ω) laser based systems were calculated to process rates of 35 cm²/s [11]. The throughput in sheets per hour including the substrate handling time is given in Table 1. Finally, the conventional line beam ELA is almost twice as fast as green laser based systems.

	Crystallization Throughput / Sheets per Hour
ELA LB 465	11.8
SLS 25 x 1.5	17.7
Green (YAG2ω)	6

Table 1: Throughput of line beam ELA, Excimer SLS and green laser annealing for 730 x 920 mm² glass substrates including glass substrate handling time. Excimer crystallization is almost more than twice as fast as green laser LTPS fabrication [6],[14].

5. Conclusion

After the line beam ELA technique has proven to create isotropic grain distributions that exceeds the performance of furnace-based non-laser techniques used for TFT-LCDs it could be shown that a carrier mobility can be reached that is more than sufficient for systems on glass (SOG) and AMOLED. It has been shown that the throughput of line beam ELA and SLS including glass substrate handling time is almost twice and threefold, respectively, as fast as green laser LTPS fabrication. Future developments will concentrate on systems with high energy stability that satisfy the increased requirements of display manufacturers for next generation LTPS quality.

References:

[1] J. Lai at al., IDMC 2005 Proceedings, pp. 41-44, 2005

[2] C. E. Nebel, S. Christiansen, H. P. Strunk, B. Dahlheimer, U. Karrer, M. Stutzmann, Phys.Stat.Sol.(a) 166 (1998) 667

[3] F. Okumura, IDMC 2005 Proceedings, pp. 311-314, 2005

[4] A.T. Voutsas, Applied Surface Science 208-209 (2003) 250

[5] S. Uchikoga, N. Ibaraki, Thin Solid Films 383 (2001) 19

[6] L. Herbst, F. Simon, U. Rebhan, R. Osmanow, B. Fechner, Asia Display/IMID 04 Proceedings, pp. 319-321, 2004

[7] J. S. Im, R. S. Sposili, M. A. Crowder, Appl.Phys.Lett. 70/25 (1997) 3434

[8] J. S. Im, M. A. Crowder, R. S. Sposili, J. P. Leonard, H. J. Kim, J. H. Yoon, V. V. Gupta, H. Jin Song, H. S. Cho, Phys.Stat.Sol.(a) 166 (1998) 603

[9] M. Matsumura, Phys.Stat.Sol.(a) 166 (1998) 715

[10] J. S. Im, R. S. Sposili, MRS Bulletin, XXI/3 (1996)

[11] R. Dassow, PHD-Thesis, University of Stuttgart (2000)

[12] C.-W. Lin et al., IDMC 2005 Proceedings, pp. 315-318, 2005

[13] Y.-H. Yeh, IDMC 2005 Proceedings, pp. 371-373, 2005

[14] S. Yura et al., IDMC 2005 Proceedings, pp. 142 – 145, 2005