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A flexible transparent heater with ultrahigh thermal efficiency and fast thermal response speed based on a simple solution-processed indium tin oxide nanoparticles-silver nanowires composite structure on photo-polymeric film

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A B S T R A C T

In this study, a composite structure consisting of indium tin oxide nanoparticles (ITO-NPs)-silver nanowires (Ag NWs) on photo-polymeric film was intensively studied for flexible transparent heater with ultrahigh thermal efficiency and fast thermal response speed. For cost-effective manufacturing, a simple solution process was employed to make low-cost composite structure by using 0.15 wt% Ag NWs and 5 wt% ITO-NPs solution. Among 3 types, namely, 2-layer (Ag NWs/ITO-NPs), 2′-layer (ITO-NPs/Ag NWs), and 3-layer (ITO-NPs/Ag NWs/ITO-NPs) sample, the composite structure was optimized as 3-layer, which raised temperature by more than 15% compared to the 1-layer sample (Ag NWs only) at the same voltage. In addition, the 3-layer sample made on Norland optical adhesive 63 (NOA 63) photo-polymeric film exhibited good characteristics as a flexible transparent heater. Optical transmittance at 550 nm (T_{550}) of the 3-layer sample was 89.92%, which was similar to that of the 1-layer sample (90.87%). However, sheet resistance (R_s) of the 3-layer sample was 19.56 Ω/sq., which was remarkably lower than that of the 1-layer sample, 78.45 Ω/sq. In addition, an ultrahigh thermal efficiency (328 °C/(W/cm^2)) was achieved from the 3-layer composite structure on the NOA 63 film. Thermal response speed of the 3-layer sample was as ultrafast as 10 s and temperature within 90 °C and 100 °C stably increased and decreased during 60 cycles when applying 5 V. Moreover, the 3-layer sample stably generated heat even under the extreme bending diameter of 5 mm, and heat-generating properties, such as thermal response speed, saturated temperature, and cooling rate, remained almost unchanged even after bending for 1000 cycles.

1. Introduction

Flexible and transparent film heaters have been studied for their application in outdoor panel displays, avionic displays, defrosters of vehicle windows, mirrors, sensors, and so on [1]. For a transparent heater, thermal response speed, steady heating temperature, temperature uniformity, and cycling stability are important performance indexes, and these indexes may dramatically influence application functions. For example, the response speed of defogging vehicle windows affects the safety of the driver considering the fast movement of vehicles [2]. In addition, considering their flexible characteristics, the heaters have to be stable even under extremely bent conditions, as well as possess highly thermal response speed and efficiency. Various transparent conducting materials including carbon nanotubes (CNTs), graphene, poly(3,4-ethylene dioxylene thiophene):poly(styrene sulfonic acid) (PEDOT:PSS), gallium (Ga) doped zinc oxide (ZnO), and silver

