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# Stretchable Interconnections for Flexible Electronic Systems

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*Abstract*—**Sensors, actuators and integrated circuits (IC) can be encapsulated together on an elastic substrate, which makes a flexible electronic system. In this system, electrical interconnections that can sustain large and reversible stretching are in great need. This paper is devoted to the fabrication of highly stretchable metal interconnections. Transfer printing technology is utilized, which mainly involves the transfer of 100-nm-thick gold ribbons from silicon wafers to pre-stretched elastic substrates. After the elastic substrates relax from the pre-strain, the gold ribbons buckle and form wavy geometries. These wavy geometries change in shapes to accommodate the applied strain and can be reversely stretched without cracks or fractures occurring, which will greatly raise the stretchability of the gold ribbons. As an application example, some of these wavy ribbons can accommodate high levels of stretching (up to 100%) and bending (with curvature radius down to 1.20 mm). Moreover, the efficiency and reliability of the transfer, especially for slender ribbons, have been increased due to the improvement of the technology. All the characteristics above will permit making stretchable gold conductors as interconnections for flexible electronic systems such as implantable medical systems and smart clothes.**

## I. INTRODUCTION

Flexible electronic systems for biomedical applications have received a lot of focus since they can provide a more comfortable contact with human body.

The structure of a flexible electronic system is shown in Fig. 1. The system consists of an elastic substrate, where functional islands are connected by electrical interconnections. Functional islands can be sensors, actuators and ICs that are usually not stretchable. These components are connected with stretchable interconnections that are required to sustain large and reversible stretching. Thus, stretchable interconnections will play a key role in flexible electronic systems.

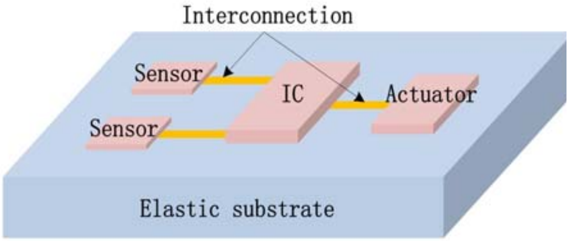

Fig. 1. Schematic illustration of a flexible electronic system.

A few groups have reported their research activities on the development of stretchable metal interconnections on elastic substrates. Skin-like metal structures have been demonstrated and can be stretched to more than 20% of their relaxed length [1, 2]. Copper films on polyimide, along with the failure mechanism have also been introduced [3]. Meanwhile, 2-D spring-shaped metallic interconnections have been designed, optimized and fabricated [4, 5]. The stretchability of these metallic interconnections can be above 100%, however, it seems not be very steady during repeated experiments [5]. All the researches aim at highly and steadily stretchable metallic interconnections, which seem to be a challenge since cracks or raptures are easy to occur on metal films when large strain is applied.

In this paper, wavy metal films are introduced by transfer printing technology. Based on this technology, metal films are transferred from silicon substrates to pre-stretched elastic substrates and form wavy geometries after the release of pre-strain. The metal films partly delaminate from the substrates and endure much smaller strain than the pre-strain. Details of the technology and experiments to demonstrate the high stretchability of the wavy metal films are both introduced in this paper.

## II. FABRICATION

The fabrication of stretchable gold interconnections mainly involves the transfer of gold ribbons from silicon substrates to pre-stretched elastic substrates. Polydimethylsiloxane (PDMS; Sylgard® 184 Silicone Elastomer from Dow Corning) is chosen as the elastic substrate material due to its low stiffness (7.1 MPa) and high elongation (140%). The base and curing agent of the elastomer were thoroughly mixed at a weight ratio of 10:1. Exposure to normal temperature and pressure for about 10minutes was usually

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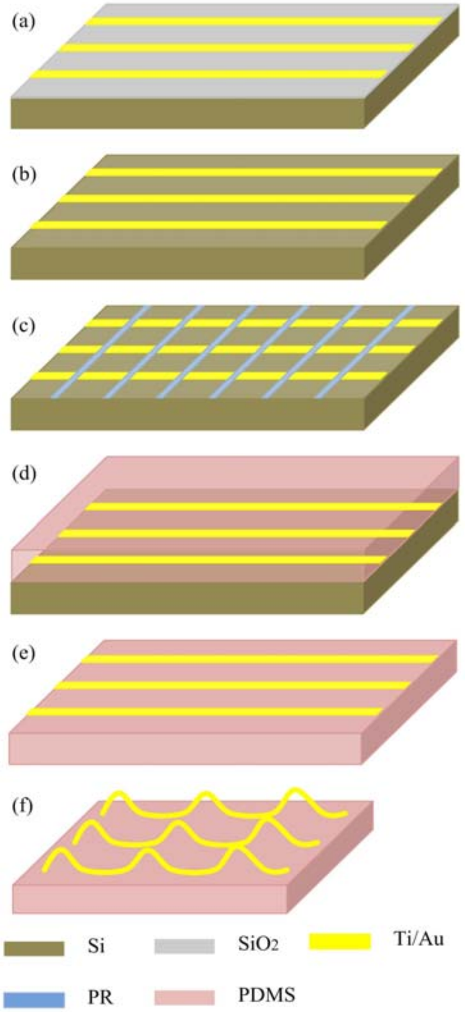

Fig. 2. Fabrication process of stretchable gold interconnections on elastic substrates: (a) Deposition and patterning of gold film; (b) Etching of silicon oxide; (c) Photolithography and etching of silicon oxide to release gold ribbons from the underlying silicon substrate; (d) Conformal contact between PDMS and gold ribbons after dry etching of photo resist; (e) Peeling of PDMS; (f) Buckling of gold ribbons after release from pre-strain.

