Closely packed and aspect-ratio-controlled antireflection subwavelength gratings on GaAs using a lenslike shape transfer

Young Min Song,[1,3] Si Young Bae,[1] Jae Su Yu,[2] and Yong Tak Lee[1,*]

[1]*Department of Information and Communications, Gwangju Institute of Science and Technology, 1 Oryong-dong, Buk-gu, Gwangju 500-712, Korea*

[2]*Depratment of Electrical Engineering, Kyung Hee University, 1 Seocheon-dong, Giheung-gu, Yongin-si, Gyeonggi-do 446-701, Korea*

[3] *ymsong@gist.ac.kr*

**Corresponding author: ytlee@gist.ac.kr*

Received January 5, 2009; revised April 16, 2009; accepted April 17, 2009; posted April 30, 2009 (Doc. ID 105863); published May 28, 2009

We report a simple and low-cost fabrication of antireflection subwavelength grating (SWG) structures on GaAs using the lenslike shape transfer by a holographic lithography and a reflowed photoresist mask. The use of an additional thermal reflow process enhances the close packing of two-dimensional SWGs with a conical shape. The aspect ratio of conical SWG was also controlled easily by adjusting the rf power during the dry etch process. The fabricated SWGs exhibited low reflection properties over a wide spectral range, in agreement with the calculated values using by a rigorous coupled-wave analysis simulation. © 2009 Optical Society of America

OCIS codes: 050.6624, 220.4241, 260.2710.

There has been increasing interest in reducing the undesirable reflection between different optical media in various applications of solar cells, photodetectors, light-emitting diodes, and transparent glasses. Although the antireflection structure based on multilayer thin-film coatings is commonly used, it has problems such as material selection, thermal mismatch, and instability of the thin-film stack [1,2]. Recently, subwavelength grating (SWG) structures with a moth-eye profile have been considered as a promising candidate for high-efficiency optical devices owing to their broadband antireflection properties [3–8]. Previously, many different methods for the fabrication of nanostructures with a tapered profile, including e-beam lithography followed by dry etching [3–5], trilayer resist nanoimprint lithography followed by a lift-off process [6], and dynamic etching [7], have been developed. However, these methods may require multiple process steps and take a long time, i.e., expensive and time-consuming processes. In this Letter, we fabricated the two-dimensional closely packed SWG structures with a conical shape on GaAs by holographic lithography and inductively coupled plasma (ICP) etching in combination with an additional photoresist (PR) reflow process, effectively suppressing the surface reflection. The simulation and measurement results of the surface reflection on the shape, height, and period of the fabricated SWG structures are also shown over a wide wavelength range of incident light.

Figure 1 shows the schematic illustration of the lenslike shape transfer procedures for the fabrication of the SWGs on GaAs. For SWG structures with tapered profiles, AZ5206 PR was spin-coated on the GaAs substrate. The dilution ratio and rotation speed were adjusted to obtain a 200-nm-thick PR layer. After prebaking on a hot plate at 90°C for 1 min 30 s, the coated PR was exposed twice to the 363.8 nm line of an Argon laser using a two-beam interference method (i.e., holographic lithography). For a hexagonal structure, the sample was rotated by 60° between exposures. The PR pillar period is ~300 nm, and the depth of the pillar is ~200 nm. To obtain smooth PR lenslike profiles, the thermal reflow process was performed at 160–200°C for 40 s on a hot plate. During the heating cycle, the amorphous resist polymer changes abruptly from the rubbery state into the glass state at the glass transition temperature [9]. The surface tension works to minimize its surface area by rearranging the masses of liquid inside the PR pillar. Consequently, PR pillars gradually become rounded in shape, leading to resultant half-spherical lens shapes. After that, the lenslike-shaped PR patterns are transferred in GaAs using dry etching for SWG structures.

Figure 2 shows the scanning electron microscope (SEM) images of the PR patterns on GaAs substrate (a) before the thermal reflow process and after ther-

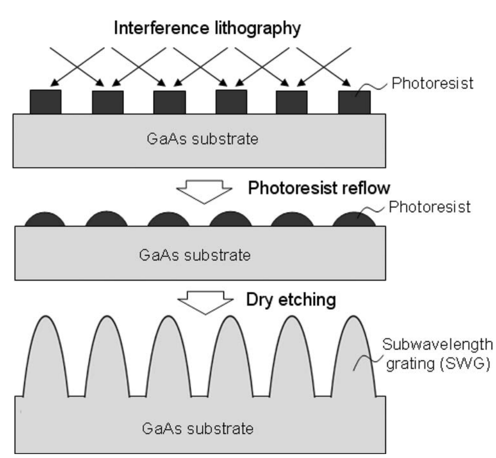

Fig. 1. Schematic illustration of the lens-like shape transfer procedures for the fabrication of the SWGs on GaAs.

