Chapter 5

Experimental Results and Discussion

5.1 Introduction

According to the simulation and fabrication presented in the previous chapters, the experimental results will be shown in this chapter. The measurement system used to evaluate efficiencies of light separation will be described first. Then the fabricated planar and pop-up PBS will be shown. After that, the measurement of PBS for 633 nm for DVD and 405 nm for HD-DVD will be performed to make sure if the fabricated membrane and micro-PBS match the design goal.

5.2 Measurement System

The configuration used for measuring optical properties of PBS is depicted. As shown in Fig.5-1, the light from laser is controlled by a density filter to avoid the over- saturation of light. The light is collimated and uniformed after passing through lenses and pinhole-1, and then narrowed by pinhole-2. Under Brewster angle incidence, the transmittance and reflectance of TE and TM modes were detected by a power meters and CCD. To evaluate the quality of the PBS, the polarization extinction ratios σ_T (for Transmission) and σ_R (for Reflection) in the unit of decibel were defined as [10].

$$\sigma_T = 10 \log_{10}\left(\frac{TM_T}{TE_T}\right) \qquad \sigma_R = 10 \log_{10}\left(\frac{TE_R}{TM_R}\right) \tag{5.1}$$

where R_{TE} and T_{TE} are the reflectivity and transmission for TE, and R_{TM} and T_{TM} for TM.

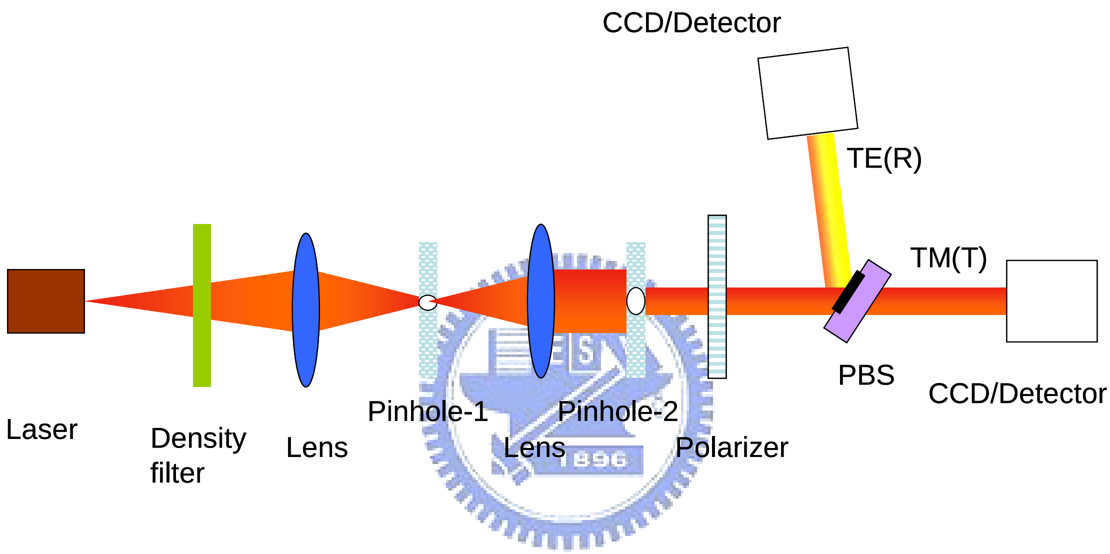


Fig. 5-1 The configuration of the measurement system

5.3 Fabrication results

Two types of micro-PBS were fabricated. One is the planar type, which is easily fabricated and can be used to measure the characteristic of the thin film. The other is the pop-up type. The planar micro-PBS was fabricated in the form of individual windows divided by the scribe lines, as shown in Fig. 5-2. The yield of good windows depends on the dimension, thickness, and quality of the thin film. The thickness of the windows was determined according to the designed optical performance with the dimension of 6×6 mm^2.

The dimension of the pop-up PBS is of 500×600 μm^2. A SiN optical layer with a diameter of 350 μm is mounted in the lifted micro-plate. The thicknesses of the SiN are 410 nm and 536 nm for red and blue ray application, respectively. In the beginning, the thin film was broken due to the stress and the stiction effect, as shown in Fig 5-3. Fortunately, the issue was solved by reducing the stress mentioned before and modifying the fabrication process. The results were shown in Figs. 5-4 (a) and (b). The micro-PBS was perpendicular to the substrate by the micro hinge and limiter. The thin-film PBS integrated with other components was fabricated. The PBS was combined with a grating and two 45°reflectors on a single substrate, as shown in Fig.5-5. Those devices were lifted to its vertical position by micro-probe after releasing. The incident light passing through the grating and PBS would reflect by reflectors. The transmitted TM mode will be reflected into the disk by reflector (1) and the reflected TE mode be reflected by reflectors (2) for monitoring the incident light.

