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Electrical resistance of island-containing thin metal interconnects on polymer substrates under high strain

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We have deposited thin metal films that include a granular indium layer on polymer substrates and observed the resistance of the film changed by a factor of less than 2, even as the sample is uniaxially stretched to the point of rupture (~38% strain). The presence of a discontinuous layer of indium islands in these films maintains the electrical conductivity by providing a bridging mechanism across the cracks formed in the underlying continuous film layers. A simple model is used to relate the applied strain to the electrical resistance of the metal films. Furthermore, we present the data for these films under cyclic loading around a cylindrical mandrel which show that there is no change in resistance under these fatigue testing conditions for 10 000 loading cycles. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2113417]

Ductile thin films with properties different from those of bulk are being widely used to replace brittle materials in flexible electronic applications such as flexible displays,[1] sensitive skin sensors,[2] electronic textiles,[3] and electronic paper displays.[4,5] Regardless of the technology used in these devices, flexible and/or stretchable conductors will be required to enable them.[6,7]

Previous research in this area has included reports on tensile strain measurements for both freestanding[8–10] and polymer-supported[11] thin films. Although these results indicate that the rupture strain for freestanding films is much lower than the corresponding bulk metals, the thin films usually have higher strength. Recently a detailed analysis of this phenomenon, supported by finite element simulations, was presented by Li *et al.*[12] The altered mechanical properties can be attributed to the microstructure and tendency of the mechanical properties of submicrometer films to exhibit strong size dependence.[13]

In search of flexible interconnects, thin gold films deposited on elastomeric substrates were recently reported by Lacour *et al.*[14] The resistance of these films was reported to change by 100% for strains $\varepsilon \sim 18\%$, and some degree of conductivity was retained up to $\varepsilon = 22\%$. In this contribution we demonstrate composite In-island-containing metal films on polyethylene terephthalate (PET) substrates that maintain electrical conductivity at strains as high as 38%—the rupture strain of PET—with an acceptably small resistance change (under 100%). These films combine the ductility of gold along with the discontinuous island structure formation of indium to mitigate the effect of crack propagation that leads to electrical opens.

The metal films were deposited onto dog-bone-shaped PET substrates to minimize the effect of kinks and edge imperfections which can lead to a premature rupture in the films. The PET substrates were first cleaned in methanol and dried under a high-pressure air jet. The metal interconnect consisted of a 5-nm Cr adhesion layer, followed by a 50-nm granular In film (both metals deposited by *e*-beam evaporation at room temperature with a deposition rate of ~0.1 nm/s). For some of the samples prepared, we deposited an additional 10 nm gold layer to increase the conductivity and encapsulate the indium layer. Under a scanning electron microscope (SEM), we observed the indium layer to be granular in nature, as shown in Fig. 1(a). Figure 1(b) shows a SEM micrograph of a sample with an additional 10 nm layer of gold deposited on top of the indium. The final samples showed a slight curvature confirming the presence of compressive stresses of the films on the semiflexible substrate. Both wide (~3 mm) and narrow (300 μm) lines were fabricated using a shadow mask.

The samples prepared were tested in a Minimat miniature tensile tester system, as shown in Fig. 2(a). The two ends of the sample were clamped by metal grips. For each sample tested, we concurrently measured the displacement and the resistance across the sample as a uniaxial strain was being applied at both ends of the grips. Prior to testing, the contact resistance of the testing system was measured to be 5–8 Ω. This is particularly important in analyzing samples with very low resistivities as this series resistance may be comparable to that of the sample.

The initial resistance R_0 of the samples were measured and compared to the theoretical values calculated from the dimensions and bulk resistivities of the individual metal films. For the Cr/In (5/50 nm) film, the resistance was measured to be $R_0 \sim 120\ \Omega/\square$. The average diameter of the indium islands was estimated to be about 600 nm. The rela-

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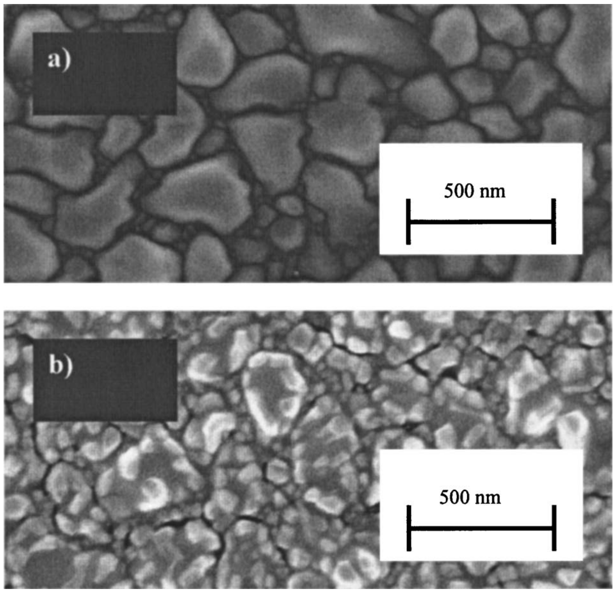

