Silicon-Nitride Based Micro Optical Components for Optical Pickup Application

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ABSTRACT

The design and fabrication of micro gratings and polarization beam splitters for potential use in micro optical pickups are presented. Silicon nitride is used as the optical material for its low absorption in the visible wavelength. The micro components are framed by a pop-up poly-silicon mechanism as in the standard surface micromachining technology.

The micro grating is a binary phase grating. The diffraction ratio between 4 and 10 can be achieved provided that the duty cycle is between 0.4 and 0.6 and the depth between 455nm and 485nm. For a grating designed for a diffraction ratio of 7, the measured ratio is 8.31.The polarizing beam splitter is a silicon nitride thin film placed at the Brewster angle. The transmittance of the TM mode of a micro polarization beam splitter was measured to be more than 98.50%.

Keywords: *Micro gratings, polarization beam splitter, optical pickup*

1. INTRODUCTION

MEMS-based optical pickups offer many advantages over conventional ones, including small size, light weight, more functionality, and easier assembly and alignment processes. A free-space micro-optical pickup [1] is composed of several optical elements, among which gratings and polarization beam splitters (PBS) play as key components. The grating can be used to split the light into three beams. The 0th order beam is for reading and writing data on the disk, while the ±1st order beams are used for tracking. The PBS splits the light into two orthogonally polarized components, the transverse electric (TE) and transverse magnetic (TM) modes. The TM mode is for reading and writing the data in the disk; while the TE mode is used for monitoring the light intensity.

For optical storage applications, the intensity ratio of the diffraction and main beams of the micro-grating needs to be controlled to within a certain range to meet the servo requirement. The ratio can be affected by the variation of film thickness, and fill factors. Therefore a sensitivity analysis of the fabrication variation is needed in the device design phase to ensure wide processing window and good yield.

In this paper, we present the design, fabrication, and measurement of a micro-grating and a micro-polarization beam splitter. First, bulk micro-machining method was used to make 2 dimensional micro-gratings and micro-PBSs. After the optical performance is characterized, they are combined with poly-silicon frame to make a pop-up type for the future application, the micro-optical pickup system, as shown in Figure 1. It consists of a fiber lens, a micro grating, a PBS, two reflective mirrors, a quarter wave plate and an objective lens mounted in an actuator. The height of the optical axis is about 300 μm. The fiber lens is used to emit collimated laser beam. After the micro-grating, the laser beam is divided into three beams: the main beam is for reading the disc, while the ±1st order beams are for tracking. Next, the laser beams pass through a polarization beam splitter, a quarter wave plate, and the objective lens before finally focusing on the disc. The reflected beams retrace the original path up until they reach the polarization beam splitter at which point they are diverted to the photodiode array.

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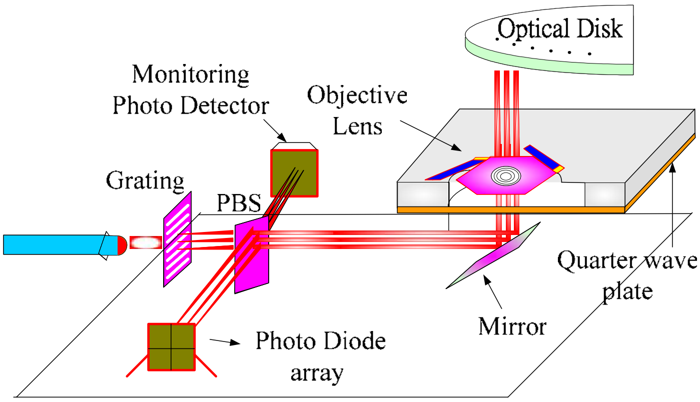


