Flexible Transparent Electrode with Embedded Metal Mesh Fabricated via Template-based Electrodeposition for Full-Plastic Bifacial Dye-sensitized Solar Cells

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Optoelectronic devices will evolve from current rigid system to flexible system to ultimate stretchable electronics. As far as transparent electrodes (TEs) are concerned, there are worldwide research efforts to look for alternatives to rigid indium tin oxide (ITO) film in order to obtain flexible/stretchable TEs to be used in future soft electronics.[1] This requires new materials with new design principles. Nanomaterials, such as carbon nanotubes, graphene, and metal nanowires have been recently explored and demonstrated their potentials to overcome shortcomings of current ITO based TEs (brittleness and earth rareness). Despite this potential, it remains challenging to achieve high conductivity and high transparency without deterioration under repeated bending and stretching cycles. In this context, metal mesh/grid [2] is emerging as a promising solution, which achieved exceptionally low sheet resistance and high optical transparency. However, widespread adoption of metal-mesh based TEs has been hindered by several challenges; its fabrication often involves the expensive vacuum-based physical deposition of metal materials from the vapor phase, its thickness may easily cause electrical short circuiting in thin-film organic optoelectronic devices and its weak adhesion with the substrate surface results in poor flexibility. We addressed most of the aforementioned issues in our latest report [3] by introducing the “embedded metal-mesh transparent electrode” (EMTE) structure featuring a metal mesh fully embedded and mechanically anchored in a flexible substrate, and a solution-based fabrication strategy involving lithography, electroplating, and imprint transfer (LEIT) for its production. Although LEIT is a cost-effective approach for fabrication of EMTEs, yet it comprises a mandatory lithography step in making each sample which limits its suitability for high-throughput and large-volume industrial production.

In this study, we demonstrate an improved technique for fabrication of EMTEs by eliminating the obligatory lithography step from the unit-production cycle of LEIT. Original mesh patterns are prepared via photolithography in a 500 nm SU-8 photoresist film on ITO glass substrate, and employed as repetitive electrodeposition template (Figure 1a). Production cycle starts with the 2µm thick metal deposition in the trenches of the mesh patterns through electrodeposition (Figure 1b). The mesh is subsequently transferred to the polymer substrate by thermal imprinting process (Figure 1c) in partial embedded form (Figure 1d). The fully embedded robust EMTE fabrication is then accomplished by second round of thermal imprinting process (Figure 1e). The prototype EMTEs exhibited an optical transmittance higher than 85 % and sheet resistance lower than 1 Ω/sq. Utilizing the EMTEs in a counter-electrode of the bifacial DSSCs, the prototype cells demonstrated power conversion efficiency of 5.87 % for front-illumination and 4.63 % for rear-illumination. In the preliminary reusability tests, SU-8 based template shows no noticeable degradation after 10 uses and therefore is a promising candidate for reusable template for large-scale manufacturing of EMTEs.

[1] K. Ellmer, *Nat. Photonics* 6, 809 (2012).
[2] H. Wu, D. Kong, Z. Ruan, P. C. Hsu, S. Wang, Z. Yu, T. J. Carney, L. Hu, S. Fan and Y Cui, *Nat. Nanotechnol.* 8, 421 (2013).
[3] A. Khan, S. Lee, T. Jang, Z. Xiong, C. Zhang, J. Tang, L. J. Guo, W.-D. Li, *Small* 12, 3021 (2016).

