Effects of Mechanical Strain on TFTs on Spherical Domes

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***Abstract*—In this paper, amorphous-silicon (a-Si:H) thin-film transistors (TFTs) were fabricated on a plastic substrate, which was then permanently deformed into a spherical dome shape after the device fabrication process. The TFTs were patterned in an island structure to prevent cracking in the device films during the substrate deformation. In the majority of the TFTs, the off-current and gate leakage current do not change substantially. Depending on the island structure, the electron mobility either increased or decreased after deformation. This change in mobility was correlated with the mechanical strain in the device islands determined by finite element modeling of the deformation process. Tensile strain caused slightly higher mobility in planar structures. In a mesa-type structure, silicon films on top of the pillars could be in compression after the dome deformation, leading to a slight decrease in mobility.**

***Index Terms*—Amorphous semiconductors, plasma chemical vapor deposition (CVD), plastic films, thin-film transistors (TFTs).**

I. INTRODUCTION

NOVEL LARGE-AREA electronics, such as electronic paper, sensor skin, and electrotextiles, requires building electron devices on flexible and deformable substrates [1]–[4]. Substrates such as organic polymers and stainless steel foils can be deformed into arbitrary shapes, but inorganic semiconductor device materials, such as amorphous silicon (a-Si:H) and silicon nitride, are brittle, and crack easily when substrates are deformed. Therefore, it is desirable to reduce the strain in device structures on deformable substrates, and to further understand the relationship between the electrical performance of the devices and the applied mechanical strain for strain below the point where failure occurs. One approach toward electronics on curved surfaces involves direct fabrication on curved or spherical surfaces [5]. However, it is difficult to adapt conventional process tools to this approach. Thus, our approach here is to fabricate first on flat substrates, then permanently deform the final device structure into a spherical dome.

To date, research on curved electronics with this "fabricate first on planar substrates" approach has focused on the cylindrical deformation of thin film devices on polymer or metal foils. For cylindrical deformation, the strain is one dimensional, and the devices can be put either in tension (bending outwards) or in compression (bending inwards) by elastic deformation [6]. Since the strain on the surfaces (where the devices are) can be kept low by reducing the substrate thickness, tight radii of curvature can be achieved for cylindrical deformation. Further experiments showed that uniaxial tensile strain raised the electron field-effect mobility, and compressive strain reduced the electron mobility in a-Si:H at room temperature [4]. The effect of strain on the electrical properties was reversible: the on-current of the transistor went back to is original value once the stress was removed.

II. SUBSTRATE DEFORMATION

In this paper, a-Si:H TFTs on plastic substrates were deformed into a spherical dome. We first fabricated TFTs using conventional technologies on a 50-μm thick polyimide (Kapton) foil substrate, and then permanently plastically deformed the foil to a spherical dome. To perform the deformation, the substrate was clamped by a circular ring of 6 cm in diameter. Pressurized gas then deformed the material within the clamped ring to a spherical dome with 66° field-of-view under pressure (Fig. 1) [7]. Deformation of a flat sheet into a spherical shape is more difficult than into a cylindrical one: in spherical deformation of a flat substrate as described above, the substrate is stretched and is in tension. Adopting a thinner substrate cannot reduce the strain, in contrast to cylindrical deformation. For example, the average radial strain in a deformed substrate can easily be calculated geometrically by the increase in length of an arc from one side of the foil to the other through the center. For a spherical dome with 66° field-of-view, the average strain is $\sim 6\%$ [7]. This level of strain generally exceeds the fracture limit of inorganic device materials ($< 1\%$), and continuous a-Si:H films crack after deformation. Previous results have shown that by patterning amorphous silicon and silicon nitride layers into isolated islands on soft polyimide substrates before deformation, the brittle islands can remain crack-free despite average strain in the substrate in excess of 5% [8]. When the device islands are not connected, most of the deformation takes place in the substrate between islands, and the substrate flows underneath the hard islands. The strain in the semiconductor layer is therefore reduced. We previously demonstrated that TFTs built on individual islands could be deformed into a

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spherical dome with no gross adverse effects, and that these transistors could be interconnected into simple circuits [8].

In this paper, we contrast the effect of deformation on two device structures—thin planar island structures and tall mesa islands — and examine the relationship between the strain in the islands and the device characteristics. To achieve larger thin islands without fracture after deformation, the substrate was held at 150 °C to soften the polymer substrate during deformation; this heating raised the maximum island size without cracking from 20 μm at room temperature to 50 μm [7]. For mesa devices, we not only patterned the semiconductor material into individual islands but also etched deep ($\sim$ 10 μm) into the substrate to create the device on a polyimide mesa structure. Mesa devices were deformed at room temperature, and islands up to 90 μm could be deformed without breaking.