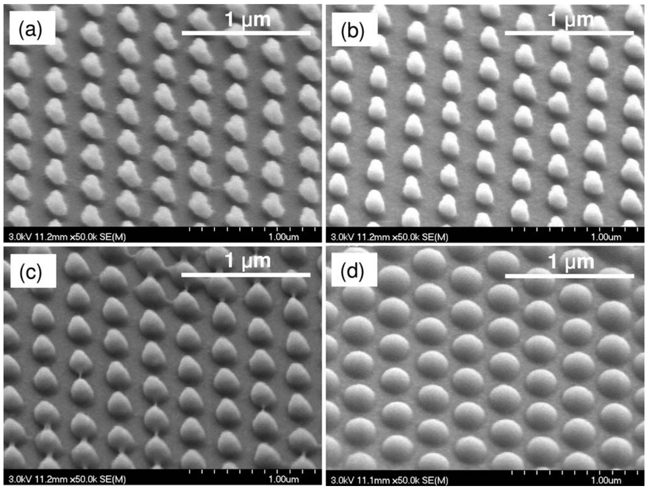

Fig. 2. SEM images of the PR patterns on GaAs substrate (a) before thermal reflow process and after thermal reflow treatments of (b) 160°C, (c) 180°C, and (d) 200°C for 40 s.

mal reflow treatments of (b) 160°C, (c) 180°C, and (d) 200°C for 40 s. At 160°C, it is not sufficient to melt the PR, so there is no difference compared with the original PR pattern. However, above 180°C, the edges of the PR pattern start melting into a mushroomlike shape, and then the melted resist structure (at 200°C) is changed into the half-spherical lens array because of the surface tension. Usually, the double exposure at 60° using the interference lithography provides a regular hexagonal grid. Some researchers have used multiple-beam interference lithography for sixfold symmetry, but there are tedious spatial-phase alignment issues between each exposure [10]. As shown in Fig. 2, it is noticeable that the use of reflow process results in a sixfold hexagonal symmetry without using any additional beam exposure under optimized condition. Moreover, the reflow process allows forming the reproducible PR pattern with good uniformity over a relatively large area. The height of the PR pattern was lowered and its area became broadened, as can be seen in Fig. 2(d). This means that the packing fraction is much larger than that of the original PR structure. Thus the lenslike PR feature helps to make an effective refractive index with a gradient profile.

As shown in Fig. 1, atoms from the PR surface and the GaAs layer are removed simultaneously using dry etching by ICP until the lens-shaped PR is completely etched into the substrate. The etch selectivity between the GaAs layer and the PR layer is strongly dependant on the ICP parameters such as process pressure, gas mixture, and rf power [11]. In this experiment, the etch selectivity of GaAs over PR can be varied from 2.5 to 4.3 simply by reducing the rf power from 150 W to 50. For comparison, two samples were fabricated with different rf powers, i.e., 150 W (SWG1) and 100 W (SWG2) for 12 min and 15 min (to remove completely the PR), respectively. Figure 3 shows the SEM images of the fabricated GaAs SWG structures: (a) SWG1 and (b) SWG2. The fabricated SWG consists of a conical shaped grating, resulting in a graded index profile [12]. The SWG2, which was fabricated by etching process with relatively high selectivity, has an aspect ratio of ~1.5, which is higher than that of the SWG1 (~0.9). Thus, the pattern modification may be attributed to the etch selectivity in the used gas mixture. This means that the aspect ratio can be controlled simply by changes of the rf power without the use of a complex gas mixture or additional process steps.

