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EXPERIMENTAL STUDY OF DIFFRACTIVE PROPERTIES OF WAVELENGTH-SIZED SINGLE GROOVE IN Si-Si_3N_4 SUBSTRATE

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Experimental results are presented for the diffractive properties of wavelength-sized single groove in Si-Si_3N_4 substrate. The experimental results show that the diffraction of wavelength-sized single grooves in a non-perfectly conducting material is more complex than that of perfectly conducting material. The diffraction intensities change with the change of polarization angle of the incident light. The diffraction intensities for TM polarization light are larger as the groove width is larger. The diffraction intensities of TM polarization light decrease gradually and that of TE polarization light increase gradually when the groove width is close to the wavelength of the incident light. The variations of diffraction intensities are quite different not only for various grooves with different widths but also for different diffraction angles for the same groove. Although the intensity variation of each diffraction order has a very regular sinusoidal dependence on the polarization angles of the incident light, the variation phase of each diffraction order is not all the same.

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I. INTRODUCTION

It is generally thought that conventional physical optics is inappropriate for dealing with the diffraction problem of microstructures having dimensions smaller than the wavelength. The diffraction theory is not quite clear for wavelength-sized microstructures. Although much work[1−3] has been carried out for the case of a transmitting slit in a perfectly conducting film, but relatively few works appeared on grooves in a non-perfectly conducting material. Some experimental results[4,5] about diffraction and scattering of microstructures are quite interesting but they did not give more information because the polarization angle of the incident light was unchanged. We have reported the experimental study of diffractive properties of wavelength-sized single grooves coated with gold film.[6] In the present paper we report the experimental study of diffraction properties of wavelength-sized single grooves in Si-Si_3N_4 substrate. The experiments show that the diffraction of wavelength-sized single grooves in a non-perfectly conducting material is more complex than that of perfectly conducting material.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 1, that was used in our previous work [6]. A CW CO_2 laser produced a maximum of 8 W of TEM_{00} power on the P20 line and had good P polarization. The output from the CW CO_2 laser was chopped at 35 Hz before impinging on the single groove, the angle of incidence being 0°. The detector was a pyroelectric probe of width 150 μm and length 10 mm. There was a deviation of about 2° between the incident light and the reflected ray from the sample. The plane of polarization of the laser radiation incident on the groove could be rotated by means of a zinc selenide half wave plate between the laser and the sample.

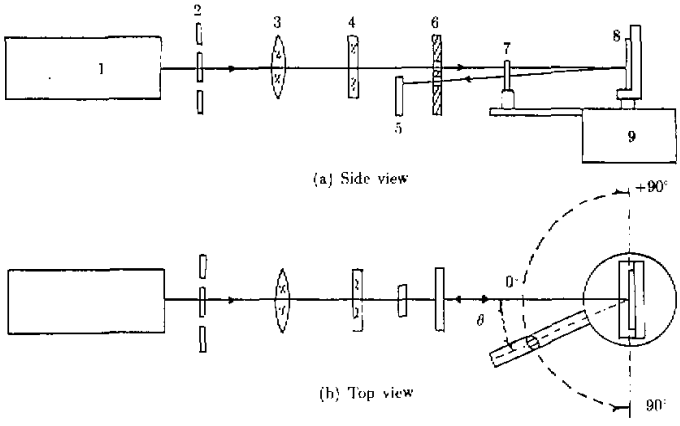

Fig. 1. Experimental arrangement. 1. CW CO_2 laser; 2. chopper; 3. lens; 4. half-wave plate; 5. screen 2; 6. screen 1; 7. detector; 8. sample; 9. motor.

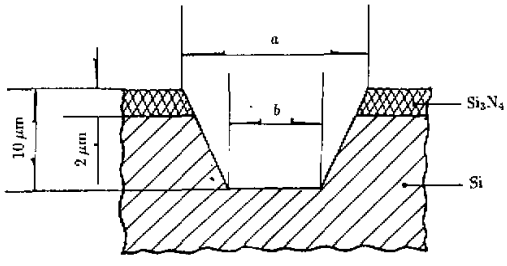

Fig. 2. Groove geometry. Values of a and b are given in Table 1.

The detector conducted scanning via an arm attached to a computer-controlled rotating

table, the sample being rigidly mounted through a hole in the centre of the table. The detector signal was fed through a lock-in amplifier into a programmable digital voltmeter and finally into the computer to control the table rotation. Typically, 900 readings were taken in a 90° scan. Finally, the experimental results were displayed on the computer.

Five single grooves were prepared by chemical etching on a Si-Si_3N_4 wafer. The geometrical sizes of the grooves are shown in Fig.2. Each groove was 20 mm long and 10 μm deep. The actual widths a and b of the top and bottom of the grooves were measured using an electron microscope. The width sizes are given in Table 1.

