# P-71: Robust-Stretchable Interconnects for Flexible Display Applications

***D. P. Wang, F. Y. Biga, A. Zaslavsky and G. P. Crawford***
**Department of Physics & Division of Engineering, Brown University, Providence, RI, USA**

## Abstract

*We report on a robust metallization scheme ideal for interconnects required in flexible display applications. Multi-layered metal interconnects including a granular discontinuous ductile indium layer, have been deposited on a variety of compliant substrates to confirm that there is a minimal change in resistance even when subjected to large mechanical strains and repeated low-strain fatigue loading. Initial analysis of deformed films also suggests there is a possibility for a self-healing process. A finite element analysis (FEA) model of the thin-metal film/polymer substrate structure, also confirms the stretchability of the granular indium islands observed to be bridging the cracked regions in the underlying conductive layers.*

## 1. Introduction

Ubiquitous computing devices with enhanced media content will require highly portable, lightweight and rugged display applications. These next generation displays are envisioned by many to be in the form of flexible displays which can be rolled out for viewing and rolled up into compact form factors to be stowed away. Figure 1 depicts an artist's rendition of a flexible display device.

**Figure 1** An artist's rendition of a flexible and rollable display which can be rolled out from a compact pen-sized form for viewing.

This continued interest in the development of flexible display applications calls for new materials and radical design methodologies. Flexible display application development poses a significant challenge primarily because of the differences in the intrinsic material properties, processing schemes and device functionality. Flexible display applications, which broadly include conformable and rollable displays [1], will require flexible and robust substrates, components, electronic and optical layers and circuitry for functionality and reliable performance. Reports on thin-film transistors (TFT) fabricated on flexible and deformable substrates, suggest that the device performance can be significantly influenced by mechanical strain, be it tensile or compressive [2]. This can be circumvented by designing islands of rigid TFT devices on flexible substrates and connecting them with robust and stretchable interconnects [3]. The external strain will be deflected away from the rigid TFT islands to the other substrate regions traversed by interconnect lines. Some possible candidates for flexible interconnects include conducting polymers, printed carbon pastes, carbon nanotube dispersions and thin metal films. The conductivity of conducting organic materials is still orders of magnitudes less that that of thin metal films. Although all the aforementioned candidates have their merits and demerits, thin metal film interconnects are much more suitable for flexible display circuitry because of their inherent high conductivity. Thin-film gold interconnects have shown promise as stretchable interconnects recently [4-6]. We present results to show that indium-island containing multi-layer thin films provide an attractive alternative for robust stretchable and flexible interconnects. Experimental results demonstrate that the multi-layer films maintain a continuous electrical path through the interconnect lines via a bridging mechanism observed in the specimen after a mechanical loading force is applied [7]. Additionally, there is a negligible (< 0.02 %) change in resistance of the interconnects when subjected to low-strain fatigue loading (> 10,000 cycles).

## 2. Material Processing

Thin-metal film interconnects were deposited onto dog bone-shaped polyethylene terephthalate (PET) and highly formable film (HFF) substrates, carefully prepared to minimize edge defects which could potentially lead to a localization of the applied strain and lead to a premature rupture in the films. Figure 2 (a) shows a photograph of the testing system and (b) a scanning electron micrograph (SEM) of a Cr/In film. The HFF substrates utilized exhibit thermal properties similar to conventional PET, however,

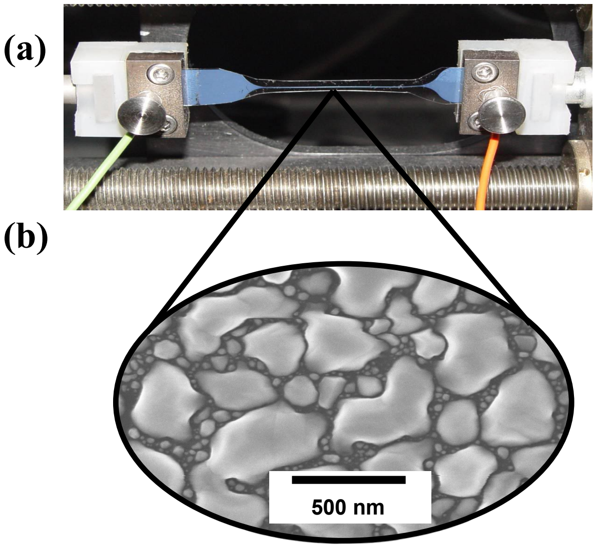

**Figure 2** (a) Photograph of a Cr/In (5/50 nm) interconnect sample loaded in tensile strain. (b) SEM micrograph showing the granular indium layer deposited on a Cr-coated PET substrate.

