Blazed silicon gratings fabricated by deflecting crystal orientation (111) silicon wafer

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Abstract. Bulk silicon wet etching can be used to fabricate silicon gratings. Wet etching depends on the anisotropic property of monocrystalline silicon. Blazed gratings for different spectral ranges can be fabricated by this method, and facets of grooves are formed by crystallographic planes of the monocrystalline silicon wafer. We develop a method to fabricate blazed gratings using deflecting crystal orientation (111) silicon wafers. The topographies of the samples are measured by SEM and atomic force microscopy (AFM), and the results indicate that the samples have grooves of good uniformity and facets of excellent optical quality. [DOI: 10.1117/1.1857533]

Subject terms: deflecting crystal orientation; (111) silicon wafer; blazed grating; bulk silicon technology; wet etching.

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1 Introduction

[1]Diffraction gratings are important dispersing elements in spectroscopic instruments, which have been the subject of considerable and sustained research because of this importance. Due to the rapid development of silicon microfabricaiton techniques, many microelectronic products such as computers have become indispensable tools for humankind. Integrated and microdevices compatible with manufacturing processes of microelectronic ones open new applications for traditional instruments and devices. The use of silicon to produce diffraction gratings was first reported by Tsang and Wang[1] in 1975. Since then, these gratings have found use in spectrometers, integrated optics, and other applications.

Silicon gratings are dispersive elements of microspectrometers, which can be used for quality inspection in industry and agriculture by reading color and results from analytical chemistry.[2] Monocrystalline silicon is an excellent material for gratings, since gratings can be manufactured directly onto the material by using well-established micromachining techniques. The groove facets of a silicon diffraction grating are defined by a set of crystallographic planes in the material, and therefore can ideally be atomically smooth and flat. Flat facets have advantages in efficiency and are more easily coated with a reflective material.

Bristol et al.[3] reported the fabrication and evaluation of silicon diffraction gratings for use in the far and extreme ultraviolet. The gratings on silicon substrate can also be used in waveguides and fibers in integrated optics[4,5] and the light trapping structures of silicon solar cells.[6] Jocelyn et al.[7] and Kiang et al.[8] have proposed the design and fabrication of an actuated diffraction grating using a surface-micromaching process, which can be used to build an integrated scanning microspectrometer, or can be used as a grating demultiplexer for multichannel wavelength-switching networks. Kong, Wijngaards, and Wolffenbuttel[9] studied a grating-type microspectrometer by silicon in the IR spectral range.

2 Design and Fabrication of the Blazed Silicon Grating

From Ref. 10, we know that the blaze angle of grating is decided by the incident angle, the period of the grating, and the blaze wavelength. In Fig. 1 the light is incident at an angle of α and diffracted at an angle of β, where both are measured from the grating normal.

The blazed condition is satisfied when the angle of incidence with respect to the facet normal is equal to the angle of reflection from the facet. Under such conditions we can derive the blaze angle ϕ from the following equations:

$$\begin{cases} \phi = \dfrac{\alpha-\beta}{2} \\ d(\sin\alpha - \sin\beta) = m\lambda \end{cases}, \qquad (1)$$

where m is the diffraction order, λ is the diffraction wavelength, and d is the grating period.

To fabricate blazed silicon gratings, we can use standard bulk silicon micromaching processes. The bulk silicon microfabrication technique is developed for micro 3-D structures on the crystal material. By removing parts of the material according to the design pattern, micropatterns can be formed. The key technique of bulk silicon microfabrication is anisotropic wet etching. Single crystal silicon possesses a specific chemical property in which the etching rate differs drastically with the crystal orientation. If the wafer is immersed in the aqueous KOH, which etches through the (100) planes about 100 times as quickly as it does the (111) planes, a sharp, self-limiting V-shaped groove (Fig. 2) will then be formed.[11]

If a (100) silicon wafer is used to fabricate gratings, only V-shaped grooves with an angle of 54.74 deg between the (111) and (100) surface can be obtained. The grooves are

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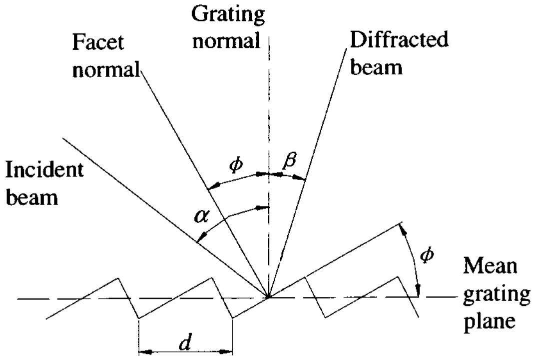

Fig. 1 Determination of the facet angle for a blazed grating.

