Design of AlN-subwavelength grating for deep ultraviolet wavelength reflector operating at 244 nm of wavelength*

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Abstract

Highly reflective reflector (> 99.9%) operating at deep ultraviolet (DUV) wavelength region around 244 nm was proposed by using subwavelength grating (SWG) patterned AlN substrate. Structural parameters of AlN-SWG were desgined for DUV reflector using the wavenumber dispersion relation of the eiegenmdoes resulting from its periodic refractive index distribution. The electromagnetic field calculated by finite-difference time-domain (FDTD) method revealed the polarization selective reflection characteristics of the designed AlN-SWG, and the SWG can achieve more than 99% reflectivity of p-polarization (the electric field is perpendicular to the grating fingers) at the DUV wavelength of 244 nm. This extremely high reflectivity, polarization selectivity and compactness of our AlN-SWG are very useful for various DUV applications, such as cavity of DUV laser diodes.

Keywords: subwavelength grating, high refractive index, deep ultraviolet, highly reflective mirror, AlN,

I Introduction

Deep ultraviolet (DUV) lights around the wavelength range of 200 nm to 300 nm possess sterilization effect for various bacterium, and the DUV lights have potential for many new generation applications, such as water-purification, food-sterilization, and photo-therapy[1]. For realizing these DUV applications, high efficiency optical elements are essential, for example reflector, polarizer, and focusing lens. Especially, the reflector with high reflectivity is one of most important and fundamental elements for huge areas, such as optical pass control. However, the design of the high efficiency optical elements in the DUV wavelength region are significantly limited because the various materials generally have very large light absorptions. This significantly restricts the development of DUV applications.

Meta-structures, which has subwavelength dimensions, are one of candidates for overcoming the issues and have a great potential for development DUV optical elements with high efficiency. The optical characteristics of meta-structures, such as reflection, transmission and absorption, can be artificially engineered by adjusting its structural dimensions[2,3]. Its tunability of optical characteristic of meta-structures have provided unique DUV applications, high efficiency focusing lens[4], waveguide[5], high reflectivity reflectors[6], and third harmonic DUV light generation[7].

Very recently, C. J. Wu *et al*. experimentally demonstrated 93% reflectivity at the wavelength of 276 nm using porous AlGaN distributed Bragg reflector (DBR), and the reflector improved efficiency of DUV light-emitting diode (LED) and laser diode (LD)[8]. However, the DBR requires 20-pairs to obtain such high reflectivity, and this is laborious for practical manufacturing DUV integration devices.

In this work, we proposed polarization selective high reflectivity mirror at 244 nm wavelength using AlN-based high refractive index contrast subwavelength grating (SWG). Using wavenumber dispersion relation of the eigenmodes resulting from periodic refractive index distribution of SWG, we designed the structural dimensions of AlN-SWG as DUV reflector. The electromagnetic field distributions were calculated by finite-difference time-domain (FDTD) method in order to reveal the reflection characteristics of the designed AlN-SWG. The FDTD calculation results show that the AlN-SWG achieved more than 90% p-polarization (electric field is perpendicular to grating fingers) reflectivity in wavelength range from 230 nm to 255 nm,

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whereas those for s- polarization (electric field is parallel to grating fingers) were typically low (maximum reflectivity is about 60%). In particular, p-polarization reflectivity reached to 99.9% at 244 nm wavelength despite of single layer AlN-SWG with subwavelength thinness. Owing to its high reflection efficiency and its subwavelength thinness, our polarization selective AlN-SWG reflector can contribute for development of DUV integration applications, such as DUV laser cavity.

II Design of AlN-SWG for DUV reflector

Figure 1 shows high contrast SWG for DUV reflector. The surface of AlN substrate was nano-structured.

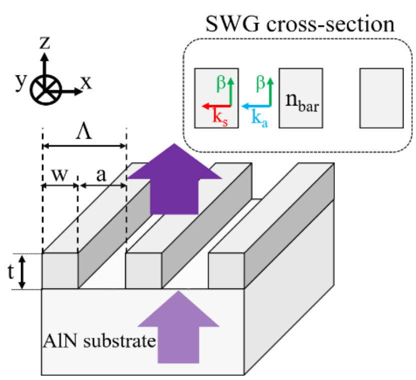

Figure 1. Schematic of AlN-SWG for high reflectivity reflector. The region surrounded region shows cross-section of the SWG.