Table 1.

Groove number			1		2		3		4		5	
Groove widths/μm			a	b	a	b	a	b	a	b	a	b
			20	1	22	4	32	12.3	42	22	51	32
Positions of theoretical minima/deg		1	32		28.8		19.3	59.5	14.6	28.8	12	19.3
		2			74.5		41.5		30.3	74.5	24.5	41.5
		3					83.4		49.2		38.5	83.4
		4									56.2	
Positions of actual minima/deg	TE	1	~ 32		27		15.5		14.5		13.5	
		2			~ 75		46		29.5		22.5	
		3							~ 51.5		50.5	
		4									~ 90	
	TM	1	28		30.5		16.5		15.5		11.5	
		2					~ 48.5		31.5		23.5	
		3							~ 56		~ 41	
		4										

III. EXPERIMENTAL RESULTS AND DISCUSSION

The data were taken as the distance between the detector and a single groove was 12 cm, each step of the synchronous scanning motor being 0.1°. Similar results were obtained as the distance between the detector and the single groove was 25 cm and each step of the scanning motor was 0.01° or 0.05°.

The angular scanning diffraction curves of groove Nos. 1, 3 and 4 are shown in Figs. 3, 4 and 5, respectively. In all figures, the top curve A corresponds to the incident light with TE polarization (the electric vector of the incident light parellel to the groove direction), and the lower curve B corresponds to the incident light with TM polarization (the electric vector of the incident light perpendicular to the groove direction). For all these grooves (Nos. 1 to 4, the groove widths $a \leq 42\mu$m, $b \leq 22\mu$m) the diffraction intensities appeared the greatest as the incident light was TE polarized and were minimum as the incident light was TM polarized.

Figures 6 and 7 show the relation between the diffraction intensities and the polarization angles of the incident light, given TE=0°. The curves in Figs. 6 and 7 were measured from grooves Nos. 3 and 4 at the peaks of the secondary maxima. Figures 8 and 9 show the rate of changes of diffraction intensities at the peaks of the secondary maxima for groove Nos. 3 and 4, respectively, given TE=0°.

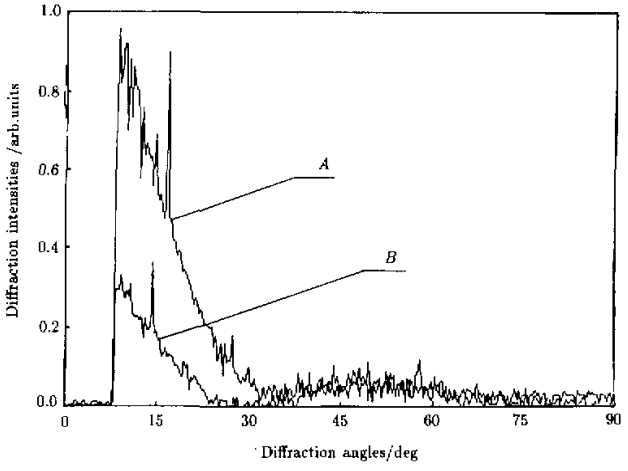

Fig. 3. Angular distribution of diffraction intensities for groove No. 1.

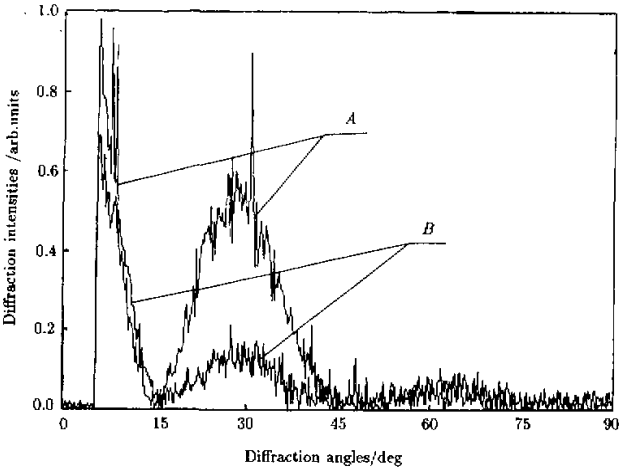

Fig. 4. Angular distribution of diffraction intensities for groove No. 3.

For grooves Nos. 1, 2 and 3, the smaller the diffraction angle, the larger the rate of change of the diffraction intensity of the secondary maximum with the incident light polarization

angle. It should be noted in Figs. 7 and 9 that the rate of change of the second secondary maximum of groove No. 4 is the largest.

