Recent Advances in Poly-Silicon Crystallization

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Abstract

We present the most recent experimental results on Thin-beam Directional X'tallization (TDX), a rapid excimer-laser-based crystallization method for creating extremely high-quality large-grained polycrystalline silicon films on glass substrates. We will present experimental data obtained with our prototype Gen 2 tool, and discuss the ability to produce different types of poly-Si material.

1. Introduction and Background

Low temperature poly-silicon (LTPS) is ideally suited for display applications where the performance offered by amorphous-Si thin-film transistors (TFTs) is insufficient. Currently the major opportunities for LTPS are found in high-resolution active-matrix liquid-crystal displays (AMLCDs) with integrated driver circuitry, system on glass (SOG) products, and the emerging field of active-matrix organic light emitting diode (AMOLED) displays. [1]

The performance and uniformity of TFTs made in polycrystalline Si material are ultimately dictated by the microstructure of the material in the active channel region of the device. The crystallization process ideally should provide material which yields high performance TFTs, along with uniform device-to-device characteristics. This must be done in a way that is cost-effective for high-volume manufacturing, by enabling high throughput rates and low cost of operation.

Traditional excimer-laser-based crystallization techniques have historically been preferred, not because they satisfy all of the above requirements, but because they provide the best combination available today. The most common approach, Excimer Laser Annealing (ELA), can be optimized to produce fairly uniform films, but as a consequence, the electrical performance of these films will be mediocre at best. Executing ELA in a regime where higher performance, large-grained material can be obtained generally degrades the uniformity and stability needed in a manufacturing environment.[2]

More recently Sequential Lateral Solidification (SLS) has been introduced as an alternative approach to forming high performance poly-Si films. [2] A specific approach known as "Two-shot SLS" has been introduced as a volume manufacturing technique that yields large-grained material with substantially better throughput than standard ELA techniques. However, the processed film does contain large surface protrusions (on the order of the Si film thickness) periodically distributed throughout the film. [3]

The TDX process represents the most recent advance in excimer-laser-based crystallization technology, and a solution that addresses the aforementioned process requirements. [4] In this approach, light from a high-repetition-rate excimer laser is shaped into a high-aspect-ratio beam with a short axis dimension on the order of 5 micrometers. (An example of the spatial intensity profile is shown in Fig. 1(a)). In the long axis direction, the beam is wide enough to cover the entire width of a glass substrate: 37cm in the current Gen2 TCZ prototype tool and 73cm in the Gen 4 TCZ-900X production tool. The focus is controlled to +/- 10μm over the length of the long beam (see Fig. 1(b)). The energy density of the beam is tuned so that each laser pulse completely melts the Si film within the irradiated zone, thereby inducing lateral growth when the film solidifies. The glass substrate is scanned beneath the beam with a constant velocity using a synchronized laser repetition rate. An example of the excellent energy stability as measured at the substrate plane is shown in Fig. 1(c).

The polycrystalline Si films formed by TDX are comprised of low-defect-density, long parallel grains. The surfaces of the crystallized films are smooth and lack the large vertical protrusions associated with Two-shot SLS. Because the long grains are oriented in a specific direction, this technique produces "directional" material in which the device properties will depend on the orientation of the device. Measurements of TFT's produced using TDX material have shown n-type