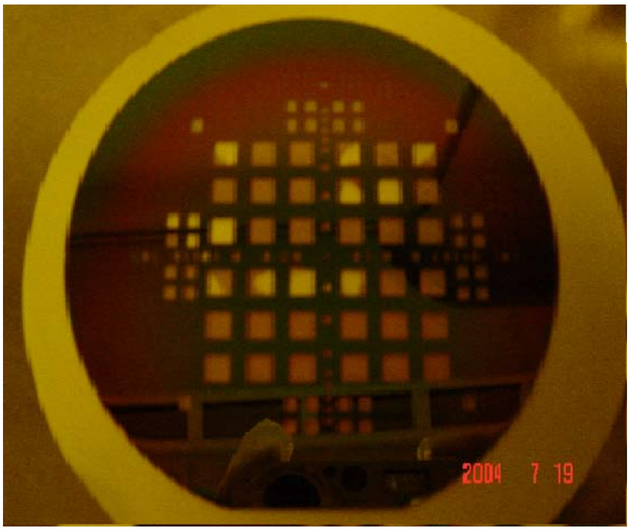


Fig. 5-2 Photograph of planar micro-PBS

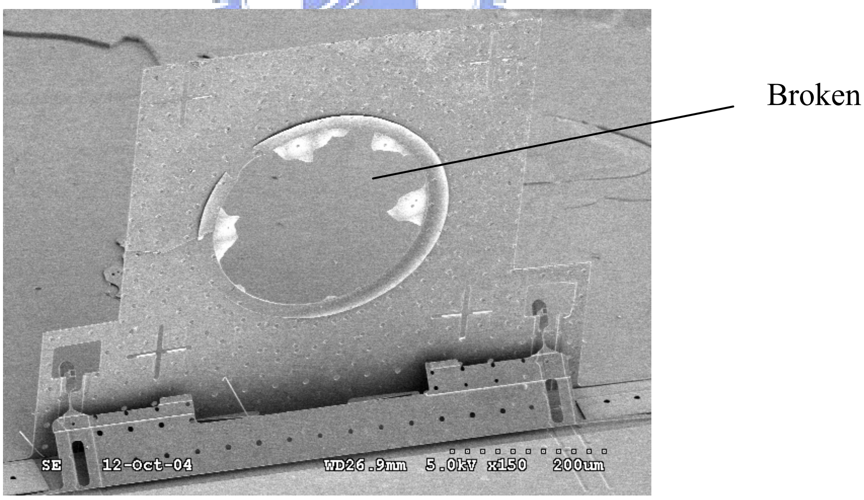


Fig. 5-3 Scanning-electron-microscope photograph of micro-PBS

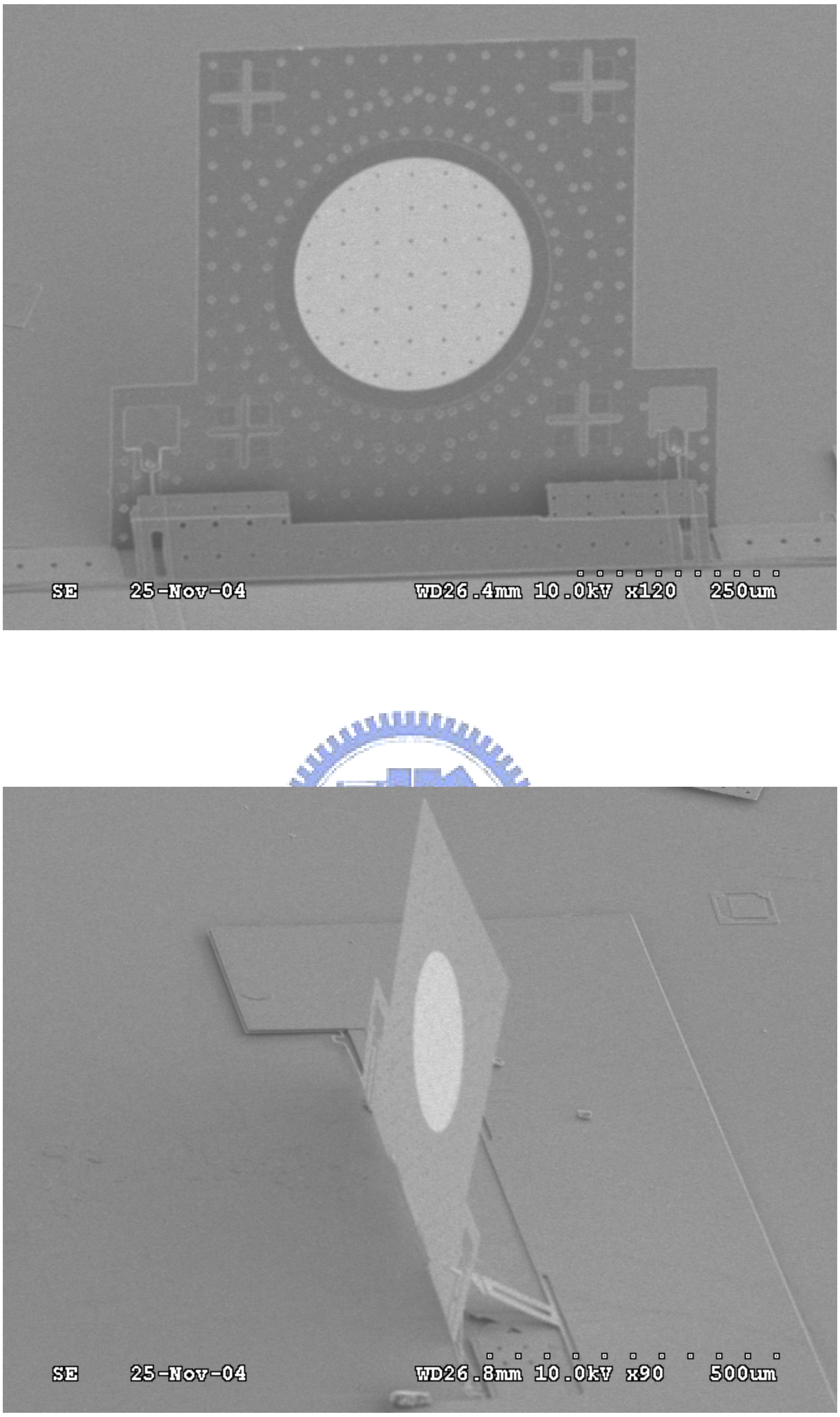


Fig. 5-4 A photograph of micro-PBS from SEM: (a) Front, and (b) Side view.

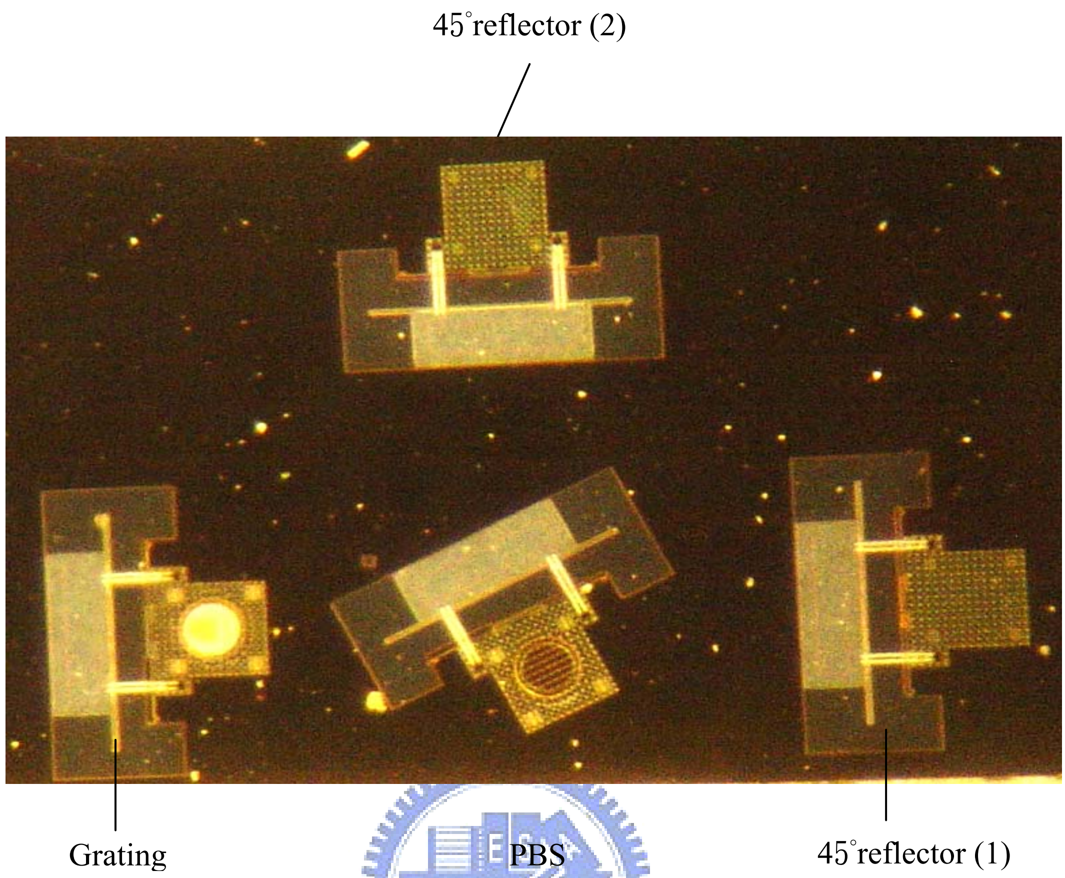


Fig. 5-5 Photograph of micro-PBS integrated with grating and 45°reflectors.