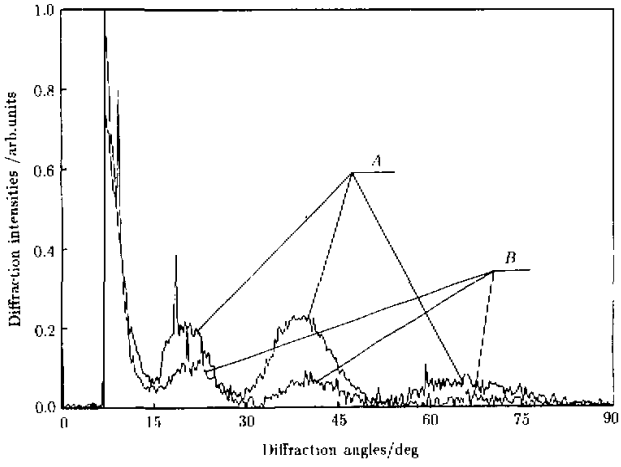

Fig. 5. Angular distribution of diffraction intensities for groove No. 4.

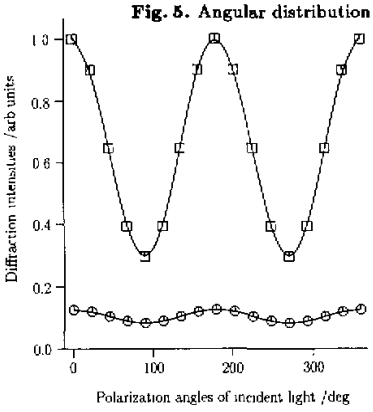

Fig. 6. Relation between the diffraction intensities and the polarization angles of the incident light for groove No. 3. □ First secondary maximum; ○ second secondary maximum.

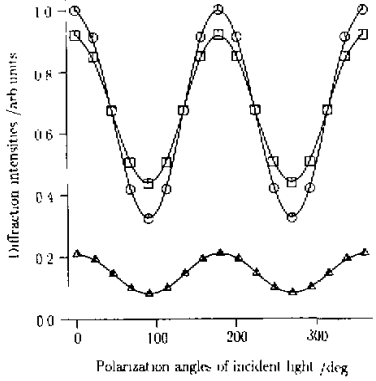

Fig. 7. Relation between the diffraction intensities and the polarization angles of the incident light for groove No. 4. △ Third secondary maximum; all the other symbols are same as in Fig. 6.

The curves in Figs. 10, 11 and 12 were obtained from groove No. 5 (the groove widths $a = 51\,\mu$m, $b = 32\,\mu$m). In Fig. 10, the curve A was obtained as the incident light was TE polarized and the curve B was obtained as the incident light was TM polarized. It can be seen from Fig. 10 that the diffraction intensity was larger in the case of the incident light TM polarized in comparison to that of the incident light TE polarized as $-35° < \theta < 35°$. However, the observation was reversed as $-90° < \theta < -60°$ and $60° < \theta < 90°$.

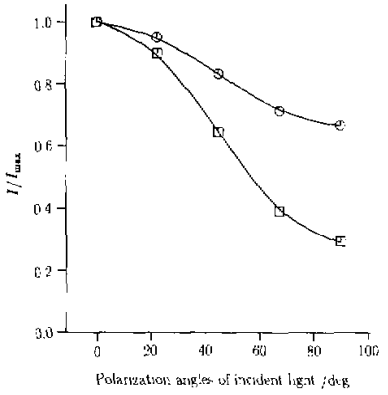

Fig. 8. Rate of change of the secondary maxima diffraction intensities with the incident light polarization angles for groove No. 3. All the symbols are same as in Fig. 6.

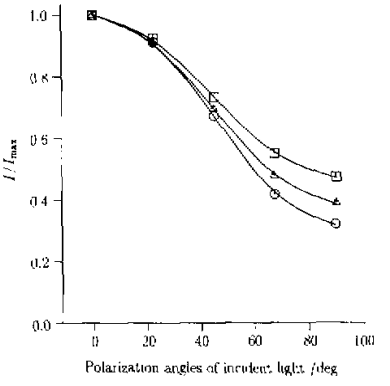

Fig. 9. Rate of change of the secondary maxima diffraction intensities with the incident light polarization angles for groove No. 4. All the symbols are same as in Fig. 7.

There is another feature that can be observed in Figs. 10, 11 and 12. The variances of the diffraction intensities following the change of the polarization angles of the incident light are most apparent near $\theta = 18°$ and $\theta = 65°$. It shows that the diffraction at the groove top was larger than that at the groove bottom as $-50° < \theta < 50°$ and the diffraction action at the groove bottom was larger than that at the groove top as $-90° < \theta < -50°$ and $50° < \theta < 90°$ because the position of the first maximum of the groove top is at θ about $\pm 18°$, and the position of the second maximum of the groove bottom is at θ about $\pm 65°$. In addition, the diffraction intensities were the greatest at θ near $\pm 18°$ when the incident light was TM polarized and θ near $\pm 60°$ when the incident light was TE polarized. It shows that the diffraction of groove bottom played an important role as the incident light was TE polarized and the diffraction of groove top played an important role as the incident light was TM polarized.