FIG. 1. (a) SEM micrograph of granular indium islands on top of a 5 μm chromium adhesion layer with a wide distribution of sizes and shapes. The average diameter of the In island $D \sim 600$ nm. (b) SEM micrograph (top view) of the multilayer Cr/In/Au (5/50/10 nm) film.

tively large size of the indium islands allows us to use the bulk electrical resistivity of In. Assuming the island to be either a truncated hemisphere with a height of 50 nm or a frustum cone with an ~20% taper and an ~60 nm slant height, we can approximate the resistance to be ~1 Ω/□. Using image processing techniques on SEM micrographs, we calculated the coverage of indium islands to be approximately 75% of the total film area. The indium-free regions are evenly distributed around all of the In islands. From this, we can deduce that most of the resistance can be attributed to the Cr layer between the islands.

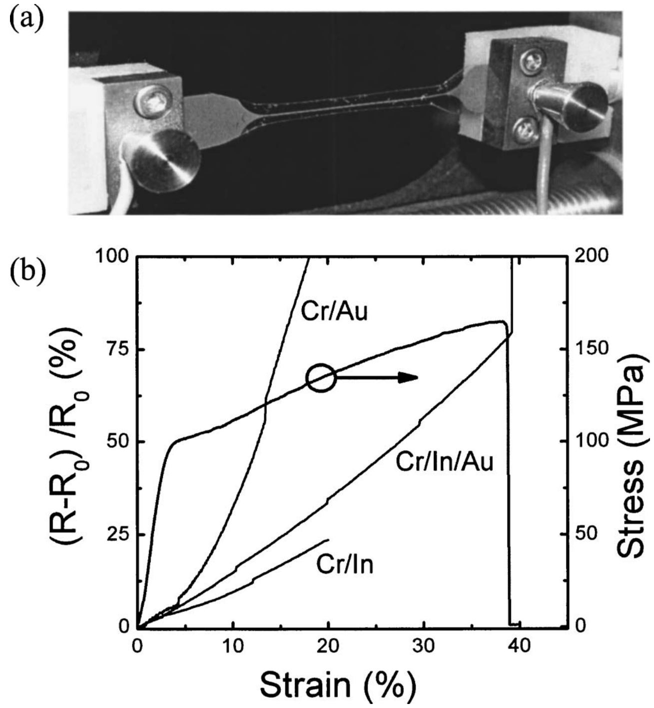

FIG. 2. (a) A photograph of dog-bone-shaped sample with a 300-μm-wide Cr/In/Au (5/50/10 nm) wire in our tensile tester. (b) Normalized resistance and stress vs strain curves of the Cr/In/Au (5/50/10 nm) film up to rupture strain (ε=38%) of the PET substrate. The measurement data for the Cr/In (5/50 nm) and Cr/Au (5/50 nm) films are also presented for comparison.

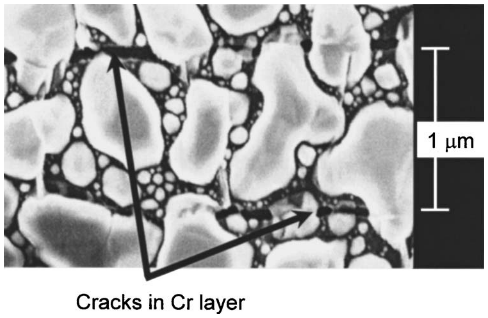

FIG. 3. SEM micrograph showing the crack formation in Cr layer of the Cr/In (5 nm/50 nm) film. The cracks are ~50 nm wide and are spaced by ~1 μm at 20% applied strain.

When subjected to large uniaxial strains, the resistance of the films increased from a prestrained value of R_0, as shown in Fig. 2(b). The resistance $R(\varepsilon)$ increases gradually at low strain ($\varepsilon < 2\%$) according to the geometrical deformation of the metal. At strains $\varepsilon \geqslant 3\%$, the continuous Cr adhesion layer cracks—a catastrophic failure for brittle conductors, such as indium tin oxide.[15] However, the presence of In islands bridging the cracks, evident in the SEM micrograph of Fig. 3, maintains the electrical integrity of the metal line.

The cracks divide the Cr film into many strips, perpendicular to the loading direction, as shown in the Fig. 3. Upon further stretching, separation between newly formed Cr strips increases, accompanied by the formation of new cracks.[16] At ε=20%, the cracks are ~50 nm wide and the Cr strips are ~1 μm wide, reducing the strain in the Cr/In film by 5%, so the residual strain (ε_r) of the Cr strips between the cracks is about one-fourth less than the total strain ($\varepsilon = 20\%$).