5.4 Measurement results

The experimental results of micro-PBS for red and blue ray application are presented. The optical performances of the SiN membrane are determined by the planar PBS. The beam profile passing through the pop-up PBS captured by CCD is used to verify the real case. The comparisons of experimental and calculated results are discussed, too.

5.4.1 The PBS for DVD

To demonstrate the optical performance of the SiN thin film, planar PBS with dimension of 6×6 mm^2 were fabricated. The transmittance and reflectance of the micro-PBS were measured at λ=632.8 nm using a He-Ne laser as the light source. The results were measured at Brewster incident angle for the deposited thin film of refractive index and absorption coefficient 2.13 and 0.0065. The thickness of the SiN thin film ranged from 390 nm to 420 nm. The transmitted TM mode and reflected TE mode agreed well with the calculations with the average value of 0.94 and 0.8, respectively, as shown in Fig. 5-6. It means the properties of the SiN thin film used for red light agree to the exception. Most of the energy of TE mode is reflected from the optical thin film; while the TM mode almost transmits.

Regardless of the insertion loss, the comparisons between the results proposed by Berkeley [18] and our micro-PBS were summarized in Table 5-1. The reflectance of TE mode of Berkeley is higher than ours; while the transmittance of TM mode is lower than ours. However, the reflectance of TE mode is strongly related to the thickness and can be enhanced by adjusting the SiN thickness. As defined in Eq. (5.1), the reflected light extinction ratio is greatly dependent on the division of reflected TE and TM modes. Similarly, the larger difference between the transmittance of TM and TE modes, the larger transmitted light extinction ratio is. As shown in Table 5-1, the extinction ratios are a little lower than that of Berkeley. The separation between the TM and TE modes of our PBS is not as much as that of Berkeley due to the scattering loss introduced by the surface roughness of the thin film. Besides, the variation of angle caused by measurement is about ±3, consequently, σ_T and σ_R. Even so, the results imply the PBS can separate the incident light into two orthogonal modes effectively.

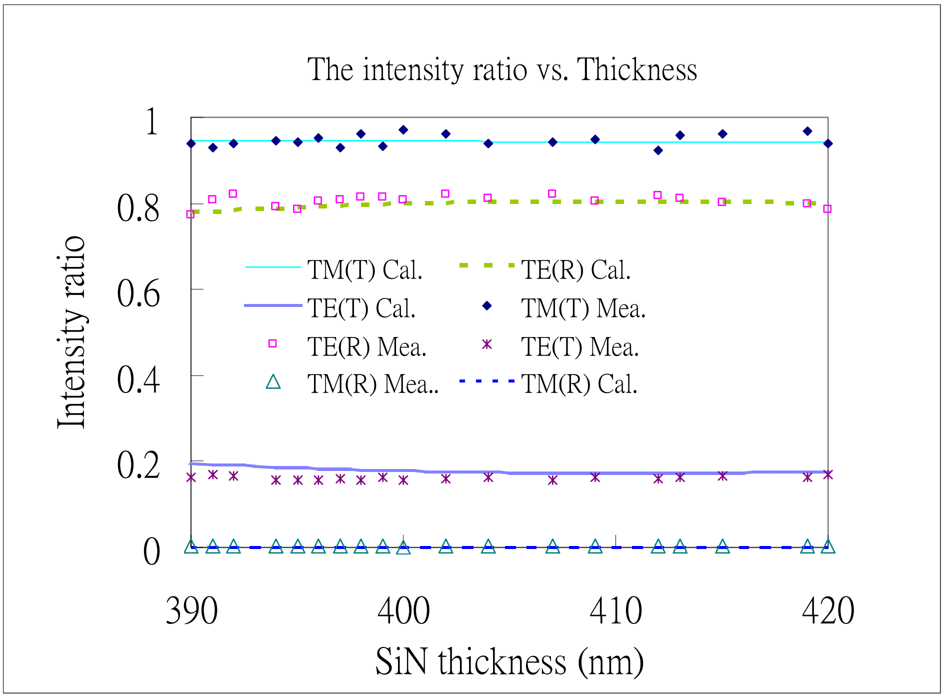


Fig. 5-6 Intensity ratio of TE and TM modes as a function of SiN thickness.

Table 5-1 The comparison of micro-PBS with the results proposed by Berkeley without insertion loss.

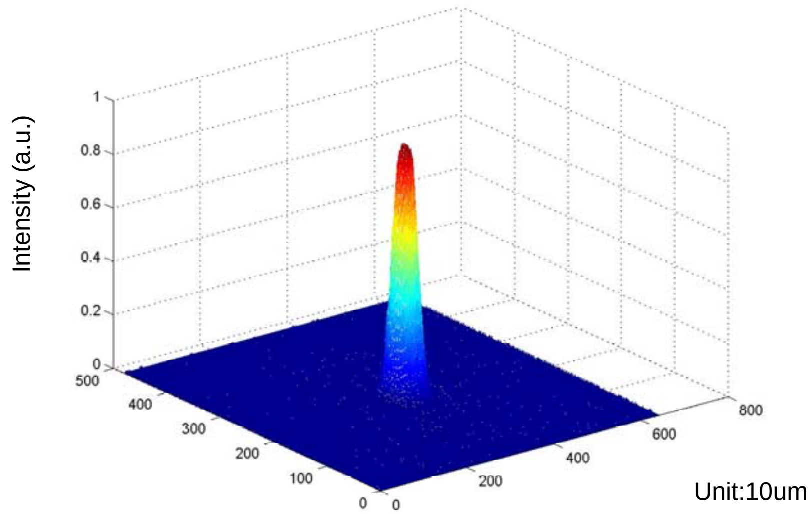
	Berkeley	NCTU
Reflectance (TE)	90.9 %	83.3 %
Transmittance (TM)	99.2 %	99.7 %
Reflected Light Extinction Ratio (dB)	21	20.9
Transmitted Light Extinction Ratio (dB)	10	9.6

For a pop-up micro-PBS with film thickness of 415 nm, the transmittance of the TM mode was measured. The profiles of incident light and the light passing through pop-up micro-PBS captured by CCD were shown in Fig. 5-7. After passing through micro-PBS, the profile changed from circular to arbitrary sharp. The changes of profile mean the energy distribution of the light was affected by the micro-PBS.