Fig. 1 Micro-machined free-space micro-optical pickup

2. DESIGN AND SIMULATION

2.1 Micro-grating

Consider the one-dimensional lamellar grating depicted in Figure 2. The period, line-width and depth of the grating are denoted by Λ, w and D, respectively. The fill factor, f = w/Λ, is defined as the ratio of the line-width to the grating period. Plane waves are incident normally on the grating supported by a silicon frame. Silicon nitride (refractive index n~2.1 at λ=632.8 nm) is used as the grating material for its low absorption in the visible spectrum. The diffraction angle for the ±1st order beams can be obtained from Λ*sinθ=λ. In the design, the θ is set around 4.35° for λ=632.8 nm, Λ is about 8.35 μm. Λ=8 μm was selected in the design. The diffraction efficiency of the diffraction grating with fill factor=0.5, which has a rectangular shaped section, can be approximated by eqs. (1) and (2) [2].

$$I_{0=}\cos^2[\pi*D(n-1)/\lambda]; \quad (1)$$

$$I_{+/-1}= (4/\pi^2)*\sin^2[\pi*D(n-1)/\lambda], \quad (2)$$

To apply the micro-grating to a micro-optical pickup, however, the ratio of the 0th order and the ±1st order diffraction beams should be controlled to within 4:1~10:1. In the fabrication, however, it is difficult to obtain the precise depth and fill factor. Therefore, a sensitivity analysis for fabrication parameters is necessary. The contour of diffraction efficiency ratio shown in Figure 3 for several values of D and f is calculated by the commercial software, Grating Solver. The diffraction efficiency ratio between 4:1~10:1 can be obtained provided that 0.4<f<0.6 and 455nm < D < 480nm. Since Λ is 8 μm, 0.4<f<0.6 means the target linewidth is 4±0.8μm. The target thickness is 467.5±12.5nm.The values are feasible in the existing fabrication technology.

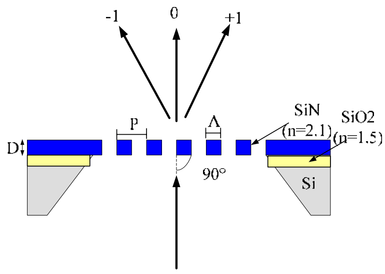


Fig.2 Parameters of the grating for a 90° angle of incidence.

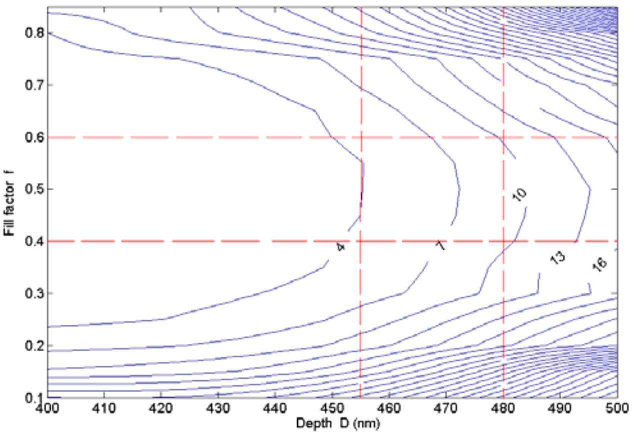
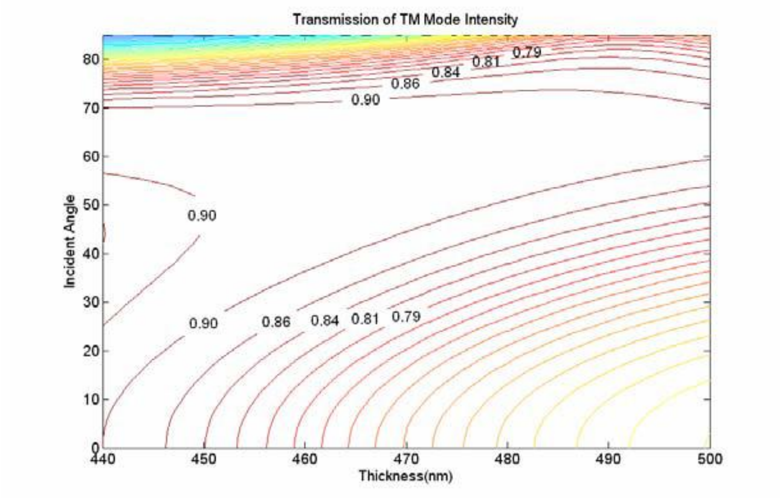