AlN was selected as SWG material because of its high refractive index value and transparency in DUV wavelength region[9]. In addition, AlN was typically used in DUV emissive devices[1], and it is highly compatible for various DUV devices. The period, thickness, bar width, and air-gap width are represented as Λ, t, w, and a, respectively. In this structure, the incident plane with wavelength λ normally entered from the AlN substrate side. In the SWG region, several order eigenmodes with different wavenumbers can be excited owing to its periodic high index distribution[2,10]. The modes propagate along SWG, and the different phases are accumulated for each modes after the propagations. The modes couples with diffractions in transmitted region, and only 0th diffraction propagates energy of light due to subwavelength period. When the lateral field profile approaches zero at the top boundary of the SWG, 0th diffraction also vanishes because of the electromagnetic field continuity. Thus, the incident light energy is fully reflected back, and this provides extreme high reflectivity. This light control concept using SWG is wavelength independent, because the propagation properties of eigenmodes can be engineered via ratio of wavelength to structural dimensions.

In previous our work, we have controlled the reflectivity and transmittance of the SWG and experimentally demonstrated high efficiency devices in visible (VIS) to ultraviolet (UV) wavelengths, such as highly polarized UV-LED[11,12], UV polarizer[13], and VIS color filters[14]. Thus, SWG can be expected to be powerful tool to realize high efficiency reflector in DUV wavelength, as well as VIS and UV wavelengths.

In order to obtain high reflectivity in DUV wavelength, we designed structural parameters of the AlN-SWG using dispersion relation of wavenumber of the eigenmodes. The x- and z-component wavenumbers of the excited modes are given by following two equations[10].

$$-k_a \tan(k_a a/2) = n_{bar}^{-2} k_s \tan(k_s w/2) \tag{1}$$

$$k_s^2 - k_a^2 = (2\pi/\lambda)^2 \left(n_{bar}^2 - 1\right) \tag{2}$$

Where β, k_a and k_s, are longitudinal (z) wavenumber, lateral (x) wavenumbers in the air-gaps and grating bars, respectively (see SWG cross-section in Fig. 1). In these equations, the n_{bar} is refractive index of AlN for p-polarization and is 1 for s-polarization. The equation (1) and (2) indicate that the period, bar width, and air-gap width determined the z-direction wavenumbers of each eigenmodes. Moreover, the mode's phases after propagation along SWG are defined as factor of βt. Thus, one can control the lateral field profile at the top boundary of SWG by adjusting structural parameters, Λ, w, a, and t. We designed structural parameters of AlN-SWG to obtain high reflectivity at DUV wavelength, and the designed AlN-SWG has Λ = 220 nm, t = 120 nm, w = 80 nm, a = 140 nm, respectively.

III Results and Discussion

In order to estimate the reflection characteristics of the designed AlN-SWG, FDTD field simulation (Fullwave: R-soft Co.) was performed. We considered the infinite length of the model for y-direction, and the SWG infinitely repeats for x-direction. For z-direction, perfect matched layers boundary condition (PML) was employed. No reflections occur at the PML boundaries, and the light outside the boundaries was perfectly absorbed. Thus, the AlN substrate is assumed to infinitely thick. We discretized the calculation region into 4 nm × 4 nm cells. For convergence of the solution, the calculation time step of 9.233×10^{-12} s was employed. The p- or s-polarized plane waves normally enter to the SWG from the AlN substrate side. To evaluate the reflection properties of the designed AlN-SWG, poynting vector of the reflected light were calculated.