ISSN0006-0966X/06/3701-0466-$1.00+.00 © 2006 SID

they can be stretched much more easily and their formability can be improved by heating. HFF substrates are particularly suitable for conformed display application because they are engineered for bending and embossing (even 90$^{o}$ corners), which may not be achievable with standard PET. For both substrates two types of films were fabricated; films deposited on the entire surface of the dog-bone shaped substrates and films patterned as thin lines using a shadowmask in the gauge length of the dog-bone shaped substrate. The multi-layered metal interconnects deposited on the polymer substrates consisted of a 5-nm chromium (Cr) adhesion layer, followed by a 50-nm granular indium (In) film and in some cases an additional 10 nm-thick gold layer to increase conductivity and encapsulate the indium layer. All the metal films were deposited by electron-beam evaporation at room temperature at a deposition rate of ~0.1 nm/sec. The samples were then loaded in a Minimat Miniature Tensile tester system. The electro-mechanical performance of different multi-layer structures based on thin films of chromium, indium and gold deposited on PET and HFF substrates was investigated.

## 3. Measurements and Results

### 3.1 Uniaxial Tensile Strain Test

The electro-mechanical performance of thin-metal films patterned as interconnects on polymer substrates were evaluated by monitoring the electrical resistance as a uniaxial tensile force was applied to both ends of the film. Figure 3 shows an illustration of the thin-metal coated polymer film before and after a uniaxial tensile strain was applied. As depicted in the illustration, cracks were observed to form and propagate in the stiffer underlying chromium layer.

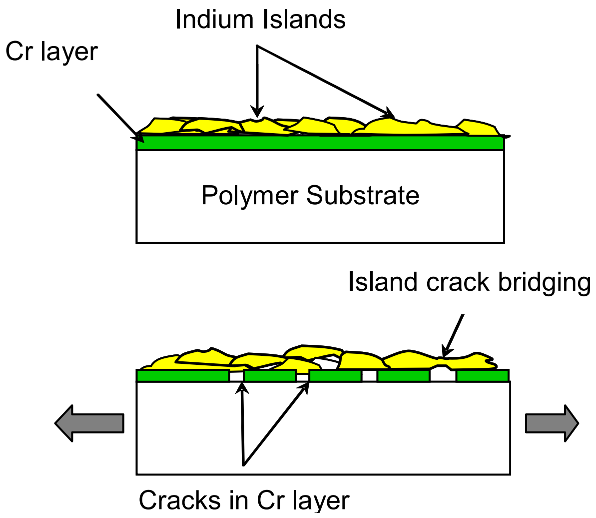

**Figure 3** Illustration of thin film structure (a) before and (b) after a tensile force is applied at both ends of the sample.

Although the electrical resistance of the interconnects was observed to increase with increasing strain, there was no abrupt change or loss of electrical integrity over a wide range of strain values for all samples tested. Interconnects fabricated on PET substrates were observed to deform uniformly over the entire gauge-length of the dog-bone shaped sample, and remained conducting until the PET substrate itself ruptured at strain of 38%.

In the HFF samples, on the other hand, the deformation was concentrated in the mid-section of the gauge-length, thus causing a localization of the stress in the interconnect. Notwithstanding this peculiar deformation characteristic of the HFF substrate, the thin-metal film interconnects were observed to be electrically conductive even after applying a strain of >100% to the HFF sample. Figure 3 shows a stress-strain curve as well as a normalized change in resistance curve, ($\Delta R/R_o = (R-R_o)/R_o$) for Cr/In/Au interconnects deposited on the two different substrates.

