Symp. Q, Materials Research Society, San Francisco, April, 2000

Mat. Res. Soc. Symp. Proc. Vol. 621 © 2000 Materials Research Society

Plastic Deformation of Thin Foil Substrates with Amorphous Silicon Islands into Spherical Shapes

Pai-hui I. Hsu, Min Huang, Sigurd Wagner, Zhigang Suo, and J. C. Sturm
Center for Photonics and Optoelectronic Materials (POEM)
Princeton University
Princeton, NJ 08544, U.S.A.

ABSTRACT

There is a growing interest in the application of large area electronics on curved surfaces. One approach towards realizing this goal is to fabricate circuits on planar substrates of thin plastic or metal foil, which are subsequently deformed into arbitrary shapes. The problem that we consider here is the deformation of substrates into a spherical shape, where the strain is determined by geometry and cannot be reduced by simply using a thinner substrate. The goal is to achieve permanent, plastic deformation in the substrates, without exceeding fracture or buckling limits in the device materials.

Our experiments consist of the planar fabrication of amorphous silicon device structures onto stainless steel or Kapton® polyimide substrates, followed by permanent deformation into a spherical shape. We will present empirical experiments showing the dependence of the results on the island/line size of the device materials and the deformation temperature. We have successfully deformed Kapton® polyimide substrates with 100 µm wide amorphous silicon islands into a one steradian spherical cap, which subtends 66 degrees, without degradation of the silicon. This work demonstrates the feasibility of building semiconductor devices on plastically deformed substrates despite a 5% average biaxial strain in the substrate after deformation.

INTRODUCTION

The applications of traditional large-area electronics, such as displays, are limited by the fact that glass substrates are rigid and easily breakable. Previous work [1,2] has demonstrated that transistors on thin metal or plastic foil substrates can be rolled around a cylinder down to 0.5mm radius of curvature with no adverse effects. In these cases, the transistor is compressed when bending inwards and elongated when bending outwards. The strain due to such cylindrical deformation can be decreased by reducing the thickness of the substrates. In this work we permanently deform the substrates into the final shape of a spherical dome. To deform a flat sheet into a spherical structure, the initial substrate is stretched so that the surface area increases. The average strain in this case is determined by geometry and is independent of the substrate thickness. Another important difference is that while the device can be either compressed or stretched when rolling the substrate, spherically deforming the substrate leaves the devices in tension in all cases.

https://doi.org/10.1557/PROC-621-Q8.6.1

EXPERIMENTS AND RESULTS

The thin film structures are first processed on planar thin foil substrates of stainless steel or Kapton® polyimide, with a typical thickness of 50 µm. The foil is placed over a circular hole and clamped by a circular ring (Figure 1). Pressurized gas is then used to deform the material inside the clamped ring into the shape of a spherical dome. A straightforward calculation can estimate the average radial strain, $\varepsilon_{avg,rad.}$, which is necessary to expand the foil to a spherical shape that subtends a given half-angle (θ).

$$\varepsilon_{avg,rad.} = \frac{\theta - \sin\theta}{\sin\theta}, \ \theta \text{ in radians} \tag{1}$$

Note that this strain is determined solely by the higher surface area of the spherically deformed cap compared to that of the original foil. Unlike the case of deforming the foil into a cylindrical shape, the strain cannot be reduced by making the foil thinner for any given subtended angle. This relationship is shown in Figure 2.