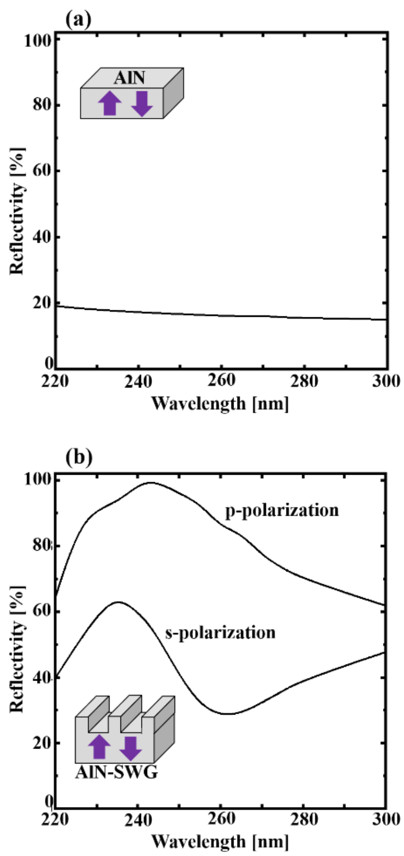

Figure 2. Calculated p- and s-polarization reflectivity of (a) bare AlN substrate (b) the designed AlN-SWG.

Figure 2 (a) and (b) show the calculated reflection properties of bare AlN substrate and the designed AlN-SWG, respectively. In the reflection spectra of bare AlN substrate, we obtain no peak of reflectivity. Also, the reflectivity is independent for the polarization of the incident light, and the reflectivity values are less than 20% around 220 nm to 300 nm wavelengths. Alternatively, AlN-SWG shows the polarization sensitive peaks of reflectivity at different wavelengths. The peaks appear at 235 nm and 244 nm wavelength for s- and p-polarizations, respectively. The p-polarization reflectivity maintains high reflectivity (> 90%) in DUV wavelength region from 230 nm to 255 nm. Especially, 99.9% of extreme high reflectivity is found at the wavelength of 244 nm. For s-polarization, the peak value at 235 nm wavelength is about 60%, and it is not high compared with that of p-polarization.

The results mean that our AlN can operate polarization selective high reflectivity mirror at DUV wavelength region, and its extreme high p-polarization reflectivity and polarization selectivity are very useful for many applications, such as cavity of laser diodes.

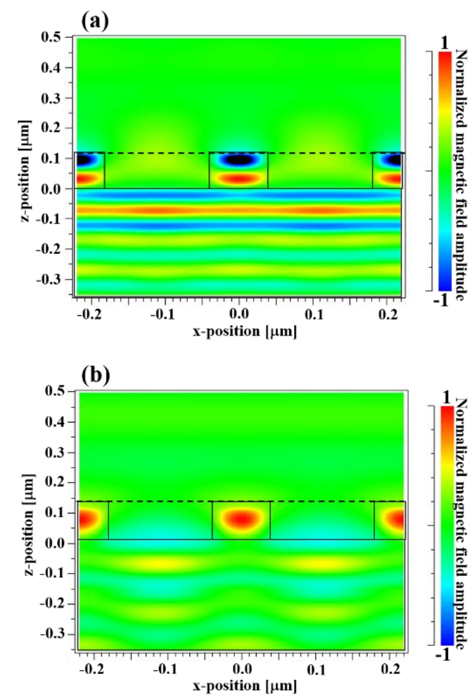

Figure 3. Normalized magnetic field distribution of p-polarization incidence at (a) 244 nm wavelength (b) 300 nm wavelength. The amplitudes were normalized by each maximum values.

In order to provide deep insight of the reflection properties, we depict the magnetic field distributions (p-polarization) around the AlN-SWG at wavelength of 244 nm (high reflectivity) and 300 nm (low reflectivity), respectively. As shown in Fig. 3(a), we can find anti phase field distribution between air-gaps and bars at top of the SWG boundary (dashed lines in Fig 3(a) and (b)), and the cancelation of average fields weakens the transmitted field. As a result, the field profile induces the extremely high reflectivity at 244 nm wavelength. In contrast, the field exists in only grating bars for the wavelength of 300 nm (Fig. 3(b)), and the lateral profiles of the field is not vanished at top of the SWG boundary. The profile cannot provides average field cancelation, and the reflectivity becomes low. The field distributions show good agreement with the reflection properties of AlN-SWG, and reveal the origin of the p-polarization high reflectivity of our AlN-SWG.

