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Highly-reflective and conductive distributed Bragg reflectors based on glancing angle deposited indium tin oxide thin films for silicon optoelectronic applications

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ABSTRACT

We investigated the highly-reflective and conductive indium tin oxide (ITO) single material-based distributed Bragg reflectors (DBRs), operating at a center wavelength of 565 nm, by a glancing angle deposition method. The porous ITO films were formed at an incident vapor flux angle of 80°, indicating the effective refractive index of ~1.258. The optical properties (e.g., reflectance and normalized stop bandwidth) were enhanced as the number of pairs was increased. The maximum reflectance and normalized stop bandwidth for the high reflectance region of >80% were estimated to be ~85% and ~8%, respectively. Furthermore, the incident angle-dependent reflectance characteristics were also investigated in the incident angle range of 20–60° for *p*-, *s*-, and non-polarization. For comparison, the theoretical optical modeling and simulation were performed using the rigorous coupled-wave analysis method, exhibiting a similar tendency with the experimental results. The effective electrical characteristics of ITO DBRs were also obtained.

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1. Introduction

Recent researches in designs of thin films have attracted great interest to realize optical components including antireflection coatings, reflectors, and optical filters for the performance improvement of optoelectronic devices such as light-emitting diodes, laser diodes, solar cells, and photodetectors [1–3] because they can provide adjustable optical properties by controlling their morphologies. Among these optical components, the distributed Bragg reflectors (DBRs) have been employed to enhance the efficiency of devices operating in a specific range of wavelengths [3–5]. The DBRs are generally composed of alternating layers of high- and low-refractive index (n) films with their corresponding quarter wavelength ($\lambda/4$) film thicknesses [4,5]. The optical performance of DBRs mainly depends on the refractive index contrast between the high-n and low-n films [6,7]. Thus, the larger refractive index contrast and higher number of pairs are required to increase the reflectance and widen the stop bandwidth. Besides, the wavelength region with high reflectance can be controlled by adjusting the $\lambda/4$ thicknesses of the alternating two films [8].

Generally, there has been much effort on the DBRs composed of two different materials (i.e., AlGaAs/GaAs [9], GaN/AlGaN [10], TiO_2/SiO_2 [11], etc.) for visible wavelength applications. However, they have fundamental limitations such as thermal expansion mismatch, material selection, low contrast ratio between films, diffusion of one material into another, and expensive processes, which increases the complexity [12,13]. To overcome these issues, the studies on single material-based DBRs, e.g., Ge [7], TiO_2 [8] and Si [14], by a glancing angle deposition (GLAD) method have been reported over the past years. In the GLAD method, the refractive index of single material films can be controlled by introducing the porosity into films with columnar structures (inclined, helical, and zigzag) [15,16]. Under high incident vapor flux angles of ≥80°, especially, the nanoporous thin films with a low-n can be fabricated due to the enhanced self-shadowing effect during the process, which allows for a large contrast in the refractive index even from the same material [16,17].

Meanwhile, indium tin oxide (ITO) has been widely used as DBRs [18,19], antireflection coatings [16], and transparent electrodes [20] for a variety of semiconductor devices due to its high electrical conductivity and optical transparency in the visible wavelength range. However, there are very few studies on DBRs composed of single-material ITO-based porous and dense films by the GLAD method at visible wavelengths, including optical and electrical properties. Additionally, ITO has almost no absorption in the visible wavelength region. Thus, it is very meaningful to study reflection and electrical properties of the ITO-based DBRs prepared by the GLAD method. In this paper, the ITO DBRs with different pairs (1–5 pairs) were prepared on the Si substrate for both the center wavelengths (λ_c) of 565 and 740 nm by the GLAD method via an electron beam (e-beam) evaporation. Their optical characteristics were investigated at various incident angles of 0–60° in comparison with the theoretically calculated simulation results using the rigorous coupled-wave analysis (RCWA) method.

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2. Experimental and numerical modeling details

Fig. 1 shows the schematic diagram for (a) the fabrication procedure of ITO DBRs on Si substrates by the e-beam evaporated GLAD method and (b) the cross-sectional scanning electron microscope (SEM) images of the ITO DBRs with 1, 3, and 5 pairs consisting of nanoporous (low-n)/dense (high-n) ITO film pair structures. For the sample preparation, the single side-polished Si substrates with a size of 1.5×1.5 cm^2 were ultrasonically cleaned in acetone, methanol, and de-ionized water, and then dried by nitrogen gas. Next, the inclined holder loaded with Si substrates and the 7 cc crucible filled with an ITO source (99.99% purity) were mounted into the e-beam evaporation system (KVE-E2004, Korea Vac. Tech. Ltd.), respectively. After that, the base pressure in a vacuum chamber was maintained to be $<1.33 \times 10^{-4}$ Pa. During the process, the deposition rate was almost kept at ~1.5 Å/s using a quartz crystal thickness monitor without substrate rotation and heating. The deposition times for the dense/nanoporous ITO films at $\lambda_c = 565$ and 740 nm were ~350 s/1110 s and ~450 s/1540 s, respectively. In the GLAD method, the porosity induced by incident vapor flux angle (θ_α) plays an important role in adjusting the refractive index. Typically, the refractive index becomes lower when the porosity is increased [16]. In order to achieve a large refractive index contrast, the nanoporous ITO films with a low-n were deposited at $\theta_\alpha = 80°$ whereas the dense ITO films with high-n were normally deposited at $\theta_\alpha = 0°$. By repeating the deposition process of nanoporous/dense ITO films, the ITO DBRs with 1–5 pairs were fabricated. Finally, all the ITO DBR samples were annealed at a temperature of 600 °C for 15 min in the atmosphere by rapid thermal annealing to enhance their electrical conductivity and optical transparency.

