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journal or publication title	Optics Express
volume	17
number	7
page range	4938-4943
year	2009
URL	http://hdl.handle.net/10097/51954

doi: 10.1364/OE.17.004938

Fabrication and characterization of nanoscale resonant gratings on thin silicon membrane

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Abstract: We report the design and fabrication of nanoscale resonant gratings which is of interest for narrow bandwidth filtering application. The linear/circular grating structures, of which the grating width is 200nm and the grating height is 260nm, are generated on silicon-on-insulator wafer. Nanoscale gratings are fabricated on the silicon device layer by a combination of electron beam lithography and fast atom beam etching. The silicon handle layer under grating region is removed by deep reactive ion etching, and the buried oxide layer is kept. The reflectance measurements are performed to characterize the optical response of fabricated freestanding nanoscale gratings. The resonant behavior of linear gratings agrees with the theoretical predication, and the polarization-independent responses of circular gratings are also experimentally demonstrated.

OCIS codes: (220.4241) Nanostructure fabrication; (050.2770) Gratings; (160.4670) Optical materials.

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1. Introduction

In recent years, considerable attentions have been paid to guide-mode resonant gratings [1-6]. When an incoming beam is grating scattered into one mode of the waveguide, a peak in the reflection spectra and a dip in the transmission spectra can be observed in the guided-mode resonant grating structures. The resonant grating filter is capable of spatial separation of wavelength components with low cost, small size, and high resolution over a specified wavelength range. Sharon et.al. have experimentally demonstrated the grating filters with spectral linewidth smaller than 0.5nm [7], and Fehrembach et.al. have reported a 0.5nm bandpass polarization independent doubly periodic resonant grating filter [8]. Various grating structures, such as asymmetric binary grating [9], bi-dimensional resonant grating [10], and freestanding silicon-nitride grating [11], are fabricated for optical application.

We aim at development of silicon-on-insulator (SOI) based resonant structures. Compared to other material systems, an inherent dual dielectric layer, namely the silicon device layer and the buried oxide layer, can be offered on commercial high-quality SOI wafers. Moreover, the SOI technology makes the fabrication process being fully compatible with microelectronics manufacturing line. Guided resonances in photonic crystal slabs and one dimensional resonant gratings fabricated on SOI wafer have been theoretically and experimentally demonstrated [12,13]. However, the silicon handle layer of reported devices is remained under the resonant structures. Some useful filtering functions, such as all-pass transmission and flattop reflection [14], are limited. And the sidelobe reflectivity is also greatly increased due to the complicated reflection from the silicon handle layer. The freestanding resonant structures, in which the silicon handle layer is removed, not only eliminate the reflection from substrate but also offer free-space optical filtering [15,16]. Since the grating is made of silicon, it can also be integrated with other silicon devices on the same chip.

Here, we demonstrate the design and fabrication of nanoscale resonant gratings on SOI wafer. Nanoscale gratings are generated on 260nm silicon device layer by a combination of electron beam (EB) lithography and fast atom beam (FAB) etching. The silicon handle layer under grating region is removed by deep reactive ion etching (DRIE), and the buried oxide layer is kept. Nanoscale linear/circular resonant gratings are successfully achieved with the grating width of 200nm and the grating height of 260nm. Reflectance measurements are performed to characterize the optical properties of the fabricated resonant gratings.

#103317 - $15.00 USD Received 28 Oct 2008; revised 21 Jan 2009; accepted 12 Mar 2009; published 16 Mar 2009

2. Device design and fabrication

In our work, guide-mode resonant gratings are designed and fabricated on SOI wafers. The optical response is simulated by using the rigorous coupled-wave analysis (RCWA) method [17]. At normal incidence the grating parameters can be designed to control the resonant wavelength and the spectral linewidth. Figure 1(a) illustrates the reflectance of the linear resonant grating structures, calculated by the commercial G-Solver software. The simulation results are based on the nanoscale linear resonant silicon grating structures with the grating filling factor of 0.1 and the grating height of 260nm on 2μm SiO_2 substrate. Resonances correspond to the TM mode (the incoming light polarized perpendicular to the linear surface structure). Based on the model, the resonant silicon gratings exhibit excellent guide-mode resonance behavior. The resonant position shifts to longer wavelength with an increase in grating period (from 1410nm to 1430nm), and the narrow spectral linewidth is high sensitivity to a small change in grating period.

Two types of resonant grating, linear grating and circular grating, are designed and fabricated with various grating periods. For the linear grating structures, off-axis beams exist due to the combination of the incidence wave vector and the periodic corrugation momentum [8,18]. As a result, the resonant peak/dip can be found to split into two parts for oblique incidence [19]. One is above the resonant wavelength of the normal-incidence, and the other is below. To overcome the strong polarization dependence, resonant grating structures composed of multi film layers have been fabricated to generate the polarization-independent resonance [8,20]. The circular grating structures employed here, consisting of the circular rotation symmetry, are proposed to demonstrate the polarization-independent optical property [21,22,23].

