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Fabrication of wire-grid polarizer with glass molded nanograting structure

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Abstract

Wire grid polarizers (WGP) are essential in photonic applications such as laser optical systems, imaging systems, and displays due to their high polarization efficiency and durability. Conventional WGP fabricated on polymer substrates face limitations in optical transmittance, mechanical stability, and thermal durability. This study introduces a cost-effective and scalable method for fabricating WGP on glass nanograting structures using Vitreous Carbon (VC) molds and oblique angle deposition (OAD) of aluminum. The proposed process addresses the shortcomings of polymer-based WGP while enabling large-area production. The VC mold was fabricated through a multi-step replication and carbonization process. A silicon master with nanograting features (500 nm pitch, 250 nm height, 50% duty cycle) was prepared using reactive ion etching and KrF laser photolithography. A polymer template was replicated via UV imprinting, and a furan precursor was replicated from the polymer template through a thermal curing process. A VC mold with a nanograting cavity (400 nm pitch, 140 nm height) was obtained by a carbonization process at 1000°C in a nitrogen-purged environment. Glass nanogratings were then formed by molding soda-lime glass at 730°C under 1.84 MPa, with SEM analysis confirming successful nanoscale replication. An aluminum layer was deposited on the glass nanograting using the OAD process, with optimized flux angles (<70°) to minimize sidewall deposition and prevent isolated nanorods. The fabricated WGP exhibited a transverse-magnetic wave transmittance of over 40% and an extinction ratio of ~40 at 600 nm, which is similar to the simulation results for the glass WGP model with slight sidewall deposition. Although the pitch of the fabricated WGP were not suitable for visible light applications, this study demonstrates the feasibility of WGP with directly molded glass nanograting structures, offering advantages in cost, scalability, and durability. The proposed method is promising for advancing photonic applications.

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1. Introduction

In the fields of photonic applications such as laser optical system, imaging system, and display, a polarizer is an essential optical component. Wire grid polarizer (WGP) on glass substrate is a promising optical component due to its good performance such as polarization efficiency and high thermal and mechanical durability in comparison with conventionally used polyvinyl alcohol (PVA) absorptive polarizer[1]. It is comprised of uniform dielectric grid with metal line which is smaller than wavelength. The WGP transmits the light having

polarization direction perpendicular to the metal wire and reflects that parallel to the metal wire. WGP have usually been fabricated by etching of a deposited metal layer on a substrate using photolithographed, laser interference lithographed, or nanoimprinted barrier patterns [2-4]. Yamada et al. [2] fabricated a 3 μm pitch aluminum (Al) WGP on a silicon substrate by wet etching of an Al layer deposited on the substrate using a photolithographed photoresist barrier. They achieved extinction ratios of 23–45 dB (200–30,000) for 0.5–3 THz electromagnetic waves (100–600 μm wavelength range). They [3] also fabricated a 230 nm pitch tungsten silicide (WSi)

WGP on a glass substrate by reactive ion etching (RIE) of a WSi layer on the substrate using a laser interference photoresist barrier, achieving extinction ratios of 100–1000 for the 650–1500 nm wavelength range. Ahn et al. fabricated a 100 nm pitch Al WGP on a glass substrate by RIE of an Al layer on the substrate using a UV-imprinted resist barrier, achieving extinction ratios higher than 2000 for the visible wavelength range. However, these processes are expensive and complicated when the structure is getting smaller. Alternatively, a fabrication method using simple deposition of metallic layer on the replicated polymer nanograting has been adapted because of its simplicity and cost-effectivity. Ju et al. [5] fabricated a 110 nm pitch bilayer Al WGP by simply depositing Al on a UV-imprinted nanograting structure and achieved an extinction ratio of $\sim 1,000$ for the 500–800 nm wavelength range. Watts et al. [6] fabricated a large-area 130 nm pitch Al WGP by oblique angle deposition (OAD) of Al on a roll-to-roll UV-imprinted nanograting structure and achieved an extinction ratio of $\sim 2,000$ for the visible wavelength range. Although large-area WGP can be fabricated by simple oblique angle deposition on a UV-imprinted nanograting structure, polarizer devices consisting of polymer materials have limitations in the optical transmittance range for infrared wavelengths and limited mechanical and thermal stability.

