

Facile Fabrication of Highly Stretchable Nanocrack Indium Film Using Magnetron Sputtering

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Abstract. Stretchable electronics, such as stretchable displays and bioelectric interfaces, require stretchable electrical conductors which can be stretched by large strain repeatedly. In this work, highly stretchable indium films were successfully deposited on PDMS substrates using magnetron sputtering. Stretchable indium films can sustain as much as 180% mechanical strain while maintaining great electrical conductivity. Compared to popular gold films, indium films have much better stretchability, light permeability and lower melting point, which can be widely used in bioelectronics.

1. Introduction

Recently, the development of stretchable electronics [1] based on Micro-Electro-Mechanical System (MEMS) [2] technologies has attracted significant attention. Stretchable electronics, for instance, electronic textiles[3], electronic skins[4,5], and microelectrodes for neural interfaces[6] in biomedical engineering, have a wide range of applications due to their outstanding stretchability and great Young's modulus matching with biological tissues. Such electronics usually contains metal thin films deposited on a polymer substrate using magnetron sputtering. A manufacturing technology for the flexible micro-electrode array [7] based on sputtering was first reported by Columbia and Princeton University [8].

To obtain stretchable electronics, metal thin films were fabricated on stretchable substrates such as poly (dimethylsiloxane) (PDMS) [9, 10]. The as deposited films can present three morphologies: smooth, nano-cracked, or buckled [11]. Previous work showed that gold films could maintain their electrical conductivity [12,13] while being stretched by a maximum 120% strain. Gold is usually used as conductive material in the fabrication of stretchable electronics. However, use of gold for fabricating stretchable electronics has not only resulted in high cost, but also many restrictions on fabrication. Recently, an alternative materials using indium films have been presented because of its low melting point that could facile to process. Up to now, there has been little research investigating the indium films.

In this study, we adopted a simple technique that allows the rapid construction of stretchable indium films using magnetron sputtering. Experimental results illustrate that indium films can be stretched at large strains as about 180%, while maintaining their electrical conductivity. Compared to



gold films, indium films have relatively high stretchability. Furthermore, due to the lower cost, stretchable indium films can be widely used in stretchable electronics.

2. Experiments

The schematics of the process flow used to fabricate stretchable indium films are shown in Figure 1. The silicon wafers ($\phi 75\text{mm}$), used as a rigid backing, were first baked for 5 min at 200°C to remove moisture and coated with a monolayer of 1H, 1H, 2H, 2H perfluorooctyl-trichlorosilane (48931-10G, Sigma Aldrich) evaporated for 10 min to produce an anti-adhesion layer, which can facilitate the removal of the PDMS membrane at the end of fabrication. The PDMS solution was mixed from the pre-polymer gel and the cross-linker (Dow Corning Sylgard 184) in a 10:1 ratio by weight, defoaming in vacuum, then spun on the silicon wafer at 600 rpm for 60 s, and cured against the molds at 80°C for at least 3 hours, in order to fabricate a $110\text{-}\mu\text{m}$ -thick PDMS membrane. The PDMS surface was oxidized in an oxygen plasma to improve adhesion. After plasma treatment on the PDMS surface, a 40-nm -thick indium film was deposited (DC power 75W, 22s) on 4-nm -thick titanium buffer layer (DC power 40W, 5s) through a pre-pattern, stainless steel mask by magnetron sputtering. After being peeled from silicon wafer, stretchable indium films are accomplished. The stretchable indium films, patterned through the mask, were similar to a dumbbell: the wire was designed to be 8mm long and 0.5mm wide, at both the ends of the wire, there were two pads squares ($1.5\text{ mm} \times 1.5\text{ mm}$), using to test the electrical resistances of the stretchable indium film.

