Stretchable wavy metal interconnects

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Buckled, wavy metal stripes are promising candidates for interconnects in flexible and stretchable electronics. To obtain wavy metal films, 5 nm of Cr (for adhesion) and 20 nm of Au were evaporated on polydimethyl siloxane (PDMS) prestretched by 25%. The metals buckle to a wave upon release of the PDMS from the prestretched position. The electrical resistance of the Au was measured as a function of applied tensile strain. Results show the metal remains electrically conductive up to 100% strain and maintains electrical continuity under repeated mechanical deformation. Presented are the sample fabrication, surface topography, and results of experiments conducted on these stretchable wavy metals.
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I. INTRODUCTION

We have made thin film metal stripes that remain electrically conductive up to 100% strain and that maintain relatively low electrical resistance ($<100\ \Omega$) under repeated deformation. Such interconnects can be utilized in retinal prostheses,[1] robotic sensor skins,[2] e-textiles,[3] and three-dimensional conformal devices. While free standing metal films fracture at strains of a few percent,[4] thin metal film bonded to an elastomeric substrate can remain conductive up strains of several percent. Lacour *et al.* demonstrated that gold film deposited onto an elastomeric substrate with built-in compressive stress maintains electrical conductivity up to 22% tensile strain.[5] The built-in compressive stress caused the metal film to buckle to ordered waves. Although the waves are stretched flat at 0.4% strain, the metal maintained electrical continuity when strained by several percent.

Thus, an initial buckled, wavy metal film on an elastomeric substrate is the key design feature of our stretchable metal interconnects. Their stretchability—i.e., the maximum strain applied to the film without electrical failure—depends on the elastomeric substrate in addition to the amplitude and wavelength of the wavy metal film, which determine the effective length of the film. Large amplitudes permit longer films. Two methods have been demonstrated for depositing a wavy metal film with large amplitudes onto an elastic substrate. (1) The film is deposited on a preshaped wavy substrate.[6] (2) The film is deposited on a prestretched substrate. When the substrate is released from the prestretched position, the film buckles to a wave.[7] The present study employs method (2).

Our stretchable metal interconnects were made by depositing 5 nm of Cr and 20 nm of Au on prestretched silicone membranes of polydimethyl siloxane (PDMS). We report on interconnect fabrication, surface topography, and electrical resistance during mechanical deformation.

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II. SAMPLE FABRICATION

Figure 1 outlines the sample fabrication. First, the PDMS substrate (Sylgard 184 by Dow Corning) is made by mixing a silicone gel and cross linker in a 10:1 ratio by weight. The mixture is spread out in a Petri dish to a thickness of 1 mm$\pm$0.01 mm and then cured at 60 °C for 12 h. Next, the membrane so formed is cut with a razor blade into 3 mm $\pm$0.5 mm wide stripes which are pre-stretched by 25%$\pm$1%. The prestretched position is maintained in a customized holder. Next, 5 nm$\pm$0.5 nm of Cr (for adhesion) and 20 nm $\pm$0.5 nm of Au are deposited by electron beam evaporation onto the prestretched PDMS through a Riston® dry photoresist mask with openings for metal stripes [Fig. 1(b)]. Finally, the Riston® is stripped in KOH, and the PDMS stripe is released from its prestretched position. The surface with the Au film buckles to a wave along the length of the sample [Fig. 1(c)].

III. EVALUATION OF THE METAL STRIPES

The electrical resistance of the interconnects was evaluated as a function of applied longitudinal strain using the microstrain tester displayed in Fig. 2. During the experiments, the sample is clamped between two jaws. One clamp

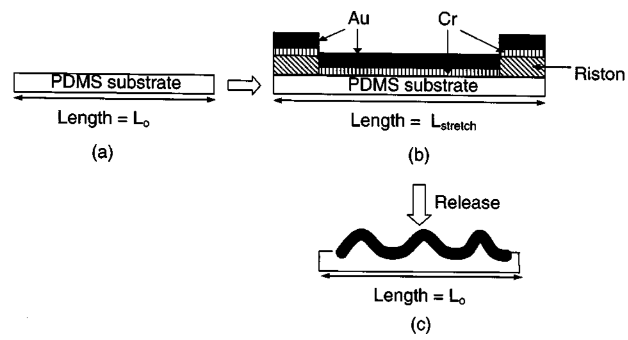

FIG. 1. Sample fabrication.

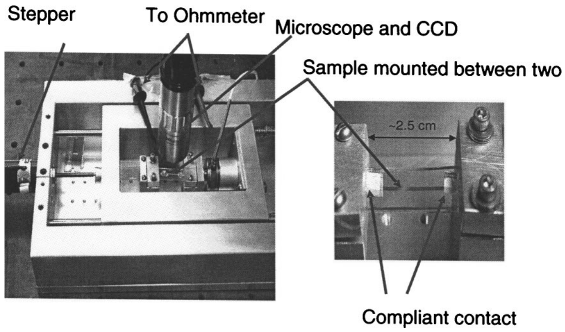

FIG. 2. Microstrain tester.

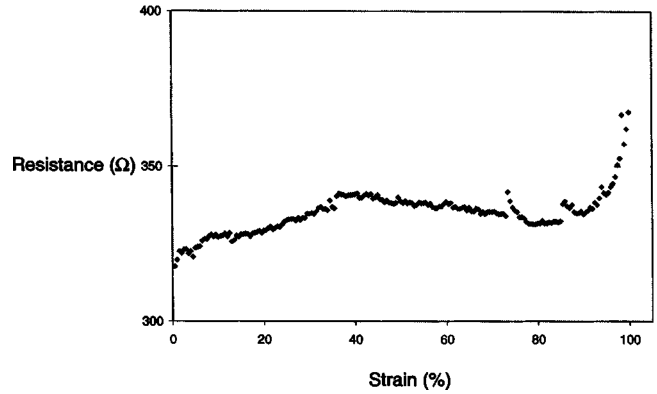

FIG. 4. Electrical resistance vs elongation as sample is stretched once from 0% to 100%.

is fixed, and the other clamp is attached to a mobile frame and pushed away, thus stretching the sample. A stepper motor controls the frame displacement. The electrical resistance is measured and the sample morphology is monitored as the metal is stretched.