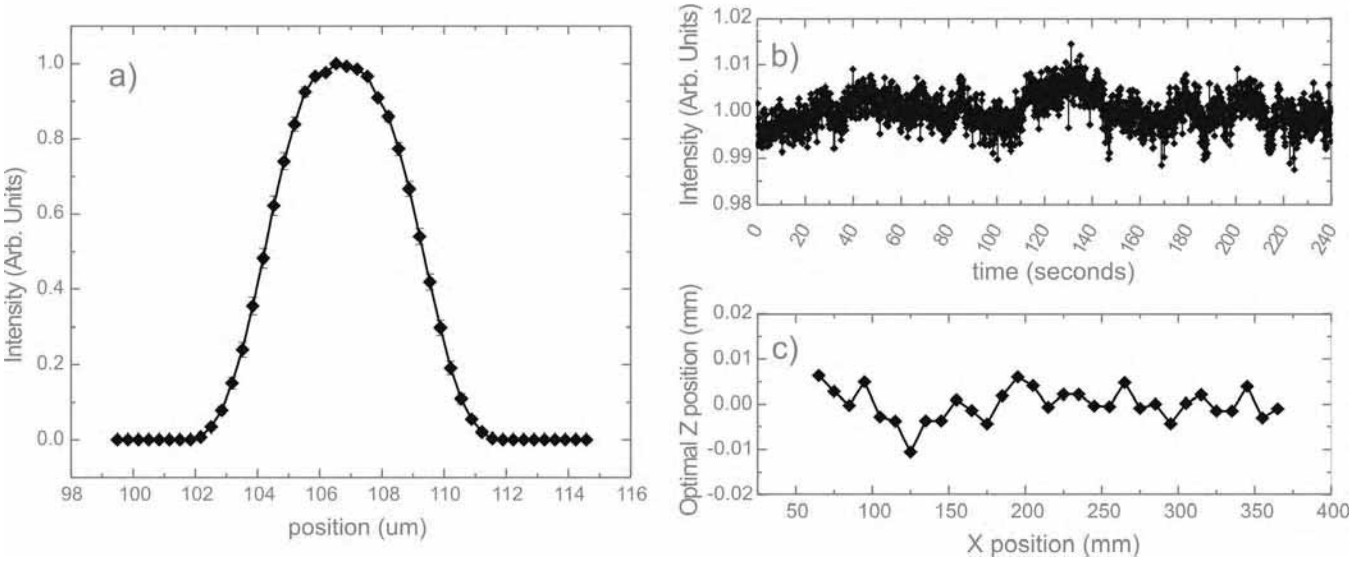

Figure 1: Selected experimental data collected from the 37cm line-beam TCZ prototype system. Shown are (a) the averaged spatial profile at the center of the beam, (b) the shot-to-shot energy data (at the substrate plane) collected at the center of the beam through a 2mm aperture over 240 seconds at 2500Hz, and (c) the optimal focus position (as defined by maximum edge steepness) as a function position along the thin beam.

field effect mobility greater than 300 cm^2/Vs in the scan direction, and more than 150 cm^2/Vs in the transverse direction.

The wide beam allows the entire panel to be crystallized in a single continuous pass. The high repetition rate of the laser (4000 – 6000 Hz) can produce throughput rates that are higher than either ELA or SLS.

2. Flexibility of Crystallization Technique

The relationships between active channel microstructure and device/circuit design must be carefully considered, and thorough optimization should be carried out with the chosen crystallization approach. Since the requirements of the crystallization process will depend heavily on the individual application, it would be an advantage to have the flexibility to produce different types of poly-Si films, which can be optimized for the specific application.

We have recently started investigating the ability of the TCZ prototype tool to form various different microstructures. The ability of a single tool to produce the microstructures associated with ELA, SLS and TDX would have several potential advantages. For example, one could conceive of an approach where the display pixel areas are crystallized using a conventional ELA type approach for maximum pixel uniformity, while the integrated driver circuit areas would be processed with a more advanced technique such as TDX, yielding higher mobility and circuit performance. In the ultimate scenario, various microstructures can be created in different regions of the film during a single scan of the substrate.

A flexible tool would also allow rapid integration into current process flow, with ability to use the same tool to implement more advanced materials in the future. Many display makers have currently optimized their production lines for ELA processing, but would like the ability to re-use their existing equipment to implement TDX or SLS type material when they are ready to introduce the new material into their production flow. This also reduces the reliability and yield issues associated with introducing a new toolset into the fab.

There are also special applications which require the stability of polycrystalline Silicon, but are willing to trade high electron mobility for small and very uniform grain size. One example is AMOLED displays, which require excellent uniformity for current driven emitters.

