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Editorial

Design of Nanostructures for Flexible Transparent Conductors

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With the rapid development of technological evolution, flexible electronics have attracted enormous interest in recent decades due to their flexibility in various working conditions, especially in wearable and implanted devices. Transparent conductors are essential components for flexible devices, such as touch screens [1,2], light-emitting diodes [3], thin-film solar cells [4,5], etc. In traditional electronics, a commercial indium tin oxide (ITO) electrode is used as a transparent conductor. However, ITO is fragile, and the conductivity of ITO will severely decline when under bending or stretching forces [6]. The rapidly growing market for flexible transparent conductors (FTCs) has greatly promoted the research of the next generation of new materials and technologies for FTCs.

Since the carbon nanotube (CNT)-based FTC was reported [7], various nanomaterials have been developed to fabricate high-performance FTCs, including metal nanowires [8,9], graphene [10], conductive polymer [11], and MXene [12]. These nanomaterials have many advantages for flexible electronics. For example, Si cannot be bent as a thick film; however, when the thickness of Si film is reduced to 15 μm, the Si film can be bent to a diameter of 4.1 mm [13]. When the thickness of polymer is reduced to 1.3 μm, the film can deform with body movement [14]. The flexibility of nanomaterials is much better than that of bulky materials or thick films. Secondly, nanomaterials are easily fabricated into special structures which can afford a higher stretching force. Hu et al. [15] embedded the copper nanowire (Cu NW) network in a polyurethane (PU) matrix to make an elastomeric FTC; it exhibited a sheet resistance of less than 100 Ohm/sq at a tensile strain of up to 60% thanks to the percolation structure. Cu NWs that were printed onto a pre-stretched PDMS exhibited a wavy structure, which could be stretched to a strain of 90% without degrading its electrical conductivity [16]. Various structures are designed for reversible and extremely stretchable FTCs, including wavy geometry, serpentine or arc-shaped interconnects, coiled structures, interconnections, and nanomesh or percolating networks [17]. Thirdly, nanomaterials are a feasible solution method which is simple and cheap. Normally, the fabrication of flexible conductors based on nanomaterials includes three steps: the preparation of nanoinks, coating the inks on flexible substrates, and the post-treatment of the flexible films. Lee et al. [18] fabricated highly conductive silver nanowire (Ag NW) FTCs using a full-solution fabrication process which could be integrated into a continuous roll-to-roll production line. These advantages of nanomaterials in FTCs have motivated researchers to study the fabrication techniques, flexible properties, and applications of FTCs based on nanomaterials.

There are many reports on the processing technologies of FTCs, including heat annealing, electrical annealing, light/laser sintering, chemical washing, mechanical pressing [19], etc. Zhang et al. [20] synthesized ultralong Cu NWs and prepared high-performance FTCs by annealing the Cu NW films in a reducing H_2 and N_2 atmosphere at 300 °C. Song et al. [21] demonstrated a current-assisted localized joule heating process to enhance the contacts between Ag NWs for highly conductive networks. The contact resistance was reduced by more than seven orders after the current-assisted heating process within seconds. Mayousse et al. [22] purified the Cu NWs via the wet treatment of the Cu NWs with glacial acetic acid to fabricate FTCs with excellent optoelectronic performance (55 Ohm/sq

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at 94% transparency). Tokuno et al. [23] demonstrated a room temperature method to make Ag NW FTCs with a sheet resistant of 8.6 Ohm/sq at 80% transparency through mechanical pressing at 25 MPa for 5 s. Ding et al. [24] introduced a simple, convenient, and fast photonic sintering method to fabricate Cu NW TCFs with a sheet resistance of 22.9 Ohm/sq and a transmittance of 80%. Until now, UV light, laser, and high-energy lamp sintering technologies were also demonstrated to be successful for high-performance metal nanowire FTCs [25]. These processing methods for FTCs have their own advantages and disadvantages. For example, the heat annealing method is suitable for most FTCs and for large-scale production; however, the required high temperature is not suitable for most flexible substrates. The chemical washing method is simple and operates at room temperature; therefore, the washed nanomaterials are easily oxidized or polluted again due to the large surface. The mechanical pressing method avoids heat generation but the large press strain destroys fragile substrates. The photonic sintering technology is fast and suitable for industrial production; however, this method is only applicable for metallic nanomaterials. We should select the proper processing technology for specific nanomaterials and situations to fabricate high-performance FTCs.

Except for the above processing methods, the FTCs based on nanostructures can also be processed using physical methods. Ji et al. [26] integrated physical-vapor-deposited Cu-doped Ag films into an optimized dielectric–metal–dielectric structure, and this film featured ultra-smooth morphology, high transparency (84%), and high electrical conductivity (18.6 Ohm/sq). The physically deposited films can also be designed with nanostructures which will perform high transmittance. Lithography technology is a useful method for making nanostructures in the production of electronics, where a mask is used on top of the physically deposited films and the mask is removed after metal etching. Guo et al. [27] presented a grain boundary as a mask to make highly stretchable and transparent Au nanomesh TFCs on elastomers using the lithography method. Besides nanosized grain, various other masks were also reported to fabricate FTCs including leaves, salt crystals, cracked films, or nanospheres [28], etc. Wu et al. [29] present a process involving electrospinnning and metal deposition for the fabrication of metal nanotrough network FTCs without junctions that exhibit superior optoelectronic performances (2 Ohm/sq at 90% transparency) and remarkable mechanical flexibility.

In conclusion, there are many studies on FTCs based on nanostructures; however, the reported FTCs are not capable for industrial production. The stability of FTCs under various conditions should be improved before their application, including under light or current, in air or humid atmospheres, etc. Moreover, the fabrication process also has some problems, the FTCs based on nanomaterials are usually uneven on a large scale, and the transmittance of the deposited FTCs is low. There are still many issues that should be resolved before the practical application of FTCs and related flexible electronics. We hope that flexible electronics will be gradually used in people's daily life in the near further.

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