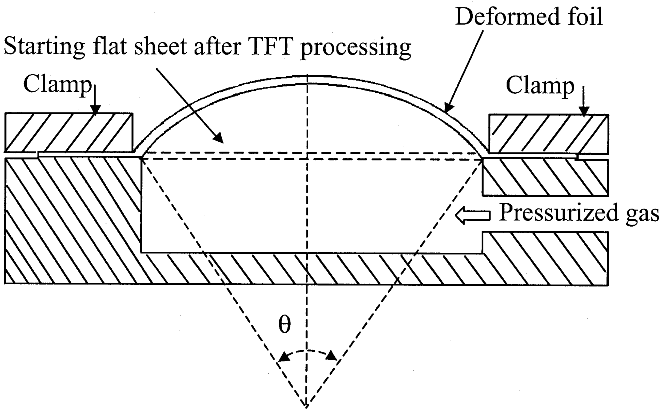


Fig. 1. Schematic diagram indicating apparatus for deforming substrates, and definition of subtended angle θ after deformation.

III. TFTs in Planar Islands

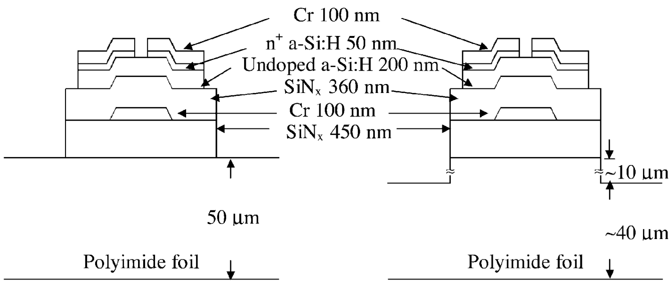
Fig. 2 shows the structure of the a-Si:H TFTs fabricated in isolated islands with the conventional staggered bottom-gate, back-channel-etch structure. Before TFT fabrication, the polyimide foil was temporarily laminated to a 4-in silicon wafer with a thin adhesive layer of silicone gel to ensure substrate flatness during fabrication. All TFT silicon layers were deposited using a three-chamber RF-excited plasma-enhanced chemical vapor deposition (PECVD) system at 150 °C substrate temperature [9]. Detailed processing steps were described in [8]. Note that as a part of the process, all device materials, including the nitride buffer layer, were removed outside of the device island area so that only the polyimide substrate was left in the inter island region.

Device characteristics of these TFTs were measured before deforming the substrate into a spherical dome. The TFTs were measured by changing V_{gs} from -20 to $+20$ V at 0.1 V interval first at $V_{\mathrm{ds}} = 0.1$ V then at $V_{\mathrm{ds}} = 10$ V. Although amorphous silicon TFT device characteristics are known to drift with device operation, for the gate voltages and measurement times current–voltage (I–V) measurement sweep was done in less than 500s) used here, the change in device characteristics due to the instability of amorphous silicon was insignificant [10]. The sample was then peeled from the wafer and deformed at 150 °C to a 66° field-of-view (one steradian) spherical dome, which corresponded to raising the center of the foil by $\sim$ 0.90 cm. After releasing the pressure, the height of the dome decreased to $\sim$ 0.78 cm due to the elastic relaxation of the substrate. After pressure release the dome curvature subtended a 58° field-of-view, corresponding to an average substrate radial strain $\sim$ 4.5%.