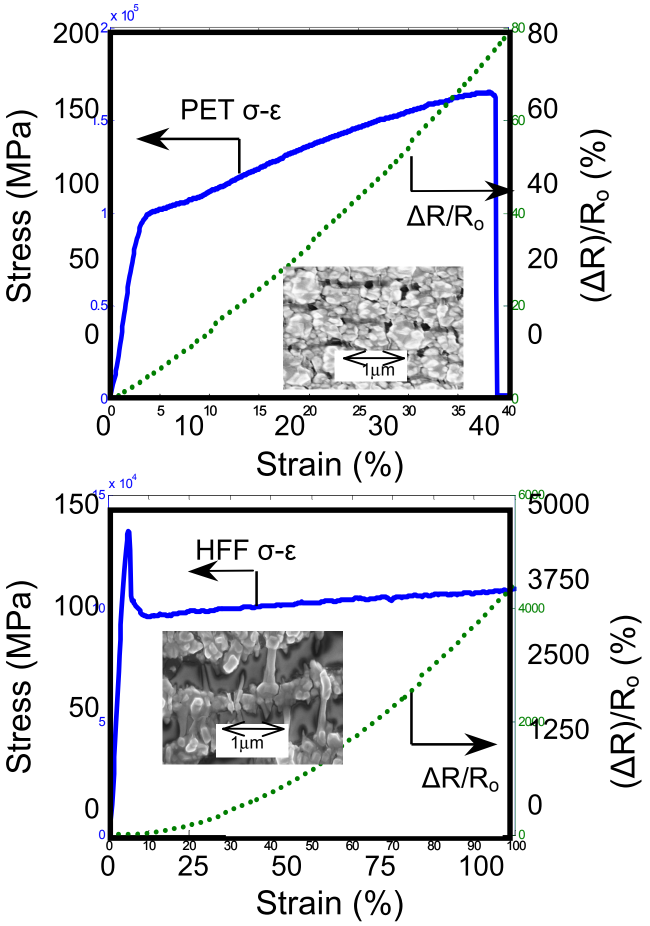

**Figure 4** Stress-strain curve with change in resistance for interconnects on a PET and HFF substrate and inset showing SEM micrographs of samples after applied tensile strain.

The normalized change in resistance of the Cr/In/Au film showed a steady increase with no catastrophic failures for both substrates, although the recorded values were two orders of magnitude higher with the HFF substrate. The observed geometric deformation in the HFF substrate which is dominated by a necking phenomena, inherently constrains the current through the film. The observed change in resistance of the interconnects deposited on a PET substrates, was observed to be <100% at an applied external strain of 38%. The resistance increase is a result of crack formation and geometry changes in the films. Cracks form perpendicular to the loading direction and increase in size and density with increasing applied strain for continuous films. The island structure of the indium layer however, deforms continuously through an elastic mechanism in which they extend across the cracks formed in the underlying chromium layer as shown in SEM insets in Figure 4.

The enhanced performance of these films under high strain can also be attributed to the ductility of the gold layer which has also been observed to be granular with smaller grain sizes compared to the indium layer.

## 3.2 Low-Strain Cyclic Fatigue Loading

Flexible electronic applications designed to undergo continuous flexing, rolling and bending during fabrication or while in use, must also be robust enough under repeated low-strain fatigue conditions. Samples of the indium island-containing films were tested on a custom built fatigue tensile-tester for 10,000 bend cycles. In this test, the thin films deposited on both PET and HFF substrates were repeatedly rolled and unraveled around a half inch diameter cylindrical mandrel. The fatigue test system as well as the results from this test is presented in figure 5.

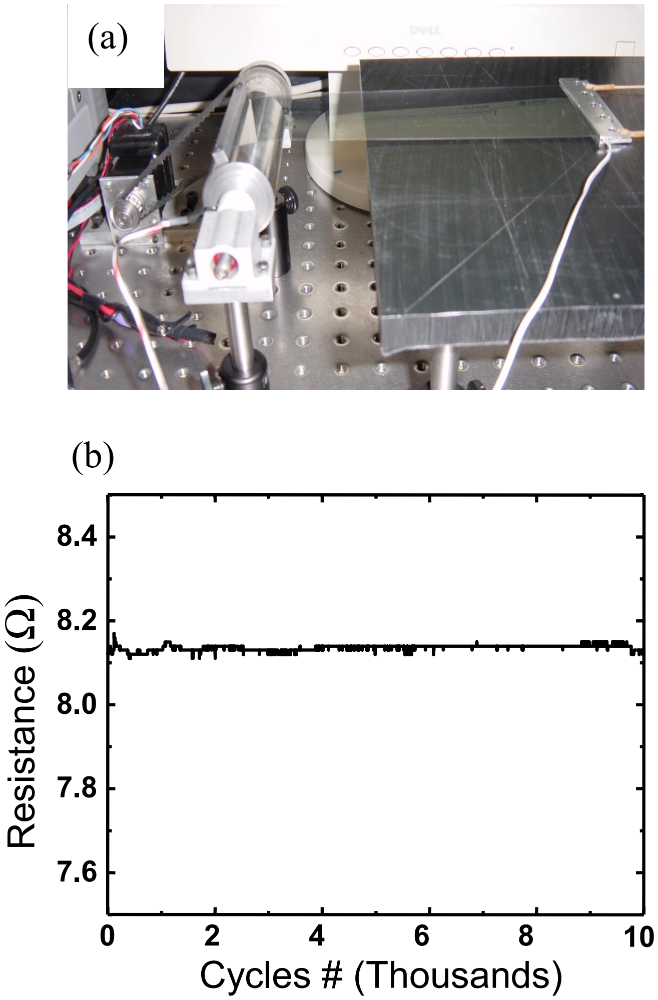

**Figure 5**. (a) Photograph of cyclic fatigue testing apparatus and (b) the measured resistance (2-point) of a Cr/In/Au film deposited on a PET substrate after 10,000 cycles showing less than a 0.01% change in electrical resistance.

