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Cu/TiN nanofiber with tunable electrical conductivity for cost-efficient transparent electrode

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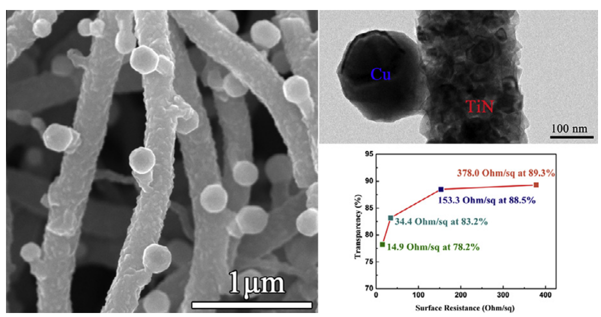
HIGHLIGHTS

- Cu/TiN hybrid nanofibers were successfully fabricated.
- The electrical conductivity of the resulting nanofiber was tunable.
- A high electrical conductivity of 320 S/cm was achieved in Cu/TiN nanofibers.
- The hybrid nanofibers also exhibited considerable thermostability.
- Cu/TiN nanofiber network can be potentially used as transparent electrode.

GRAPHICAL ABSTRACT



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ABSTRACT

Cu/TiN hybrid nanofibers were successfully fabricated by applying nitridation procedure to CuO/TiO_2 nanofibers. Through modifying the nitridation temperature, the electrical conductivity of Cu/TiN nanofibers was tunable, which could achieve a high value of 320 S/cm-approximately three times that of TiN nanofibers. The oxidation resistance property of the resulting Cu/TiN nanofibers was assessed. With the excellent chemical stability of TiN composition, hybrid Cu/TiN nanofibers possessed greatly enhanced thermostability. Moreover, by taking advantage of readily fiber patterning using electrospinning, Cu/TiN nanofiber networks were assembled as transparent electrodes, which reached an optoelectrical achievement of 34.4 Ω/sq at 83.2% transparency. Given its low-cost, enhanced thermostability, together with considerable optoelectrical achievement, Cu/TiN nanofiber is therefore expected to offer a new platform for cost-efficient transparent electrode.

1. Introduction

By simultaneously possessing high electrical conductivity and high optical transparency in the visible spectral range, transparent electrodes have gained much attention for their potential use in electronic and optoelectronic devices, such as solar cells, organic light emitting diodes and flat-panel display [1–6]. In the past few decades, tin-doped indium oxide (ITO) has been widely used as an effective transparent electrode because of its high visible transmittance as well as low sheet resistance. However, due to the low storage of indium in the earth and the low efficiency of traditional vacuum sputtering ITO process (only 3–30% of indium reaching the substrate), the costly price of ITO transparent electrode severely limits its future large-scale use [7–10]. Therefore, developing cost-efficient transparent conductive materials to replace ITO as new kinds of transparent electrode becomes an urgent need [11,12].

The emerging attractive transparent electrode candidates mainly include carbon nanotubes [11], graphene [12], and metallic

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nanowires [13]. The optoelectrical performances of carbon nanotube- and graphene-based transparent electrodes were still far from their theoretical levels and therefore, were lagged behind those of ITO films. More recently, silver nanowires were successfully developed and were put forward as a new kind of competitive alternative to ITO [14–18]. However, as a noble-metal, the high price of silver relatively hinders its application in industry. Along the same lines, copper nanowire networks have attracted increasing attention due to their various advantages, for instance, low price, facile synthesis process, high electrical conductivity as well as improved optical transparency of the unique nanowire network construction. As reported in the literatures [19–21], the performances of copper nanowire transparent electrodes were comparable to or even better than that of ITO. However, the actual utilization of copper nanowires still faces many difficulties and challenges, since the high chemical activity of copper makes it easy to be oxidized into copper oxide [22]. The occurrence of oxidation process is even easier for copper nanowires on account of their large specific surface area, which can result in a huge decrease in electrical conductivity. For instance, copper nanofibers were previously reported to act as an insulator when annealed at 160 °C in air [23]. In this context, searching for new cost-efficient transparent conductive materials with enhanced oxidation-resistant property is relatively important and desirable.