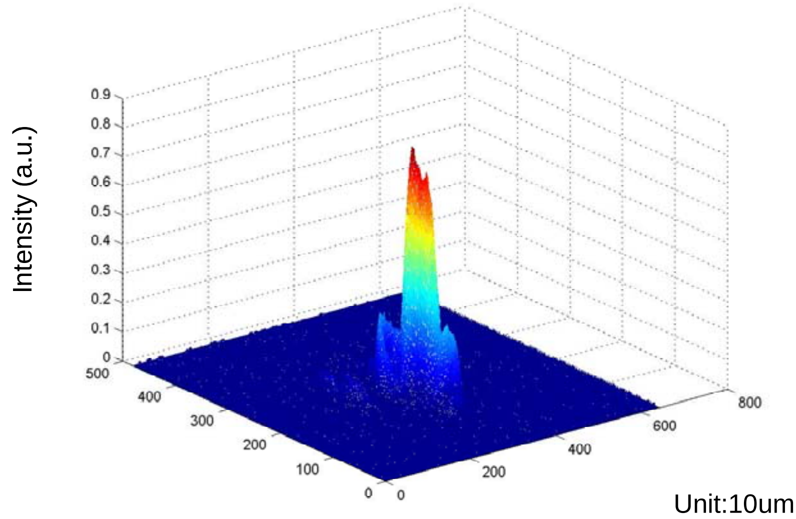
Figs. 5-8 and 5-9 are the profiles analyzed by Matlab. From the cross-section view shown in Fig. 5-9, the Full Width - Half Maximum (FWHM) are about 0.4 mm 0.48 mm before and after the PBS. In addition, the shapes of the beams are different and some noises occur around the main beam. The normalized intensity of the incident light is 0.95 while the light passing through the sample is 0.84. Although there are some deviations from the calculated value of 94 %, the transmitted TM mode of 89 % can be used for reading and writing the data in the disk. Moreover, the results show that SiN thin film can be applied in the pop-up system without changing its performance.

(a) (b)

Fig. 5-7 The beam profile captured by CCD. (a) incident light and (b) the light passing through PBS.

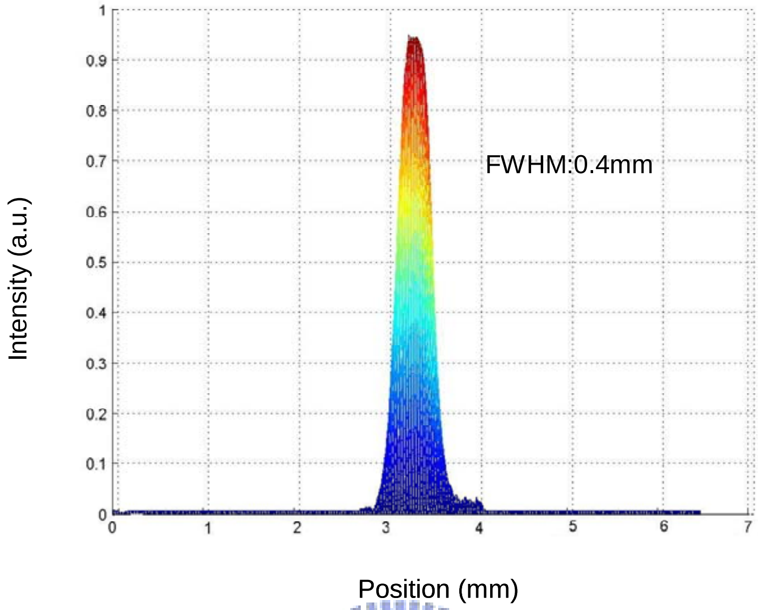


(a)

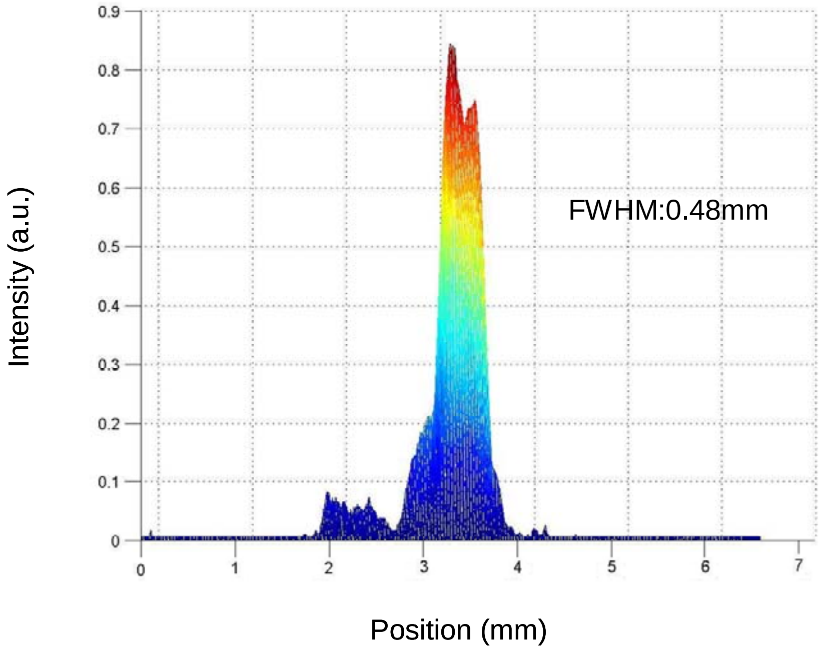


(b)

Fig. 5-8 The 3-D intensity profile of the light. (a) before and (b) after passing through the micro-PBS.



(a)



(b)

Fig. 5-9 Cross-sectional beam profile (yz plane) of the light. (a) before and (b) after passing through the micro-PBS.

5.4.2 The PBS for HD-DVD

The planar PBS was fabricated to demonstrate the optical properties of the SiN for blue ray application. At Brewster angle incidence, the measurement was measured at λ=405 nm using a GaN semiconductor laser as the light source with the thickness varies from 480 nm to 730 nm. As shown in Fig. 5-10, the transmission of TM mode agrees well with the calculation. The transmittance of TM mode depends on the thickness of the thin film. Therefore, it is expected that the transmittance will increase with reduced thickness. The reflectance and the transmittance of TE mode are more sensitive to the SiN thickness compared to the TM mode. More deviation between the calculated and measured can be observed, as shown in Fig. 5-11. The reflectance of TE mode is lower than the calculation due to the curvature of the thin film and the roughness of the surface. Meanwhile, the transmittance of TE mode matches with the calculation.