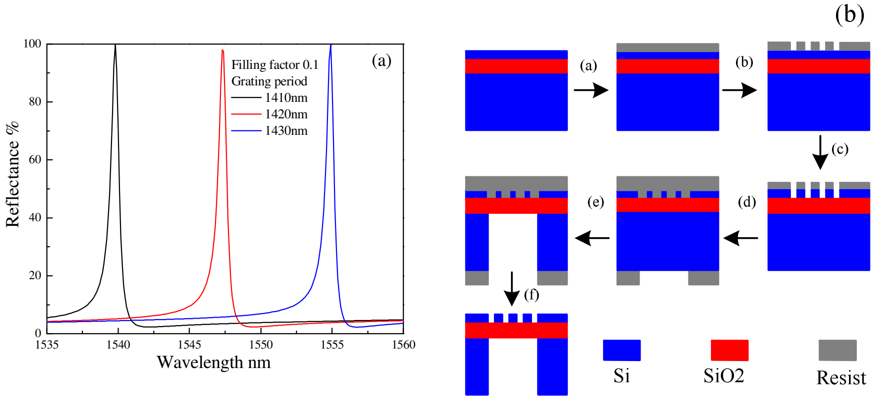

Fig. 1. (a) Reflection spectra (TM mode) of the nanoscale resonant gratings calculated by RCWA. The grating filling factor is 0.1, and the grating height is 260nm. The grating period is 1410nm, 1420nm, and 1430nm, respectively. (b) A schematic of fabrication process for the nanoscale resonant gratings.

The fabrication process is schematically illustrated in Fig.1(b). The nanoscale resonant gratings were fabricated on a SOI wafer with 260nm thick silicon device layer, 2μm thick buried oxide layer, and 200μm thick silicon handle layer. Grating patterns were defined using electron beam (EB) lithography (JEOL EB JBX-5000LS). First, a positive EB resist (ZEP520A, ZEON Co.Ltd.) was spin coated onto the silicon device layer (step a). Resonant grating structures were patterned using EB lithography. After EB writing, the exposed areas of the EB resist were dissolved during development (step b). The grating patterns were generated in the resist as a template, and the silicon device layer was etched by FAB (Ebara FAB-60ML) in step c. The FAB etching was performed with an etching rate of 15nm/min at the high voltage of 2.0KV and the accelerated current of 20mA. Next, the fabricated silicon device layer was protected using thick photoresist, and the silicon handle layer was patterned by photolithography to open a window for DRIE (step d-e). The buried oxide layer acted as an etch stop for DRIE of the silicon handle layer from the backside. After removing the photoresist by O_2 ashing, the nanoscale resonant gratings were generated (step f).

3. Experimental results and discussion

A field-emission scanning electron microscope (FE-SEM, Hitachi S-4500) is used to characterize the fabricated grating structures. Figure 2(a) shows the fabricated linear nanoscale silicon gratings. The compressive stress of the buried oxide layer which is generated by the bonding process of SOI wafer is released to deform the fabricated silicon grating slightly. It's better to ensure the period of the silicon grating by introducing the crossbars. In our work, the support structures are used to divide the large grating area into grating arrays, reliving the residual stress of the buried oxide layer. In every grating array, there consists of 50-period grating with the grating length of 30μm, and the supporting arms have a width of 1μm. The grating period and the grating width are designed to be 1410nm and 200nm, respectively. And the grating height is 260nm, the same as the silicon device layer. Figure 2(b)&(c) show the magnified views of the fabricated linear silicon gratings.