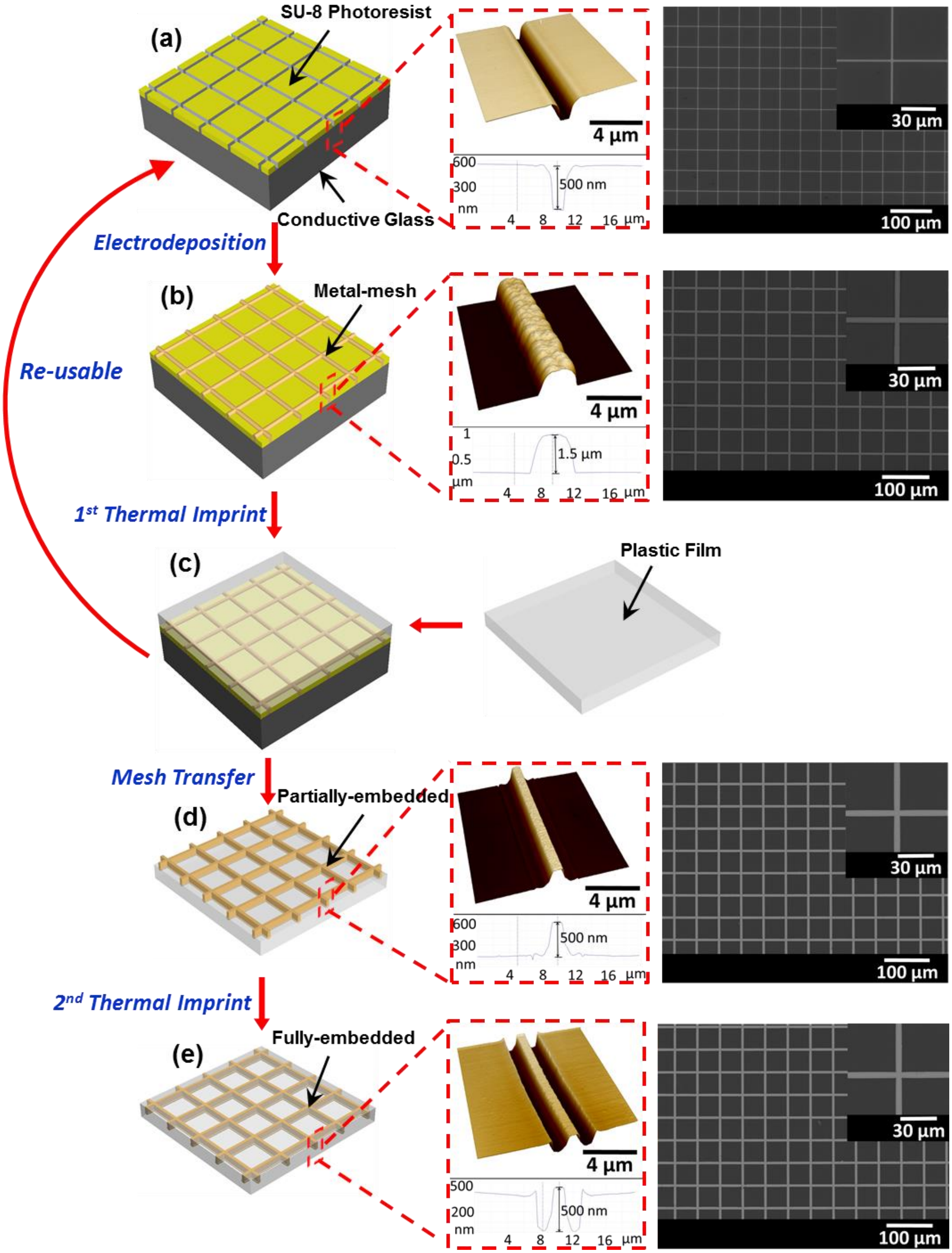

Figure 1: Schematic illustration of the Process and Morphological characterization (AFM (left) and SEM (right)) of the sample at different fabrication stages **(a)** Mesh patterns formed in SU-8 resist coated on a conductive substrate by photolithography **(b)** Electrodeposition of metal inside the resist trenches to form a uniform metal mesh **(c)** Heating and pressing the metal mesh into a plastic film **(d)** Peeling off the plastic film with the metal mesh transferred in a partially embedded form **(e)** Second heating and pressing the metal mesh into plastic film.