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Numerical Design of SiO_2 Bridges in Stretchable Thin Film Transistors

Byung-Jae Kim, Kyung-Yea Park[1], Jong-Hyun Ahn[1], and Youn-Jea Kim[2*]

Graduate School of Mechanical Engineering, Sungkyunkwan University, Suwon, Gyeonggi 440-746, Korea
[1]*School of Advanced Materials and Science, SungKyunkwan University, Suwon, Gyeonggi 440-746, Korea*
[2]*School of Mechanical Engineering, Sungkyunkwan University, Suwon, Gyeonggi 440-746, Korea*

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An amorphous indium–gallium–zinc oxide based inverter (a-IGZO inverter) was fabricated. Subsequently, its mechanical characteristics were investigated. A numerical method was adopted to optimize the a-IGZO inverter design. This optimization secured mechanical stability. The curvature at the edge of the SiO_2 pad and the thickness of the indium–tin-oxide (ITO) electrode were accounted for in the models. The new model improved the mechanical stability when it was stretched by a total of 5% of its length along the *x*-axis and did not exhibit fractures or cracks. In contrast, the referenced model fractured under the same condition. It has been verified by both experiments and simulations that newly designed models obtain mechanical stability.

1. Introduction

Transparent oxide semiconductors (TOS) are widely studied for applications in optoelectronic devices. Amorphous indium–gallium–zinc oxide (a-IGZO) thin film transistors (TFTs) are high performance TOS that are attractive alternatives to polycrystalline silicon (poly-Si) TFTs, because they provide better uniformity in terms of device characteristics, such as the threshold voltage and mobility.[1,2] In addition, both ZnO and a-IGZO can potentially replace hydrogenated amorphous silicon in TFTs due to their high charge carrier mobility and low deposition temperature. However, the electrical performance of flexible TFTs must be insensitive to mechanical bending and stretching.[3)] In this regard, many research institutions have strived to improve not only the high electrical performance of TFTs but also the mechanical characteristics, such as elasticity and durability under artificial conditions.[3–5)] In this paper, a structure analysis of a-IGZO based inverter was conducted to increase its mechanical stability. As shown in Fig. 1, the newly designed model is shaped differently than the referenced model. In particular, the differences are seen at the electrode and SiO_2 bridge. The new model improved the mechanical stability when it was stretched by a total of 5% of its length along the *x*-axis. Conversely, the referenced model fractured under the same condition. Some different model cases were analyzed and the optimum model that can be applied for flexible electronic devices was proposed. The results were verified by both experiments and simulations.

2. Sample Preparation

Figures 2 and 3 show an optical microscope image of the fabricated a-IGZO based inverter and schematic side view of the device, respectively. The first, an array of IGZO transparent thin film transistors (TTFTs) was fabricated on a carrier substrate coated with germanium (Ge) and SiO_2 as sacrificial and protection layers, respectively. For oxidation of as-deposited Ge film, Ge was annealed at over 400 °C because it dissolves in water as an oxide.[6,7)] The devices were coated with a protective layer (~1 µm) of epoxy-based negative photoresist (SU-8),[8)] to position the device layers near the neutral mechanical plane (NMP). The location of the NMP in the IGZO device layers, which was weakest against an applied strain, facilitated non-destructive bending

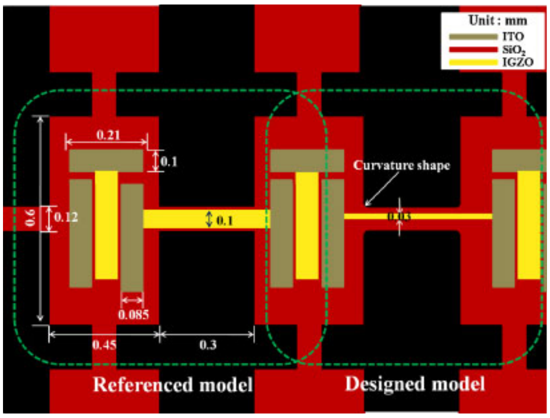


Fig. 1. (Color online) Schematic simplified referenced and newly designed models for simulation.

of the devices.[5,9)] Next, reactive ion etching through a patterned layer of photo resist removed certain regions of the SU-8/SiO_2/Ge to isolate the active device islands mechanically connected by thin bridges. The thin device array was then lifted from the carrier substrate by removing the underlying Ge layer with water. The released thin device film was transfer-printed onto a pre-strained elastomeric substrate. Relaxing the pre-strain (ε_{pre}) led to compressive strain that formed wavy configurations in the thin bridges and the device regions.[10)] The wave lengths and heights were determined primarily by the thickness of the device layers as well as the elastic properties of the device layers and SU-8. The bottom SiO_2 was uniformly bonded to the SU-8 surface by covalent –O–Si–O– bonds between the silanol (Si–OH) groups on the SU-8 and silicon oxide. Such silanol groups on the top surface of SU-8 formed through UV/ozone exposure for the surface activation of SU-8.[4)]