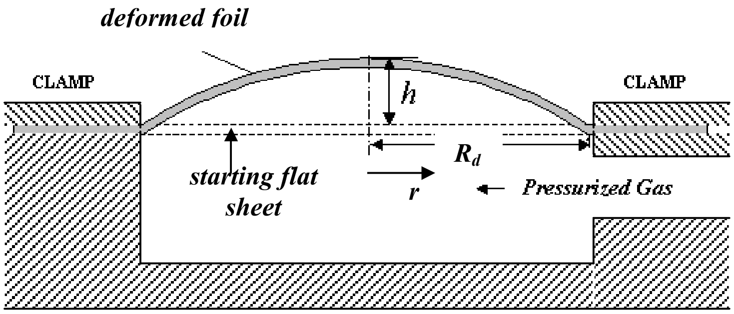


Figure 1. *Design of the apparatus used for deformation.*

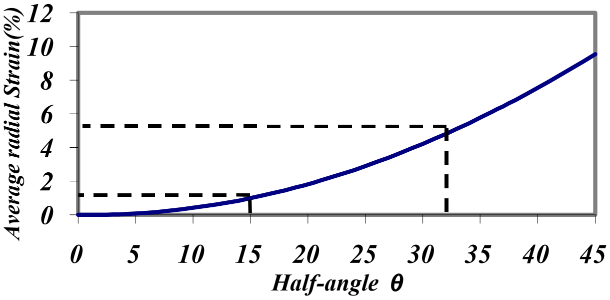
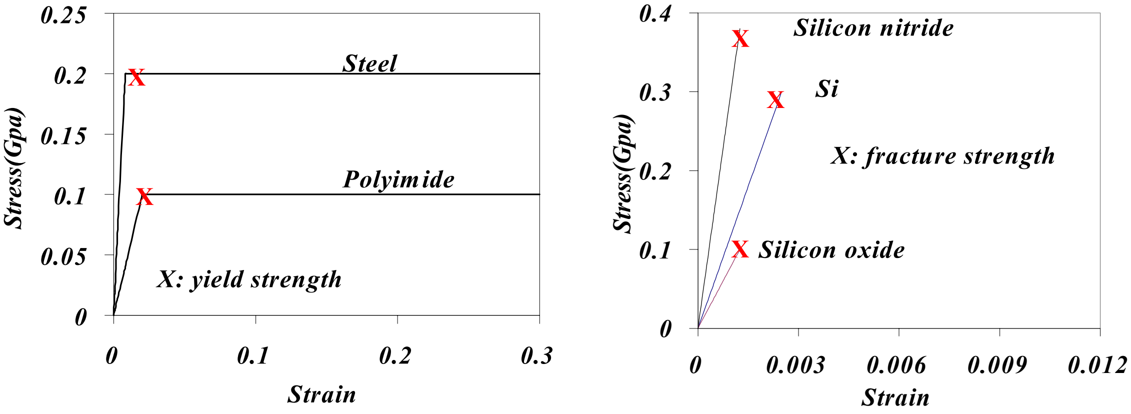


Figure 2. *Average radial strain vs. half-angle. For a subtended half-angle of 15°, the average strain is 1%, and for a subtended half-angle of 33° (corresponding to one steradian of solid angle), the average strain is 5%.*

https://doi.org/10.1557/PROC-621-Q8.6.1

When plastic or ductile metals are subjected to large strains, they deform plastically as seen in Figure 3. Therefore the deformation largely persists after the pressure is removed. For example, Figure 4 shows the height vs. radius of a 25 µm stainless steel sheet after the pressuring gas has been released. The foil was deformed into the shape of a spherical dome with a half-angle of 33°. On the other hand, inorganic semiconductor materials are brittle and can only be elastically deformed. For the 66° field of view spherical cap (Figure 4), the average strain is 5%, which far exceeds the breaking limit of the semiconductor materials. The brittle materials we examined include a sandwich of 100 nm amorphous silicon on top of 400 nm Si_3N_4 (Figure 5(a)). A uniform layer of such brittle materials deposited on the substrate cracked after it was deformed into a 66° dome.