As shown in Figs. 3, 4, 5 and 10, we found that as the polarization angle of the incident light is changed not only the diffraction intensity but also the positions of diffraction maxima and minima are changed.

Table 1 gives the widths of the five single grooves and the corresponding theoretical angles of diffraction minima from groove tops and bottoms and the actual measured angles of the diffraction minima. The angles of theoretical minima may be calculated by the following formula:

$$\sin\theta = \frac{\lambda}{l}, \frac{2\lambda}{l}, \cdots . \tag{1}$$

It can be seen from Table 1 that the positions of diffraction maxima and minima for

groove No. 2 to groove No. 4 were shifted in the 0° direction as the incident light was TE polarized. However, the positions were shifted in the direction of ±90° as the incident light was TM polarized. The opposite result was obtained from groove No. 1, and the situation for groove No. 5 becomes complex.

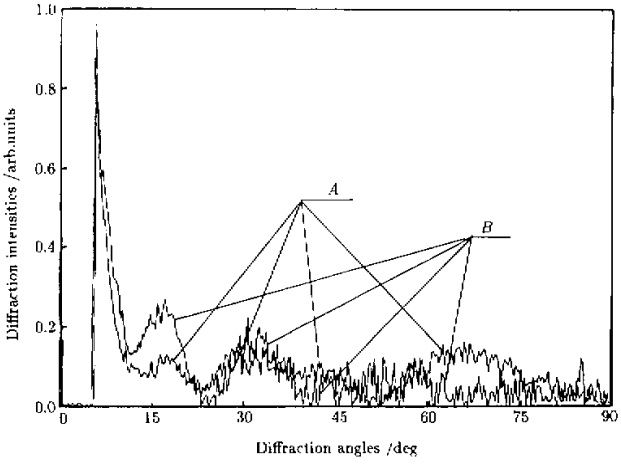

Fig. 10. Angular distribution of diffraction intensities for groove No. 5.

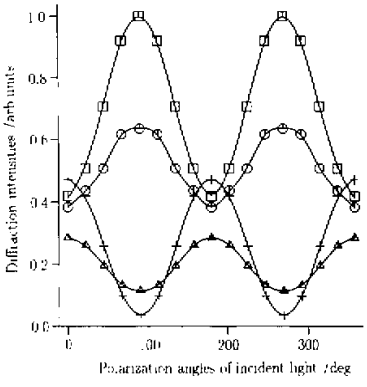

Fig. 11. Relation between the diffraction intensities and the polarization angles of the incident light for groove No. 5. + Fourth secondary maximum, all the other symbols are same as in Fig. 7.

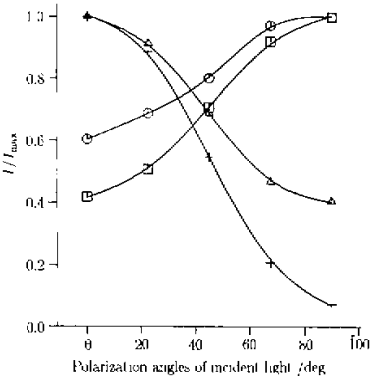

Fig. 12. Rate of change of the secondary maxima diffraction intensities with the incident light polarization angles for groove No. 5. All the symbols are same as in Fig. 11.

In summary, the experimental results show that the diffraction intensities change with the polarization angle of the incident light. The diffraction intensities for TM polarization

are larger as the groove widths are larger. While the groove width colse to the wavelength of the incident light, the diffraction intensities for TM polarization decrease gradually and the diffraction intensities for TE polarization increase gradually. The variations of the diffraction intensities depend not only on the various grooves with different widths but also the different diffraction angle for the same groove.

From Figs. 6, 7 and 11, we can see that although the intensity variation of each diffraction order has a very regular sinusoidal dependence on the polarization angles of the incident light, it coincides with that of the results of the single grooves coated with gold film[6], the variation phase of each diffraction order is not all the same.

We have given the experimental results of the diffractive properties of wavelength-sized single grooves in Si-Si_3N_4 substrate as the angle of incident light is 0°. However, the experimental results show some situation opposite to that of Ref. [6] for a conducting surface, where the diffraction intensity is higher for the incident light TM polarization than the case of TE polarization. These results show that the single groove of conducting surface and the single groove of non-perfectly conducting surface have very different diffractive properties as the single groove dimensions are comparable to or smaller than the wavelength of the probing light.

ACKNOWLEDGEMENTS

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