The results clearly show that there is negligible change in the resistance of the interconnects due to fatigue loading conditions. The apparent fluctuation in the measured resistance can be attributed to the resolution and inherent vibrations present in the test system.

## 3.3 Finite Element Analysis

A finite element model of the multi-layer thin-film system was developed to predict the dominant deformation mechanisms contributing to the apparent change in electrical resistance and also to determine film thicknesses required to optimize the mechanical and electrical properties of the interconnects. This static model comprises ductile indium islands on top of a relatively stiff chromium adhesion layer, tightly bonded to a conformable substrate. Geometric considerations for the model and material properties used in this simulation are presented Figure 6 and Table 1 respectively.

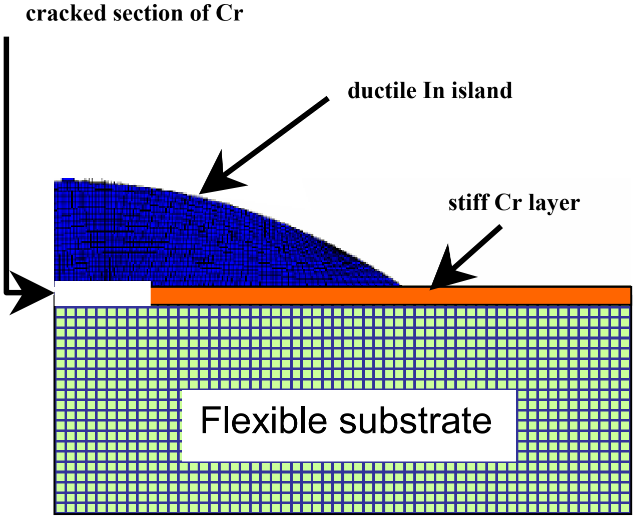

**Figure 6** FEA model depicting half the cross-sectional area of an In island on top of a stiff Cr film deposited on a flexible

| Material | In | Cr | PET |
|---|---|---|---|
| **Position** | Top | Middle | Bottom |
| **Young's modulus** | 10Gpa | 100GPa | 5Gpa |
| **Poisson's ratio** | 0.3 | 0.3 | 0.45 |

**Table 1** Parameters for components used in FEA simulation.

The geometry of the indium islands was reduced to a quadrant, taking into account symmetry considerations and assuming a simple hemisphere structure. The simulation was run for different island sizes, crack lengths and spacing and substrate thicknesses. Although, simulation was initially setup to capture the deformation mechanism in both the elastic and plastic regime, we noted that the plasticity effects deviated from our experimental observations. Nevertheless, this model confirms the significance of the granular indium layer as a prerequisite for the "super-

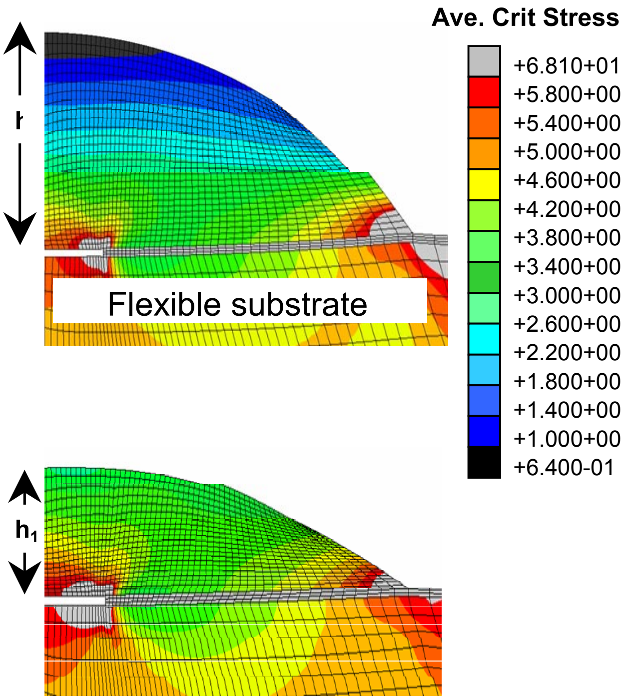

**Figure 7** FEA simulation results show the stress distribution for varying In island heights ($h > h_1$).

elastic" behavior observed in these thin-film structures. The ductile islands, which in most cases have dimensions greater than the cracks formed in the underlying regions, are able to stretch across the open cracks to form pathways for electrical signals. Additionally, the ductility of the indium material enhances the stretchability of island structures thus extending the maximum possible strain which can be sustained without an electrical open line.