(a) *(b)*

Figure 3(a). *Ideal stress-strain relationship for substrate materials. For compliant materials, the deformation is first elastic (linear region in the above diagram). After the deformation reaches the yield strength, the deformation becomes permanent (plastic deformation).* ***(b)*** *Ideal stress-strain relationship for brittle materials. The typical breaking strain limit is smaller than 1% for such ceramic materials [3]. The curves in both figures are an approximation of the stress-strain relationship for perfectly elastic/plastic materials. In practice, materials do no exhibit perfectly linear correlation between stress and strain.*

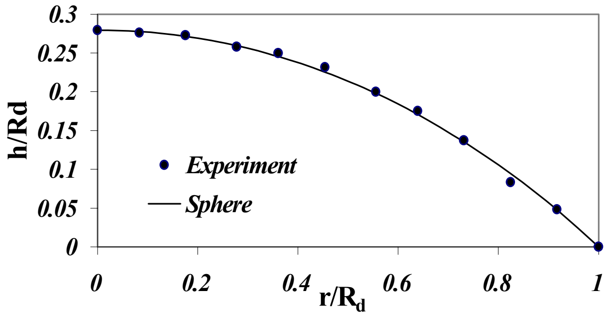
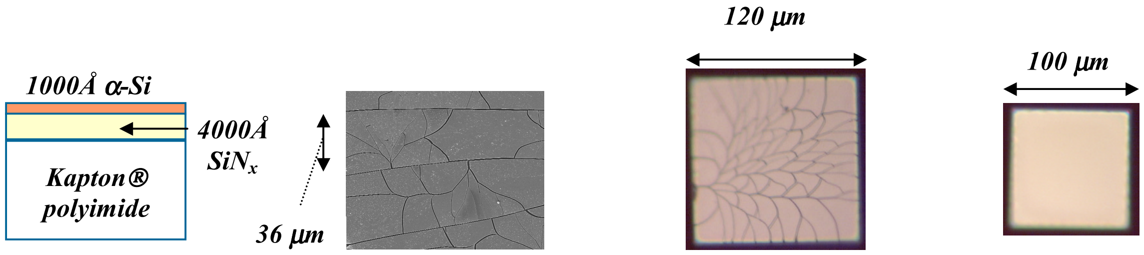


Figure 4. *Height of deformed 25 µm stainless steel sheet as a function of radius, with the height and radius normalized by the radius of the deformed region* R_d. *The solid line represents a spherical shape subtending a half angle of 33°.*

https://doi.org/10.1557/PROC-621-Q8.6.1

To overcome this limitation, we then examined the concept of fabricating islands of hard material (for eventual devices) on soft substrates. The qualitative concept was that the soft substrate could flow beneath the island so that the island itself might not be excessively strained. This was tested using a sandwich of 100 nm of amorphous silicon and 400 nm of silicon nitride deposited on 50 µm of Kapton® polyimide. Both layers were deposited by PECVD at 200°C and then patterned into square islands by dry etching. Using such a process, and performing deformation at 150°C, islands up to 100 µm without cracks could be obtained.

The likelihood of obtaining crack-free islands depends primarily on the size of the island (with smaller islands easier to obtain) and secondarily on the island density. The results are presented in Figure 6.



(a) *(b)* *(c)* *(d)*

Figure 5. *Semiconductor materials on flexible substrates after the substrates are deformed with 5% average strain.* ***(a)*** *Schematic amorphous silicon and silicon nitride stack on 50µm thick Kapton® polyimide film.* ***(b)*** *SEM photo of the silicon/silicon nitride stack after the Kapton® polyimide substrate is deformed into the desired spherical cap with 66° filed of view.* ***(c)*** *Optical micrograph of 120 µm island silicon/silicon nitride islands after deformation. The edge of the picture is out of focus due to curved surface.* ***(d)*** *Optical micrograph of 100 µm island after deformation at 150°C.*

