IOP Conf. Series: Materials Science and Engineering **265** (2017) 012008 doi:10.1088/1757-899X/265/1/012008

Facile Fabrication of Highly Stretchable Nanocrack Silver Film using Magnetron Sputtering

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Abstract. Recently, stretchable electronic devices have been growing rapidly, such as bioelectrical interfaces, wearable and implantable electronics. Apparently, their stretchability highly depends on the surface structure. In this paper, highly stretchable nanocrack silver films were deposited using magnetron sputtering, which can be stretched by a maximum 150% strain while maintaining great electrical conductivity. Experimental results show that, compared to popular gold films, silver has relatively high electrical conductivity and better stretchability.

1. Introduction

Stretchable electronics[1-3]have great potential for serving as bioelectrical interfaces due to their better deformability[4] and biological compatibility[5]. Because of their outstanding deformability, the stretchable devices can also widely used as electronic skin[6,7], artificial prosthesis[8,9] and artificial retina[10]. Since the flexible micro-electrode array[11,12] first reported by Columbia[13] and Princeton University, stretchable electrodes have attracted significant interest and provides a promising method for wearable and implantable electronics.

To achieve stretchability, metal electrodes with nanocracks are fabricated on flexible substrates such as poly (dimethylsiloxane) (PDMS)[14,15]. Apparently, the surface structure, nanocracks, play an important role in the stretchability of metal films, which keep the electrodes conducting while being stretched at large strains. Previous work revealed that the nanocrack gold films could be stretched by a maximum 120% strain while maintaining their electrical conductivity [16]. The stretchable electronics are usually made from gold. Nevertheless, the electrical conductivity of gold is relatively low compared to other metals such as silver, cooper. Furthermore, as a kind of noble metal, gold is exceedingly expensive and thus the application of gold electrodes is extremely restrained. During the past decade, silver electrodes have been researched intensively due to its great electrical conductivity. However, up to now, the work of stretchable silver films are less reported.

Traditional electrodes are made usually by electroplate process[17,18], it plays an important role in electrical connection of sensitive electronic components. However, electroplate is a complicated and high-cost process to produce the electrodes. In this paper, we adopted a facile method to fabricate the stretchable nanocrack silver films using magnetron sputtering. Results illustrate that the silver films can be stretched by a maximum 150% strain while maintaining great electrical conductivity. In addition, compared to gold films, silver films have relatively high and better stretchability. Moreover, because of the lower cost, stretchable nanocrack silver film can be widely used in wearable devices.

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2. Experiments

Figure 1 shows the process sequence for fabricating stretchable nanocrack silver films schematically, used as a rigid backing during fabrication, a silicon wafer (φ75mm) was first baked for 5 min at 200 ℃ to remove moisture and coated with a monolayer of 1H,1H,2H,2H perfilorooctyl-trichlorsilane (48931-10G Sigma Aldrich)to facilitate the removal of the PDMS membrane at the end of fabrication (figure 1(a)). The PDMS was mixed from the pre-polymer gel and the cross-linker (Dow Corning Sylgard 184) in a 10:1 (w / w) ratio, degassed in vacuum, spun on the silicon wafer at 600rpm for 60s, and then cured in an oven at 80℃ for at least 3 hours in order to obtain a 110μm thick PDMS membrane (figure 1(b)). To improve adhesion, the PDMS surface was first oxidized in an oxygen plasma for 30w, 30s (figure 1(c)). Patterned by a 200um thick stainless steel mask layer (figure 1(d) and (e)), a 20nm thick silver film was deposited (DC power 60W, 20s) on 4nm thick titanium buffer layer (DC power 40W, 5s). The fabrication process ended with manually peeling the PDMS membrane from Si wafer (figure 1(f)). On each Si wafer, several stretchable silver films are fabricated at the same time. They are subsequently cut with a pair of scissors into individual devices for electromechanical characterization. The stretchable silver film were similar to a dumbbell: the wire was designed to be 8mm long and 0.5mm wide, and at both the ends of the wire, there were 2 pads squares (1.5 mm × 1.5 mm), using to test the electrical resistances of the stretchable silver film.

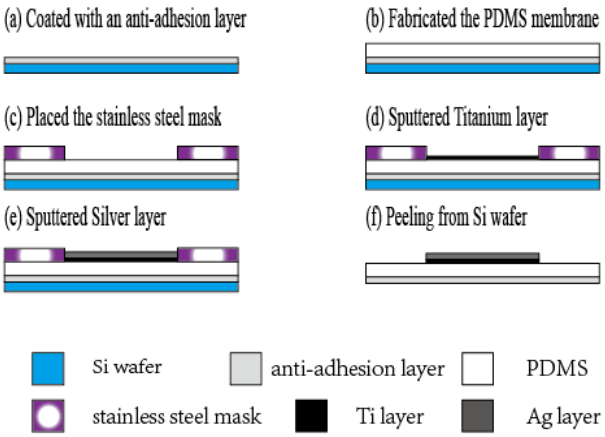

Figure 1. the processing sequence for fabricating the stretchable silver film.

3. Results and discussion

3.1 Crystalline structure and morphology

Figure 2(a) illustrates the typical XRD patterns of silver films. Diffraction peaks observed at 2θ= 38.1◦, 44.2◦, correspond well with (1 1 1), (2 0 0) 3C-syn silver phase (JCPDS No. 04-0783). Since no other impurity diffraction peaks are present, no other image is observed in the diffraction pattern, all diffraction peaks in the XRD pattern can be indexed to a silver with lattice constants of a=4.08 Å. The thickness of stretchable silver film is about 20nm, measured by AFM, demonstrated in Figure 2(b).

