SLS of Si Films on Polymer Substrates: Materials and Devices

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Abstract

A number of research groups and companies have succeeded in employing various SLS schemes to create low defect-density Si films on glass substrates for making high performance TFTs. In this paper, we first point out that SLS can be utilized to just as effectively handle crystallization of thin Si films on polymer substrates, and then present preliminary results on high-performance circuits that are built using the materials.

1. Introduction

The availability of low-defect-density crystalline Si on flexible substrates is viewed as being instrumental in realizing advanced display products that are rugged, conformal, and lightweight. Direct deposition or solid-phase crystallization techniques are not well suited for these applications as they are often incompatible with polymers and furthermore produce polycrystalline Si (poly-Si) films with high defect densities.

Excimer-laser annealing (ELA) has been shown to be capable of producing reasonable quality films directly on polymer substrates. This approach, however, is generally characterized by a high running cost, a low throughput, and a narrow and poorly defined processing window. Additionally, its potential to meet future demands as regards high-performance TFTs is intrinsically limited by the small-grained polycrystalline microstructure that results from the process.

In order to address such shortcomings associated with the ELA technique, the sequential lateral solidification (SLS) [1] technology has been previously invented and developed; it was designed to deliver better materials in a more efficient and effective manner. As a matter of fact, the SLS process has already shown itself to be fully capable of producing Si films with lower defect density than can be obtained via ELA. More significantly and as expected, SLS has proceeded to accomplish the task of producing the better materials while delivering of superior processing attributes.

Until recently, however, ELA has been the only crystallization technique that was successfully implemented on polymer substrates [2-4]. It is worthwhile to note here that the performance of the low-temperature polycrystalline Si (LTPS) devices fabricated on ELA-processed Si films on polymer has attained the same level of performance reported for the LTPS devices that have been fabricated on the ELA-processed Si films on glass substrates. This correlation indicates, quite forcefully, that various polymer-substrate-related technical issues (e.g., photolithography on polymers, low-temperature thin-film deposition, and polymer-compatible doping and activation) can, in principle, be effectively addressed. This, in turn, signifies that the poor microstructural quality of the ELA processed Si films as being, at this point, the fundamental bottleneck that limits the characteristics of LTPS TFTs that are directly fabricated on polymer substrates. As has already been accomplished for Si films on glass substrates, implementing SLS to crystallize Si films, now on polymer substrates, represents one potential way to progress beyond the "ELA" bottleneck. (For a recent review of the LTPS technology on flexible substrates, see for example [5])

2. SLS on polymer substrates

It is appropriate to begin the discussion of SLS of Si films on polymer substrates by first pointing out that the very success of ELA in terms of crystallizing Si films on polymer substrates does not necessarily imply the success of SLS on polymers. This is so because, in fact, in comparison to ELA, SLS can be identified as being thermally and mechanically substantially more taxing to the polymer substrates. In SLS; (1) higher energy densities are employed as they are required to induce complete melting of the films, (2) longer pulse durations are typically utilized in order to enhance lateral growth, and (3) significantly higher levels of thermal stress are encountered as the

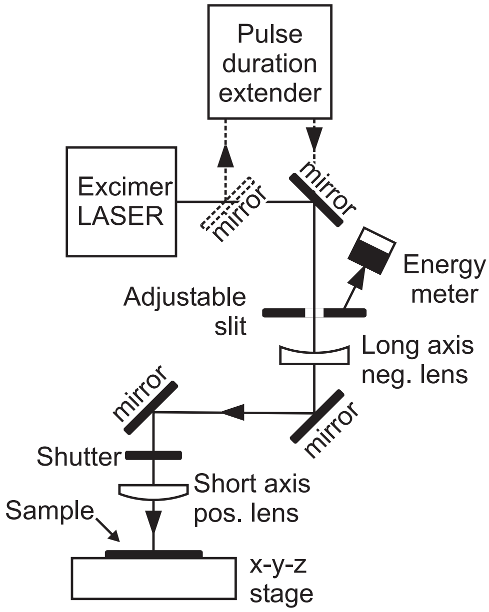

Figure 1: Schematic diagram of a single-axis projection SLS system configured to perform line-scan SLS of Si films. The system was utilized to produce directionally solidified Si films utilized for making devices and circuits.