In this study, we fabricated a WGP by oblique angle deposition of Al on a glass nanograting structure instead of a polymer nanograting. Glass nanogratings are typically fabricated by RIE using photolithographed, nanoimprinted, or laser interference lithographed etch barriers [7]. Although RIE of glass substrates is a well-established process, it is time-consuming due to the low etching rate of glass and the complexity of the etch barrier patterning process.

Among the various glass shaping methods, the glass molding process is suitable for low-cost, large-area, and mass production of glass micro/nanostructures. One of the key issues in the glass molding process is the mold material, which requires high strength, hardness, and durability at high temperatures. Fouzy et al. [8] fabricated a 1 μm pitch glass-molded grating using a Si mold, which was fabricated by RIE of a photolithographed barrier and coated with a 40 nm thick silicon nitride layer to prevent adhesion issues between the Si mold and the glass material. Since adhesion problems occur in glass molding, repeated anti-adhesion coatings must be applied to the mold surface, as the coating layer can be damaged during repeated molding processes. Among the mold materials suitable for glass molding, vitreous carbon (VC, also called glassy carbon) is the most promising because it not only exhibits high mechanical strength at elevated temperatures but also provides excellent release properties without requiring an anti-adhesion coating. Mekaru et al. [9] fabricated glass-molded microstructures on Pyrex and quartz glass substrates using an RIE-processed VC mold, and Mori et al. [10] fabricated a glass-molded 500 nm pitch nanograting using an RIE-processed VC mold with a size of $6 \times 6 \text{ mm}^2$. However, the RIE-processed VC mold fabrication method used in previous studies is expensive and unsuitable for large-area mold production.

In our previous research, we demonstrated a low-cost and large-area VC mold fabrication method by carbonizing a replicated high-carbon-yield polymer precursor, enabling the

production of various glass-molded micro- and nanopatterned components [11–14]. In this study, we fabricated a glass nanograting using the glass molding process with a VC mold featuring nanoscale cavities and realized a wire-grid polarizer by OAD of an aluminum layer onto the fabricated glass nanostructure.

2. Fabrication of glass WGP

In order to fabricate a glass nanograting by glass molding a VC mold with negative pattern of nanograting is firstly required. The fabrication procedure of VC nanomold is shown in fig. 1 (a)–(f). A silicon master, which is pitch 500 nm, height 250 nm, and duty cycle 50%, was fabricated by reactive ion etching process using KrF laser photolithographed barrier pattern (a). A polymer template was replicated from silicon master by UV imprinting process (b, c) and a Furan mixture composed of Furan resin, ethanol, and initiator was poured on the polymer mold (d). To avoid a micro air bubble defects in furan precursor, the furan mixture was polymerized at room temperature for 5 days and then cured at 100°C for 1 day (e). Through the carbonization process in furnace with N_2 purged environment at maximum temperature of 1000°C, VC mold with nanograting cavities was successfully achieved (f, g). During the carbonization of the furan precursor, inherent shrinkage of the grating structure occurred due to the thermal decomposition of the material. This shrinkage was not isotropic [15]. The measured pitch of the VC mold was 400.4 nm ($\sim 20\%$ shrinkage), and the grating height was 140.6 nm ($\sim 42\%$ shrinkage). To obtain the glass nanograting, glass molding process using soda-lime glass was performed with temperature 730°C and pressure 1.84MPa in N_2 purged environment (h, i). The measured pitch and grating height of glass molded nanograting were 399.1 nm and 139.1 nm, respectively. This indicates that replication errors in glass molding with the VC mold are negligible due to the similar thermal expansion coefficients of VC and glass materials.