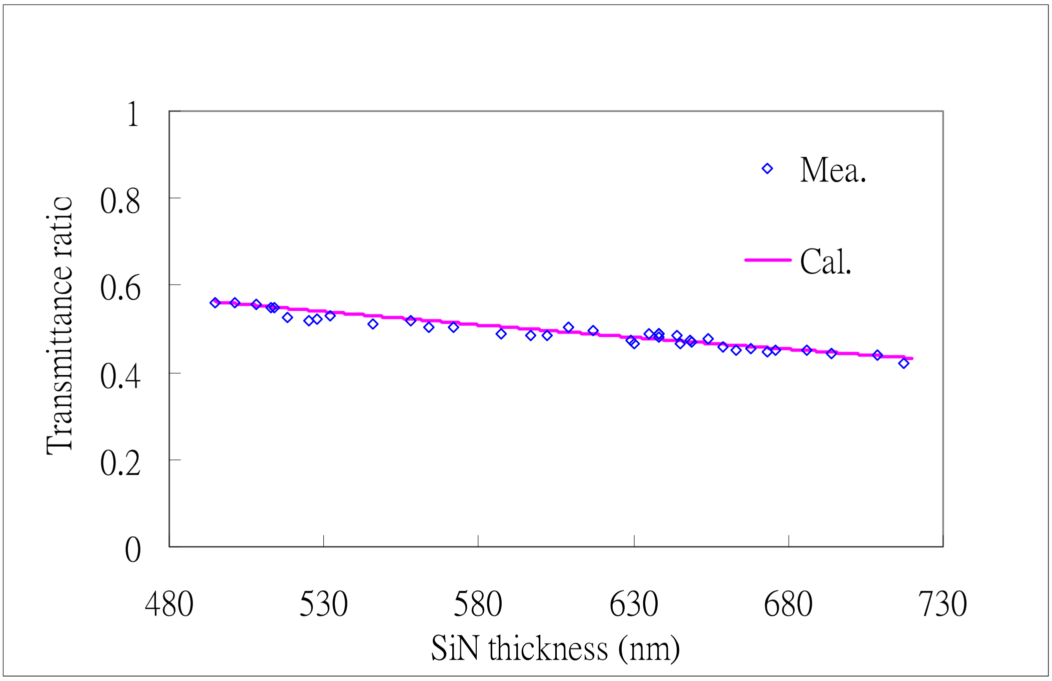


Fig. 5-10 Transmittance of TM mode as a function of SiN thickness.

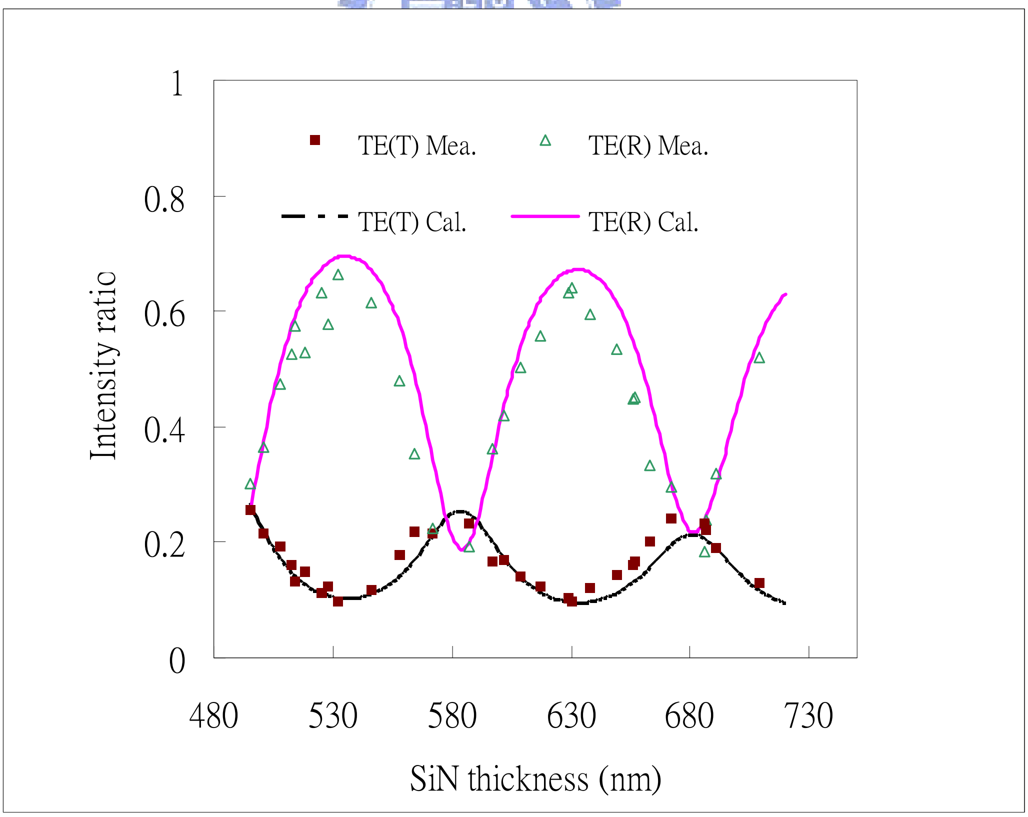
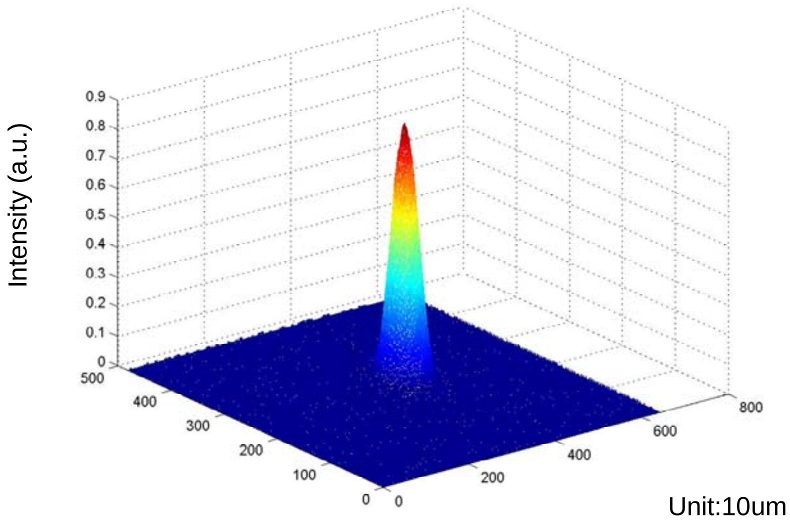


Fig. 5-11 Transmittance and reflectance of the TE mode as a function of SiN thickness.