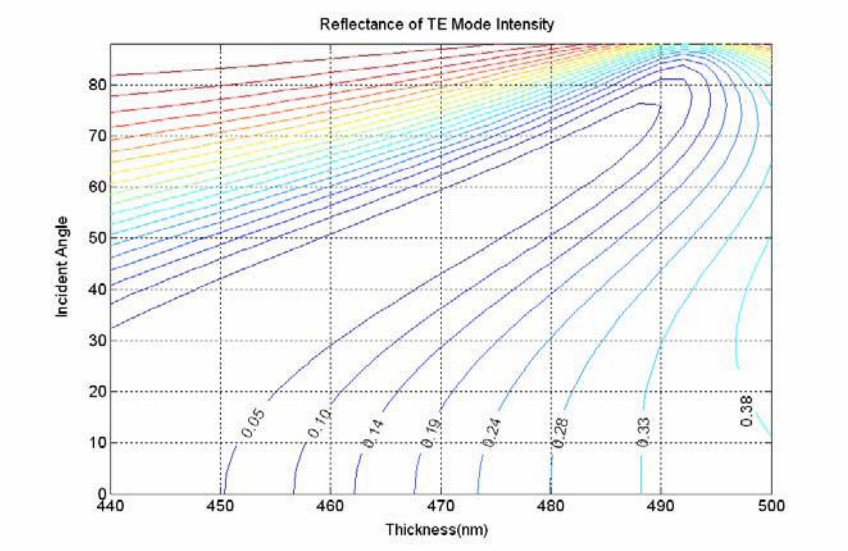
Fig.3 Sensitivity of the diffraction efficiency ratio to the fill factor f and the grating depth D.

2.2 Micro-PBS

In the micro-optical system, the micro-PBS passes the TM mode laser beams straightly through. However, two passes (out and back) through the quarter wave plate rotates the polarization of the return beam to be TE mode and it is reflected by the micro-PBS toward the photodiode array. Therefore the design target of the micro-PBS is to have maximum transmittance of TM mode and detectable reflectance of the reflected TE mode. At the Brewster angle, the TM mode will be totally transmitted, leaving the reflective light to be pure TE mode. The transmitted light is still a mixture of TE and TM mode, yet by choosing a proper thickness z of the thin film, the reflectivity of the TE mode can be easily turned to be the desired value. With an collimated incident light, the reflection (R) and transmittance (T) of a thin dielectric film with refractive index n_f can determined by its characteristic matrix [3]. From this matrix, the transmittance of TM mode is maximum and equal to 1 while the incident angle is the Brewster angle $\theta_B = \tan^{-1}(n_f)$. Simulation shows that the transmissive intensity of TM mode and the reflective intensity of the TE mode are functions of the thickness of SiN and incident angle, as shown in Fig.4 (a) and (b). For refractive index $n_f = 2.1$ at $\lambda = 632.8$ nm, θ_B is about 66°. From 300 to 500 nm wthin $\theta_B \pm 10°$, the transmission of TM mode intensity is larger than 90%, while the reflectance of TE mode intensity varies much with the SiN thickness. In order to fabricate the micro-grating and the micro-PBS in the same fabrication step on the single chip, the thickness target of the micro-PBS is to be 467.5 nm. Under the condition, the reflectance of the TE mode is about 25 %, which is small but still meets the system requirement.



(a)



(b)

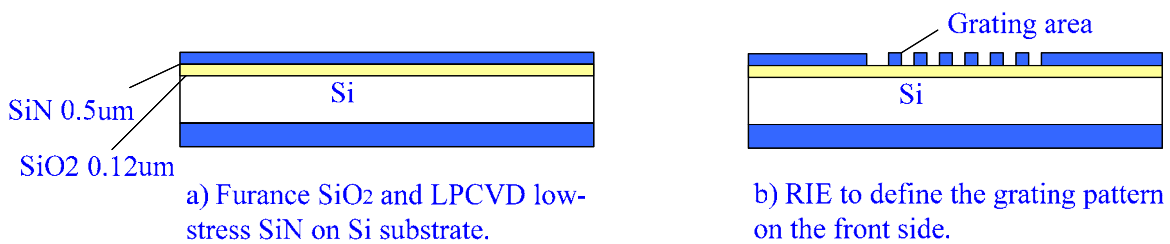
Fig.4 Intensity contours for (a) the transmittance of TM mode, and (b) intensity reflectance of TE mode vs. incident angle and thickness of SiN

3. FABRICATION

To fabricate the devices, bulk micro-machining method was used to make two dimensional micro-gratings and micro-PBS to demonstrate their optical performance. Then surface micro-machining was used to mount the optical components with poly-silicon frames for the pop-up devices.