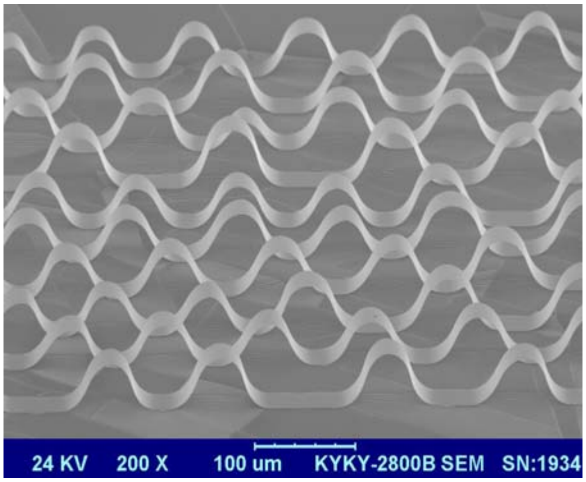

Fig. 3. SEM image of 25-µm-wide wavy gold interconnections after release from pre-strain of 50%.

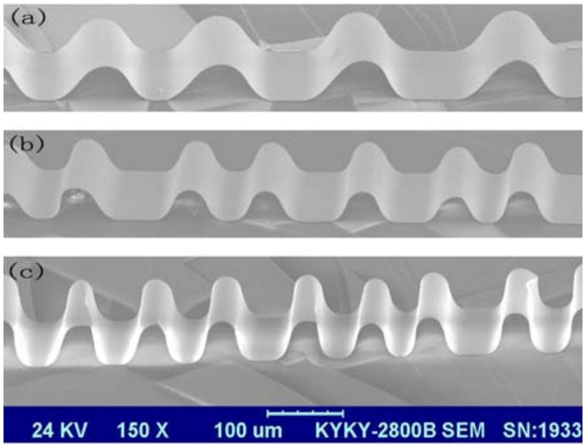

Fig. 4. SEM images of 100-µm-wide wavy gold interconnections after release from pre-strain of (a) 25, (b) 50 and (c) 100%.

adequate for de-airing. The mixture was cured for 30 minutes at 90 C$^o$ and cut into strips which were used in the following transfer process.

The fabrication process is summarized in Fig. 2. A $SiO_2$ layer (5000 Å) was formed on silicon substrates by thermal oxidation. Metal films of titanium (270 Å) and gold (1000 Å) were successively deposited and patterned with lift-off process, to fabricate gold ribbons. (Fig. 2a) With photo resist (PR) and gold ribbons acting as etching masks, the $SiO_2$ layer was etched with buffered hydrofluoric acid (Fig. 2b). Parallel lines of photo resist were patterned across the silicon wafer. Then the gold ribbons were released from the underlying silicon substrates after etching of the $SiO_2$ layer with concentrated hydrofluoric acid (40%). Lines of photo resist were approximately perpendicular to the gold ribbons and prevented the ribbons from washing away in the etchant. The ribbons were cleaned in de-ionized (DI) water and jet dried with a nitrogen gun. (Fig. 2c) Dry etching of the photo resist by oxygen plasma was carried out using RIE system with rf power of 150 W, oxygen gas flow of 30 sccm, pressure of 24 Pa and etching time of 30 min. Then a flat strip of PDMS (~1 mm thick) was mechanically stretched by home-made tester and brought into conformal contact with the ribbons. (Fig. 2d) Peeling the PDMS away made the ribbons adhere to the PDMS surface (Fig. 2e). Releasing the pre-strain in the PDMS led to the buckling of gold ribbons. Finally, wavy gold ribbons were formed on PDMS substrates. (Fig. 2f)

The size of the gold ribbons is determined by the photolithography. Gold ribbons with width ranging from 5 µm to 100 µm were fabricated and transferred to elastic substrates that were pre-stretched by 25, 50 and 100%. The length of the ribbons is not limited by the fabrication process above and can be designed according to the requirement of a flexible electronic system.

The step in Fig. 2c introduces photo resist lines to protect the released gold ribbons. This is an improvement of the transfer printing technology of J. Rogers et al. [6] by which slender gold ribbons (e.g. 50 µm wide and 10 mm long for example) are easy to wash away during the etching and cleaning.