IV Summary

AlN-SWG reflector operating in DUV wavelength range was proposed. Using the wavenumber dispersion relation of eigenmodes, the structural dimension of AlN-SWG was designed to realize high reflectivity at DUV wavelength region. The reflection characteristics of the designed AlN-SWG were investigated by FDTD field calculation. The polarization selective reflection characteristics of designed AlN-SWG were obtained, and the extremely high p-polarization reflectivity of 99.9% was found at the wavelength of 244 nm. Also, the calculated field distribution revealed that the cancelation of average field at top boundary of the SWG induced the extremely high reflectivity. The high reflection efficiency and its subwavelength thinness of the proposed AlN-SWG reflector are of great use for development of DUV integration applications, such as DUV laser cavity.

Acknowledgements

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References

[1] H. Amano *et al.*, "The 2020 UV emitter roadmap," J. Phys. D: Appl. Phys. 53(50), 503001 (2020).

[2] Chang-Hasnain, C. J., Yang, W., "High-contrast gratings for integrated optoelectronics," Adv. Opt. Photon. 4(3), 379-440 (2012).

[3] Staude, I., Schilling, J., "Metamaterial-inspired silicon nanophotonics," Nat. Photonics 11(5), 274-284 (2017).

[4] Zhang, C., Divitt, S., Fan, Q., Zhu, W., Agrawal, A., Lu, Y., Xu, T., Lezec, H. J., "Low-loss metasurface optics down to the deep ultraviolet region," Light: Sci. Appl. 9(1), 55 (2020).

[5] Mahmood, N., Mehmood, M. Q., Tahir, F. A., "Diamond step-index nanowaveguide to structure light efficiently in near and deep ultraviolet regimes," Sci. Rep. 10(1), 18502 (2020).

[6] Li, Q., Zhang, Q., Bai, Y., Zhang, H., Hu, P., Li, Y., Yun, F., "Deep-UV hexagonal bron nitride (hBN)/BAlN distributed Bragg reflectors fabricated by RF-sputtering," Opt. Express 11(1), 180-188 (2021).

[7] Ahmadivand, A., Semmlinger, M., Dong, L., Gerislioglu, B., Nordlander, P., Halas, N. J., "Toroidal dipole-enhanced third harmonic generation of deep ultraviolet light using plasmonic meta-atoms," Nano Lett. 19(1), 605-611 (2019).

[8] Wu, C. J., Kuo, C. Y., Wang, C. J., Chang, W. E., Tsai, C. L., Lin, C. F., Han, J., "Deep-UV porous AlGaN distributed Bragg reflectors for deep ultraviolet light-emitting diodes and laser diodes," ACS Appl. Nano Mater. 3(1), 399-402 (2020).

[9] Pastrňák, J., Roskovcová, L., "Refraction index measurements on AlN single crystals," Phys. Status Solidi B 14(1), K5-K8 (1966).

[10] Karagodsky, V., Sedgwick, F. G., Chang-Hasnain, C. J., "Theoretical analysis of subwavelength high contrast grating reflectors," Opt. Express 18(16), 16973-16988 (2010).

[11] Takashima Y., Shimizu, R., Haraguchi, M., Naoi, Y., "Polarized emission characteristics of UV-LED with subwavelength grating," Jpn. J. Appl. Phys. 53(7), 072101 (2014).

[12] Takashima, Y., Tanabe, M., Haraguchi, M., Naoi, Y., "Highly polarized emission from a GaN-based ultraviolet light-emitting diode using a Si-subwavelength grating on a SiO_2 underlayer," Opt. Commun. 369, 38-43 (2016).

[13] Taksshima, Y., Tanabe, M., Haraguchi, M., Naoi, Y., "Ultraviolet polarizer with a Ge subwavelength grating,"Appl. Opt. 56(29), 8224-8229 (2017).

[14] Takashima, Y., Haraguchi, M., Naoi, Y., "Dual-wavelengths filter operating at visible wavelength region using subwavelength grating on waveguide structure," Opt. Rev. 26(5), 466-471 (2019).