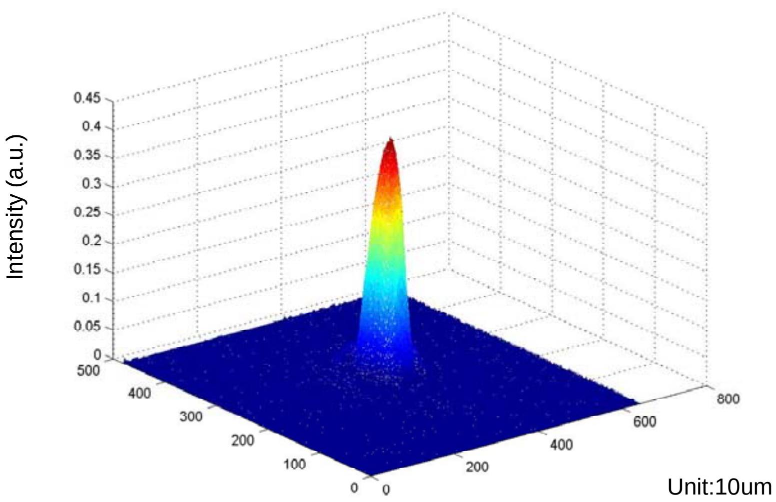
For a pop-up micro-PBS with average film thickness of 488 nm, the profiles captured by CCD and results analyzed with MATLAB are presented. The results are similar to that in red ones, as shown in Figs. 5-12~5-14. The changes of position and noises are related to the quality of the SiN thin film. The similarity between the profiles before and after passing through the micro-PBS means the smoother and flatter surface of the membrane due to the higher tensile stress of the SiN membrane used in blue light. The normalized intensity of the incident light is 0.87 while the light passing through the sample is 0.43. The transmittance of TM mode was 50 %, compared to the calculated value of 56 %. The measured 45~50% intensity attenuation of transmitted TM modes agrees with the calculation using the measured absorption coefficient k from the Ellipsometer. The transmittance of the TM mode through the PBS can be further enhanced by decreasing the thickness while maintaining the mechanical strength of the film. For the micro-optical pickup application, the design target is to have maximum transmittance of TM mode and detectable reflectance of the reflected TE mode. By choosing a proper thickness z of the thin film, the transmittance of TM mode can be easily turned to be the desired value.

(a) (b)

Fig. 5-12 The beam profile captured by CCD.(a) incident light and (b) the light passing through PBS.

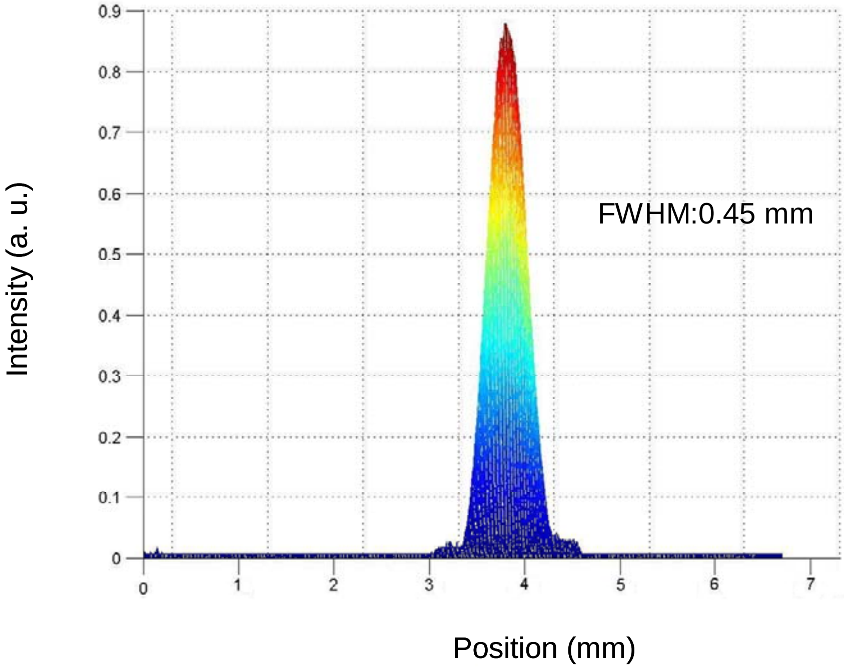


(a)

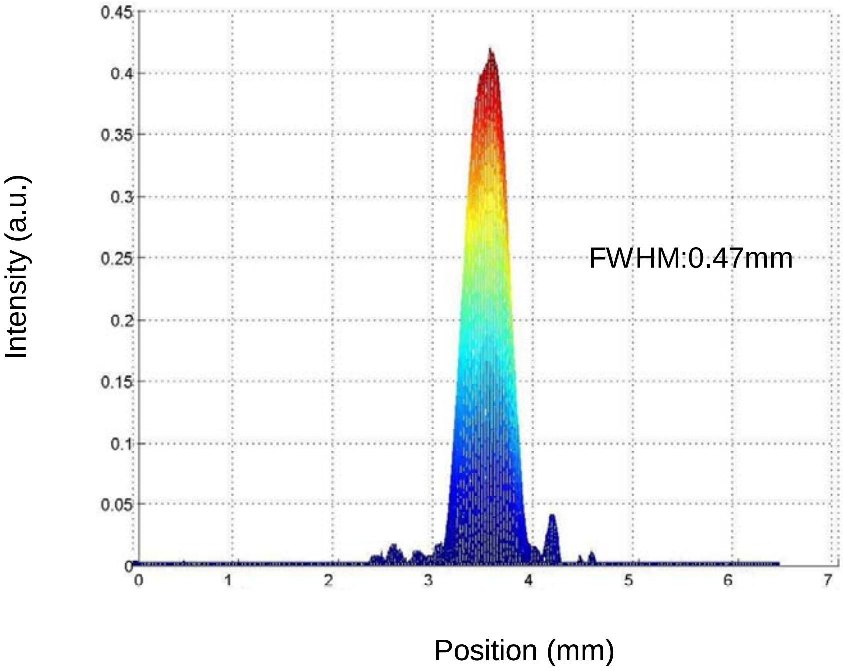


(b)

Fig. 5-13 The 3-D intensity profile of the light. (a) before and (b) after passing through the micro-PBS.



(a)



(b)

Fig. 5-14 Cross-sectional beam profile (yz plane) of the light (a) before and (b) after passing through the micro-PBS.

5.5 Discussion

As we mentioned before, the maximum intensity in the diffraction image is weaker than the incident intensity after passing through the micro-PBS because of the aberrations. It is shown that when a system suffers from a primary spherical aberration that the wave-front in the exit pupil departs from the Gaussian reference sphere by less than a quarter wavelength, the intensity at the Gaussian focus is diminished by less than 20 %-a tolerable loss of light [15]. The intensity decrease by 6.58 % and 37.57 % for red light and blur light, respectively. The aberrations and deviation from the calculation can be attributed to the following reasons. First, light passing through those etching holes and dimples on the SiN membrane shown in Fig. 5-15 will affect the extinction ratio. In addition, the roughness caused by deposition and etching and measured by AFM (atomic force microscopy) as 13 nm (root-mean-square value) will cause the difference of optical path and results in the aberration accordingly. Second, due to the existence of stress, the curvature of the SiN membrane shown in Fig. 5-16 is not infinite, which is a major cause of the aberrations as well. Third, the angle between the PBS and the substrate deviates slightly from 90 degrees, which would affect the incident angle, as shown in Fig. 5-17.