To first order, the transistors are little affected by the deformation process. All devices were measured near the top of the dome, where the strain in the substrates (and in the islands) is biaxial. The threshold voltage (V_{th}) and the electron mobility in saturation (μ_{n}) are calculated from the transfer characteristic in saturation at the source-drain voltage $V_{\mathrm{ds}} = 10$ V. Deformation raised the average mobility (of five devices tested) from 0.39 to 0.42 cm^2/Vs (an increase of $\sim$ 8%), and reduced the average threshold voltage from 2.1 to 1.6 V. The subthreshold slope changed from 0.55 to 0.60 V/dec. The gate currents remained below 1×10^{-11} A [8]. To further probe the effects of deformation, a polyimide substrate with a separate batch of similarly fabricated devices was deformed into a spherical dome with a 30° field-of-view, which corresponded to raising the center of the foil by $\sim$ 0.40 cm (average radial strain in the substrate $\sim$ 1%) when the pressure was applied. Because the strain was low, the deformation of the substrate was elastic, and could be done at room temperature. After the pressure was released, the substrate returned to its original shape. In this case, the threshold voltage changed from 1.9 to 2.5 V, and the mobility changed from 0.29 to 0.30 cm^2/Vs (average of five devices), an increase of only 3%, which was less than the accuracy of the measurement. It shows that the effect of elastic substrate deformation was reversible. This demonstrates that the change in the previous case (spherical deformation) is due to the plastic substrate deformation. These results were summarized in Fig. 3. The difference in initial as-fabricated characteristics for these three groups is within the normal variability of research-grade TFT processing from substrate to substrate in our single substrate deposition system. In our experiments, the device characteristics of the deformed devices stayed relatively unchanged after the initial deformation, which is similar to results seen for flat devices after fabrication.

IV. TFTs in Mesa Islands

To study the effects of the mechanical strain alone, it was desirable to design a device structure with lower strain so the plastic substrate deformation could be done at room temperature. The solution was the mesa island structure [Fig. 2(b)]. The device fabrication process was similar to the planar structure. The major difference was that after gate nitride layer and buffer nitride were patterned to make device islands, the sample was etched with oxygen plasma to define the mesa pattern into the polyimide. The photoresist (from the previous SiN$_x$ lithography step) and the device islands themselves served as masks. $\sim$ 10 μm deep polyimide pillars were etched. This step was followed by removing n$^+$ a-Si:H in the channel region to complete the device fabrication process. The spherical deformation (a height of $\sim$ 1.00 cm, which is a 74° field-of-view, corresponding to an average radial strain $\sim$ 7%) was done at room



(a) (b)

Fig. 2. (a) Cross section of the TFT planar island device structure and (b) cross section of the TFT-on-mesa structure.

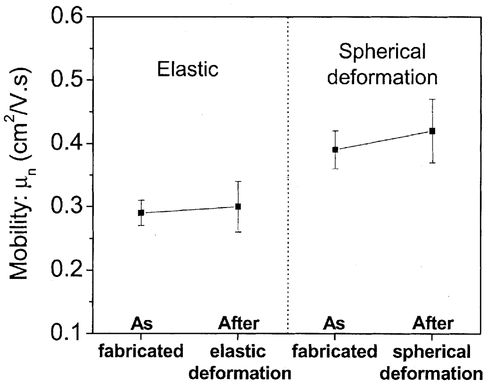


Fig. 3. Comparison of the change in electron mobility (μ_{n}). The first sample was elastically deformed, and the second sample was deformed to a height of $\sim$ 0.78 cm after pressure release at 150 °C.

temperature. After pressure release, the dome relaxed back to a spherical dome of a height of 0.75 cm (a 56° field-of-view, corresponding to an average substrate radial strain $\sim$ 4%). TFTs with SiN_x islands smaller than 90-μm remained crack-free after deformation. Fig. 4 shows the transfer and gate leakage characteristic of a TFT on a 90-μm SiN_x island before and after deformation. The off-current and leakage current did not change significantly (for an average of five devices), but the electron mobility decreased (4%), and the threshold voltage increased (14%), after deformation (Fig. 4).

The fact that only smaller islands remained intact after deformation indicated that strain in the island increased with its size. Therefore, if the changes in the electrical properties after deformation were due to the resulting mechanical strain, islands of different sizes would be expected to behave differently. Fig. 5 summarized the changes in electron mobility after deformation for islands of different sizes. Such measurements versus island size were not possible in the case of planar islands because only one island size (40 μm) was large enough for planar TFTs with probe pads and did not crack, even with deformation at 150 °C. The data demonstrate that the mobility decreased after deformation, and that on average, the decrease was larger in smaller islands. In our experiments, the threshold voltage and subthreshold slope increased after deformation although there is no clear trend with island size. We postulate that the increase in the threshold voltage and the subthreshold slope reflected the usual dangling-bond instability of a-Si:H TFTs [11] since they changed significantly even for elastically deformed sample. We will focus our discussion on mobility, which does have a consistent trend due to strain.