Two types of experiments were conducted: stretching up to electrical failure and electrical behavior under repeated deformation. Electrical failure is defined at the point where the electrical resistance of the sample changes from a few kilohms to several megohms. During the first experiments, the sample was stretched in steps of 0.5% strain every minute, and ten resistance readings were taken during each step. During repeated deformation, the strain oscillated between 0% and 15% strain over time, and the sample was stretched by a 1% step every minute.

IV. RESULTS AND DISCUSSION

Optical micrographs of the wavy metal are pictured in Fig. 3. Figure 3(a) is a top view of the surface of the as-prepared Au stripe in its prestretched state, while Fig. 3(b) displays the Au surface immediately after release from the prestretched position. After evaporation and still in the prestretched position, the Au film buckles. The wave crests are perpendicular to the sample length. After release from the prestretch, cracks span the length of the sample. When the sample was released from the prestretch and its length decreased, its width increased due to the Poisson effect: longitudinal cracks appear in the Au film [Fig. 3(b)].

Electrical resistance data of the sample as the strain was increased from 0% to 100% are exhibited in Fig. 4. The initial resistance at 0% strain is 316 $\Omega \pm 1$ Ω, while the theoretical resistance of the Au film evaporated on glass is 8 $\Omega \pm 1$ Ω. The resistance increased by 24.7% to 394 Ω at 100% strain. At 100% strain, the metal remained electrically conductive, despite being stretched to twice its original length. After release from 100% strain, the sample surface was observed under the scanning electron microscope. Figure 5 shows the sample microstructure before and after it was stretched to 100%. It appears that the sample morphology did not change as the strain was increased from 0% to 100% and released back to 0%. The strain rate was 0.5% per 60 s. Small parallel cracks ($\sim$2 μm) cover the sample. They are not connected. The Au film buckled in between the cracks.

The electrical resistance of the sample as the strain was cycled between 0% and 15% is displayed in Fig. 6. One full cycle is completed in $\sim$30 min$\pm$1 min. A sample different from that, which had been stretched by 100%, was used. The initial electrical resistance of this sample was 45 Ω. While the minimum resistance remained approximately 40 Ω, the maximum resistance of 106 Ω during the first cycle decayed over cycling to 61 Ω. Note that the periodicity of the electrical resistance was twice that of the mechanical cycling since the resistance peaked twice during one cycle from 0% to 15% to 0% strain.

V. CONCLUSION

Elastic stripes of thin metal films were fabricated by depositing Au onto a 25% prestretched, elastomeric substrate.

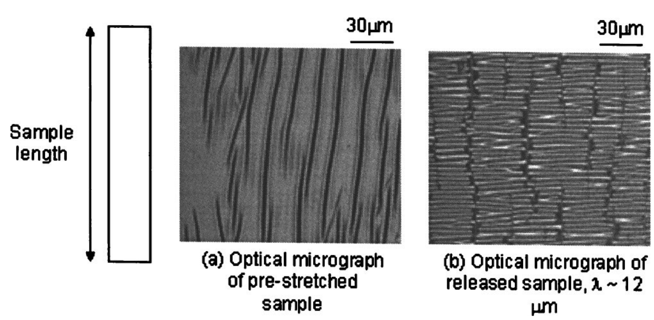

FIG. 3. Surface of metal stripes.

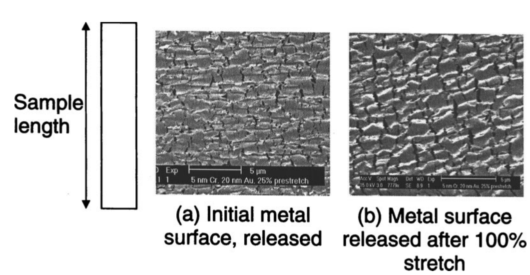

FIG. 5. Surface of stripe (a) released after fabrication and (b) released after stretched by 100%.

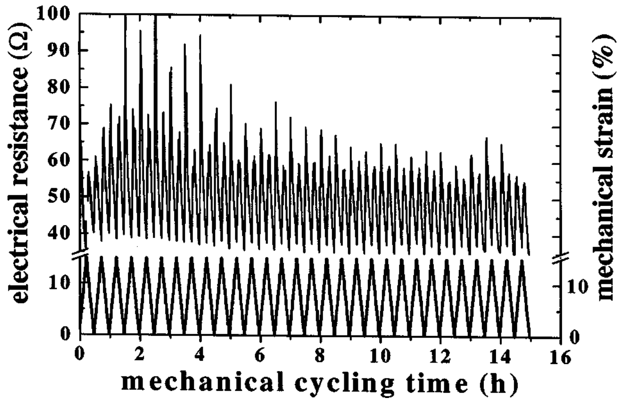

FIG. 6. Electrical resistance measured during mechanical cycling.

These stripes remain electrically conductive when stretched up to twice their original length and under mechanical cycling between 0% and 15% strain. The metal morphology does not appear to change significantly when the metal is strained between 0% and 100%. These results show that such metal stripes are promising candidates for interconnects in flexible and stretchable electronics.

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