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Leading-edge deep-ultraviolet (DUV) technology is studied for fabrication of DBR gratings on InP-based chips. In this work, we present the design of layer stacks of uniform DBR gratings for DUV fabrication and the prediction of how stitching errors in fabricated DBR gratings affect the spectral response. A numerical model based on the transfer-matrix method is utilized to calculate the spectral response of both uniform and non-uniform gratings. We have successfully analyzed the reflection properties as a function of the design parameters of DBR gratings. We have demonstrated that stitching errors in DBR gratings have negligible effect on the reflection spectrum.

1. Introduction

The Distributed Bragg Reflectors (DBR) have been widely used in multi-wavelength and tunable laser sources in the last years[1]. The integration of the DBR gratings in the Indium-phosphide (InP)-based photonic integrated circuits (PICs) has hence attracted considerable attention[2]. However, the fabrication of the DBR gratings on the InP platform requires a grating period of about 238 nm, which is beyond the resolution limit of most conventional lithography techniques. In Bragg gratings, the period Λ is given by the Bragg condition

$$\Lambda = \frac{\lambda_{\mathrm{B}}}{2n_{\mathrm{eff}}}$$

where λ_{B} is the Bragg wavelength and n_{eff} is the effective index of grating material[3]. So far, the e-beam lithography (EBL) has been used to achieve the state-of-the-art performance, which has the drawbacks of high cost and being time consuming [3]. A leading-edge deep-ultraviolet (DUV) scanner with the capability of making feature sizes down to 100 nm with wafer-scale processing, makes itself a good candidate in the integration process for the DBR gratings[3]. The photomask, or reticle, that contains the image to be patterned by the scanner, is fabricated by EBL. Therefore, the stitching errors in the reticles for the DUV scanner, are still a concern. The DUV scanner has a lens system that projects the reticle pattern and reduces the size, typically by a factor 4 to 5. Thus, it also reduces the stitching error by the same factor. On the other hand, the larger reticle pattern area calls for an increased number of writing fields in EBL, which leads to an increased number of stitching errors. Therefore, a study on the effect of the stitching error size and number is necessary.

In this work, we design the layer stacks of uniform DBR gratings for DUV fabrication and evaluate how stitching errors in the fabricated DBR gratings affect the spectral response. A numerical model based on the transfer-matrix method (TMM) is utilized to calculate the spectral response of both uniform and non-uniform gratings. We have successfully analyzed the reflection properties as a function of the design parameters of

DBR gratings. We demonstrate that stitching errors in DBR gratings have negligible effect on the reflection spectrum.

2. Transfer-matrix method

The TMM is a powerful method to calculate the reflectance and transmittance of a multilayer structure[4]. Figure 1(a) is the principle diagram that the TMM is used to solve a uniform grating with a period of Λ and a length of L. The coupling behavior of the Bragg gratings can be described by a set of coupled mode equations[4]. They can be solved by the TMM to a 2×2 transfer matrix F for each period of the grating, which relates the forward- and backward-propagating field amplitudes. The 2×2 transfer matrix T of the entire grating is then obtained by multiplying the individual transfer matrices. The reflection coefficient is calculated by the relation $R = T_{21}/T_{11}$. Figure 1(b) shows the principle diagram of solving a non-uniform grating, which can be regarded as M sections of uniform gratings along the z direction with different periods of Λ_1, Λ_2 to Λ_M and a length of L'. The incident light propagates through each uniform section i that is described by a 2×2 transfer matrix F_i. Similarly, the total transfer matrix T' is obtained by multiplying the individual transfer matrices.

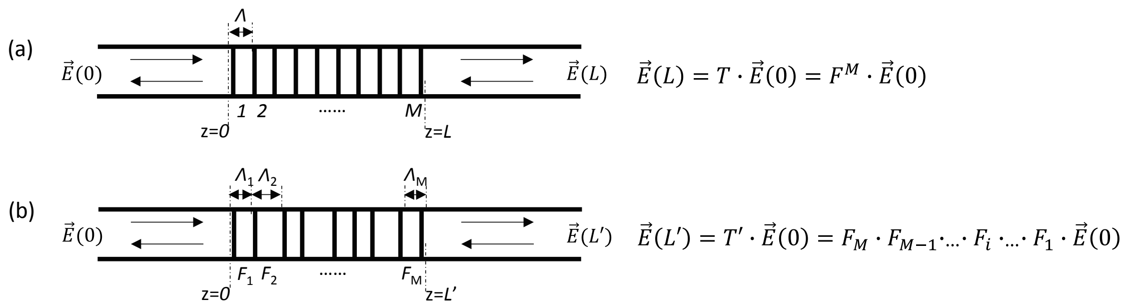

Figure 1: Illustration of transfer matrices of (a) uniform and (b) non-uniform Bragg gratings.

