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Nanostructured transparent conductive films: Fabrication, characterization and applications

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ABSTRACT

Commercial indium tin oxide (ITO) has several drawbacks for optoelectronic applications such as high cost due to indium scarcity and high temperature deposition process, mechanical brittleness, and the complicated manufacturing process where lithographic patterning is needed. Its brittle nature can lead to cracking when used in applications involving bending, such as touch screens and flexible displays. Therefore, novel transparent conducting films (TCFs) based on nanomaterials with a similar or improved optoelectronic performance and good mechanical flexibility are needed for next-generation stretchable and wearable devices. Carbon nanotubes, graphene and metallic nanowires have been explored as alternatives, and they show great promise for a wide variety of optoelectronic applications. In particular, graphene films have a higher transmittance over a wider wavelength range than single-walled carbon nanotube (SWNT) films. For equivalent sheet resistance, the graphene films exhibit optical transmittance comparable to that of ITO in visible wavelength, but far superior transmittance in infrared spectral region. This article provides the state-of-the-art reviews on the synthesis, optoelectronic properties, applications and challenges of these nanostructured materials for fabricating TCFs.

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1. Introduction

Transparent conducting films (TCFs) represent a class of materials having high electrical conductivity and excellent optical transmission at visible wavelengths. Accordingly, TCFs have found applications in a wide variety of optoelectronic and photovoltaic devices including flat panel displays, touch panels of phones and tablet computers, solar cells, organic light emission diodes (OLEDs), antistatic and electromagnetic interference shielding materials as well as heating elements for defrosting window panels of aircrafts and vehicles. The prospects for the TCF applications look promising due to rising demand for the displays, touch panels and photovoltaics [1]. Till to present, vacuum sputtered transparent conductive oxides (TCOs) such as indium tin oxide (ITO), fluorine doped tin oxide (FTO) and aluminum-doped zinc oxide (AZO) thin films are largely used as the transparent electrodes for these devices. In particular, ITO with high transparency and low sheet resistance is favored over other TCOs [2–4]. However, ITO cannot keep pace with the current development of optoelectronic devices in terms of economic and technical considerations. Indium is a high-cost, precious metal and the ever increasing consumption due to high demands will exhaust its resources in the near future. The high-temperature vacuum deposition of ITO is a relatively slow, expensive coating process. Furthermore, ITO films of brittle nature limit their application in flexible and portable electronic products. Recent demands for mechanical flexibility of electronic devices and uncertainties in the availability of indium motivated the search for alternatives. Several materials like transparent conductive polymers, carbonaceous nanomaterials and metal nanowires have been developed for possible replacement of ITO.

In recent years, fast development in nanotechnology opens new opportunities for synthesizing nanomaterials with unique chemical, mechanical and physical properties. Carbonaceous nanomaterials such as graphene and carbon nanotubes (CNTs) with extremely high elastic modulus of ~1 TPa, good mechanical flexibility, high optical transmittance and electrical conductivity are being considered as excellent candidates for transparent conductive electrodes (TCEs) [5,6]. Graphene is a two-dimensional (2D) building block material for carbon materials of all other dimensionalities. It is a single atomic layer of sp^2 hybridized carbon atoms packed densely in a honeycomb lattice, and can be wrapped up into 0D buckyball, rolled into 1D carbon nanotube, or stacked into 3D graphite (Fig. 1) [7]. For practical applications, graphene films are deposited on metallic substrates using chemical vapor deposition (CVD) process. Those graphene/metal stacking films must be transferred onto non-conducting substrates for forming TCEs. The lowest sheet resistance of the currently available CVD-graphene films is higher than that of ITO. However, chemical doping can improve the conductivity of graphene electrodes substantially. Single-walled carbon nanotubes (SWNTs) are highly resilient and can sustain a large strain of 40% with no sign of brittleness [8]. Individual SWNT displays low electrical resistivity of $\sim 10^{-6}\ \Omega$ cm [9,10]. However, bulk CNT network films exhibit higher resistivity or lower conductivity than ITO due to the presence of contact resistance amongst the nanotube junctions.

Apart from the carbonaceous nanomaterials, metallic nanostructures such as metal nanowire networks and metal nanogrids