Al-Induced Crystallization of Si Thin Films on Flexible Glass Substrates

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Abstract:

Highly-oriented silicon (Si) films on flexible substrates are attractive for thin-film electronic and energy applications. Ultra-thin flexible glasses are of special interest for substrate use because they offer flexibility and higher thermal stability than polymers. Thus, the goal of this project was to investigate the growth of silicon (Si) films on 50 µm thick flexible glasses, using an aluminum-induced crystallization (AIC) process. AIC lowers the Si crystallization temperature to temperatures below the softening temperatures of the glasses; furthermore, it produces Si films with large grains and preferential orientation. Large-grain polycrystalline Si thin films of 30 nm thick and 100 nm thick were successfully grown on 50 µm thick flexible glass substrates. Films 30 nm thick demonstrated larger grain size but higher electrical resistance than 100 nm thick films. Mechanical flexibility was tested by bending the samples around a tube of radius 5.75 cm, close to the maximum curvature radius of the glass substrate (~ 4.5 cm). Bending caused the samples (glass substrates with Si films on top) to fracture but did not produce any new cracks or delamination in the films themselves; bending also did not change the films' electrical resistance. These results suggested high flexibility of the Si films. In comparison, bare glasses (with no films) did not fracture, further suggesting the Si films added stress to the glass substrates.

Introduction:

Silicon (Si) thin-film technology has garnered widespread attention for its advantageous properties over bulk silicon materials. Compared with bulk Si substrates, Si thin films grown on inexpensive substrates allow for far more cost-effective manufacture and handling of Si devices. Commonly used substrates for Si films include conventional (rigid) glasses and polymers. However, both substrates have drawbacks. While conventional glasses have high thermal stability, they are heavy and inflexible, making installation of these materials difficult and expensive. Polymers are lighter and flexible but have low thermal stability, so they cannot be used for high-temperature or high-power applications [1]. Therefore, research has recently turned to ultra-thin flexible glasses (thickness: ≤ 100 µm), which contain both flexibility and high thermal stability. Si thin films grown on these flexible glasses open up new possibilities for small, lightweight, bendable, and durable devices. Potential applications range from high-efficiency thin-film solar cells to flexible biosensors to scrollable displays.

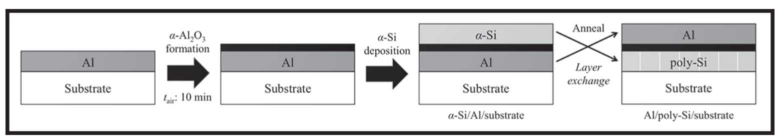

Figure 1: Schematic of the AIC process.

Aluminum-induced crystallization (AIC) offers a convenient way to grow Si films on flexible glasses. Amorphous Si (α-Si) cannot be deposited directly on glass because the Si crystallization temperature is ~ 600°C, which exceeds the softening temperatures of the glass substrate (T_g ≤ 600°C) [2]. The addition of aluminum (Al) lowers the Si crystallization temperature to temperatures below T_g (in this case, 450°C), allowing Si to be crystallized without deforming the glass substrate. Figure 1 illustrates the scheme of the AIC process.

First, Al is deposited on the glass substrate and exposed to air for 10 minutes to form α-Al_2O_3, which is important for controlling crystal orientation of Si. Si is then deposited on top. Annealing causes Si atoms to diffuse through the Al_2O_3 layer into the Al layer, and Al atoms are pushed to the top. This results in complete layer exchange of Al and Si, giving rise to Si films with large grains and preferential orientation [3].

Experimental Procedure:

Al films were deposited (thicknesses: 30 and 100 nm, deposition rate: 1.5Å/s) onto flexible glasses (Nippon Electric Glass, OA-10G 50 µm) via electron-beam evaporation. The films were exposed to air for 10 minutes

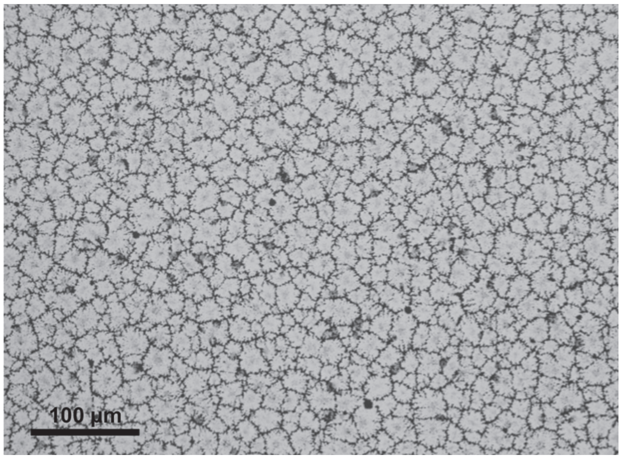

Figure 2: Optical microscopy image of 30 nm thick Si film.