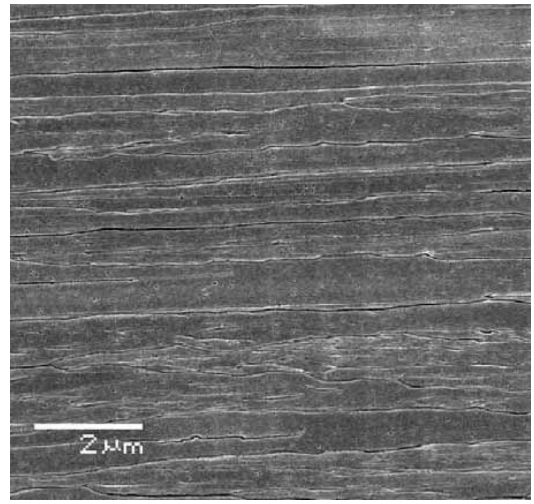

Figure 2: SEM image of a defect-etched Si film (125 nm, PECVD deposited on SiO_2 coated polyimide) directionally crystallized via line-scan SLS.

sample will be subjected to considerable lateral temperature gradients in addition to the ever-present vertical temperature gradients.

Despite the aforementioned challenges, we have recently presented preliminary results that suggest that various SLS schemes could indeed be implemented on polymer substrates (by optimizing the sample preparation procedures) [6] and that TFTs and circuitry can be successfully fabricated on the SLS-generated materials [7]. In this paper, we provide updated information regarding our materials- and device-related efforts on directly producing high performance devices and circuits on polymer substrates by applying SLS to generate and provide low-defect density Si films on the substrates.

3. Experimental

Previously, we have demonstrated the SLS process on freestanding polyimide substrates that were placed on a vacuum chuck [6]. Polyimide (PI) was selected, at least as a preferred starting polymer material, since it can accommodate device fabrication processing temperatures as high as ~300 ˚C. For the work presented here, we have applied the polyimide on top of support Si wafers via a spin coating technique; this configuration was chosen to permit subsequent fabrication of devices within a standard Si IC fabrication facility.

We have tested various SiO_2 and SiN_x deposition techniques to create reliable and robust buffer layers. For this work, a 1-μm-thick SiO_2 buffer layer and a 125-nm-thick amorphous Si film were deposited on top of the polyimide layer using PECVD (at 300˚C) and sputtering, respectively. Si films and SiO_2 or SiN_x buffer layers that were deposited at various conditions have been first evaluated for laser crystallization using simple flood irradiation experiments. Sample analysis using optical microscopy was then employed to reveal the nature and quality of the irradiated samples and the findings were then used to adjust and optimise the deposition conditions accordingly for producing excimer-laser-processing compatible samples. Only those samples that were prepared to have a well-defined process window for complete melting were laser crystallized using SLS.

Directionally solidified Si films were obtained via line-scan SLS using the irradiation setup shown schematically in Figure 1. In this single-axis projection system, the laser beam (XeCl, 308 nm) is shaped into a long and narrow line (a few um wide by several cm long) beam, which is scanned over the surface of the sample using high-precision translation stages [8, 9].

Devices and circuits were fabricated using a low temperature CMOS process that did not exceed 300˚C in order to ensure the compatibility with the polyimide layer. Automated probing was performed