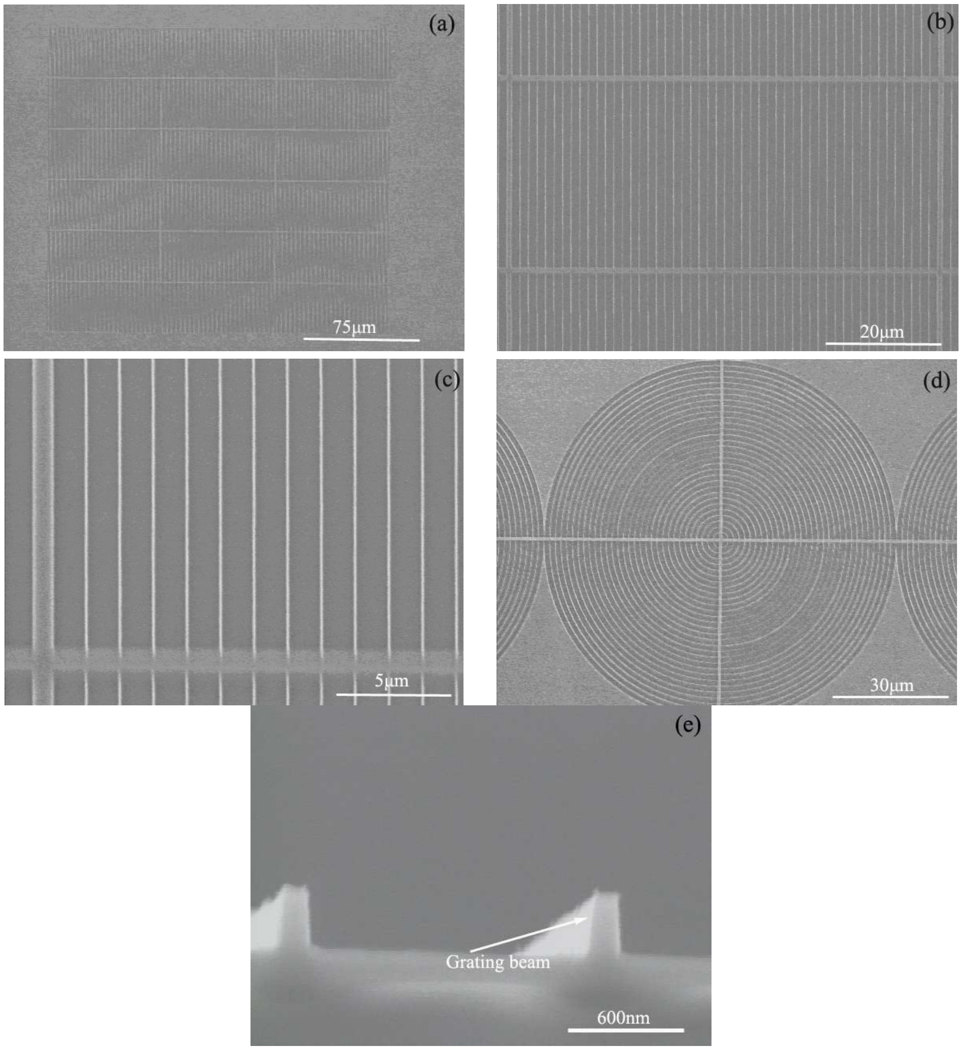

Fig. 2. SEM micrographs of fabricated resonant gratings. (a) the whole image of fabricated linear grating,(b)&(c) the magnified view of linear grating, (d) the fabricated circular grating; (e) the cross sectional image of the fabricated grating on a referenced wafer.

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The circular silicon gratings are also fabricated to benefit from the circular rotation symmetry. Figure 2(d) illustrates the nanoscale circular silicon gratings. The grating period, width and height are designed to be the same as the linear gratings. Cross arms with the width of 800nm are connected to the circular gratings. And circular grating arrays, consisting of 30-period gratings, are employed here to reduce the residual stress. Figure 2(e) illustrates the cross-section of the fabricated nanoscale grating on a referenced SOI wafer.

To investigate the optical properties of the fabricated nanoscale resonant grating, a beam of polarization controlled light from a tunable laser (Agilent 81682A) is used as the light source. The tunable laser operates at a 1460-1580nm range, with a 0.03nm spectral step. The polarized light beam is incident onto the nanoscale resonant grating by an infrared objective lens (Numerical aperture: 0.25), and reflected light is collected and sent to an infrared spectrometer. Figure 3(a) shows the spectral responses of linear gratings measured as a function of the wavelength under the illumination of TM polarized light. The spectral responses of TE polarized light (the light polarization parallel to the grating lines) are not demonstrated here. The reflectance spectra under TE polarization are obtained by rotating the sample with an angle of 90°, and no resonant peaks are observed. The experimentally measured resonant positions are 1505.54nm, 1514.12nm and 1521.89nm for grating period of 1410nm, 1420nm and 1430nm, respectively under TM polarization. The broadening linewidth is observed, the reflectance peak at 1521.89nm, as example, is measured with a full-width at half-maximum (FWHM) of approximately 10.5nm. Figure 3(b) shows the resonant responses of linear gratings with different thickness of buried oxide layer. The reflectance spectra for 1.83μm are used to explain the shifts of the measured resonant wavelength because the thickness of the buried oxide layer is not precise 2μm in reality. For a 1.83μm thick buried oxide layer, the calculated resonant positions are 1511.3nm, 1518.4nm and 1525.6nm for grating period of 1410nm, 1420nm and 1430nm, respectively. An approximately 7nm shift of resonant position is observed in response to a 10nm increase in grating period. Compared to the theoretical model, the measured shift agrees with the simulated data, however, the resonant peaks in reflection spectra shift to short-wavelength, and the linewidth is a little large. The difference is thought to be caused by fabrication errors and design parameters: (1) a little overetching is introduced in FAB etching; (2) thin SiO_2 layer is also etched in DRIE process, and the remained SiO_2 layer is smaller than 2μm; (3) the nonuniformity issues caused by the residual stress of the SiO_2 layer also influence the optical response of the fabricated nanoscale grating; (4) the 30μm long grating beam is a little short and the optical behavior is also affected by the supporting arms. Many of the optical response caused by the fabrication errors and structure parameters are remarkably complicated. The complexity is often a result of deviation from an ideal nanoscale silicon grating, shifting the resonant position and broadening the linewidth.