3. Results and Discussion

3.1 Experiments

Experiments were conducted in order to verify the newly designed model's ability to mechanically stabilize a-IGZO inverter device. Figure 4 shows the experimental results for both the referenced and newly designed model 2. The left side of the device was fixed when it was stretched by a total 5% of its length in $+x$-direction using a bending machine. In the referenced model, SiO_2 pad design fractured at the vertical edge. Furthermore, the indium–tin-oxide (ITO)

*E-mail address: yjkim@skku.edu

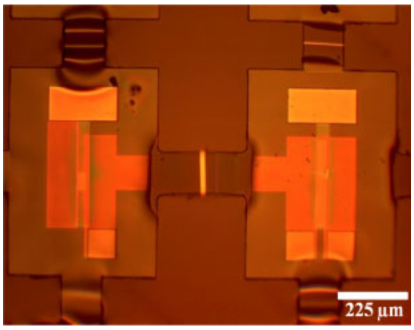


Fig. 2. (Color online) Optical microscope image of the fabricated a-IGZO based inverter.

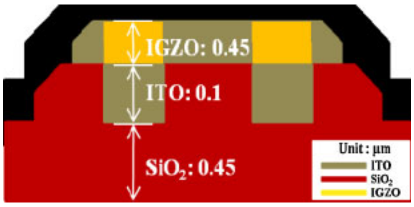


Fig. 3. (Color online) Schematic side view of the a-IGZO based inverter.

Table I. Model cases for numerical analysis.

	Referenced model	Newly designed model 1	2	3	4
Radius of edge (mm)	0	0.02	0.025	0.03	0.035
Width of ITO (mm)	0.1	0.03			

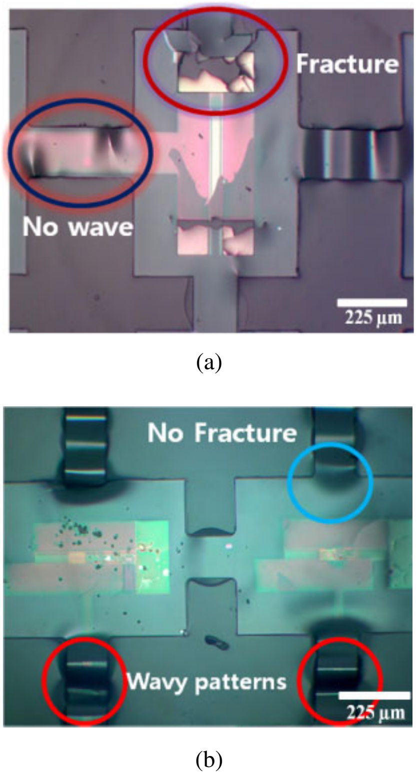


Fig. 4. (Color online) Optical microscope images of the experimental results: (a) Referenced model and (b) designed model.

Table II. Mechanical properties of materials.

	ITO[14]	SiO_2[15]	IGZO
Young's modulus (GPa)	116	70	137
Poisson ratio	0.35	0.17	0.36

interconnector did not exhibit wavy patterns when it had a width of 0.1 mm. On the other hand, the newly designed model 2 containing a curvature edge and a radius of 0.025 mm provided mechanical stability. This model contained a decreased stress concentration in comparison to the vertical edge. Furthermore, designed model 2 did not exhibit any fractures or cracks. In addition, the ITO interconnector formed wavy patterns when its width was reduced from 0.1 to 0.03 mm. Wavy patterns provide high flexibility and elasticity, thus offering great possibilities for the development of stretchable electronics.[11,12]

3.2 Numerical details

The numerical analysis focused on a comparative analysis for strain and stress distribution among the referenced and newly designed models. Simulations were performed for five models on the x–y plane using COMSOL-Multiphysics.[13] Triangular elements were generated using the free mesh method over the entire layer for the simulation. The number of elements in the grid system and the degrees of freedom of all the layers were 384,240 and 1,541,626, respectively. Table I provides the radii of curvature of the SiO_2 bridges and the widths of the ITO interconnector. Simplified models for simulation were constructed using the SiO_2 pad, IGZO active layers and ITO drain as shown in Fig. 1. Mechanical properties of each material applied for simulation are shown in Table II,[14,15] and the IGZO was assumed to have similar

