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Variable optical reflectance of a self-supported Si grating

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Variable reflectance of a self-supported Si grating mirror is reported. A grating suspended in air consisted of an array of 300 nm wide, 300 nm thick, and 20 μm long beams. The period of the grating was varied with an electrostatic microactuator from 600 to 720 nm. A broadband reflection in the wavelength longer than the grating period was observed, which was caused by a resonant interference of the light wave propagating along the grating similar to the guided-mode resonant gratings. Increasing the period of the grating with a microactuator, the reflection spectrum changed. The results were explained by the theoretical calculations based on rigorous coupled-wave analysis. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2193989]

Diffractive optical elements are widely used for spectroscopy, laser beam scanner, aberration compensation, etc. Due to the progress of fabrication technology in recent years, the researches on the optical elements having the structures smaller than the wavelength of light have been activated. The guided-mode resonant grating (GMRG) has been intensively studied for highly efficient filters.[1,2] A weakly modulated grating generates a very narrow band reflection. On the other hand, strongly modulated gratings overcome the splits of the filtering resonance for angles of incidence.[3] In addition, the strongly modulated grating can have either broad or narrow spectral characteristics. More recently, a broadband mirror has been designed theoretically and demonstrated experimentally using the resonance of the strongly modulated GMRG structure.[4,5] The high reflectance is caused by the resonant interference between the lights leaked from the waveguide grating. This kind of grating is a powerful tool for variable reflection and wavelength selection.

On the other hand, tunable gratings always attract a high level of attention in many research fields. A tunable GMRG was also studied using the optoelectronic effect in active semiconductor.[2,6] Although the tuning is fast, the range for tuning is small (<1 nm). Microelectromechanical systems (MEMSs) are also promising for the control in reflection intensity and wavelength. In the case of the subwavelength grating, a photonic crystal with a microactuator was studied theoretically.[7] However, the variable GMRG with the microactuator has not been studied.

In this letter, a variable GMRG with a microactuator is studied. The GMRG consists of a 300 nm thick self-suspended grating with a variable period from 600 to 720 nm by an electrostatic comb actuator. A broadband reflection has been observed in the red wave region and varied with the increase of the period.

Figure 1 shows the schematic diagram of the proposed variable grating. The proposed device consists of a self-supported subwavelength grating and an electrostatic comb drive actuator. All beams of the grating are connected by the springs at their ends. Pulling the edge of the grating with an electrostatic comb actuator, the grating expands with equal spacing between the grating beams. The area of the grating is 50 μm wide and 50 μm long. (It is divided into four parts in the actual fabrication.) The grating is designed to be 300 nm thick and the period is 600 nm with the beam width of 300 nm under stationary condition. The comb actuator is 450 μm wide, 100 μm long, and 5 μm thick. The gaps between the combs are 4 μm.

The schematic diagram of the grating cross section is shown in Fig. 2(a). A simple rectangular grating is suspended above the Si substrate. The gap between the grating and the substrate is 4 μm, which is equal to the thickness of the SiO_2 layer of silicon on insulator (SOI) wafer. In a conventional GMRG, the grating is patterned on a slab-type waveguide made from a high index material. The indices of the substrate and superstrate are lower than that of the waveguide. In the proposed device, the waveguide is a suspended Si layer, and the cladding layer corresponds to the air. Therefore, it may be considered that the modulation depth of the grating is 100% in the proposed devices.

The reflectance of the grating shown in Fig. 2(a) has been investigated theoretically using rigorous coupled-wave analysis (RCWA). Figure 2(b) shows the reflectance as a function of the wavelength and the grating period. The calculated reflectance is shown in the gray scale. The white and black colors correspond to 100% and 0% reflectances respec-

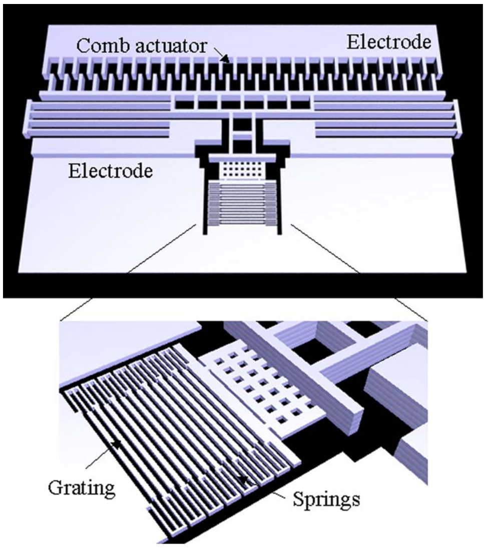

FIG. 1. (Color online) A schematic diagram of a pitch-variable guided-mode resonant grating.