The performance of SiN thin film used for blue ray can be further enhanced by improving the stress and absorption issues. In addition, the aberrations can be reduced by solving the curvature of the thin film. Therefore, some solutions are proposed to solve these issues. About the stress issue, a sandwich structure of oxide/ nitride/ CVD-oxide (ONO) method [25] by modifying the process flow is developed for stress reduction, where a lower SiH2Cl2 to NH3 ratio of 3 can be used to reduce the absorption. As a result, the transmittance of TM mode and reflectance of TE mode can be improved to be about 87 % and 64 %, respectively. Based on the aforementioned process and parameters, the current fabricated pop-up PBS can easily integrate with other components on the Si substrate, as displayed in Figs. 5-18 and 5-19. After releasing, the oxide layers are etched away and the SiN is mounted between the poly-silicon plates. Moreover, the extinction ratio can be further improved by using double structure. From the calculations, although the transmittance of TM mode of 81.82 % is slightly lower than single layer structure, the reflectance of TM mode can be improved to be about 95 % by the double layers structure. In addition, integrating the thin film technology with SOI wafer is expected to solve the curvature issue, as shown in Fig. 5-20.

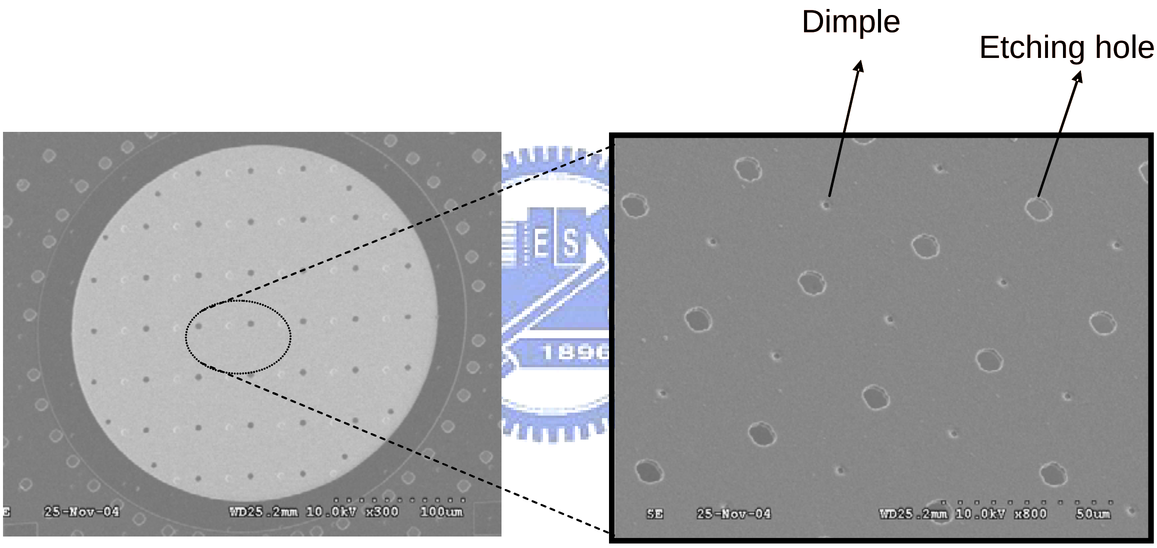


Fig. 5-15 The SiN thin film. (a) mounted in the poly-silicon plate and (b) enlarged picture with dimples and etching holes.

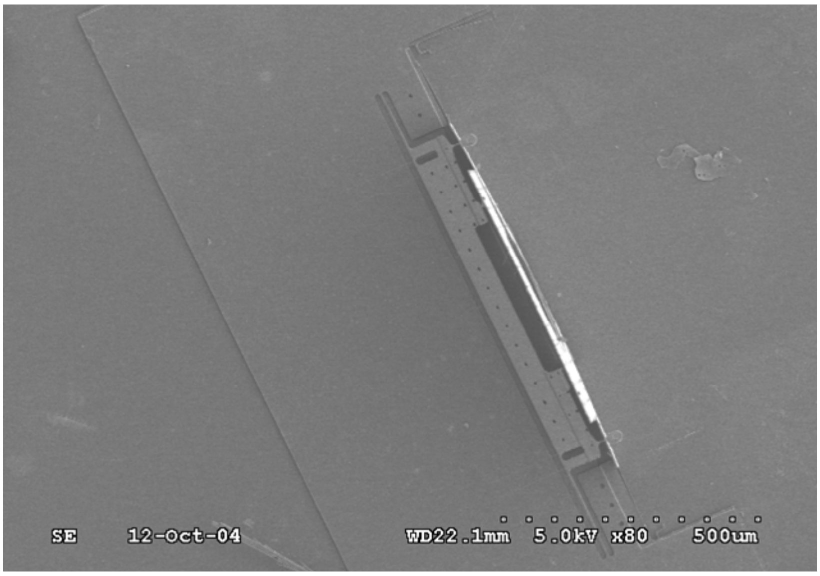


Fig. 5-16 The micro-PBS with curvature.

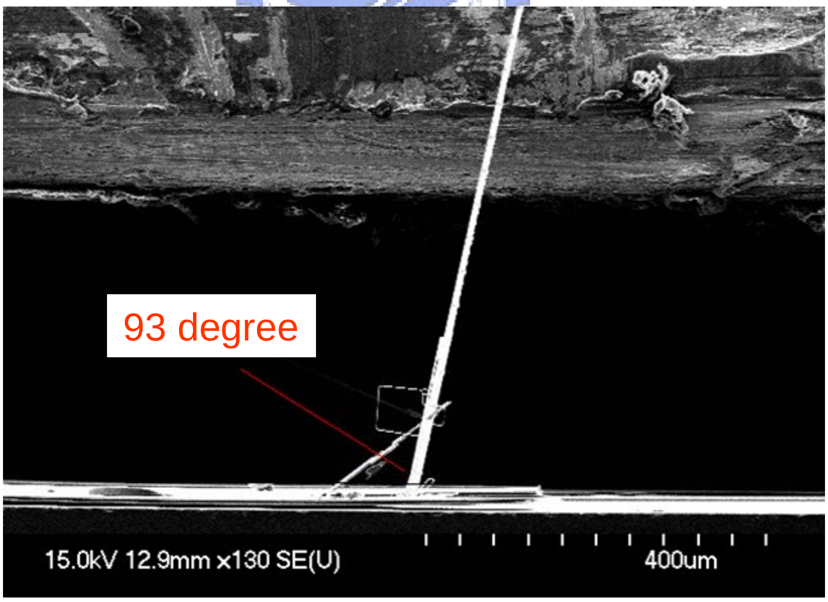


Fig. 5-17 Angle between the micro-PBS and the substrate.