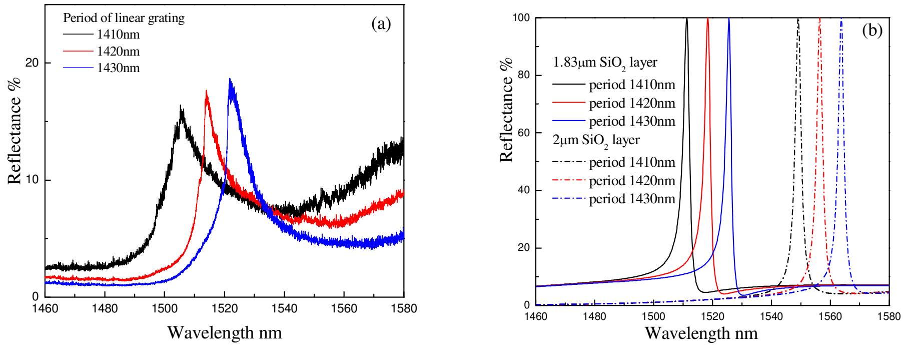

Fig. 3. (a) Measured reflection spectra of fabricated linear gratings versus wavelength; (b) Simulated reflection spectra of linear gratings with different buried oxide layer.

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Theoretically, circular gratings can demonstrate an inherently polarization-independent response at normal incidence due to their circular rotation symmetry. Figure 4 illustrates the spectral responses of circular gratings. The measured resonant positions are 1509.33nm, 1517.18nm and 1523.84nm for grating period of 1410nm, 1420nm and 1430nm, respectively, which are in good accordance with the calculated data well. The corresponding linewidths are approximately 8.5nm, 7.8nm and 6.8nm, respectively. The filling factor decreases with increasing the grating period because the grating widths are all designed to be 200nm. Compared to the data in Fig.4(a), the data in Fig.4(b) are obtained by rotating the sample with an angle of 90°. The resonant positions shift to longer wavelength with an average value of 9.47nm, which may be caused by alignment error in the patterning and measurement. Although the shift of resonant position takes place, the polarization-independent responses of the circular gratings are experimentally demonstrated.

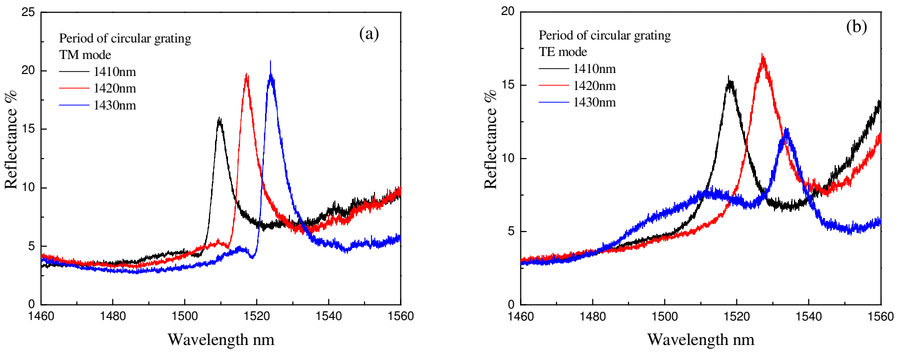

Fig. 4. (a) Measured reflection spectra of fabricated circular gratings versus wavelength; (b) Measured reflection spectra of sample by rotating 90 degree with respect to measurements in Fig.4(a).

5. Conclusion

A SOI process is employed here to fabricate nanoscale resonant grating based on RCWA model. The linear/circular grating structures, of which the grating width is 200nm and the grating height is 260nm, are fabricate on the silicon device layer by a combination of EB lithography and FAB etching. The silicon handle layer under grating region is removed by DRIE, and the buried oxide layer is kept. The freestanding nanoscale resonant gratings are well fabricated, and the reflectance measurements are performed to characterize the optical response of fabricated nanoscale gratings. The resonant behavior of linear gratings agrees with the theoretical predication, and the polarization-independent responses of circular gratings are also first experimentally demonstrated.

Acknowledgements

This work was supported by the Research Project, Grant-In-Aid for Scientific Research (17068002).