## 3.4 Theory of Resistance-Strain Relation

Despite the crack formation in the Cr layer and the complicated shape change of In islands across them, the resistance-strain relation of the film on PET substrate follows a simple relation. The In grains observed in a 50-nm-thick film have diameter, D~600 nm, much larger than the crack below 40% strain. Since the highly ductile nature of the indium islands permits them to deform and follow the change of the Cr film, the Cr layer with or without the In layer on top will deform the same way, which has been confirmed by the SEM observation for different samples. Between the cracks, the film and substrate (PET) will first deform elastically at small strain, which only happens below 5% for PET and 2~3% for metal. The change of the resistance will be

$$\Delta R_{1\mathrm{elastic}} = (1+\varepsilon_r)/(1-\gamma\,\varepsilon_r)^2 - 1, \tag{1}$$

where $\varepsilon_r$ is the residual strain in the Cr film, which is smaller than the total stain ($\varepsilon$) applied and $\gamma$ is the poison ratio. At higher strain from 5% to 38%, the film will undergo plastic deformation and the film resistance will increase by a factor given by

$$\Delta R_{1\mathrm{plastic}} = (1+\varepsilon_r)^2 - 1. \tag{2}$$

On the contrary, across the cracks, the In islands will deform more than the total strain, due to the high concentration of the strain. The film resistance will increase by a factor given by

$$\Delta R_2 = (1 + d/D)^2 - 1, \tag{3}$$

where d is width of the cracks and D is the In island diameter. The total resistance change will be

$$\Delta R = \Delta R_1 + \Delta R_2 (\varepsilon - \varepsilon_r). \tag{4}$$

Since the cracks only forms a small percentage (50nm out of 1µm at $\varepsilon = 20\%$) of the total area, the total resistance is determined mainly by the region between the cracks $\Delta R_1$, which agrees with the experiment. To fully solve this problem, we need to analyze a resistance network, with high resistance blocks (Cr) and low resistance blocks (In) and calculate the change of resistance when some of the high resistance blocks are replaced with insulating cracks. This analysis is still in progress.

## 4. Conclusion

In this work, we have shown that the inclusion of a granular layer of indium islands enhances the ultimate stretchability and reliability of thin-film interconnects. Preliminary investigations and results not included in this report also suggest that a self-healing mechanism can be realized via electrical or thermal activation of the indium islands into the voids created in the brittle cracked regions of the stiff chromium layer. Stretchable interconnects which could also provide self-healing capabilities could potentially offer developers of flexible electronics the much needed electrical and mechanical properties to develop robust applications.

## 5. Acknowledgements

The work at Brown University is supported by the MRSEC/NSF (DMR 0079964) and by NSF ECS-0223943 and NSF CCF-0403958.

## 6. References

[1] G. P. Crawford, ed., *Flexible Flat Panel Displays*, New York: Wiley, (2005).

[2] H. Gleskova, S. Wagner, W. Soboyejo, and Z. Suo "Electrical response of amorphous silicon thin-film transistors under mechanical strain," J. Appl. Phys. 92 pp. 6224-6229, (2002).

[3] P-H. Hsu, M. Huang, H. Gleskova, Z. Xi, Z. Suo, S. Wagner, and J. C. Sturm, IEEE Trans. on Elect. Dev. 51, p. 371 (2004).

[4] T. Li, Z. Huang, Z. Suo, S. P. Lacour, and S.Wagner, " Stretchability of thin metal films on elastomer substrates", Applied Physics Letters 85 (16) 3435, (2004).

[5] S. P. Lacour, J. Jones, S. Wagner, T. Li and Z. Suo, Proc. IEEE 93, 1459 (2005).

[6] D. S. Gray, J. Tien and C. S. Chen, Adv. Mater. (Weinheim, Ger.) 16/5 393 (2004).

[7] D. P. Wang, F. Y. Biga, A. Zaslavsky and G. P. Crawford, J. Appl. Phys. 98, 086107 (2005).