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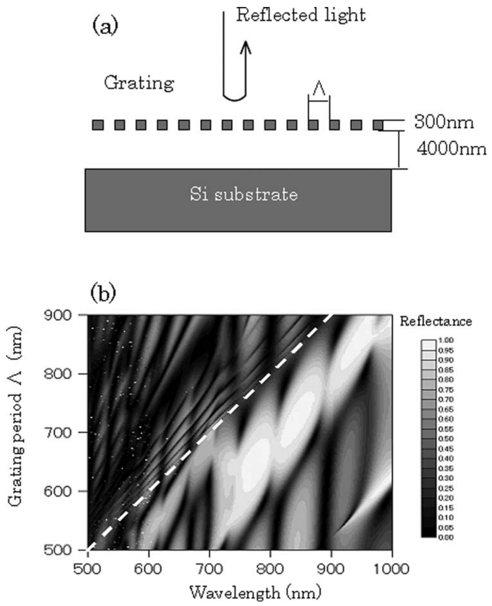

FIG. 2. (a) Cross-sectional model of the grating. (b) Reflectance calculated as a function of wavelength and grating period.

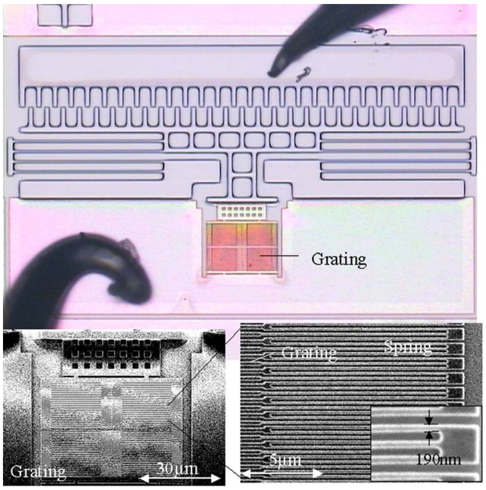

FIG. 3. (Color online) Optical and electron micrographs of the fabricated devices.

tively. The grating period changes from 500 to 900 nm with the duty ratio of 0.5. The grating is assumed to be 300 nm thick and suspended 4 μm above the substrate. Due to the thin Si layer, here, the absorption of Si is neglected for simplicity. The incident light is assumed to impinge normally on the grating with TE polarization.

In Fig. 2(b), it is shown that high reflectance is obtained in a broad subwavelength region, which is the area below a dotted line showing the grating period equal to the wavelength. This high reflectance is caused by the resonance of the strongly modulated GMRG. The broadband reflection by a Si GMRG on a transparent substrate (sapphire) has also been reported in Ref. 3. Compared to the reported results, the broadband reflection is modulated in Fig. 2(b), which is caused by an interaction between the grating and the Si substrate. Assuming that the Si substrate is removed, the continuous broad reflection region appears. The width of the bright reflection region depends on the refractive index of the GMRG. Since the silicon is a high index material (3.8 in the visible region), the broadband reflection appears for the strongly modulated grating. However, if we select carefully the size of the grating beams, a narrow band (<10 nm) reflection can be obtained in a limited region, as shown in Ref. 3. Furthermore, selecting a low index material such as SiO_2, it can be shown that single mode resonance with a narrow band (<20 nm) appears and shifts with the increase of the grating period even for the strongly modulated gratings.[8]

On the other hand, in the region above the dotted line shown in Fig. 2(b), ordinary diffraction is generated. The grating is considered as a thin transmission phase grating to generate the higher order separated beams. Therefore, the reflection in the vertical direction (the zeroth order beam) is smaller in the region above the dotted line.

