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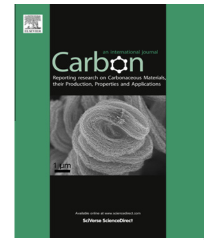

Highly flexible and stretchable carbon nanotube network electrodes prepared by simple brush painting for cost-effective flexible organic solar cells

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ABSTRACT

We developed highly flexible and transparent carbon nanotube (CNT) network electrodes prepared by a simple brush-painting method for the production of cost-effective flexible organic solar cells (FOSCs). By direct, rapid brush-painting of CNTs on a polyethylene terephthalate (PET) substrate using a conventional paintbrush made of nylon fibrils, we achieved percolated CNT network electrodes with a low sheet resistance of 286 Ω/square, a high diffusive transmittance of 78.45%, and superior mechanical flexibility at room temperature. The electrical, optical, and mechanical properties of the brush-painted CNT electrodes were investigated as a function of the number of repeated brush-painting cycles. In particular, brush-painted CNT electrodes showed outstanding flexibility in several test modes, including outer bending, inner bending, twisting and stretching, which are critical requirements in flexible electrodes. Notably, the brush-painted CNT network electrodes had a constant resistance change ($\Delta R/R_0$) within outer and inner bending radii of 5 mm during dynamic fatigue testing. FOSCs fabricated on the brush-painted CNT electrode showed a power conversion efficiency of 1.632%, indicating the possibility of using brush-painted CNT electrodes as cost-effective flexible and transparent electrodes for printing-based low cost FOSCs.

1. Introduction

Flexible organic solar cells (FOSCs) are increasingly being developed as next generation photovoltaic devices, because of their light weight, low fabrication cost, simple printing-based processing, and superior flexibility [1–6]. In a recent report on the performance of organic solar cells, a power conversion efficiency (PCE) as high as 10–12% was achieved, implying that mass production of low cost FOSCs will occur in the near future [6,7]. To improve the performance and decrease the fabrication cost of FOSCs, development of cost-effective transparent electrodes with low sheet resistance, high transmittance, and superior flexibility is imperative because the series resistance, exciton formation efficiency, and mechanical durability of FOSCs are critically related to the electrical, optical, and mechanical properties of transparent electrodes [8]. Outstanding mechanical flexibility of the transparent electrode is very important for FOSCs to compete with conventional Si-based thin film photovoltaics. Although most FOSCs have been fabricated on high-cost Sn-doped In_2O_3 (ITO) films grown by a vacuum-based sputtering process, there is a demand for cost-efficient and

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high performance transparent electrodes. To meet those requirements, various types of transparent electrodes, such as conducting polymers, carbon nanotubes (CNTs), graphene, Ag nanomesh, Ag nanowires, and oxide–metal–oxide multilayers are being extensively investigated. Considering the high cost of indium-based oxide material and vacuum-based processing of ITO films, development of cost effective indium-free and vacuum-free transparent electrodes is very important [9–16]. Among the several options to replace ITO films, a percolation network of CNTs has been suggested as a promising candidate for transparent electrodes in FOSCs. This is because CNT electrodes have an inherently low resistivity, a high specular transmittance, superior flexibility, and can be formed using a simple fabrication employing conducting CNT ink [17–25]. Axel et al. reported that a CNT network electrode prepared by a spray coating method had a sheet resistance of 400 Ω/square and an optical transmittance of 80%, which is worse than conventional ITO films [21]. Dan et al. reported that a CNT electrode prepared by the Meyer rod coating method had a sheet resistance of 100 Ω/square and a specular transmittance of 70%, which are better than the best values obtained from graphene electrodes [22]. Until recently, most CNT electrodes have been fabricated using solution-based coating techniques such as transfer printing, drop casting, air-spray coating, and Meyer rod coating [17,22–25]. However, most solution-based coating techniques have critical drawbacks. Transfer printing leads to irregular morphologies in CNT films. Drop-casting always results in coffee rings and discontinuous CNT films. CNT films fabricated by air-spray coating result in less dense and non-uniform networks of CNTs [25]. Therefore, the development of a lower cost and simpler CNT coating process is imperative. As another simple coating method, a brush painting technique was recently suggested for cost-efficient OSCs [26]. In our previous works, Ag nanowire and PEDOT:PSS showed enhanced low sheet resistance and high optical transmittance even though they were fabricated by simple brush painting at room temperature [27,28]. However, there have been no reports on simple brush-painted CNT network electrodes or their application in cost-efficient FOSCs.

In this work, we report the characteristics of highly flexible and transparent CNT electrodes fabricated by simple brush-painting for use in cost-effective FOSCs. By directly brush-painting the CNT on a polyethylene terephthalate (PET) substrate, a low sheet resistance, high diffusive transmittance, and superior flexibility were achieved, which are required for the fabrication of high performance FOSCs. The electrical, optical, and mechanical properties of brush-painted CNT electrodes as well as the performance of the FOSCs were investigated as a function of the number of brush-painting cycles.

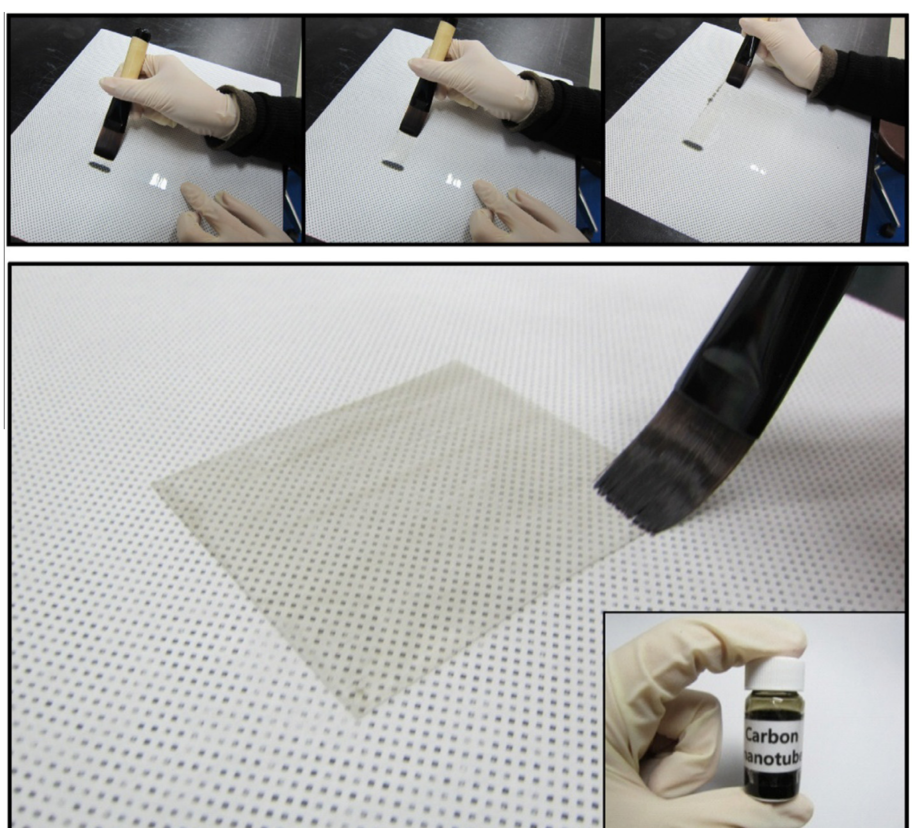

Fig. 1 – Picture of brush printing process (upper panels) to fabricate transparent CNT network electrodes and transparent 3-brush CNT electrode. (A colour version of this figure can be viewed online.)