As shown in Fig. 1(b), it can be observed that the ITO DBRs with different pairs were well fabricated on Si substrates. The one-pair DBR is composed of an alternative high-n/low-n ITO film structure deposited at $\theta_\alpha = 0°/80°$. To reduce the thickness deviation in the nanoporous ITO films between the near and far points on substrates for the DBR with multiple pairs in the GLAD process without substrate rotation, the films were deposited at $\theta_\alpha = 80°/-80°$, as shown in Fig. 1(b). At $\theta_\alpha = 80°$, the inclined columnar nanostructures within the film were formed due to the enhanced self-shadowing effect and limited atom mobility, which creates the low-n ITO film with a relatively high porosity [16,17]. The porosity within the film can be estimated by the Bruggeman effective medium approximation [21]. The porosity of the ITO film at $\theta_\alpha = 80°$ was estimated to be ~70%. In this calculation, we assumed that the normally deposited ITO film at $\theta_\alpha = 0°$ has a zero porosity. The $\lambda/4$ thicknesses of the ITO films at $\theta_\alpha = 0$ and 80° were calculated to be approximately 72 and 112 nm, respectively, by $n = 1.956$ at $\theta_\alpha = 0°$ and $n = 1.258$ at $\theta_\alpha = 80°$ for the λ_c value of 565 nm. For the actually deposited films, the thicknesses of 72 ± 5 nm at $\theta_\alpha = 0°$ and 112 ± 10 nm at $\theta_\alpha = 80°$ were relatively well matched

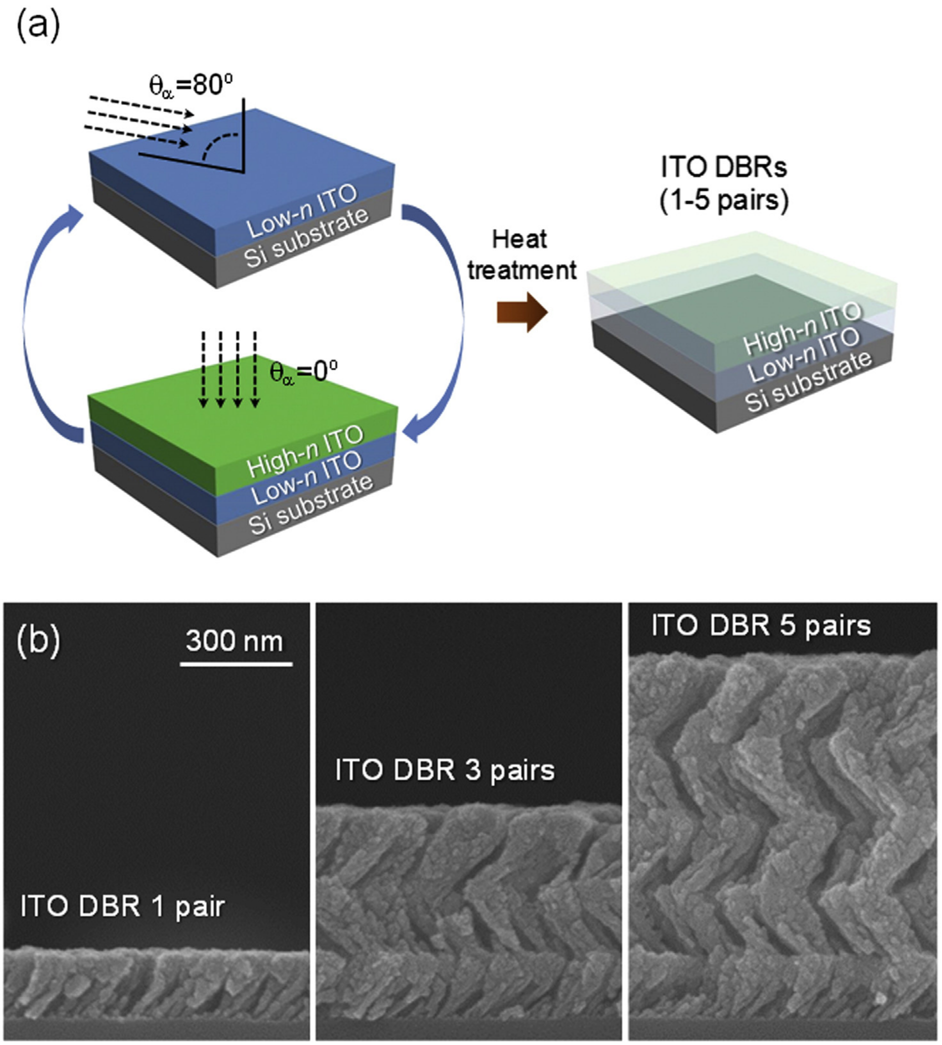

Fig. 1. Schematic diagram for (a) the fabrication procedure of ITO DBRs on Si substrates via the e-beam evaporated GLAD method and (b) cross-sectional SEM images of the ITO DBRs with 1, 3, and 5 pairs consisting of nanoporous (low-n)/dense (high-n) ITO film pair structures.

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