3.1 Two-dimensional type micro-grating and micro-PBS

The micro-grating was fabricated based on the bulk micromachining technique. The fabrication steps are shown in Figure 5. Firstly, a 0.12 μm-thick silicon oxide and 0.5 μm-thick low stress silicon nitride were deposited on the silicon substrate. The deposition was carried out at 850℃ and 180 mTorr. The flow rate ratio between the dichrolosilane SiH_2Cl_2 (DCS) and NH_3 wa 5. Then RIE was used to pattern the grating. A 0.5um-thick silicon oxide was then deposited by PECVD to protect the front surface. The tension stress in such a silicon nitride layer was about 200 MPa, as calculated from the radius of curvature of a silicon wafer with and without a silicon nitride layer on one of its surfaces. After annealing at 1050℃ for two hours, the stress can be further reduced to below 50 MPa. Then, the backside pattern was defined by RIE and the suspended membrane was formed by KOH back-side etching. Finally, the silicon oxide layer was removed by HF. The size of the micro-grating is 0.35x0.35 mm^2. The fabrication steps for the micro-PBS are similar**.** The difference is that no patterning on the front side of the chip for a micro-PBS was needed. Figure 6 and 7 show the microscopic photographs of a micro-grating and a micro-PBS, respectively.



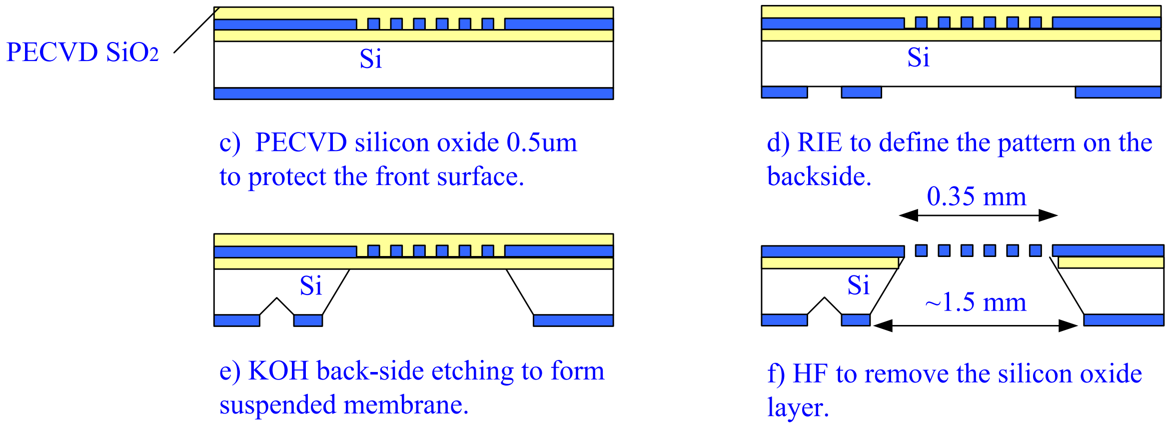


Fig.5 Fabrication process of the micro-gratings

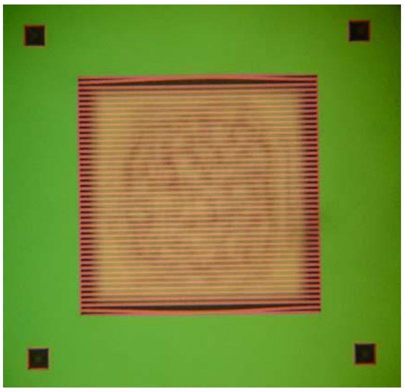


Fig.6 Microscopic photograph of the planar micro-grating

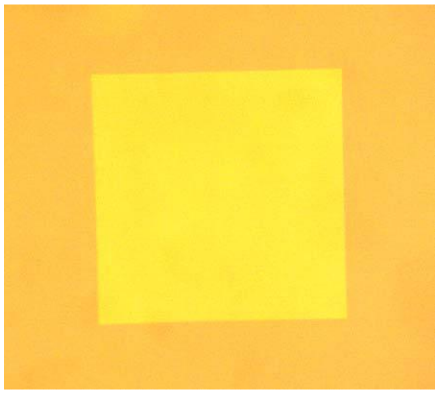
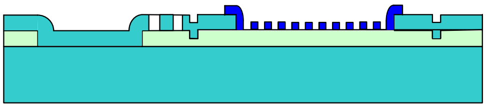


Fig.7 Microscopic photograph of the planar micro-grating

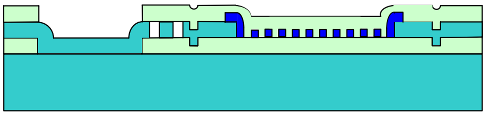
3.2 Pop-up type micro-grating and micro-PBS