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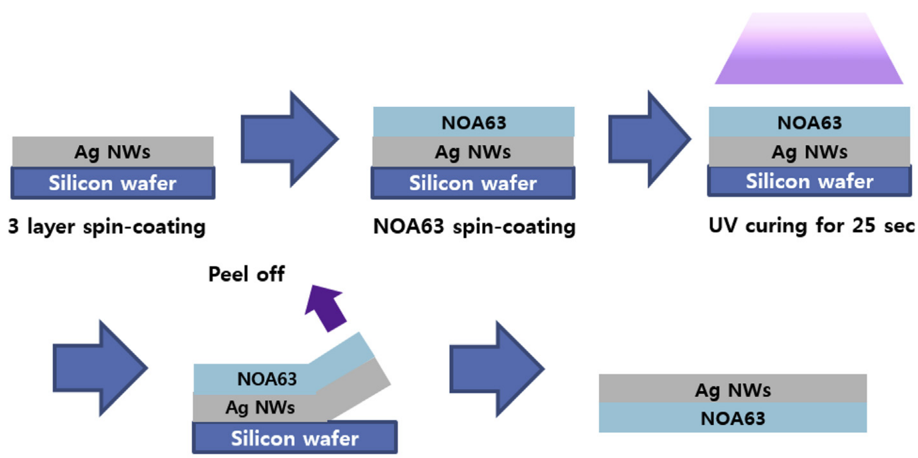
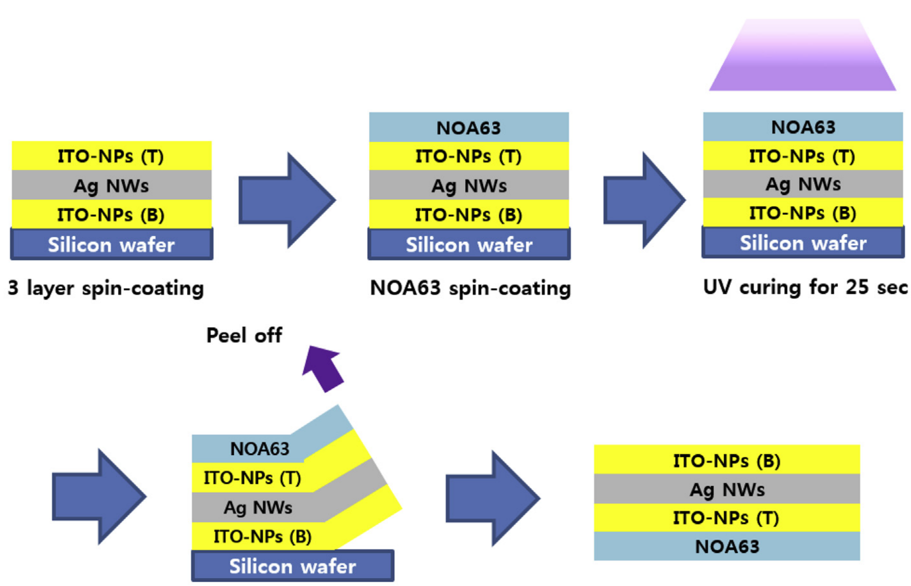
nanowires (Ag NWs) have been investigated for flexible transparent heaters [3]. In this context, Ag NWs having relatively low sheet resistance (R_s) are appropriate, as higher temperatures can be attained as the R_s of the heaters is lower when others are fixed [4].

Although Ag NWs have been considered to satisfy the demands due to their low R_s and flexibility, some issues still remain unsolved, such as thermal response speed and thermal efficiency at low voltage, as well as and high flexibility. In addition, the manufacturing process of the heaters should be cost-effective at large scales [5]. Available methods to raise cost-effectiveness include (a) the all solution-processed method and (b) the lowering concentration of Ag NWs while maintaining low R_s. However, in principle, the density of the Ag NWs must be higher for lowering of R_s of a transparent heater. For a high density of Ag NWs, a high concentration of 0.5 wt% Ag NWs [6] is required, and the high concentration inevitably raises manufacturing cost. To decrease the manufacturing cost, Cheong et al. [7] employed aluminum zinc oxide (AZO) layer to improve electrical conductivity with the lowered concentration of 0.2–0.35 wt% Ag NWs. Although the authors made a good flexible transparent heater consisting of the AZO thin film over the Ag NWs layer, expensive DC sputtering process is essential to make the AZO thin film. Meanwhile, Ji et al. [2] reported transparent heater consisting of poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) as a conductive polymer on the Ag NWs layer by the solution process. In their report, the heater was made on 1.1 mm thick glass and its thermal efficiency and thermal response time to 45 °C were 179 °C/(W/cm^2) and 107 s, respectively. In addition, Pyo et al. [8] reported a flexible transparent heater consisting of PEDOT:PSS on the Ag NWs layer. The authors attempted the inverted layer-by-layer solution processing method and made a good heater on the colorless polyimide (cPI) substrate. Pyo et al. [8] used Ag NWs of the concentration of 0.3 wt% and the flexible transparent heater with R_s of 30 Ω/sq, as well as optical transmittance at 550 nm (T_{550}) of 87% including the substrate. Its thermal response time was about 40 s to reach the goal temperature.

Although Pyo et al. [8] achieved favorable results, flexible transparent heaters still require lower power consumption, higher



(a)



(b)

Fig. 1. Fabrication procedure of flexible and transparent electrode with ITO-NPs/Ag NWs/ITO-NPs structure using NOA63. ITO-NPs (T) and ITO-NPs (B) indicate the ITO-NPs top layer and the ITO-NPs bottom layer, respectively.