3. Simulations

A schematic picture of the layer stacks of a shallow etched passive waveguide with DBR gratings is shown in Figure 2(a). We use an n-doped InP substrate, a 500-nm-thick Q1.25 waveguide layer, an n-doped InP layer in between the waveguide layer and the grating layer and a p-doped top cladding with a thickness of 1.5 µm. The period (Λ) of the DBR gratings is 238 nm. The thickness of the grating layer (T), the distance between the waveguide layer and the grating layer (D) and the length of the DBR gratings (L) are studied to analyze the reflection properties of the DBR gratings. Figure 2(b) is a contour plot of the calculated coupling coefficient (κ) as a function of T and D. It indicates that the increased confinement factor (Γ) of the propagation light in the grating layer, which is caused by an increased thickness T or a decreased distance D, leads to a higher coupling coefficient κ. Most importantly, T and D can be defined easily in this way for obtaining a certain coupling coefficient in a multi-project wafer run. Calculated reflection spectra, based on TMM, at different κ and L of DBR gratings are shown in Figure 2(c) and 2(d), respectively. It shows the higher κ leads to stronger reflection and broader bandwidth, and the larger L leads to stronger reflection and narrower bandwidth of DBR gratings.

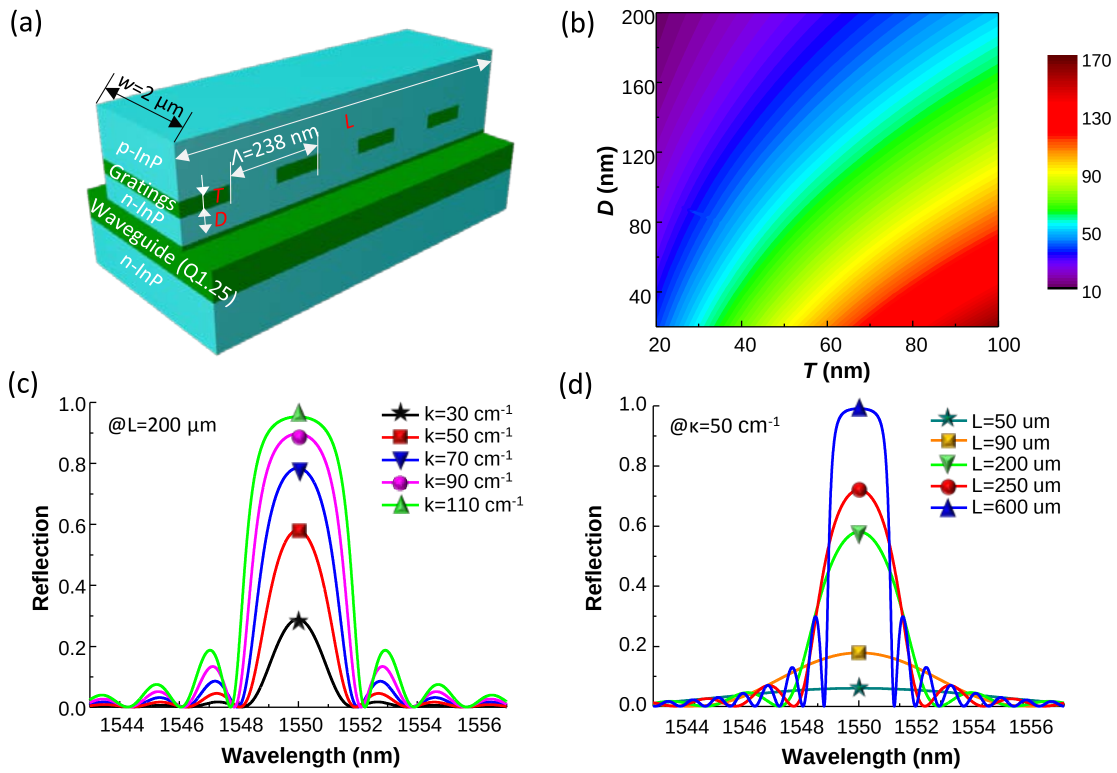

Figure 2: (a) Schematic picture of designed uniform DBR gratings; (b) Contour plot of the calculated coupling coefficient (κ) as a function of the thickness of the grating layer (T) and the distance between the waveguide layer and the grating layer (D); Simulated reflection spectra at (c) different κ and (d) lengths (L) of DBR gratings.