The pop-up type micro-grating was fabricated using a two-layer poly-silicon surface micromachining process as shown in Figure 8. The three-dimensional micro-grating consists of a low-stress silicon nitride grating mounted on a poly-silicon supporting frame. The support frame is held perpendicular to the substrate by integrated micro-spring latches. To fabricate the device, a 2-μm-thick PECVD silicon dioxide was first deposited on the silicon substrate as the first sacrificial layer. 0.75-μm-deep dimples and 2-μm-deep anchors were then fabricated in the sacrificial layer (Figure 8a). The first structural polysilicon layer was deposited by LPCVD with a thickness of 2μm. The polysilicon layer was then patterned to form a micro-frame with a 300μm-diameter aperture. After that, a low stress silicon nitride optical layer was deposited, aiming for a thickness slightly greater than the target value. The thickness was further reduced to the target value at the HF releasing step. After the low stress silicon nitride layer was etched to form the micro-grating (Figure 8b), a second 2-μm-thick PECVD silicon dioxide layer was deposited and anchors patterned (Figure 8c). Finally, the second structural polysilicon layer was deposited with a 2-μm thickness. The polysilicon layer was then patterned to implement the micro-spring latches overlapping the micro-frame (Figure 8d). The wafer was annealed for one to two hours at 1050℃ in nitrogen to reduce the residual film stress. After dicing, the structure was released in 49 wt% HF solution. The micro-grating was then lifted to its vertical position by using a micro-probe, (Figure 8e). The fabrication steps for the pop-up micro PBS are similar. The final result is shown in Fig. 9.

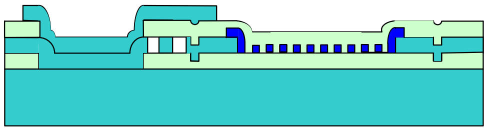
(a) Dimple Etch and Anchor-1 Etch after Silicon Dioxide-1 Deposition



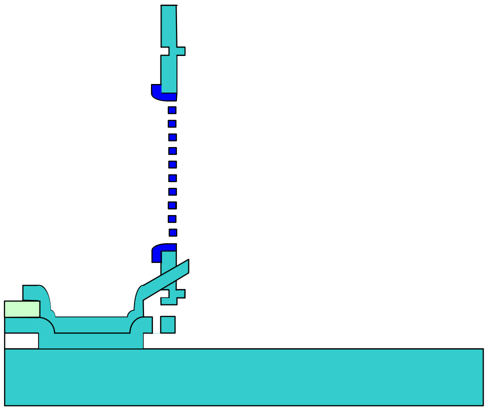
(b) Low Stress Silicon Nitride Deposition and Patterning after Poly-1 Deposition and Patterning



