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A highly conductive and flexible metal mesh/ultrathin ITO hybrid transparent electrode fabricated using low-temperature crystallization

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ABSTRACT

The low-temperature processing of transparent electrodes on polymer substrates is an increasingly important issue in lightweight and flexible optoelectronic devices and low-temperature processing is essential since most polymer substrates cannot withstand high temperatures. We analyzed the electrical and optical characteristics of indium tin oxide (ITO) films according to the various crystallization conditions and confirmed that the low-temperature crystallized ITO has a rhombohedral structure. The ultrathin ITO films were crystallized at a temperature of 250 °C, which is lower than the glass transition temperature of polyimide substrates, and a hybrid transparent electrode with a metal mesh was formed. Our hybrid transparent electrode had a high transmittance of 77.4% and a low sheet resistance of 6.3 Ω/sq. After 1000 bending cycles at a bending radius of 6 mm, the hybrid transparent electrode maintained a sheet resistance of 6.5 Ω/sq. We applied rhombohedral ITO to the device rather than the commonly used cubic ITO, and as a result, it showed excellent electrical properties and better bending-stress stability.

1. Introduction

Flexible optoelectronic devices such as solar cells, light-emitting diodes (LEDs), and photodetectors have been actively studied in recent years for wearable devices and/or biomedical applications [1–5]. Most commercial electronic devices use indium tin oxide (ITO) thin films, which have high performance and chemical durability, as a transparent electrode. It has also shown its versatility in various applications, including as a substrate to help grow ZnO nanowires and as a strain gauge that can operate at temperatures of up to 1400 °C [6–9]. However, their bending stability is markedly low because of their rigid and brittle properties [10], and to improve this, several studies have reported hybrid transparent electrodes that combine the advantages of varied materials [11–19]. Li et al. reported a flexible hybrid transparent electrode combining conducting polymer and Ag mesh on a polyethylene terephthalate substrate [14], while Yoon et al. demonstrated a graphene/MoO_3 hybrid transparent electrode on a polyethylene naphthalate (PEN) substrate with good bending stability [15]. Im et al. developed an Ag nanowire and a very thin hybrid ITO transparent electrode on glass fabric-reinforced plastic substrate [16], but the cost of fabricating the conducting polymer, graphene, and glass fabric-reinforced plastic substrate was high, so the electrodes were not considered suitable for mass production. In addition, the analysis of low-temperature annealing conditions for flexible substrates has also so far been insufficient. In the case of rigid substrates, high-temperature annealing (>250 °C) of the ITO films is possible and good performance has been achieved. On the other hand, for polymer-based flexible substrates, there is a limit on the annealing temperature (≤250 °C), which has so far resulted in poor electrical and optical properties.

We previously reported hybrid transparent electrodes for application in rigid GaN-based LEDs [20,21]. Based on this experience, we herein demonstrate a flexible hybrid transparent electrode combining metal mesh and ultrathin ITO (uITO) on colorless polyimide (CPI) film. This design using uITO and metal mesh has

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