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Polarization and incidence angle-dependent transmittance of transparent nickel electrodes with various thicknesses

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ABSTRACT

The polarization and incidence angle-dependent transmittance of thin nickel film with various thicknesses deposited on glass substrates was first investigated by using a modified UV–Vis spectrometer. The thin nickel films showed relatively high uniform transmittance over a wide range of wavelengths, 300–1100 nm. The thickness-dependent dielectric and optical constants extracted from the experimental transmittance are significantly distinct from those of the thick nickel film. In particular, the p-polarized light transmittance largely increases with larger incidence angle, but the s-polarized light transmittance behavior is opposite from that of p-polarized light. The difference of the polarization-dependent transmittance increases parabolically with the incidence angle.

1. Introduction

The demand for flexible transparent conducting electrodes (TCEs), which are able to transmit the full spectrum of solar energy, increases daily with the technological importance of electro-optic devices, such as solar cells, light-emitting devices, touch screens, mobile phones, flexible optical devices, flat panel displays, flexible displays, electrochromatic devices, and sensors [1–9]. Among TCEs, doped metal oxides have been heavily studied and utilized. In particular, ITO (tin-doped indium oxide) deposited on glass has been extensively utilized for these electro-optic areas due to its low sheet resistance and high optical transmittance of visible light [1–5,8].

However, as the application of transparent electrodes has become more diverse, ITO and other metal oxide-based TCEs face several challenges [1–4]. First, typical metal oxides have an energy band gap of ~3.5 eV, which makes them have significantly low transmittance at wavelengths less than 350 nm. Second, metal oxides are brittle and thus inadequate for flexible opto-electronic device applications such as flexible TCEs. Third, metal oxides typically require high temperature processes to achieve high conductivity. This could deteriorate the physical properties of the devices. Fourth, the multiple-constituent components of metal oxides require careful processing to achieve the required physical properties. Finally, the instability of the market price of indium is expected due to its scarcity as a resource in the near future [1–4,10–12].

Unlike the compound materials mentioned above, stable single element transparent conducting electrodes such as transition metal [13] have become attractive because they are intrinsically ductile, have three-order of magnitude higher conductivity compared to that of metal oxides and ITO, can be deposited even at room temperature, and have magnetic properties. Very thin transition metallic film shows high and uniform transmittance over the wide wavelength region, which covers the full solar spectrum range, as well as facileness in the fabrication process due to single element deposition. Further, the transition metal conducting electrodes, such as opto-spintronics and magneto-optic switching devices as transparent electrodes, can be utilized for future applications [13–16].

In this letter, light polarization and the incidence angle-dependent transmittance of nickel film shows a correlation with its thickness, surface morphology and sheet resistance. In particular, we modified a conventional UV–Vis spectrometer to study the polarization and incidence angle-dependent transmittance of thin nickel film deposited on glass. This study suggests that thin nickel film can be useful as a functional transparent electrode for various electro-magneto-optic applications.

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2. Experimental

The glass substrates were cleaned by ultrasonication in isopropyl alcohol and acetone for 15 min. Then the thin nickel film was deposited on the glass substrates at the Ar pressure of 2.7 mTorr by using a radio frequency (RF) sputter at the RF power of 40 W with the flow rate of 21.4 standard cubic centimeters per minute of argon gas. The axis of the sputter and the surface normal of the substrate had an acute angle of 55°. For the uniform thickness of the deposition of nickel, the substrate was rotated during the deposition, and the thicknesses of the nickel film were controlled by varying the deposition time. Additionally, the nickel film with gradually varied thickness also was deposited on 15 cm × 15 cm corning glass substrates with a thickness of 500 μm without rotating the substrate. The sheet resistance of the thin nickel film on the glass pieces cut into 1.5 cm × 1.5 cm squares was measured by a four-probe station, and the average sheet resistance was obtained from nine data taken from nine different locations on each piece of glass. The transmittance of thin nickel film was characterized by a UV–Vis spectrometer (SCINCO co. S-4100). To study the incidence angle-dependent and polarization-dependent transmittance, the UV–Vis spectroscope was modified by inserting a polarizer and a rotatable sample holder as shown in Fig. 1a. The transmittance characteristics of the employed film polarizer are shown in Fig. 1b. The film polarizer was properly working at wavelengths below 850 nm as shown in Fig. 1b. The transmittance of the observed total transmittance was normalized by the transmittance of the glass based on the relation of $T_F = T_T/T_S$, where T_F, T_S and T_T are the transmittance of the film, the substrate and the measured total transmittance, respectively. The surface structure of the nickel film on glass was investigated by using an atomic force microscope (AFM) with non-contact mode. The scan sizes were 1 μm × 1 μm, 3 μm × 3 μm, and 5 μm × 5 μm.