In the course of our investigations, we have found that the throughput of the TCZ tool will depend on the

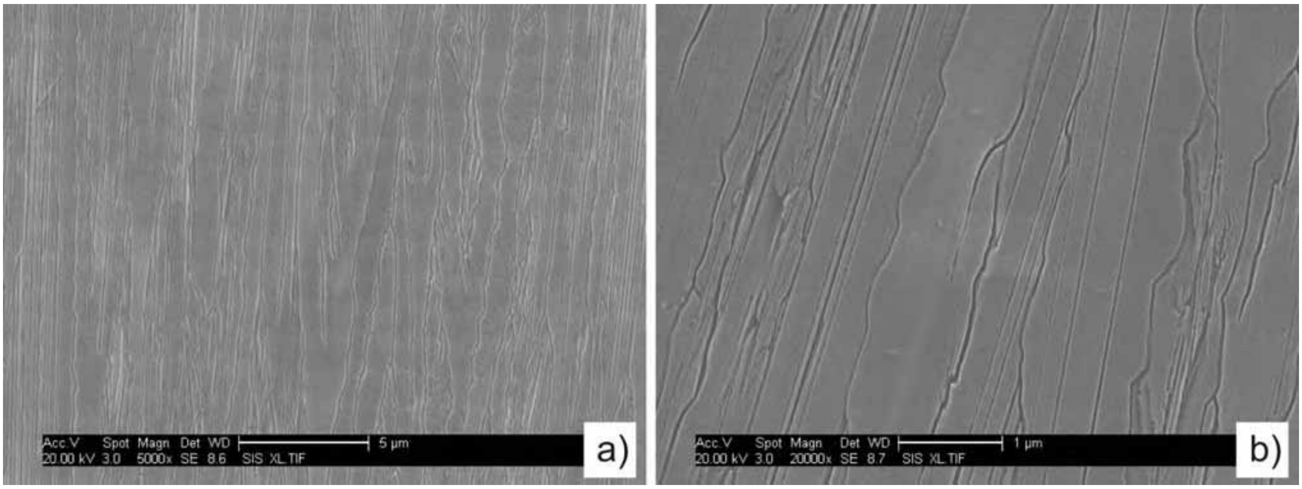

Figure 2: SEM images of defect-etched elongated-grain polycrystalline silicon films formed with the TDX process using a ~5µm wide (FWHM) by 36cm long beam. The images are taken from a 125nm Si film with a per-pulse step size of ~ 1µm, and are shown at (a) low and (b) high magnification .

type of crystal material that is desired. For ELA material, calculations show the throughput of the TCZ tool would be approx. twice the current ELA production tools. For SLS type material, calculations show the throughput for the TCZ tool would be more than twice the current SLS tool. The combination of increased flexibility and improved throughput would continue to lower the production cost for display makers.

Finally, we are aware that the TDX type material is new, and has not yet been validated under production conditions. As mentioned earlier, the material is “directional”, and to take full advantage of the high mobility, the display makers will have to develop new device layouts and masks. The ability to choose between different types of material provides time and flexibility to develop the next generation display processes.

3. Results

An SEM image of a defect-etched poly-Si film formed using the TDX process is shown in Fig. (2). This material shows the elongated grain structure that is typical of TDX material. Using the current TCZ prototype tool, which has a 37cm long beam, we have demonstrated material of this quality uniformly distributed throughout an entire Gen 2 panel.

By changing only the operating conditions, we have also been able to demonstrate uniform large-grained and fine-grained polycrystalline Si materials using the same prototype system. The beam properties remained essentially the same as shown in Fig. 1.

To produce material similar to the “Two-shot SLS” system, we adjusted the step size to 3µm. The resulting material is shown in Figure 3. In Fig. 3(a), periodic perpendicular grain boundaries are formed with the same spacing as the inter-pulse step distance. The nearly parallel grain boundaries running between these periodic boundaries are clearly seen in the image of Fig. 3(b), as is the high quality of the grain structure.

Small-grained polycrystalline Silicon, similar to the material produced by current ELA systems, was formed by reducing the energy density set point to below the complete melting threshold of the Silicon film. An example of the microstructure obtained is shown in Fig. 4. The average grain radius is on the order of 300nm.

