Flexible Transparent Conductive Film with Embedded Nanoscale Metal Mesh Fabricated through Electrospinning and Template-based Electrodeposition

Cuiping Zhang, Arshad Khan, Jingxuan Cai, and Wen-Di Li
Department of Mechanical Engineering, Univ. of Hong Kong, Hong Kong
liwd@hku.hk

Indium tin oxide (ITO) film is the most commonly used transparent conductive electrode (TCE) technique nowadays with its high transmittance and desirable conductivity. However, due to its limited resources, high fabrication cost, and brittleness [1], researchers are seeking for alternative TCE solutions with abundant resources, ease of fabrication, and applicability in stretchable and flexible electronic applications. Metallic nanowire network, especially silver nanowire network, is one of the most promising alternatives to ITO [2], and is cost-effective with opulent resources and solution-based fabrication process. Also, it has been reported to show excellent stability in stretchable and flexible electronic devices. However, the high contact resistance between nanowires, inhomogeneity and non-reproducibility due to the random allocation of metallic nanowires are the key problems that hinder its further development. Meanwhile, although higher length to diameter ratio of the metallic nanowires leads to better TCE performance, achieving aspect ratio larger than 3000 on silver nanowires is a very tough task [2].

In this study, we develop a solution-processed fabrication method for nanoscale metallic network that can be electrodeposited using a nanofiber template, as shown in Figure 1. First of all, an insulating dielectric (SiO_2) layer with 100 nm thickness is sputtered on top of a piece of smooth ITO glass. Then, polymer nanofiber network is electrospun on the SiO_2 layer, followed by thermal evaporation of 20nm chromium as an etching mask. After the lift-off of the polymer nanofiber network, the SiO_2 layer underneath the nanofibers is exposed and reactive ion etching is applied to selectively remove the SiO_2 until the exposure of the ITO surface. Metallic nanofiber network is fabricated by the electrodeposition of metal in the etched trenches. Finally, the metallic nanofiber network can be transferred to polymer substrates through imprint transfer process and the template is cleaned and reused in subsequent electrodeposition cycles. Figure 2 shows the metallic nanofiber networks transferred into cyclic olefin copolymer (COC) film after the 1st, 2nd and 4th electrodeposition-imprinting- transferring fabrication cycles. The metallic nanofiber networks fabricated in different cycles show promising consistency to each other, proving the feasibility of template-based fabrication by this method.

Since the electrospun nanofiber can be as long as tens of centimeters [3], metallic nanofibers have much higher aspect ratio than the chemically synthesized metallic nanowires. The transmittance and conductivity of these TCEs could be further optimized by adjusting the nanofiber network structure in the electrospinning process. COC substrates provide the potential of flexibility of our TCEs and we also plan to utilize elastic substrates to fabricate stretchable TCEs based on this template-based fabrication method in the future.

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2. Sannicolo, T., et al., *Metallic Nanowire‐Based Transparent Electrodes for Next Generation Flexible Devices: a Review.* Small, 2016.

3. Beachley, V. and X. Wen, *Effect of electrospinning parameters on the nanofiber diameter and length.* Materials Science and Engineering: C, 2009. **29**(3): p. 663-668.

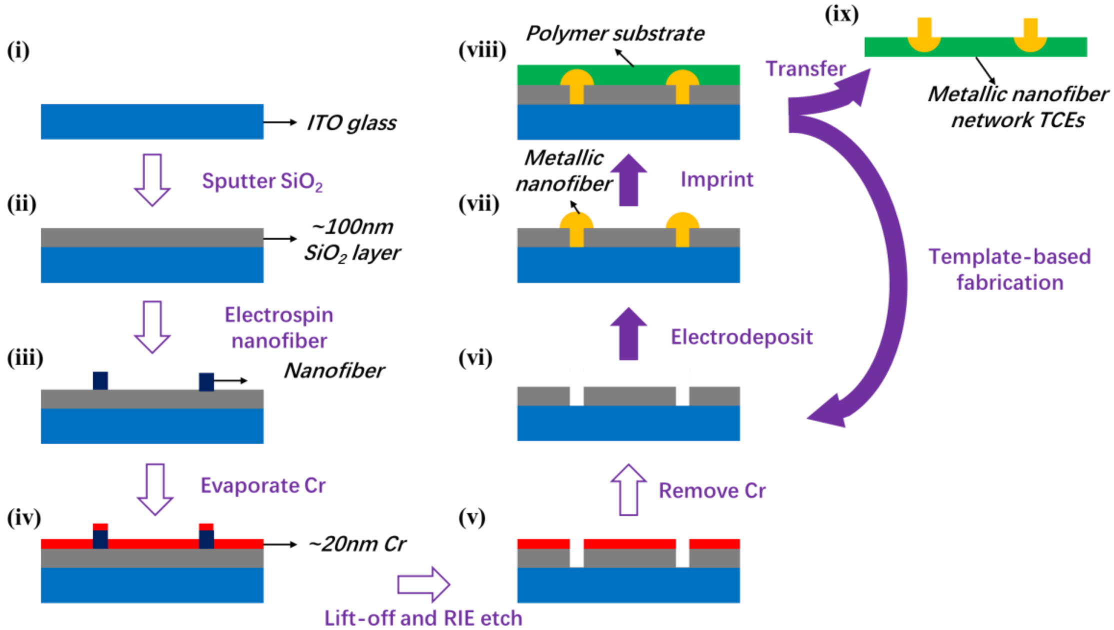

Figure 1. Schematic of template-based fabrication procedures of metallic nanofiber network TCEs. The open arrows show the procedures to fabricate the nanofiber template, and the solid arrows illustrate the steps of the electrodeposition-imprinting-transferring cycles to fabricate metallic nanowire network TCEs using the nanofiber template.

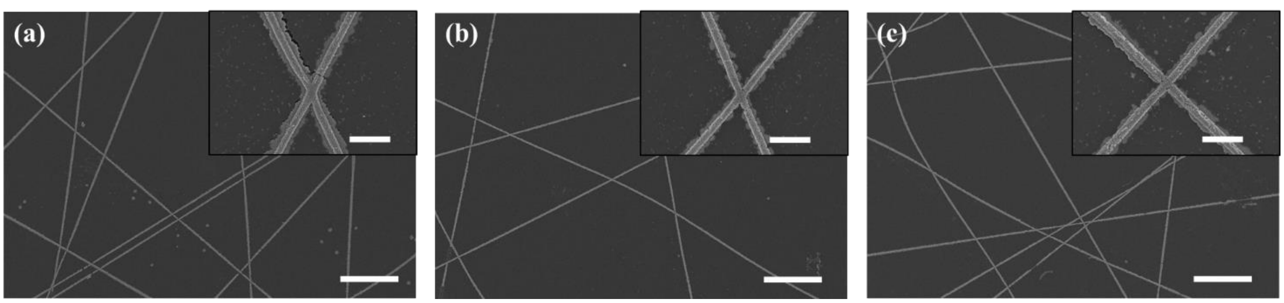

Figure 2. SEM pictures of the metallic nanofiber network in COC TCEs after (a) the 1^{st}, (b) the 2^{nd}, and (c) the 4^{th} electrodeposition-imprint-transferring fabrication cycles. (Scale bar: 10 um for over-view images and 1 um for zoom-in pictures)