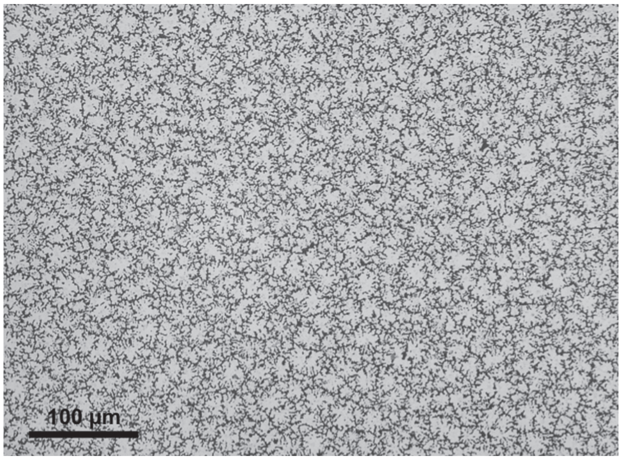

Figure 3: Optical microscopy image of 100 nm thick Si film.

to form α-Al_2O_3. Amorphous Si films, with identical thicknesses as Al, were deposited on top. The samples were annealed at 450°C (4 hours for 30 nm films, and 10 hours for 100 nm films) in N_2 to cause AIC. Al was etched off with Aluminum Etch Type A.

Morphology and electrical resistance of the films were characterized by optical microscopy and ohmmeter measurements. Mechanical flexibility was tested by bending the samples eleven times on each side (alternating between each side) around a tube of radius 5.75 cm. Changes in morphology, such as cracks or delamination, were observed via optical microscopy. Bare glasses (with no films), annealed under identical conditions, were also bent eleven times on each side for comparison.

Results and Conclusions:

Si films with thicknesses of 30 nm and 100 nm were successfully grown on 50 µm thick glasses via AIC. Optical microscopy demonstrated the films to be polycrystalline and large-grained. The 30 nm films (Figure 2) had a grain size of ~ 16 µm, while the 100 nm films (Figure 3) had a slightly smaller grain size of ~ 14 µm. Using an ohmmeter, the 30 nm films were measured to have a resistance of ~ 3-5 MΩ, and the 100 nm films had a resistance of ~ 130 kΩ.

Bending the samples (glass substrates with Si films coated on top) up to a total of eleven times fractured them into a few pieces, but produced no additional cracks or other new changes in the films themselves. Electrical resistance of the films was not changed either. The lack of change in morphology or electrical resistance suggested high flexibility of the Si thin films.

The flexibility of the samples was compared with that of bare glasses (with no films). The bare glasses, annealed under identical temperatures and durations, did not fracture in the bending tests. This suggested that the Si films, while highly flexible, added stress to the glass substrates, causing them to become more brittle than the bare glasses. Introduction of internal compressive stress by Al during annealing might explain this additional stress on the glasses [4]. However, cracks at the edges of the glass substrates and defects (e.g., black spots) in the films were observed prior to bending and could have made the samples more fragile, thus distorting the bending test results.

Future Work:

Further investigation into the flexibility of the Si films, especially possible external factors in the bending tests, will be necessary. External factors, such as cracks (from cutting the glasses, cleaning, and handling) and stress from metal tweezers, could have made the samples more fragile and prone to breaking. Plastic tweezers are softer than metal tweezers and will be used instead in the future. In addition, the Si films were not "clean-looking" and contained defects, which were likely caused by contamination from the surrounding environment. Screening out such external factors in the bending tests will help assess the flexibility of the Si films more accurately.

Acknowledgments:

I would like to thank Mel Hainey, Jr., and Dr. Joan Redwing for their mentorship and support in the lab. I am also thankful to the Penn State Nanofabrication Laboratory staff and the NNIN REU Program. This research was made possible by the National Science Foundation (NSF) under Grant No. ECCS-0335765.

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