(c) Silicon Dioxide-2 Deposition and Anhor-2 Etch



(d) Poly-2 Deposition and Patterning



(e) Full Release and Assemblying

Fig.8: Fabrication process of the pop-up micro-grating

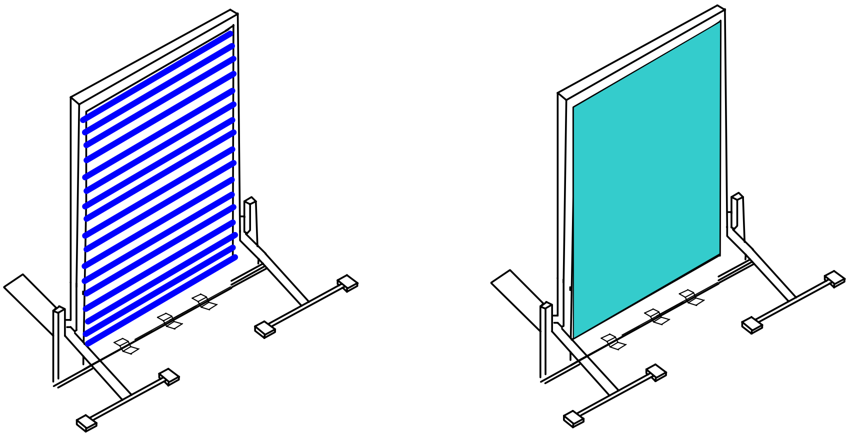


Fig. 9 Schematic diagram of the pop-up micro-grating and micro PBS.

4. MEASUREMENT AND DISCUSSION

4.1 Two-dimensional micro-grating and micro-PBS

To measure the diffraction ratio of the low stress silicon nitride grating, a He-Ne laser at λ=632.8nm was used as the light source. The light from the laser was partially polarized, so a polarizer was used to adjust the polarization until the TE and TM components having equal intensities. Then an aperture with a diameter of 300 μm was used to reduce the beam size to be comparable with the micrograting. The diffracted rays from the grating were then measured by a power meter as shown in Figure 10. The CCD image of the far-field diffraction pattern of the grating is shown in Figure 11. The measured diffraction angle is 4.5°, which agrees well with the theoretical value of 4.53°. The intensity ratios derived from the measurements of the planar micro-grating are listed in Table 1. The depth and fill factor of the micro-grating were obtained in test structures near the micro-grating by using an Ellipsometer and an Atomic Force Microscope (AFM). The diffraction ratios, η, of sample 2 and sample 3 meet the expected specification, 4:1~10:1. The depth of sample 1 is lower than the low limit of the design value. Its diffraction ratio still meets the demand. The deviation from the theoretical values is mainly due to etching rate difference between the test structure and the grating, which led to a depth difference of 5nm per mm in the experiment. In addition, the sidewall and the surface of the grating were roughened during the process, which introduces phase difference and thus impacts the energy distribution of the diffracted beams. The same method was used to measure the intensity ratios of a pop-up micro-grating with depth 480nm and fill factor 0.45. The measured value was 8.31, comparable to the theoretical value, 9.1.

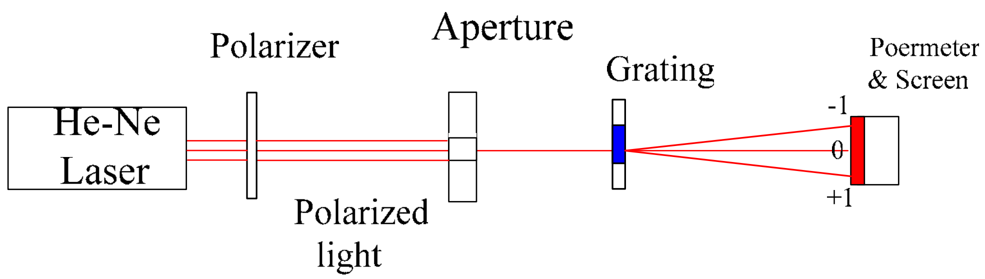


Fig.10 Schematic diagram of the diffraction measurement

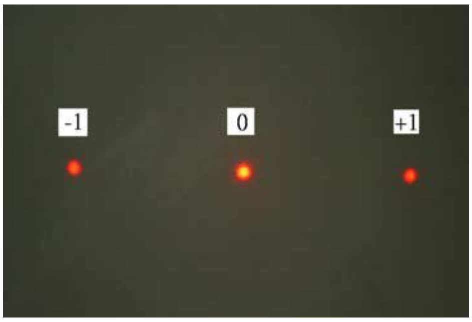


Fig.11 Images of the far-field diffraction pattern of the micro-grating.