The reticle for the DUV scanner for fabrication of the DBR gratings is written by EBL. In EBL, a large area pattern is divided into smaller writing fields, which are then stitched together by stage movement to generate the large area pattern, as shown in Figure 3(a). However, stage movements cause maximum stitching errors with of ±20 nm for 500 µm main field of the evaluated machine[5]. The DUV scanner (ASML PAS 5500/1100B) has a lens system with 4 times reduction, which leads to a reduction of the stitching error by 4 times to ±5 nm, while increasing the number of stitching errors by a factor 4 as well. First, we evaluate the effect of the location, size and number of stitching errors in a 600-µm-long DBR gratings based on TMM for non-uniform gratings. Figure 3(b) shows the reflection spectra of DBR gratings with stitching errors of $\Delta L = \Lambda/2$, corresponding to a phase shift of π, at different locations $x = 0.2L$, $0.3L$, and $0.5L$, respectively. The π phase shift opens a narrow transmission resonance at central wavelength, which is stronger when the stitching error is closer to the center of the grating. In Figure 3(c), the effect of stitching errors at the center of gratings with different sizes of $\Delta L = 0$ nm, 5 nm, 20 nm and 80 nm corresponding to phase shifts of 0, 0.04π, 0.17π and 0.67π, respectively, is illustrated. It shows that DUV with an accuracy of ±5 nm leads to negligible changes in the reflection spectrum. Further, to investigate the effect of the increased number of writing fields, we calculated the reflection spectrum of a DBR grating with 4 stitching errors of 5 nm at locations $0.2L$, $0.4L$, $0.6L$ and $0.8L$. It shows also negligible change, compared to the ideal DBR gratings, see Figure 3(d).

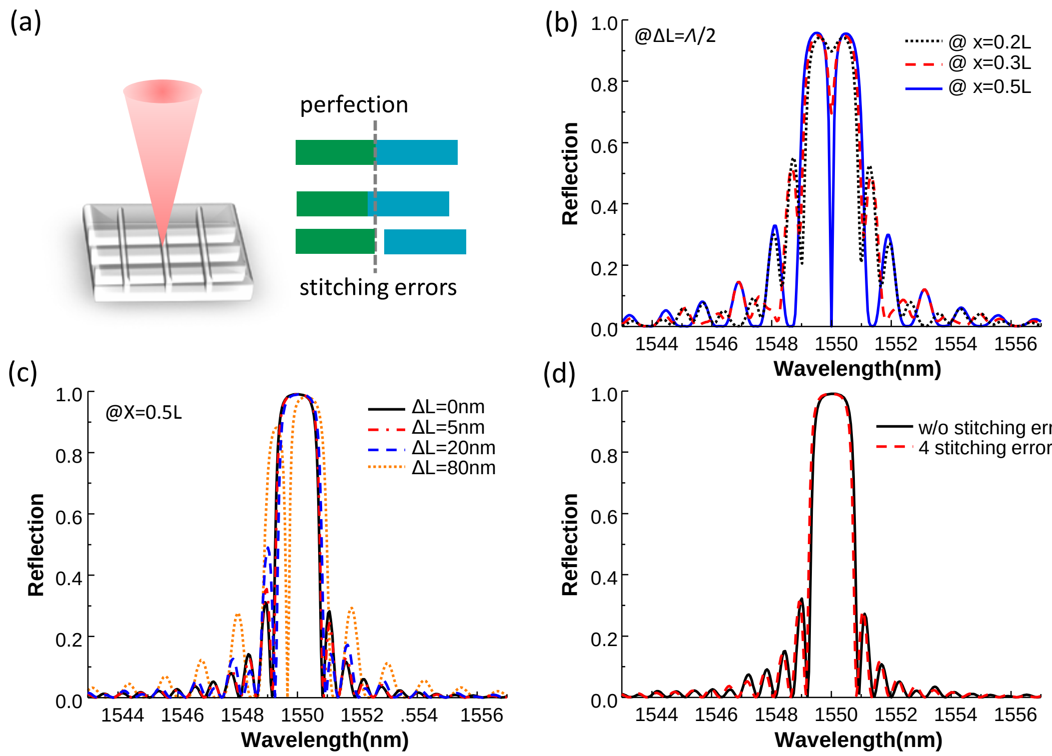

Figure 3: (a) Schematic picture of stitching errors; Simulated reflection spectra with stitching errors at (b) different locations and (c) different sizes; (d) Comparison of reflection spectrum between DBR gratings with 4 stitching errors of 5 nm at locations of $0.2L$, $0.4L$, $0.6L$ and $0.8L$ respectively and an ideal DBR grating without stitching errors.

4. Conclusion and acknowledgement

The reflection properties of DBR gratings are analyzed as a function of the design parameters. Based on the simulation results, the coupling coefficient and grating length can be chosen for a specific application. It is shown by simulation that the stitching errors in DBR gratings by utilizing the DUV scanner have negligible effect on the reflection spectrum. The processing of DBR gratings utilizing DUV and the design of DBR-based circuits are on-going.

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