To study the effects of strain on mobility due to multiple deformations, a separate set of devices on mesa structures was fabricated [12]. The polyimide pillars for this sample were $\sim$ 8 μm deep. The same sample was deformed 3 times. In the first experiment, we deformed the substrate into a spherical dome with a height of $\sim$ 0.45 cm (a 36° field-of-view, corresponding to average strain $\sim$ 1.5%) when the pressure was applied. Because the strain was low, the deformation in the substrate was elastic. After the pressure was released, the substrate returned to its original planar shape. The TFT characteristics after this elastic deformation were measured. The substrate was then deformed again into a spherical dome with a height of $\sim$ 0.65 cm (a 50° field-of-view, corresponding to average strain $\sim$ 3%). The deformation was permanent with a height of 0.40 cm (a 30° field-of-view, corresponding to average strain $\sim$ 1%) after pressure release. TFT characteristics were measured after deformation. Finally, the substrate was deformed into a spherical dome with a height of $\sim$ 0.90 cm (a 66° field-of-view, corresponding to average strain $\sim$ 6%). After pressure release, the dome was with a height of $\sim$ 0.65 cm (a 50° field-of-view, corresponding to average strain 3%). The TFT characteristics were summarized in Fig. 6 (The devices shown here are all on a 40 μm SiN_x island with gate length $L = 4$ μm and gate width $W = 14$ μm). The mobility (μ_{n}) decreased very slightly, and the threshold voltage (V_{th}) increased after the first elastic deformation. After the last deformation, $\sim$ 10% increase in V_{th} and $\sim$ 10% decrease in μ_{n} were observed. No substantial changes in the off-current and the gate-leakage current were recorded.

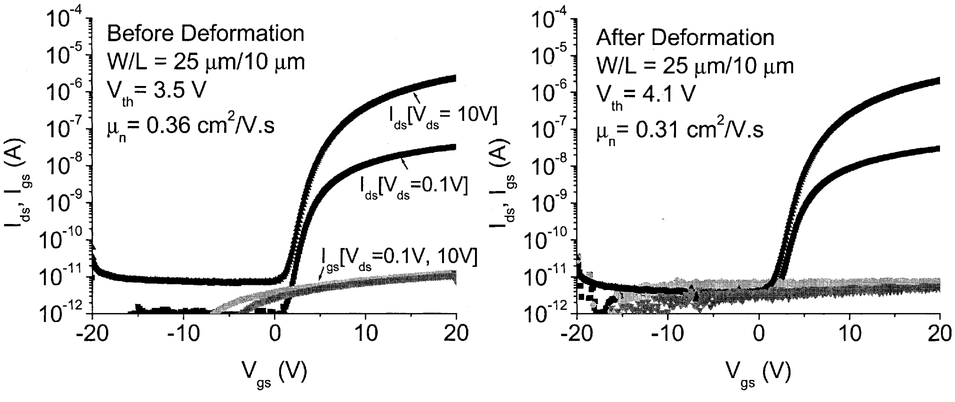
V. DISCUSSION

A. Mechanical Modeling

To estimate the strain in the silicon islands, a commercially-available finite element analysis program (ABAQUS) was used to examine the strain distribution in the thin film island/substrate structure near the top of the dome, where the strain is uniform in the plane of film (biaxial). We assumed the Youngs modulus E is 200 GPa for all TFT layers, and measured the stress-strain parameters of the polyimide substrate at room temperature, which was then used to model the room temperature deformation of the mesa structures. For the planar samples, we estimated the mechanical properties of polyimide (Kapton® E) at deformation temperature (150 °C) by scaling the properties at room temperature according to the temperature effect on the stress-strain relationship of a similar polyimide film (Kapton® HN) described in [13]. The test structure consisted of a 1-μm-thick round silicon islands (50 μm in diameter) on a 50-μm-thick polyimide substrate in the cylindrical coordinate with the z-axis perpendicular to the center of the silicon island. The details of this modeling are reported elsewhere [14], and the highlights relevant to this work are reported here.

B. Planar Devices and Tensile Strain

The radial strain was calculated in the planar device island after 150 °C deformation for a case where the boundary of the test structure was first deformed with 6% strain and then relaxed



(a) (b)

Fig. 4. Mesa TFT characteristics for a device on a 90 μm SiN$_x$ island with gate length $L = 10$ μm and gate width $W = 25$ μm. (a) After fabrication and (b) after room temperature deformation to a height of $\sim$ 0.75 cm after pressure release.