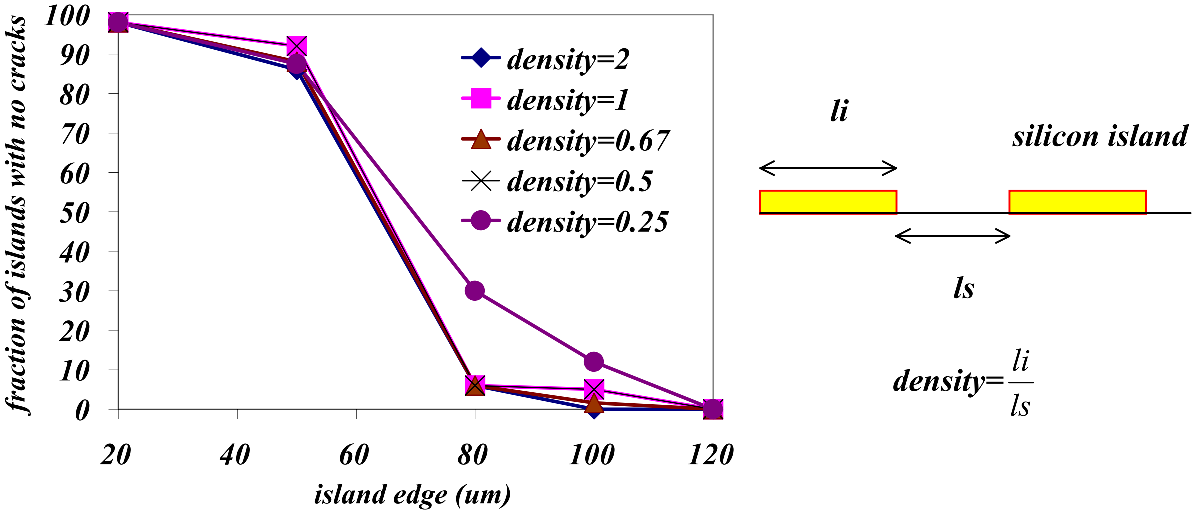


Figure 6. *Fraction of square α-Si/Si₃N₄ islands on polyimide with no cracks after the substrate is deformed with 5% average strain as a function of the island edge, for different island densities. The island density is defined as the island edge size over the island spacing.*

https://doi.org/10.1557/PROC-621-Q8.6.1

MODELING AND DISCUSSION

To further understand the deformation of the islands, we used ABAQUS [4], a finite element analysis program, to model the strain distribution in the substrate. The test structure consisted of 0.5 µm thick square silicon islands on a 50 µm thick polyimide substrate in the cylindrical coordinate with the z-axis perpendicular to the center of the silicon island. The whole structure was then deformed under the same boundary conditions as in the experiment. The results of this analysis for the island on the top center of the dome are shown in Figure 7.

