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Effective deicing of vehicle windows and thermal response of asymmetric multilayered transparent-film heaters

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A B S T R A C T

For the effective deicing of the windows of electric vehicles, we fabricated asymmetric multilayered transparent (AMT) film heaters exhibiting a low resistance (5.4 Ω/sq.) and high visible transmittance (88%), resulting in the highest figure of merit (759) reported to date. Also, the simulated transmittance of the AMT films better matched the experimental results when considering the microstructure of the reaction layer between the Ga-doped ZnO and Ag layers. Herein, an unconventional approach considering heat transfer by conduction is described because heat loss from the thick glass (>3 mm) inevitably occurs in the real-world application of vehicle windows. We formulated and simultaneously solved two derivative heat transfer equations considering the thermal loss in the thick glass and heat transfer in the heating films to accurately predict the temperature of the outside glass. To verify our model, we performed a heating test by inserting heated windows in a small-scale automobile model and were able to accurately predict deicing time and heating rates.

1. Introduction

Transparent conductive electrodes (TCEs) have attracted considerable attention for a wide range of applications such as flexible displays [1,2], thin-film transistors [3,4], solar cells [5,6], and transparent heaters [7–17]. Transparent heaters are widely used in the heating of microchannel chips, outdoor panel displays, military equipment, sensors, and vehicle windshield defrosters or defoggers [7–9]. In particular, the demand for transparent heaters for automobile glass has been increasing rapidly, especially with the advent of electric vehicles. In practical applications, in which transparent heaters for automobiles are used in low-temperature environments, the removal of ice is more challenging than that of frost. Fig. 1a shows that clear visibility can be ensured for the windshield of a car by removing ice using transparent heaters. Since it takes a long time to remove ice by blowing warm air onto the windows using heat from the engine, a common deicing method is to manually scrape the frozen or snow-covered windows with a silicone or plastic tool. Transparent heaters on automobile glass can be used to realize the more effective removal of ice and snow, which is also more comfortable and convenient for the driver. Such technology requires specific electrical and optical performance; hence, materials selection is critical.

To date, indium tin oxide (ITO) films have been widely used for transparent-film heaters because of their low resistivity and high transparency [2]. However, ITO film heaters present several challenges associated with their high cost (due to the limited supply of indium) and their ceramic nature that leads to films being brittle. Other candidate transparent conductive oxides (TCOs) considered as alternatives to ITO are impurity-doped zinc oxide (ZnO) [18] materials, such as In-doped ZnO (IZO) [19,20], Ga-doped ZnO (GZO) [21], and Al-doped ZnO (AZO) [22,23], which have received considerable attention owing to their low cost resulting from the abundance of Zn and their nontoxicity. However, the resistivity of ZnO-based films tends to abruptly increase as they become thinner [24]. Some attempts have been made to lower the resistivity of very thin ZnO-based TCO films, including the use of an oxide/metal/oxide (OMO) structure, where an ultrathin metal layer is inserted between two oxide layers [25,26].

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