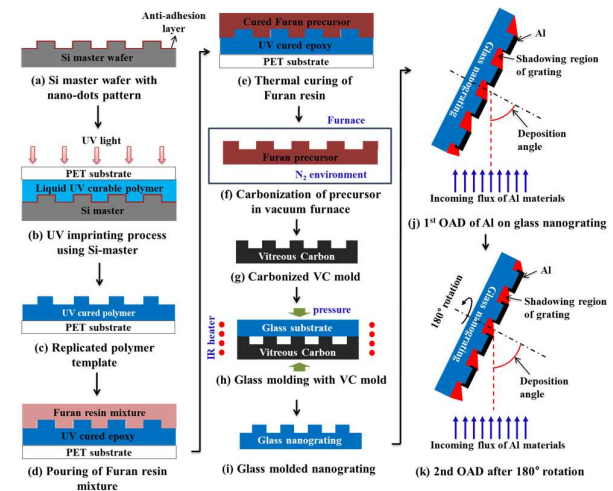


Fig. 1. Fabrication procedure of fabricated wire-grid polarizer with glass nanograting by proposed method

Fig. 2(a) and (b) show the SEM images of fabricated VC mold and glass imprinted nanograting. It clearly shows the glass molding process with VC mold prepared by replication and

carbonization of furan resin is successfully applicable to the nanoscale pattern. To realize a wire grid polarizer, a 70 nm thick Al layer was deposited on glass nanograting by two step OAD process. OAD process can generate a metal grid in accordance with the nanograting structure due to shadowing effect[16]. However, if incoming flux angle was steepest, metal generates an isolated nanorods on the top of nanogratings[17]. Since the isolated nanorods can deteriorate the optical performance of WGP, the incoming flux angle was set to be less than 70° in this study. To prevent the sidewall deposition, which can decrease the transmittance performance, the incoming flux angle increased as much as possible. Fig. 1(j) shows a schematic of the OAD process on the glass nanograting. Since the glass grating substrate is positioned at a tilting angle of 70° (deposition angle), the Al layer is deposited only on the top of the grating. However, slight sidewall deposition is unavoidable. To fabricate a symmetric metal grid on the glass nanograting, we implemented a 2nd OAD process, which was applied after rotating the substrate by 180° , as shown in Fig. 1(k). From Fig. 2(c), it is clearly shown that the two-step OAD process successfully forms an Al grid on the top parts of the glass nanograting with a symmetrical shape.

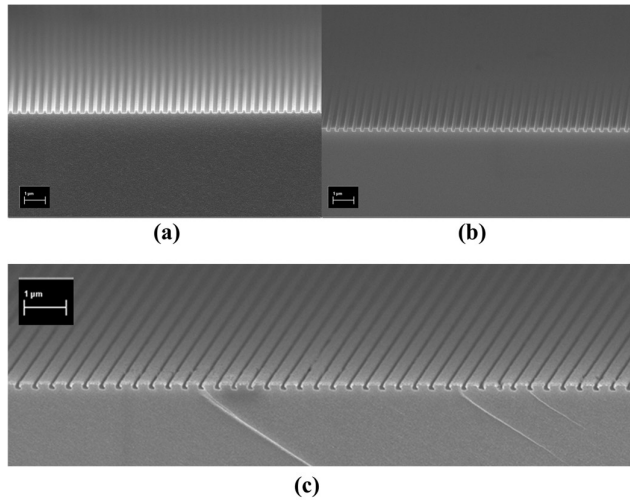


Fig. 2. SEM image of (a)vitreous carbon mold, (b)replicated glass nanograting and (c)fabricated wire grid polarizer in fabrication procedure.

3. Evaluation of the fabricated glass WGP

A direct and straightforward method to evaluate the performance of a WGP in the visible wavelength range is to take photos of the WGP on an LCD monitor before and after 90° rotation, because the light emitted from the LCD monitor is polarized. Although the grating pitch of the fabricated glass WGP is not sufficiently small for an ideal visible light range WGP, its polarization effect in the visible light can be observed, as shown in Fig. 3. This may be due to slight sidewall deposition during the OAD process. Since the thin Al layers formed on both sides of the glass nanograting with a pitch of ~ 400 nm, the effective pitch of the sidewall-deposited Al can be considered ~ 200 nm.