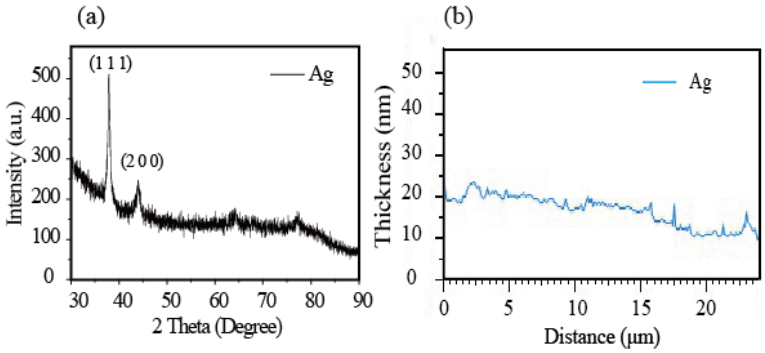

Figure 2. Characterization of stretchable silver film. (a) XRD pattern. (b)AFM image.

Figure 3 presents the scanning electron microscopy (SEM) image of stretchable nanocrack silver

film on PDMS membrane. There are lots of nanocracks on the surface of the film. The initial cracks in the films distributed with random orientation uniformly (Figure 3(a)) and their length are from several to hundred nanometers. While the film is being stretched, some of the initial cracks propagate and extend into large scale to ease local stress. The typical structures of the cracks on the film being stretching are marked with red arrow in Figure 3(b). When the film is stretched thereafter, some of the initial cracks grow to larger scale cracks permanently. Figure 3(c) shows that the micro-scale 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 silver films can maintain conduction. Obviously, the crack structure is indispensable to the stretchability of the silver films.

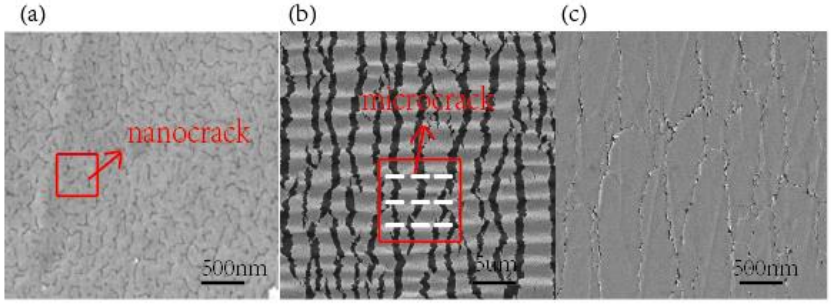

Figure 3.SEM images of a stretchable silver film on PDMS membrane (a) before; (b) under, and (c) after stretching. The red rectangles in both (a) and (b) show the typical structures of cracks.

3.2 Electrical properties of stretchable silver film

In order to tracking the maximum strain of stretchable silver film, the resistance between the two testing rectangle is measured before, under and after stretching. The stretchable silver film sample can be stretched up to the maximum strain as high as about 150% while the silver film maintains conduction (see the black curve in Figure 4(a)). Furthermore, during hundreds of stretching-releasing cycles, the resistance has been examined. Figure 4(b) shows that the value of the resistance during cyclic deformation is stable and repeatable. The maximum strain of silver films increase to 150% compared to that of the stretchable gold film in our previous work (see the red curve in Figure 4(a)), which is 120%. In addition, the resistance of the gold film is about 5 times higher than that of the silver, which indicates that the silver films have better electrical conductivity.

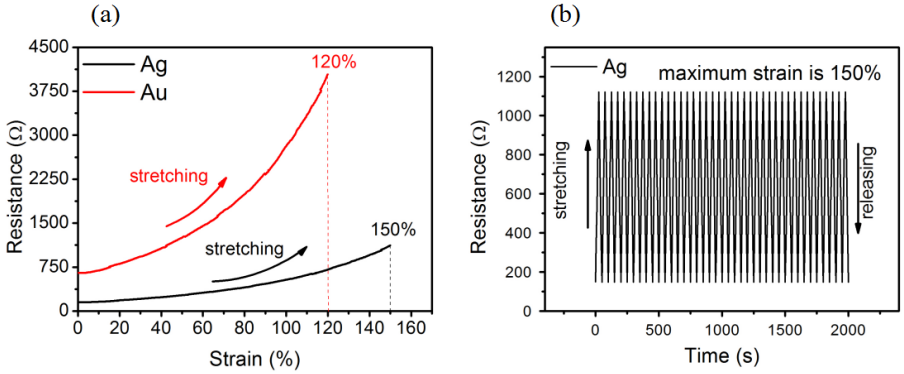

Figure4. Electrical resistance of stretchable film on PDMS membrane: (a) the compared stretchable silver film with gold film; (b) Electrical resistance of a stretchable silver film on PDMS membrane under cyclic strain of 150%. The up and down arrows lines represent the process of stretching and releasing.

4. Conclusion

In this work, we successfully fabricated the stretchable nanocrack silver films using magnetron sputtering. Results illustrate that the films can be stretched by a maximum 150% strain while maintaining great electrical conductivity. SEM images show that the initial cracks in the film

distributed with random orientation uniformly. While the film is being stretched, some of the initial cracks extend into large scale. During stretching, both ends of the cracks are connected, therefore, the silver films can maintain conduction. Results reveal that, compared to gold, silver films have relatively high and better stretchability. In addition, the price of gold is about 75 times higher than that of silver, which indicates that the application of silver film is extremely extended.

Acknowledge
This work was supported by National Natural Science Foundation of China (61374013), National Program on Key Basic Research Project (973 Program, 2015CB755500), Shenzhen "Layout of Disciplines" Program on Basic Research Project (JCYJ20160331174854880), and China Postdoctoral Science Foundation 59th (162438).

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