Despite the cracks in the Cr layer, the resistance $R(\varepsilon)$ of this composite film increases only gradually and the normalized change in resistance, $\Delta R \equiv [R(\varepsilon) - R_0]/R_0$, does not exceed 100%, even as ε reaches 38%. The In islands observed in a 50-nm-thick film have diameter, $D \sim 600$ nm, much larger than the ~50 nm cracks at 20% strain (see in Fig. 3). The highly ductile nature of the indium islands permits them to bridge the cracks. Between the cracks, the film and substrate (PET) will first deform elastically at small strain (<5% for PET and <2%–3% for metal). In this regime, the change of the resistance can be described as

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

where ε_r is the residual strain in the Cr film and γ is Poisson's ratio. At higher strain, the film will undergo plastic deformation, which will conserve the volume of metal.[17] The film resistance will increase by a factor given by

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

Conversely, across the cracks, the In island resistance will increase by a factor roughly given by

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

where d is width of the cracks and D is the In island diameter. Since the cracks only form a small percentage (50 nm out of 1 μm at $\varepsilon = 20\%$) of the total area, the total resistance change will be dominated by the region between the cracks, $\Delta R_{\text{plastic}}$ of Eq. (2), in good agreement with the data in Fig. 2(b).

For our Cr/In film, the resistance of the film only changes by 25% at $\varepsilon = 20\%$. The In islands permit a huge strain without failure, but the initial resistance is relatively high. To decrease R_0, we deposited an additional 10-nm layer of gold to obtain a Cr/In/Au (5/50/10 nm) film. The addition of the Au capping layer decreased R_0 down to $\sim 2\ \Omega/\square$ from the measurement, as opposed to the 120 $\Omega/\square$ for the Cr/In (5/50 nm) film. Figure 2(b) shows the comparison of three different films that we have tested. At the rupture strain point of the PET substrate (38%), the resistance change ΔR of the Cr/In/Au is less than 80%. We observed that on top of a crack, the bridging indium island will first deform in its vertical direction and lower its height when stretched. This mitigates the effect on the gold layer from extending and developing cracks. Even though the film may stretch quite significantly near the cracks and increase the resistivity of the gold layer, the indium island will still conduct well. A detailed model is still needed to relate the applied strain to the electrical resistance of the granular metal films.

For comparison, the Cr/Au (5/50 nm) films were also fabricated, using the same *e*-beam evaporation method. In the absence of In islands, the resistance $R(\varepsilon)$ of the Cr/Au interconnects increases much more quickly, as shown in Fig. 2(b), although they still exhibit comparable performance to Cr/Au films reported by others.[14] However, under SEM, our Au film is also observed to be granular (although the grain size of 20 nm is much smaller than for In). Whether the granularity of the Au contributes to the mechanical robustness of our films is still under investigation.

Another important aspect of flexible interconnects is their resistance to fatigue under repeated strain cycling.[18] For fatigue testing we cyclically loaded and unloaded a Cr/In/Au film sample around a cylindrical mandrel (reaching a maximum strain $\varepsilon = 2\%$) for 10 000 cycles and observed no change in resistance. These results are presented in Fig. 4. Fatigue testing is particularly important for applications such as rollable displays, where users will ravel and unravel the displays numerous times within the service lifetime of the device. Our data demonstrate that Cr/In/Au films will thus be a good candidate for such applications.

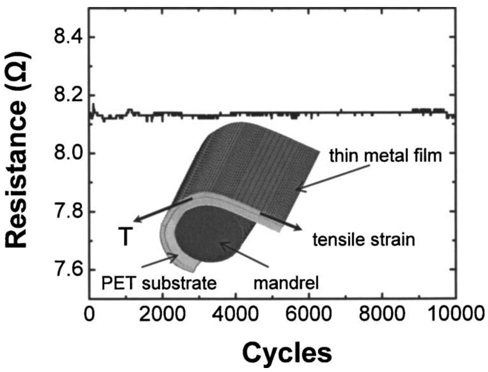

FIG. 4. Fatigue test showing no change of resistance for the Cr/In/Au (5/50/10 nm) film after 10 000 cycles. Inset shows the tensile strain developed in the film wrapped around a mandrel. The maximum strain was 2%.

In conclusion, we have successfully fabricated thin ductile In-island-containing metal interconnect films supported on polymer substrates which maintain electrical connectivity at strains up to 38%. Despite this extremely high strain, the normalized resistance of the film was observed to change by less than a factor of 2. SEM analysis revealed the bridging mechanism of the In islands across cracks formed in the other metal layers, maintaining the electrical integrity of the interconnect.

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