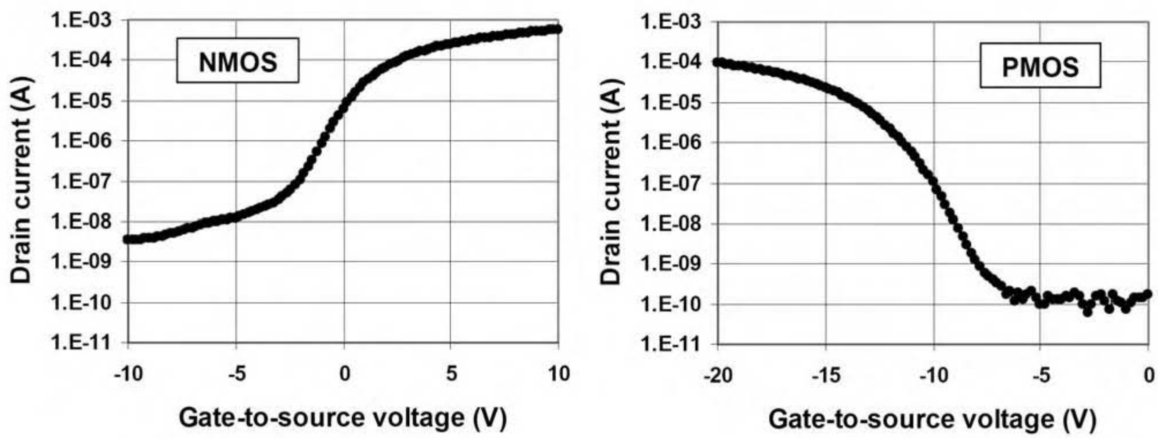

Figure 3: Transfer characteristics of n-channel and p-channel TFTs (L=10 μm, W=100 μm) for a drain–source voltage of 1 V.

on more than 20,000 n-channel and p-channel TFTs to provide statistically meaningful data.

4. Results

An example of the directionally solidified microstructure obtained via line-scan SLS performed on the same Si-SiO_2 layer stack (as was used for device fabrication) is shown in Figure 2.

Two representative transfer characteristics of TFTs (L=10 μm and W=100 μm) fabricated using the sputter-deposited and directionally solidified Si film on polyimide are shown in Figure 3. The field-effect mobilities are 191 cm^2/Vs and 45 cm^2/Vs, and the threshold voltages are 1.1 V and –13.9 V for the n-channel and the p-channel devices respectively. The p-type threshold voltages were typically found to be around –10 V. (Although such high values of the threshold voltage do not allow for low supply voltages, we note how the situation may be remedied in a routine manner by simply adjusting the values using channel doping.)

Finally, 5-stage CMOS ring oscillators with 2-μm channel lengths and a 15-V supply voltage were measured to operate at 100 MHz for an average inverter delay of 1.0 ns per stage. These are thought to be the highest-frequency circuits ever built using transistors that have been directly fabricated on polymer substrates.

5. Discussion and Summary

Critical analysis of experimental results we have obtained thus far concerning the SLS of Si films on polymer substrates allows us to conclude the following points: (1) samples with a sufficiently wide energy-density window for SLS processing can be prepared at low deposition temperatures on polymer substrates, (2) surface planarity of Si films on both non-supported as well as laminated (or spun-on) PI films can be sufficiently flat to perform projection-irradiation-based SLS processing of the films (without going into an unacceptable level of defocus), and (3) the SLS process as has previously been developed for crystallizing Si films on glass substrates can be readily implemented for polymer substrates (without encountering any mechanical and structural degradation to the film-substrate stack).

The results presented in this paper further confirm that the line-scan SLS scheme can be utilized in order to crystallize as-deposited amorphous Si films on polymer substrates. Moreover, our preliminary device-related investigations (carried out using the fabrication procedures that can be pointed out as being not yet fully optimized and refined, as these results still fall short of those obtained using the same type of materials on glass substrates [10]) demonstrate, nevertheless, that high-performance TFTs and circuits can be obtained directly on the polymer substrate using the SLS processed Si films.

In conclusion, we envision that the SLS approach may eventually enable low-cost, high-throughput manufacturing of advanced active-matrix LCDs and OLED displays on plastic substrates. To this end, we are confident that it would be possible, moreover, to ultimately develop an SLS approach that can be integrated directly into a highly efficient roll-to-roll manufacturing process.

6. Acknowledgements

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7. References

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