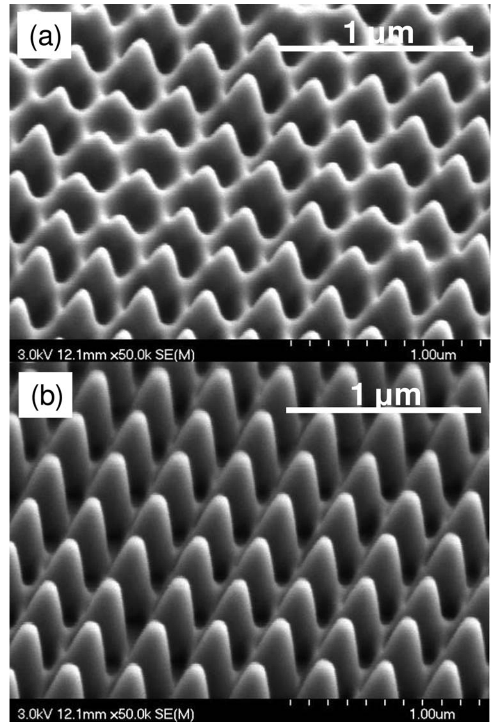

Fig. 3. SEM images of the fabricated GaAs SWG structures with different rf powers: (a) 150 W for 15 min (SWG1) and (b) 100 W for 12 min (SWG2).

The reflectance of the fabricated SWG structures at normal incidence was measured by using a UV-VIS-NIR spectrophotometer (Cary 5000, Varian). Figure 4(a) shows the measured reflectance as a function of the wavelength for the fabricated GaAs SWG1 and SWG2 structures. The measured and simulated reflectances of bulk GaAs were shown as a reference. The inset shows the SWG structure with a truncated cone profile used in this simulation. The reflectance spectrum of bulk GaAs is calculated by the well-known complex refractive index, in excellent agreement with the measured results (>30%). As shown in Fig. 4(a), two SWG samples on GaAs decreases drastically the reflection loss compared with that of a flat GaAs surface. The measured reflectance values of the SWG1 and SWG2 are below 5% over a wide wavelength range of 300–1100 nm. The simulated reflectance spectra of the fabricated GaAs SWG1 and SWG2 structures were shown together with measured results in Fig. 4(b). The theoretical calculations of reflectance were done by using the rigorous coupled-wave analysis (RCWA) proposed by Moharam [13]. The model was constructed by mean shape of the SEM image, and it is assumed to be a truncated cone for simplicity as shown in the inset of

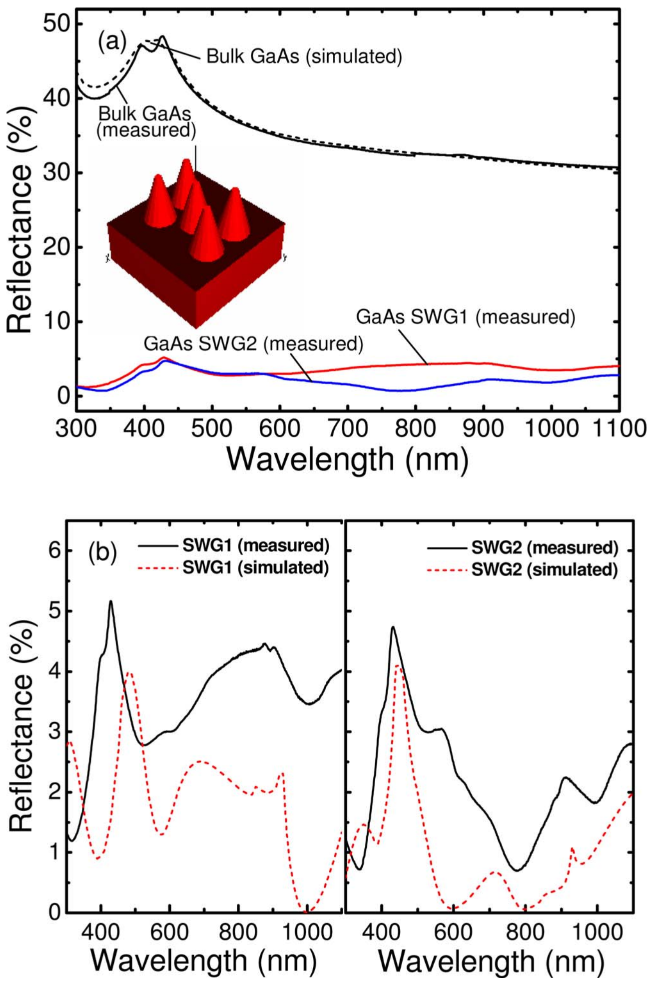

Fig. 4. (Color online) (a) Measured reflectance as a function of wavelength for the fabricated GaAs SWG1 and SWG2 structures. The measured and simulated reflectances of bulk GaAs were shown as a reference. The inset shows an SWG structure with conical profile used in this simulation. (b) Simulated reflectance spectra of the fabricated GaAs SWG1 and SWG2 structures were shown together with measured results.