In the fabrication, a SOI wafer with a 5 μm thick upper Si layer and a 4 μm SiO_2 layer was used. The upper Si layer was etched to make the grating and the comb actuator by reactive ion plasma (STS Co. Ltd.). In the region to form the grating, the upper Si layer was etched to be 300 nm thick by controlling the etching time. Protecting the grating area by photoresist, the rest of the upper Si layer was etched again to implement the comb actuator. After the photoresist was removed, the left 300 nm thick Si layer was patterned by electron beam lithography to become the 600 nm period gratings with a duty ratio of 0.5. A fast neutral atom beam (Ebara Co. Ltd.) was used for etching the grating. Finally the 4 μm thick SiO_2 layer under the upper Si layer was removed by vapor HF. Without using liquid HF, the sticking between grating beams and the substrate was prevented.

The spectral response of the light reflected from the grating was measured by a spectrometer. The fabricated grating was illuminated with white light from a tungsten lamp through microscopic objective (10×, NA:0.25). The light reflected from the grating was collected by the same objective and the central part of the grating was measured by a spectrometer (Ocean Optics Co. Ltd.) through a circular fiber bundle.

Figure 3 shows the optical and electron micrographs of the fabricated device. The 5 μm thick comb actuator is precisely connected with the 300 nm thick grating, as shown in Fig. 3. The grating is self-supported without sticking. The narrowest structure is 190 nm wide at the spring part of the grating. The displacement of the actuator connected to the edge of grating was measured as a function of the applied voltage. The maximum displacement was 11 μm at the voltage of 165 V, and meanwhile the grating period increased from 600 to 720 μm (about 20%). When the grating was expanded by the comb actuator, with the increase of the grating period, the reflected light became weak, but the resonant wavelength did not change.

Figure 4 shows the spectral responses measured as a

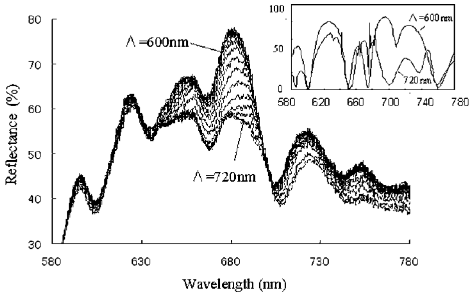

FIG. 4. Reflectance as a function of the wavelength.

function of the wavelength with the grating period as a parameter under the illumination of TE polarized light. Although the intensity of the light source (the tungsten lamp) changed gradually as a function of the wavelength, it was calibrated by the intensity from a reference aluminum mirror to obtain the reflectance. The grating period is varied from 600 to 720 nm with the increase of the voltage from 0 to 165 V by a step of 10 V. A high reflectance of 78% is obtained around the wavelength of 680 nm. The reflectance much higher than the Fresnel reflectance from a flat Si substrate (40% at 700 nm) is obtained. Increasing the grating period, the reflectance peak decreases from 78% to 60%. The reflectance in the region above 650 nm also decreases. In the region lower than 650 nm, little change is obtained, as shown in Fig. 4. It is considered that one of the resonant reflections of the self-supported GMRG is suppressed with the increase of the grating period.

The reflectance calculated by taking the light absorption by Si into account is shown in the inset of Fig. 4. The maximum reflectance is 86% at 695 nm, which is larger than the measured value of 78%. The decrease of the measured reflectance may be caused by the roughness of the grating, which is generated in the thinning process of the Si layer. The roughness was measured for five samples after the thinning process and the average value was 2.8 nm. As shown in the calculated results, in the region from 680 to 730 nm, a large depression of resonance is seen with the increase of grating period from 600 to 720 nm. The calculated results explain qualitatively the measured variation in reflectance.

In this letter, the variable reflectance of the GMRG was first reported. The high reflectance was caused by the guided-mode resonance. Varying the grating period from 600 to 720 nm, the reflectance of the grating was decreased. The characteristics of the grating were analyzed by the numerical calculations based on RCWA. This phenomenon can be used in several variable devices such as laser mirror,[9] attenuators, and equalizers. Especially, variable broadband mirrors can be fabricated in the infrared region since a high reflection mirror without variable function has already been reported in Ref. 5. On the other hand, after further calculations, a narrow band filter with the tunable function can be obtained in the case of the grating made from the low index materials such as Si_3N_4 and SiO_2.[8]

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