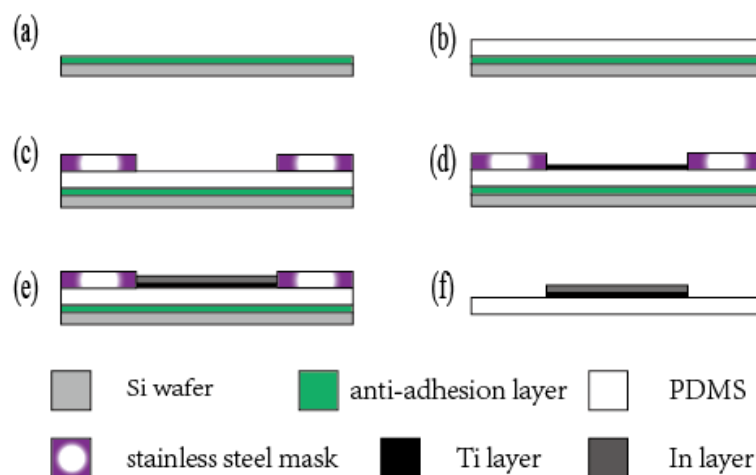


Figure 1. The processing sequence for fabricating the stretchable indium film.

3. Results and discussion

3.1. Crystalline structure and morphology

Figure 2(a) illustrates the typical XRD patterns of indium films. Diffraction peaks observed at $2\theta = 32.9^\circ, 36.3^\circ, 39.1^\circ, 54.4^\circ, 56.5^\circ, 63.2^\circ, 67.0^\circ$, correspond well with (1 0 1), (0 0 2), (1 1 0), (1 1 2), (2 0 0), (1 0 3) and (2 1 1) 3C-syn indium phase (JCPDS No. 05-0642).

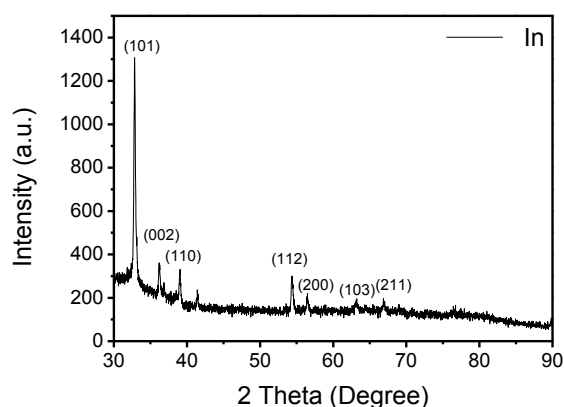


Figure 2. The XRD pattern of stretchable indium film.

Figure 3 presents the scanning electron microscopy (SEM, NOVA NanoSEM 450, FEI) image of the stretchable nano-crack indium film on PDMS membrane. Figure 3(a) shows the SEM image of the film before stretching. There are lots of initial nano-cracks on the surface of the film, which were uniformly distributed with random orientation. While the film is being stretched, some of the initial nano-cracks propagate and coalesce into large microscale cracks to ease local stress, which can be seen in Figure 3(b). It is said that because of these nano-cracks, the indium film can be stretched in a large scale. Figure 3(c) shows that the microscale cracks close when the film release, and some of the large scale cracks cannot restitution permanently. During stretching, both ends of the cracks are connected, therefore, the indium films can maintain conduction. Obviously, the crack structure is indispensable to the stretchability of the indium films.