Fig. 4(a). Although the measured reflectance spectra exhibit slightly higher values than expected ones from the simulation, the trends agree well. It is clear that the SWG2 with a higher aspect ratio has clearly lower reflectance than the SWG1 in visible and near-IR wavelength ranges.

The effect of the cone height, which is related to the aspect ratio, on the reflectance was theoretically investigated. Figure 5(a) shows the contour plot of the variation of reflectance as a function of cone height and wavelength for a 300 nm period of the array. As the cone height is increased, the reflectance tends to decrease. At cone heights above 450 nm, antireflection properties of <0.5% were obtained over a wide spectral range. In the case of optical device applications, however, it is evident that a taller cone

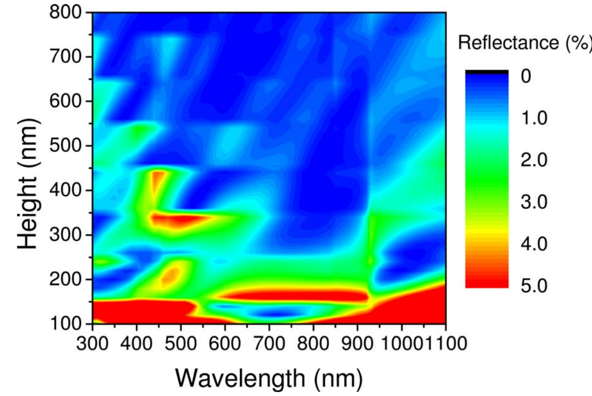

Fig. 5. (Color online) Contour plot of the variation of reflectance as a function of cone height and wavelength for a 300 nm period of the array.

generally requires complex process steps. Hence, for a specific application the cone height should be carefully chosen according to this plot.

In conclusion, we demonstrate closely packed and aspect-ratio-controlled antireflection SWG structures with conical profiles on GaAs using a lenslike shape transfer by a PR reflow process together with RCWA simulation, indicating a good antireflection property in visible and near-IR wavelengths. This fabrication technique is cost-effective and applicable for large areas in specific device applications by optimizing the cone height and the period of array.

This work was supported by the Technology Innovation Program of the Ministry of Knowledge Economy (MKE, Korea).

References

1. S. Walheim, E. Schaffer, J. Mlynek, and U. Steiner, Science **283**, 520 (1999).
2. P. Lalanne and G. M. Morris, Proc. SPIE **2776**, 300 (1996).
3. Y. Kanamori, M. Sasaki, and K. Hane, Opt. Lett. **24**, 1422 (1999).
4. Y. Kanamori, H. Kikuta, and K. Hane, Jpn. J. Appl. Phys. Part 1 **39**, L735 (2000).
5. S. A. Boden and D. M. Bagnall, Appl. Phys. Lett. **93**, 133108 (2008).
6. Z. Yu, H. Gao, W. Wu, H. Ge, and S. T. Chou, J. Vac. Sci. Technol. B **21**, 2874 (2003).
7. C. C. Striemer and P. M. Fauchet, Appl. Phys. Lett. **81**, 2980 (2002).
8. K. Kintaka, J. Nishii, A. Mizutani, H. Kikuta, and H. Nakano, Opt. Lett. **26**, 1642 (2001).
9. P. Nussbaum, R. Volkel, H. P. Herzig, M. Eisner, and S. Haselbeck, Pure Appl. Opt. **6**, 617 (1997).
10. A. Fernandez and D. W. Phillion, Appl. Opt. **37**, 473 (1998).
11. M. Karlsson and F. Nikolajeff, Appl. Opt. **41**, 902 (2002).
12. D. G. Stabenga, S. Foletti, G. Palasantzas, and K. Arikawa, Proc. R. Soc. London, Ser. B **273**, 661 (2006).
13. M. G. Moharam, Proc. SPIE **883**, 8 (1988).