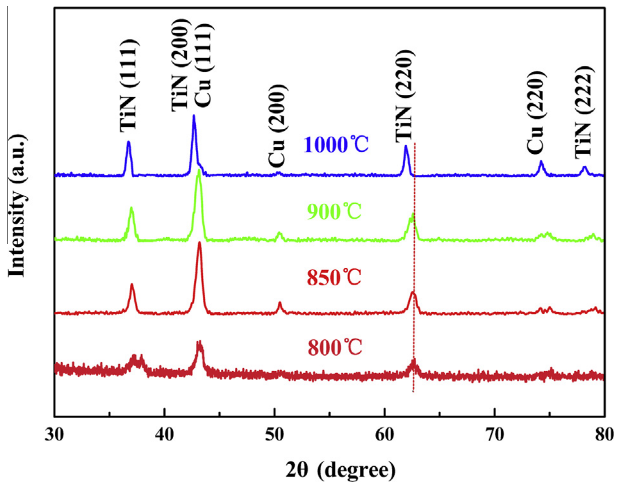

Fig. 1. XRD spectra of the Cu/TiN nanofibers nitrided at temperatures ranging from 800 to 1000 °C.

Toward this goal, here we focus on the integration of copper into conductive ceramics. TiN has been generally fabricated as protective coatings against oxidation and chemical corrosion on the metal substrate surface. Taking its high thermal stability, high electrical conductivity, and inexpensive price into consideration, TiN was chosen as the ceramic matrix. Accordingly, Cu/TiN hybrid nanofibers were readily produced with tunable electrical

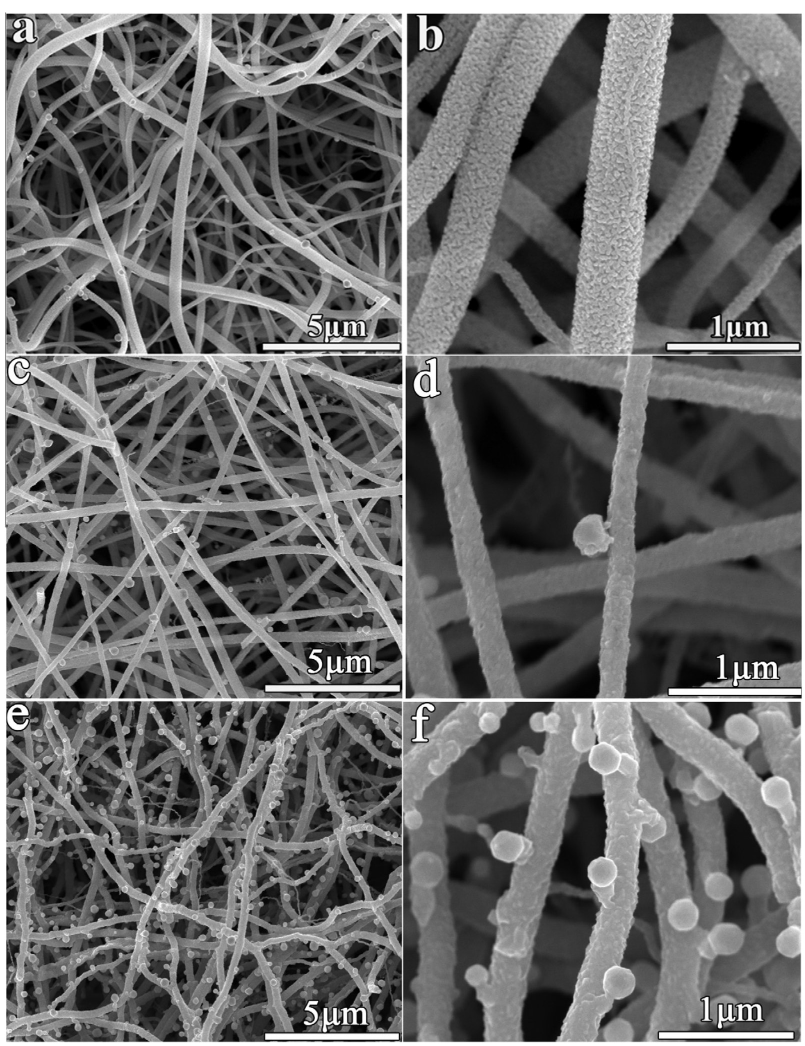

Fig. 2. SEM images of the Cu/TiN nanofibers nitrided at various temperatures in ammonia: (a),(b) 800 °C, (c),(d) 850 °C, (e),(f) 900 °C.