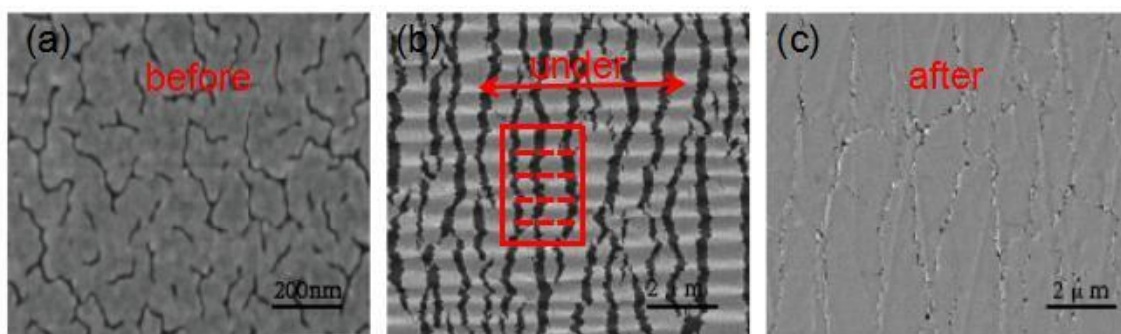


Figure 3. SEM images of stretchable indium films on PDMS membrane (a) before; (b) under; and (c) after stretching. The red double arrow line in (b) shows the direction for stretch, and the typical structures of cracks are marked with red rectangle.

3.2. Electrical properties of highly stretchable indium films on PDMS membranes

From Figure 4, we can see that the maximum strain while the indium film maintains its conductivity could be stretched as much as about 180% (see the black curve in Figure 4(a)). Herein, the strains where the resistance is increase rapidly are defined as electrical function rupture, however, the indium film is still mechanically robust. Furthermore, through testing many indium films, the results demonstrates that the maximum strain value of 180% is highly repeatable. Despite the resistance increases in pace with stretching, the changes in resistance are reversible. And the electrical characteristics of stretchable indium film during hundreds of stretching-releasing cycles also being investigated (Figure 4(b)), the results reveal that the value of the resistance is stable. The maximum strain of indium films increase to 180% compared to that of the stretchable gold film in our previous

work (see the red curve in Figure 4(a)), which is 120%, which demonstrates that the stretchable indium film has better stretchability.

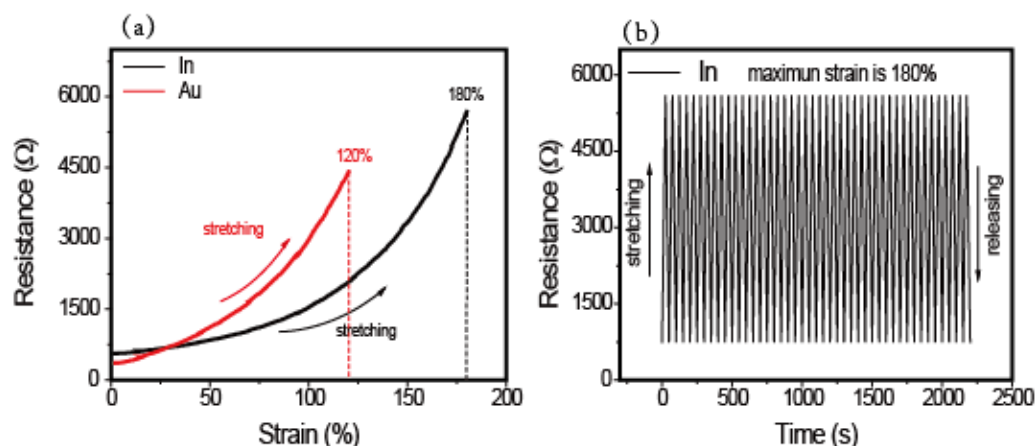


Figure 4. Electrical resistance of stretchable film on PDMS membrane: (a) the compared stretchable indium film with gold film; (b) Electrical resistance of a stretchable indium film on PDMS under cyclic strain of 180%. The up and down arrow lines represent the process of stretching and releasing.

4. Conclusion

In this work, we successfully fabricated the stretchable indium films on 110 μm thick PDMS membrane using magnetron sputtering. Stretchable indium films are fully elastic and withstand stretching to 180% strain, while maintaining their electrical conductivity. The stretchability of indium films depends on the initial nanocrack morphology on the metal, which was shown by SEM images. In addition, the price of gold is about 205 times higher than that of indium, which indicates that the application of indium film is extremely extended.

Acknowledgements

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