4. Discussion

We have previously presented the TDX concept and, in doing so, suggested that it would be possible to combine the inherent advantages of polycrystalline Si material with efficient volume-oriented production capabilities. By building a working prototype tool,

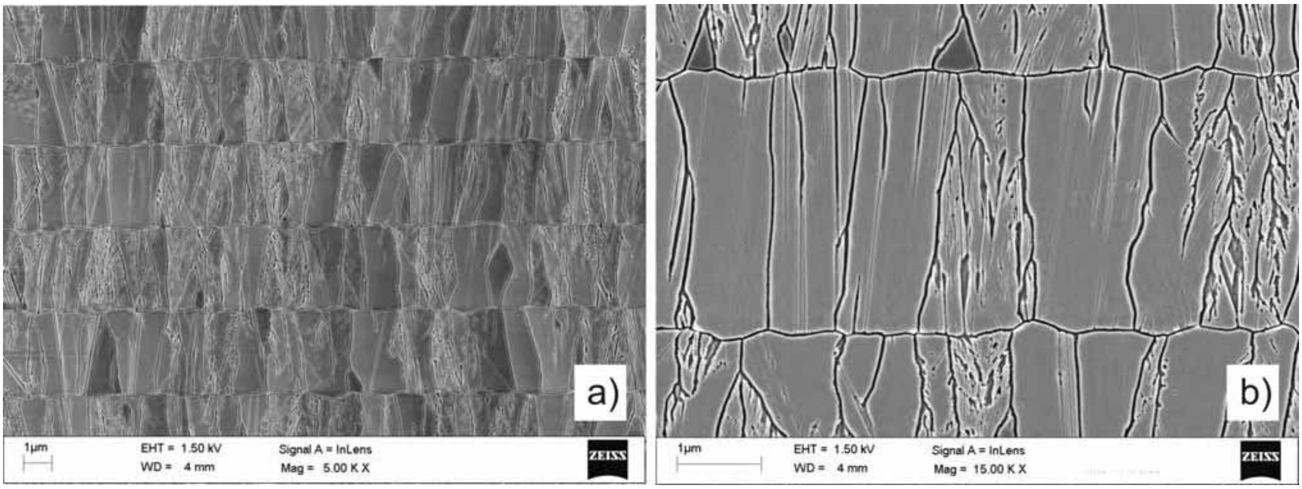

Figure 3: SEM images of defect-etched 50nm large-grain polycrystalline Si films formed using a ~5µm wide (FWHM) by 36cm long beam. The a) low and b) high magnification images were taken from a film crystallized using an effective interpulse step distance of 3µm; larger step distances are also possible.

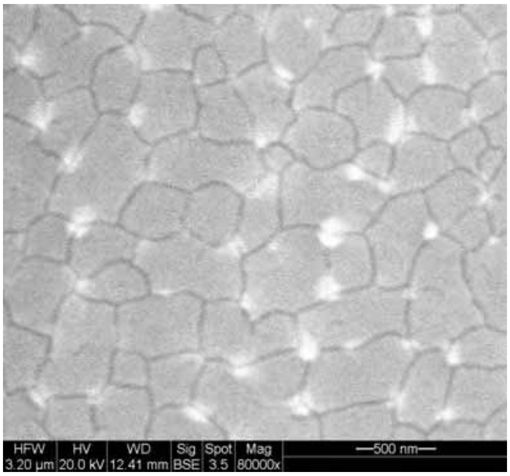

Figure 4: SEM image of defect-etched 50nm small-grained polycrystalline silicon film formed using the same prototype system designed for TDX. In this experiment, the energy density was set below the film's complete melting threshold.

we have successfully demonstrated that the TDX method is not only well-suited for forming high-quality poly-Silicon films with excellent material properties, but is able to produce such material with throughput rates exceeding those offered by all other competitive technologies.

We have now demonstrated the capability of the TCZ tool to form materials very similar to those that are generated by o alternative approaches. The results presented here have all been obtained with the same prototype equipment, which demonstrates the ease and flexibility of the tool design.

The ability to create various microstructures has several benefits. It allows engineers to utilize the tool to generate both manufacturing-worthy and development- and optimization-ready material nearly simultaneously. The value added greatly reduces the burden associated with adopting a new toolset.

Even more noteworthy is the ability to create various materials within a single film during a single scan. By tailoring the crystallization approach to the desired material quality in specific regions of the silicon film, the process can be made to be extremely efficient while generating material well-matched to the application's requirements. Such flexibility could be enabling to an entirely new class of products.

5. Conclusion

We have shown recent experimental data from the TCZ prototype crystallization tool. Some spatial beam properties and relevant temporal statistics were presented. The equipment was shown to be capable of creating a wide variety of microstructures, and was therefore suggested to be an extremely flexible manufacturing approach.

6. References

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