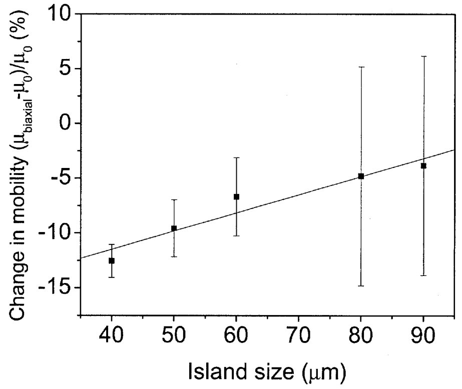


Fig. 5. Change in electron mobility of mesa TFTs after deformation for islands of different sizes.

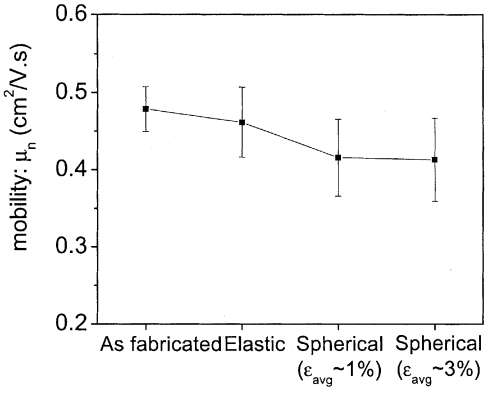


Fig. 6. Mesa TFT: Electron mobility after elastic deformation, first spherical deformation to a height of $\sim$ 0.40 cm after pressure release, and second spherical deformation to a height of $\sim$ 0.65 cm after pressure release. The average substrate strain given in the spherical deformation is calculated from the fixed height after pressure release, assuming a spherical shape.

to 5% strain in the substrate (corresponding to a height of $\sim$ 0.90 cm with pressure on, and $\sim$ 0.80 cm after pressure release) [14]. The radial strain at the center of the island at the maximum deformation is $\sim$ 0.33% (tension) while pressure was applied. After the pressure is unloaded the strain is reduced to $\sim$ 0.29%. The strain is maximum (and also biaxial) at the center of the island (channel region of the device) and decreased to near zero at the edge of the island. The fact that the strain in the device island is much less than the average substrate strain by an order of magnitude confirms that the island concept reduces the island strain.

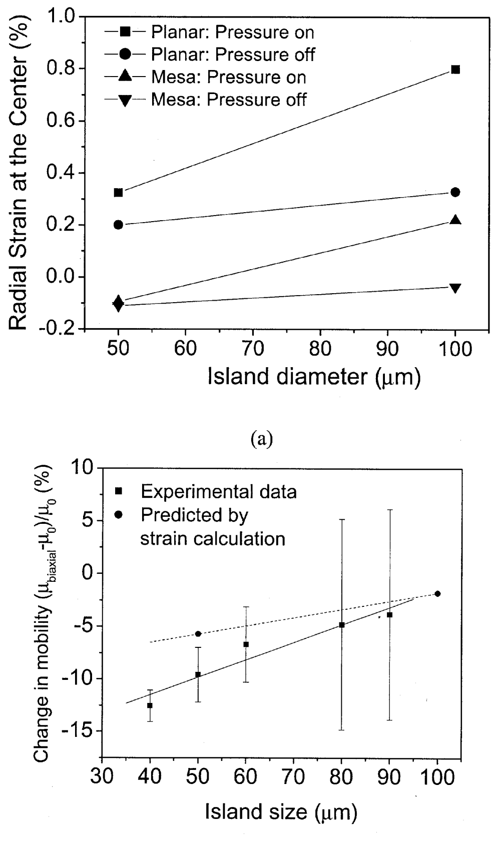
The change in the device characteristics of a-Si:H devices as a function of strain has been studied by several authors [4], [15]–[17], even though the lack of long-range order in the amorphous materials should attenuate any piezoresistive effect. The results of these measurements suggested that the piezoresistive effects depend on the method of material preparation and the conductivity type. Uniaxial tensile strain is reported to raise electron field-effect mobility in a-Si:H TFTs fabricated in our lab by a similar process [4]. The relation is linear

$$\mu_{\text{uniaxial}} = \mu_0(1 + 26\varepsilon) \tag{1}$$

where μ_0 is the mobility without strain (devices as fabricated), ε represents uniaxial strain in amorphous silicon, and tensile strain has a positive sign. For simplicity, we assume the effects of biaxial strain on the mobility is the superimposition of the effects due to uniaxial strain in the parallel and the perpendicular directions, and that the effect in the perpendicular direction is equal to that described in (1)