To quantitatively confirm the performance of the wire-grid polarizer (WGP) with a glass-molded nanograting structure in the visible range, a fiber-optic-compatible halogen light source

(HL-2000, Ocean Optics, Inc., USA) and a spectrometer (USB2000+, Ocean Optics, Inc., USA) were used. The light from the source was collimated, controlled by an aperture and a polarizer, and then illuminated onto the sample, which was mounted on a rotational stage. The transmitted light was collected by a collimating lens and measured using the spectrometer. The transmission spectra of transverse-electric (TE, parallel to the grating lines) and transverse-magnetic (TM, perpendicular to the grating lines) polarized light for the fabricated WGP with the glass-molded nanograting structure are shown in Fig. 4. The results indicate that the TM transmittance wave exceeded 40%, and an extinction ratio of ~ 40 was achieved at ~ 600 nm wavelength.



Fig. 3. Photograph image of fabricated wire-grid polarizer with glass molded nanograting structure on LCD monitor.

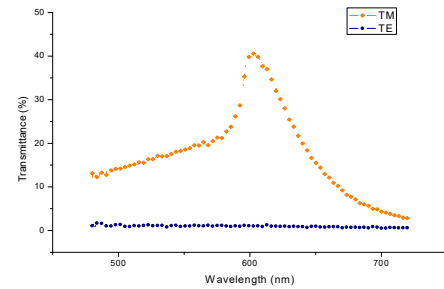


Fig. 4. The measured transmittance spectra of fabricated wire-grid polarizer with glass molded nanograting structure.

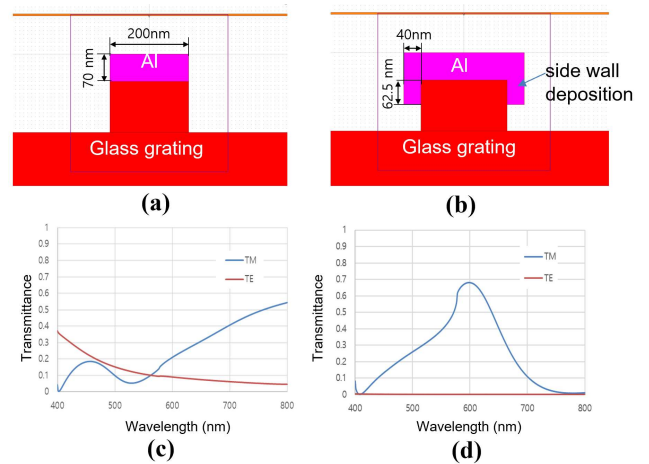


Fig. 5. (a), (b) Rsoft simulation model and (c), (d) simulated spectra for TE and TM polarized light; (a), (c) are the model and simulation model for the ideal glass WGP with pitch of 400 nm with 70 nm Al grid, and (b), (d) for glass WGP with considering slight sidewall deposited Al.

To confirm the polarization effect of the fabricated glass WGP in the visible range, a rigorous coupled wave analysis (RCWA) simulation was carried out using RSoft (Synopsys Inc., USA). Fig. 5(a) and (b) show the simulation models for (a) the ideal glass WGP and (b) the glass WGP with slight sidewall deposition. Fig. 5(c) and (d) show the simulated TM and TE transmission spectra for (c) the ideal WGP and (d) the WGP with sidewall deposition. It is noted that the ideal model does not show a clear polarization effect. However, a polarization effect was observed in the glass WGP when considering the slight sidewall deposition. In addition, the trend of the simulation results for the glass WGP with sidewall deposition is similar to the experimental results. It clearly shows that the polarization performance of the fabricated WGP is due to the sidewall deposition of Al layer.

4. Conclusions

A WGP with glass molded nanograting structure was realized by the glass molding process with VC mold and two step OAD process. Although the pitch of the fabricated glass WGP was suitable for near-IR light, we observed some polarization effects for visible light in both qualitative and quantitative measurements. These polarization effects in the visible wavelength range were confirmed to be due to the unexpected slight sidewall deposition. While the measured polarization performance is not as high as that of previous research results for the WGP in the visible wavelength range, and the near-IR wavelength range polarization performance of the fabricated glass WGP has not been evaluated due to the lack of a measurement setup, this study clearly demonstrates the feasibility of WGPs with directly molded glass nanograting structures, offering advantages in cost, scalability, and durability. The measurement of polarization performance of the fabricated glass WGP in near-IR wavelength ranges and the evaluation of the superior thermal characteristics of the fabricated glass WGP are the subject of on-going research.

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