Table 1. Optical performance of the planar micro gratings

Sample No.	Measured Depth(nm)	Measured Fill Factor (nm)	Measured Diffraction Ratio	Calculated Diffraction Ratio
1	445	0.43	4.15	2.94
2	455	0.56	5.30	4.14
3	460	0.45	4.08	4.69

4.2 Pop-up micro-grating and micro-PBS

The configuration used for measuring optical properties of micro-PBS is similar to that for the micro grating. A λ = 632.8 nm collimated He-Ne laser beam was directed toward PBS. Under Brewster angle incidence, the transmittance and reflectance of TE and TM mode by a power meter. The measured values with the theoretical values are plotted in Fig. 12. The transmission of TM mode intensity closely matches the theoretical curve. Since the reflectance of TE mode intensity varies significantly with the SiN thickness, more deviation from the theoretical curve are observed for the measured SiN thickness is an average value. Around the thickness target 467.5 nm, reflectance of the TE mode is about 21.4 %.

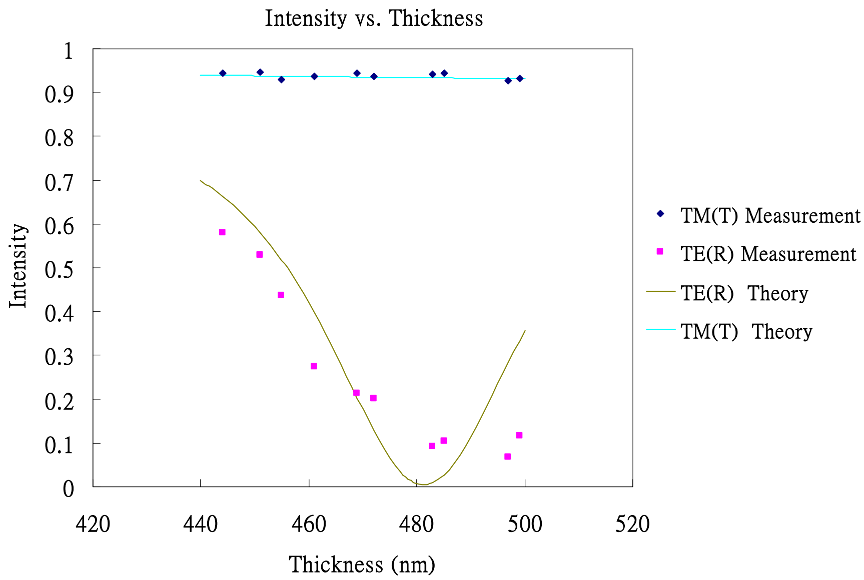


Fig. 12 The measured normalized intensity of TM mode and TE mode for different SiN thickness.

As shown in Table 2, a nearly 100% transmittance of the TM mode can be achieved by a single SiN PBS at Brewster incident angle. The difference between the experimental results and the calculation are mainly attributed to the scattering loss introduced by the surface roughness of the low stress SiN. The same method was used to measure the diffraction ratio of a pop-up type micro-grating with grating depth 480nm and fill factor 0.45. The measured diffraction ratio was 8.31.

5. SUMMARY

Two types of micro-gratings and micro PBSs based on low stress silicon nitride were demonstrated. For the micro-grating, the optical diffraction ratio about 4~5 was successfully observed and agreed with the simulation. Experimental evidence indicated that diffraction can be controlled by the grating depth and fill factor. For the micro PBS, the TM transmission can reach upon 98%, which can be achieved by controlling the incident angle. These results can be regarded as a promising way for optical-MEMS pickup in optical data storage application.

6. REFERENCE

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