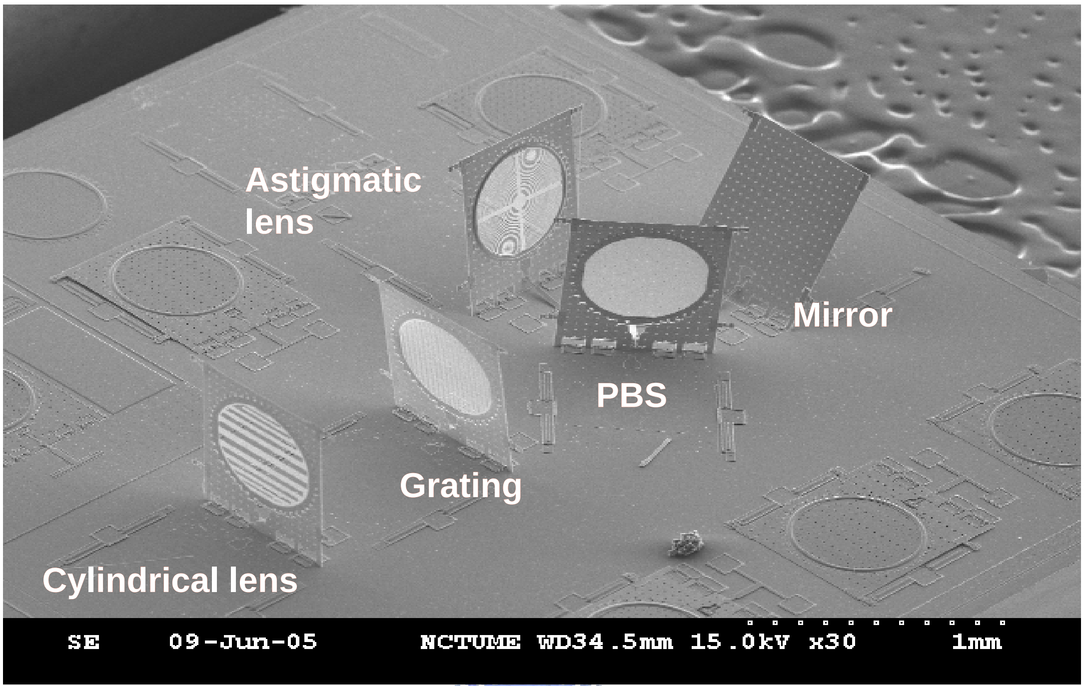


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Fig. 5-18 The other components integrated with the pop-up micro-PBS.

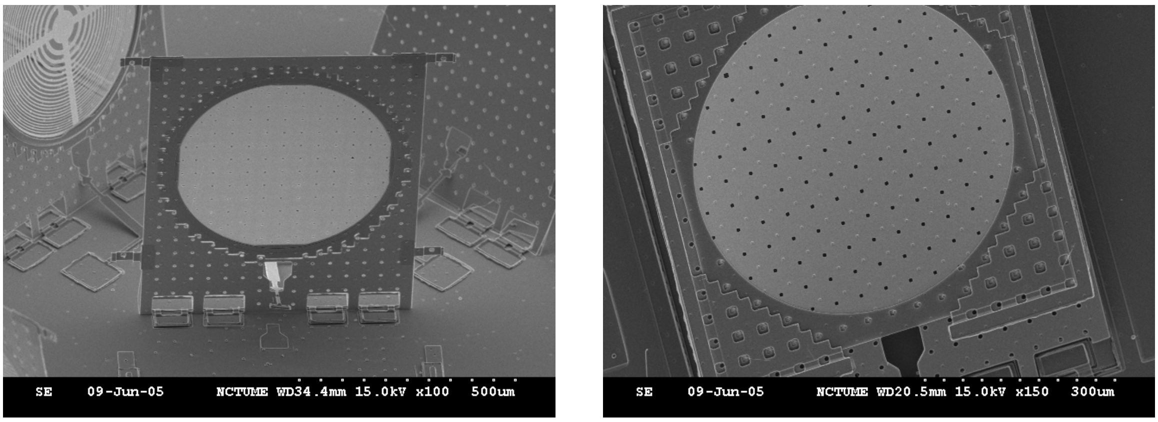

Fig. 5-19 The micro-PBS with modifying process. (a) the front view and (b) the enlarged view.

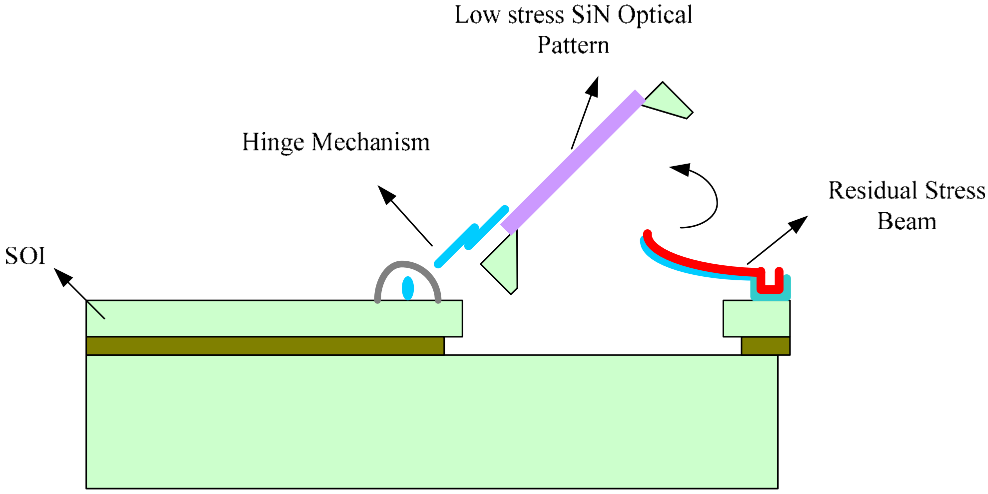

Fig. 5-20 The PBS integrated with the SOI wafer.

5.6 Summary

A nearly 100 % transmittance of TM mode and 84 % reflectance of TE mode can be achieved by a single SiN PBS at Brewster incident angle for red light without considering the insertion loss. With absorption coefficient k=0.0065, the transmittance of TM mode are 94 % for planar PBS and 89 % for pop-up PBS, respectively, which are useful for the optical system. In addition, the near low stress SiN was demonstrated to have acceptable transmittance and reflectance for both of TM and TE modes in blue spectra. The difference between the experimental results and the simulation are mainly attributed to the scattering loss introduced by the surface roughness and curvature of the low stress SiN. The performance of the SiN thin film can be further improved by modifying the fabrication process and the parameters.