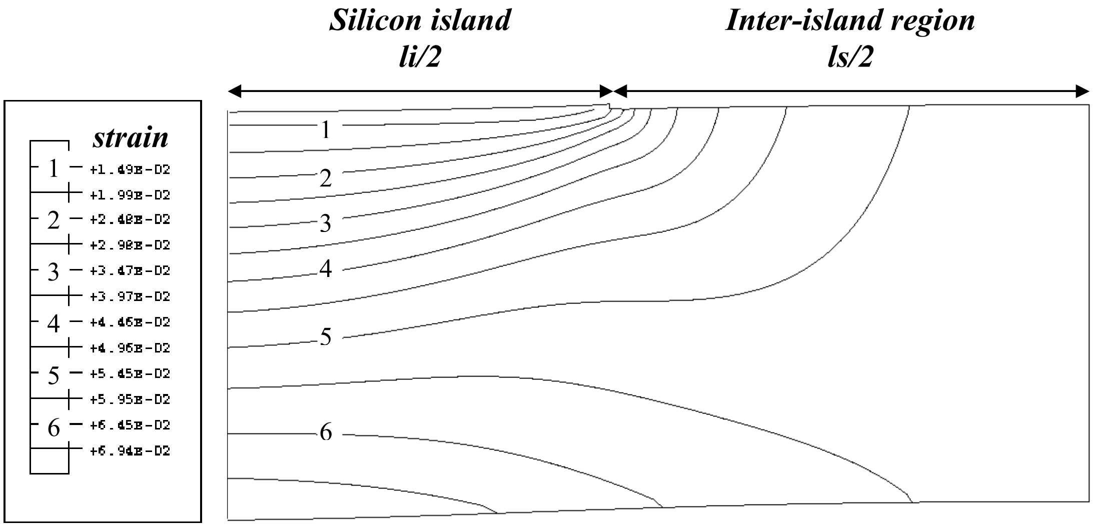


***Figure** 7. Contour plot of circumferential strain distribution in the 50 µm thick substrate after deformation into a one-steradian dome from finite element analysis. The island is 0.5 µm thick with length of li. The island to island spacing is ls. Contour lines labeled 1 to 6 indicate strain linearly increasing from $1.5x10^{-2}$ to $6.5\ x10^{-2}$.*

The simulation of the strain distribution (Figure 7) highlights two important facts:

1. The stiff island confines the substrate underneath itself. The strain in the top substrate, which is just below the island, is small and quite uniform.
2. The strain increases as one moves radially away from the island. In the inter-island region, the strain in the substrate is so high that the substrate is plastically deformed.

By patterning the uniform silicon layer into isolated islands, the plastic deformation takes place in the inter-island region. This is the main reason why the silicon islands are intact despite a 5% average strain in the substrate after deformation. For an island without cracks, the strain in the island must be less than the maximum strain at its fracture strength. Our experimental results show that few islands larger than 100 µm are intact after deformation. This indicates that the strain in the island increases with its size. Finite element analysis demonstrates that the strain in the island indeed correlates to the island length, and the strain is not strongly dependent on the island spacing when the island is small (Figure 8).

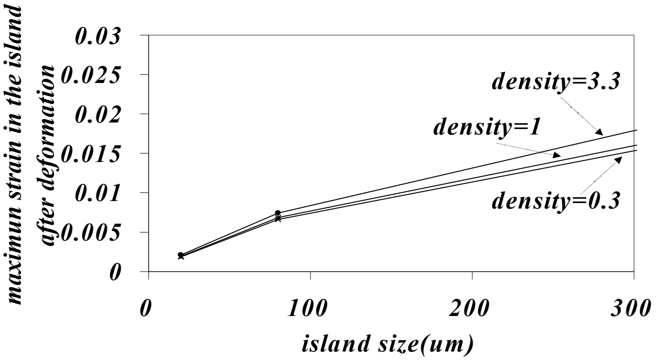


Figure 8. *Maximum strain as a function of the island size for 0.5 μm thick square silicon islands on 50 μm thick polyimide substrate after the substrate is deformed into a one-steradian dome. The island density is defined as the island size over the island spacing.*

Figure 8 demonstrates that the plastic deformation occurs in the inter-island region. When the substrate is plastically deformed, the yield strength is almost constant, and the sheer strength that stretches the island is independent of the inter-island area. Therefore, the island spacing is a weak factor in the fracture mechanism.

SUMMARY

The concept of developing spherically-shaped electronics by deforming thin foil substrates with patterned device islands on their surface has been investigated. We find that the strain in the island increases with the island size, but is only weakly dependent on island density. 100 μm silicon islands on a plastically deformed substrate in the shape of a spherical dome subtending 66° have been fabricated so it appears feasible to build circuits in such structures.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support from DARPA/ONR and the assistance of H. Gleskova with PECVD deposition.

REFERENCE

1. E. Y. Ma, S. D. Theiss, M. H. Lu, C. C. Wu, J. C. Sturm, and S. Wagner, Thin Film Transistors For Foldable Displays, *Tech. Dig. Int. Electron Devices Meet.*, p. 535-538 (1997).
2. H. Gleskova and S. Wagner, Failure Resistance of Amorphous Silicon Transistors Under Extreme In-plane Strain, *Appl. Phys. Lett.*, **75**, 3011 (1999).
3. W. D. Callister, JR., *Materials Science and Engineering: An introduction*, 4th ed.(John Wiley & Sons, Inc., New York, 1997), p. 401.
4. ABAQUS, Version 5.8, Hibbitt, Karlsson & Sorensen, Inc., Rhode Island, 1999.