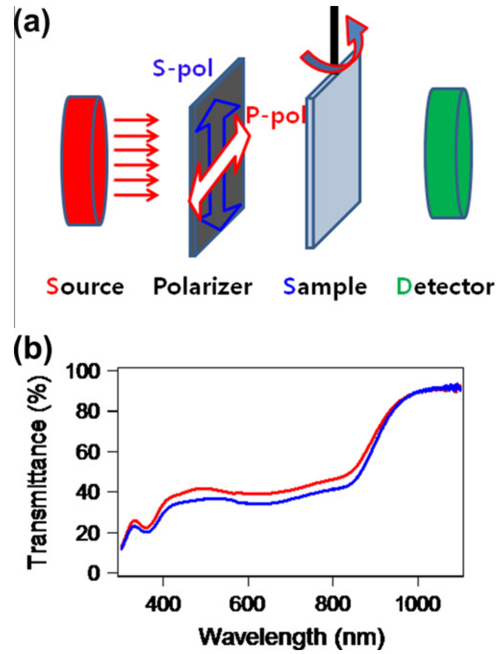

Fig. 1. (a) Schematic showing the modified UV–Vis spectrometer by inserting a polarizer and a rotatable sample holder. (b) The transmittance characteristics of the employed thin film polarizer.

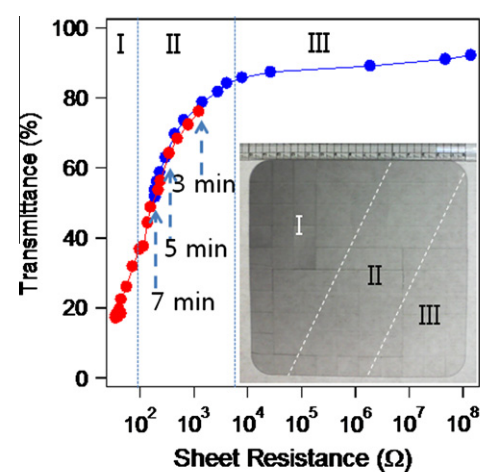

Fig. 2. Transmittance vs. sheet resistance of nickel film deposited on glass by sputtering without rotating the substrates during the deposition for 3 min (blue) and 10 min (red). The inset shows the nickel film deposited on glass for 3 min without rotation of the substrate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

The sheet resistance and the UV–Vis transmittance at the wavelength of 550 nm were measured at various locations of the nickel films with various thicknesses deposited on glass for 3 min (blue) and 10 min (red) as shown in Fig. 2. The nickel thin film with various thicknesses was obtained by an anisotropic deposition of nickel film, which was deposited without rotating the glass substrate during the deposition. As a result, the thickness of the nickel film on glass was gradually varied as shown in the inset optical image of Fig. 2. The transmittance exponentially increases with the sheet resistance [1]. The deposited nickel film can be categorized into three regions based on optical transparency and sheet resistance as marked in the optical image. Region I is relatively dark with low sheet resistance, region III is fairly transparent with large sheet resistance, and region II is intermediate. The transmittance vs. sheet resistance curve strongly suggests that regions I, II, and III can be categorized into continuous and relatively thick, continuous but thin and semicontinuous or discrete regions, respectively.

This high sheet resistance (region III) suggests that the nickel film is semicontinuous or discrete in structure with voids. That is the nickel coverage is below the percolation threshold. Therefore, the high sheet resistance originated from the broken conduction channel and the enhanced scattering rate of carriers due to the small grain size [17].

The relatively high sheet resistance of region II indicates that the coverage of the nickel film is higher than the percolation threshold. However, the conduction mechanism could depend on the tunneling through the grain boundaries even though the grains touch each other.

Even though region I shows relatively low sheet resistance, the sheet resistance is large compared to that of the very thick film. This suggests that the carrier scattering on the surfaces cannot be ignored because the film thickness is thinner than the mean free path of electrons (> 5 nm) [17].

Since we are interested in the development of a thin nickel layer as a multifunctional TCE, the study focused on region II, which shows reasonable transmittance and sheet resistance. For the detailed study, the uniform thin nickel film was deposited on glass substrates by rotating the substrates during the deposition. The corresponding sheet resistance of the deposited nickel films on glass for 7, 5, and 3 min were 0.24, 0.33 and 2.47 kΩ, respectively, as indicated in Fig. 2.