$$\mu_{\text{biaxial}} = \mu_0(1 + 52\varepsilon). \tag{2}$$

Under such an assumption, the relative increase of mobility for a biaxial strain of 0.29% along the direction of the channel is 14%. This result is 1.75 times larger than our experimental results of planar structures (devices with an increase of $\sim$ 8% in mobility after deformation). Three reasons could cause this discrepancy. First, the substrate deformation of the planar devices was done at 150 °C, and such heating could also change the dependence of mobility on strain from that at room temperature as was measured by Gleskova *et al.* [4]. Second, due to the uncertainties in the mechanical properties of device materials used in the finite element analysis, and the simplicity of the model (e.g., round islands in the numerical model versus square islands in the experiment), the exact strain in the device is uncertain. The device is also not uniform over the island as assumed in the model. Third, the simple assumption of (2) that



(a)

(b)

Fig. 7. (a) Predicted strain at the island center as a function of the island diameter for 1-μm-thick circular silicon islands on a 50-μm-thick polyimide substrate stretched with 6% strain at the substrate boundary when pressure is on and after pressure release with 4% strain at the substrate boundary) at room temperature and (b) experimental change in mobility and change predicted by final strain at island center in Fig. 5.

the applied strain parallel and perpendicular to the current path has equal effects could be incorrect. We conclude that qualitatively, the planar devices are in tension; however, at present not enough is known to quantitatively predict the mobility change of the planar a-Si:H TFTs from the predicted strain.

C. Mesa Devices and Compressive Strain

The calculated radial strain at the center of a 50 μm mesa island deformed at room temperature by application of 6% average strain at the boundary of the test structure was found to be $\sim -0.09\%$, corresponding to compression, not tension [14]. After the pressure was released (corresponding to a 4% fixed strain in the entire structure), the strain magnitude increased to $\sim -0.11\%$. Fig. 7(a) summarized the calculated strain at the island center as a function of island diameter for both mesa and planar islands with pressure on and off. With pressure on, the tensile strain is less in mesa structure than planar structures, as expected. For mesa device with a diameter less or equal to 100 μm, after pressure release, the center of island on mesa were found to be in compression. The compression at island center in light of the average substrate expansion depends on the island thickness and the mesa height [14]. The compression is more significant in small mesa islands. It demonstrates that it is possible to fabricate devices with structures less sensitive to the substrate deformation so it endures little or no strain even if the substrate is expanding. The concept of controlling and tuning the strain and its sign (either tension or compression) during deformation might be useful for flexible electronics applications.

Fig. 5 shows that the mobility of TFTs on such mesa pillars decreased after deformation, with a larger decrease observed on smaller islands than on larger islands. (e.g., 5% reduction on 100 μm islands versus 12% reduction in 40 μm islands.) This is explained by the compression strain that increases as the size decreases in mesa islands. Assuming the earlier relation of $\mu_{\rm biaxial} = \mu_0(1 + 52\varepsilon)$ for biaxial strain in amorphous silicon, the change in mobility predicted by the calculated strain versus island size is shown with the experimental data in Fig. 7(b). The correlation of a more pronounced mobility reduction in small islands is clear, although the quantitative agreement is not good. Reasons for a lack of better quantitative agreement could include modeling limitations (i.e., uncertainties in the mechanical properties of substrate and device materials, and simplicity of the round island model, etc.) and the uncertainties in the piezoelectric effects of amorphous silicon TFTs under biaxial strain.

Figs. 3 and 6 showed that elastic deformation had little effect on the electron mobility for both the planar (increased by only 3%) and mesa structures (decreased by only 4%). We conclude that elastic deformation at room temperature does not permanently alter mobility, which is consistent with previous work on uniaxial cylindrical deformation.

VI. SUMMARY

In this paper, we examined the effect on a-Si:H transistors of plastically deforming their polyimide substrates into spherical shapes. In continuous layers of inorganic semiconductor materials, the deformation of the substrate induced excessive tension so that the device layers fractured during deformation. By patterning continuous amorphous silicon and silicon nitride layers into isolated islands, a-Si:H transistors can be made to withstand the deformation without fracture as we expand the substrate to a spherical dome. The strain in such device islands after deformation is biaxial, and is related to the island geometry. Though the substrate is plastically expanded to a spherical dome, device islands can experience either tension or compression depending on the deformation conditions. We have analyzed the mechanical problem and related it to order for the change in mobility due to such spherical deformation.

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