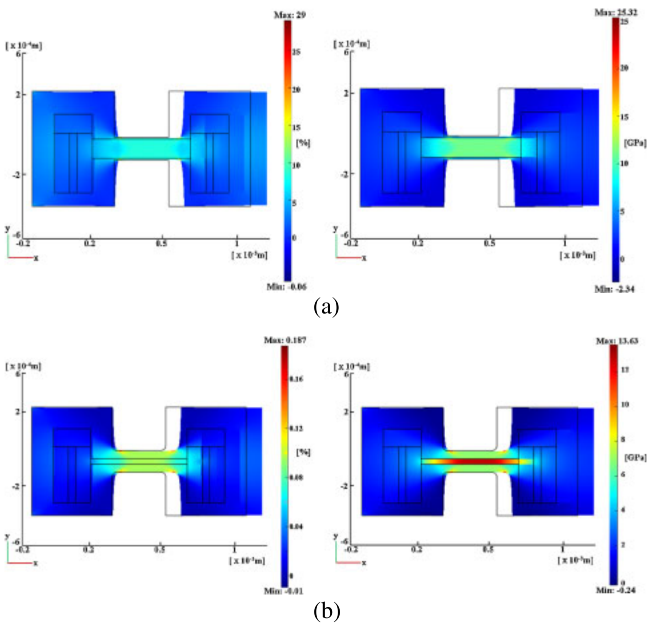
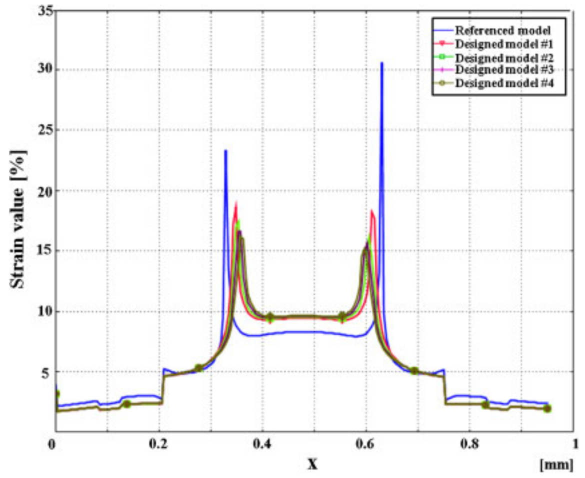
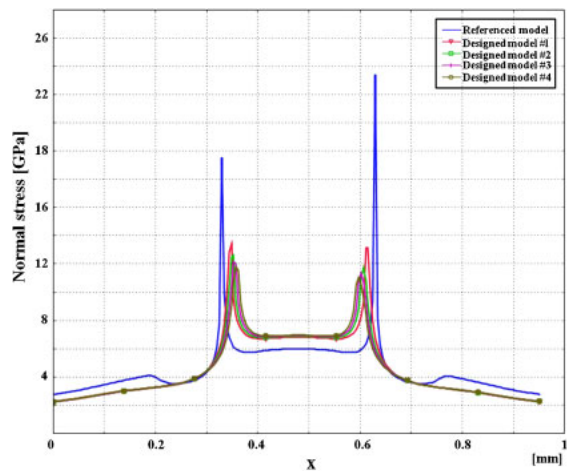


Fig. 5. (Color online) Simulation results by finite element method: (a) Strain and stress distribution on the referenced model and (b) strain and stress distribution on a designed model 2.



(a)



(b)

Fig. 6. (Color online) Results of strain and stress distributions on the device: (a) Strain values along the *x*-axis on the device and (b) stress values along the *x*-axis on the device.

properties as the ZnO. Under these conditions, simulation models were stretched by a total of 5% of its length in $+x$-axis. Figure 5 shows the simulated strain and stress distribution on the referenced model and the designed model 2. Both models possessed the same dimensions as the models used in the experimental studies. Figure 6 presents the graph of the strain and stress distributions in the x-axis along the cross section line passing through the edge of the SiO_2 bridge. The maximum stress and strain values on each model were observed at the corner of SiO_2 bridge. The referenced model exhibited maximum stress and strain values two times higher than the designed model 2. The results may be attributed to the fact that the curvature disperses the stress and strain concentration around the bridge. Models 3 and 4 in which the radii of curvatures were over 0.025 mm exhibited nearly the same results as model 2.

4. Conclusions

An IGZO based inverter was fabricated and investigated. The IGZO based inverter was designed to improve the mechanical stability of high performance flexible electronics. Both experimental and simulation results validated the mechanical stability of the device's new design. The following conclusions were obtained.

1) The maximum stress values at the edge of the SiO_2 bridge of the referenced and designed model 2 were 25.32 and 13.63 GPa and the strain values were 0.29 and 0.187, respectively. These values were acquired from the simulation.
2) Experimental results show that fractures occurred at the vertical edge of the SiO_2 bridge of the referenced model. Conversely, designed model 2 did not exhibit any cracks or fractures.
3) The curvature shape provided mechanical stability to the device as it dispersed the stress and strain concentration at the corner of the SiO_2 bridge.

Acknowledgements

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