## III. EXPERIMENTS AND RESULTS

Figure 3 shows a SEM image of 25-µm-wide wavy gold interconnections after release from pre-strain of 50%. The gold ribbons partly delaminated from the PDMS substrates, which happened when the large pre-strain on PDMS substrate released. In the cases of small pre-strains, wrinkling will occur and the substrate will deform coherently with the ribbons [6].

In Fig. 3, the wave length was ~100 µm and the amplitude ~45 µm. The wavy geometries do not have a strict periodicity, which may be due to the non-uniformity (e.g. interfacial defects) of the PDMS surface. But this seems to have no influence when the wavy geometries are used as interconnections. Figure 4 shows SEM images of 100-µm-wide wavy gold interconnections after release from pre-strain of 25, 50 and 100%. The wave number of the ribbons increases with the pre-strain.

The wavy gold ribbons can be reversely stretched without cracks or fractures occurring. Shapes of the wavy gold ribbons (wave length and amplitude) will change to accommodate the applied strain. The ribbons will be straight and intact when the applied strain is approximately equal to the pre-strain. Meanwhile, little changes in the resistance of the ribbons were observed during the stretching. Therefore, the stretchability can be thought to be above the pre-strain which is usually much more than the fracture strain of free-standing gold films (~1%).

A direct benefit of the large stretchability is the high level of mechanical bendability. This feature is illustrated in Fig. 5, in which the stretchable gold ribbons are wrapped around a slender cylindrical bar. The gold ribbons were 100 µm wide and were transferred to a 1.10-mm-thick PDMS substrate with pre-strain of 50%.

The surface strain in PDMS can be simply calculated based on elementary bending mechanics of thin films. In Fig. 6, the schematic bending of the gold ribbons is shown and the surface strain in PDMS can be calculated by

$$\varepsilon = (0.5\times h)/(r+0.5\times h)$$

where $\varepsilon$ is the bending-induced surface strain in PDMS, $h$ the thickness of the PDMS substrate, and $r$ the radius of the cylindrical bar.

Taking the measurement datum ($h$=1.10 mm and $r$=1.20 mm) into the equation above results in the surface strain in PDMS of 31%.

When the interconnections were encapsulated with another layer of PDMS, the mechanical bendability can be furthermore raised [7]. Ideally, if the upper and lower PDMS layers have the same thickness, the interconnections will locate at the neutral plane and accommodate any bending.

As mentioned above, the gold ribbons are protected by photo resist during the etching of $SiO_2$. Thus, long and narrow ribbons can be fabricated and transferred.

## IV. DISCUSSION AND CONCLUSION

Transfer printing technology has been improved and introduced to fabricate wavy gold interconnections. High levels of stretchability and bendability have been achieved, which permits making the wavy metal films as interconnections for flexible electronic systems.

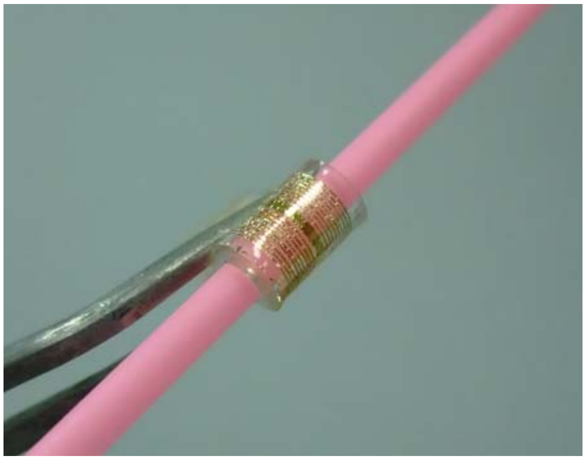

Fig. 5. Optical image of stretchable gold interconnections wrapped around a slender cylindrical bar.

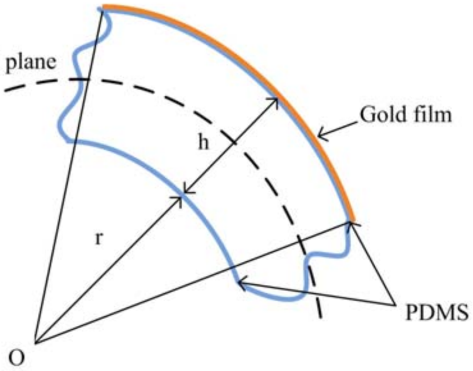

Fig. 6. Schematic bending of the stretchable gold ribbons on PDMS.

Stretchable and foldable integrated circuits have been achieved by utilizing the transfer printing technology [7]. However, a flexible electronic system may consist of kinds of devices that are fabricated with incompatible technologies such as MEMS (Micro Electromechanical System) and IC technologies. In these cases, a functional island-based flexible electronic system in Fig. 1 seems to be a good choice. In such a system, functional components are bonded to interconnections by conductive polymer or solder and then connected to other functional components.

The improved transfer printing technology can be extended to transfer other stiff films onto elastic substrates. The films will be well protected in the whole process, which is crucial and can increase the efficiency and reliability of the transfer, especially in the transfer of fragile films.

## ACKNOWLEDGMENT

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