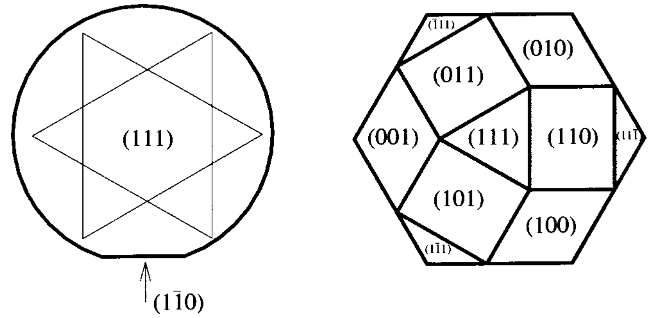

Fig. 3 The structure of (111) silicon wafer.

composed of two (111) surfaces, which is decided by the crystallographic structure of silicon. If we want to make blazed gratings with other angles, we can slice and polish silicon wafers by tilting the material. Both (100)[12] and (110)[11] silicon wafers are used to manufacture blazed gratings by this tilting method. In the case of (100) silicon wafers, the smaller the blazed angle is, the bigger the tilting angle. The crystal orientation can usually be deflected with a small angle for commercial products, so it is difficult to acquire gratings with a small blazed angle by using the (100) silicon wafer. And the (110) silicon wafer is much more adaptive to making rectangular gratings due to its crystal structure.

The (111) silicon wafer is shown in Fig. 3, usually using (1$\bar{1}$0) as its reference plane. We can get this structure of the (111) silicon wafer from a silicon cube. The two equilateral triangles in Fig. 3 are other {111} plane cross lines with the (111) plane. Due to the properties of silicon crystal in the alkalescent aqueous, we cannot process directly on a (111) silicon wafer by wet etching without other assistant artifices.

If we want to use a polished (111) silicon wafer to make gratings, we need to deflect an angle from [111] orientation to [001], which will also be the blazed angle of the gratings. According to the wavelength and working conditions, the angle can be decided by Eq. (1), and will be formed by (111) and (11$\bar{1}$) planes with a value of 109.48 deg. The surface without a SiO_2 mask will be etched in the KOH aqueous, and the etching will self-stop at the meeting point of the two {111} planes. Then we can acquire the blazed grating as shown in Fig. 4(c). How the small blazed angle in the deflecting crystal orientation silicon (111) wafer is formed is shown in Fig. 4. The gratings with a blazed angle of 4 deg were made by this method.

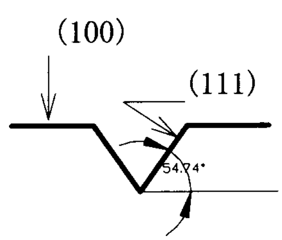

Fig. 2 The V groove of (100) silicon wafer etched in KOH aqueous.

The bulk silicon micromaching process to fabricate blazed gratings can be divided into about ten main steps. First, a polished deflecting crystallographic direction (111) silicon wafer is chosen as a substrate. Then a layer of SiO_2 is thermally grown on the wafer by oxidization, which is carried out in a program-controllable oxidation and diffusion furnace for 20 min, attaining a 150-nm-thick layer of SiO_2. A layer of AZ5214 photoresist was then spun on the SiO_2 mask. To obtain a layer thin enough to yield a complete exposure in the troughs, the wafer was spun at 4000 rpm for 40 s.

The wafers were exposed with a KarlSuss MA6 UV photolithographer. Then the wafer was developed in AZ300MIF for about 30 to 60 s. After development, the wafers were baked at 120 °C on a hotplate for 3 min to harden the remaining resist.

After hardened on the hotplate, the wafers were ready to be etched. HF buffer solution was used to open the window on the SiO_2 mask layer at room temperature. The remaining photoresist was removed by acetone. The wafers were then dipped in a 41% aqueous KOH bath. Under the SiO_2 masking, the silicon wafers were etched in the solution to get the V grooves at 80 °C.

3 Topography Measurements of Gratings

Surface quality is very important for a grating, which can be tested by an atomic force microscope (AFM) and scanning electron microscope (SEM). The purpose of the testing was to evaluate the quality of the etched gratings. The results are shown in Figs. 5, 6, and 7. The basic profile of grooves can be seen from Fig. 5, which is observed by an optical microscope at 1000 magnification. The period of this sample grating is 4 μm.

A SEM has a higher resolution than an optical microscope, which can attain about 20 nm. Figure 6 is the SEM image of this blazed grating fabricated by (111) silicon at 5000 magnification. The flat-tops are due to the strips of SiO_2 mask, which seem much narrower than the blazed facets. Flat-tops are not the best result, because they can

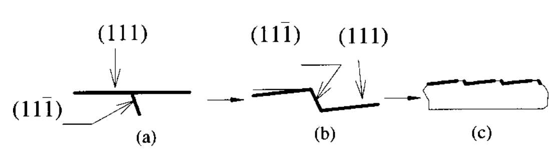

Fig. 4 Blazed grating made of (111) silicon wafer.

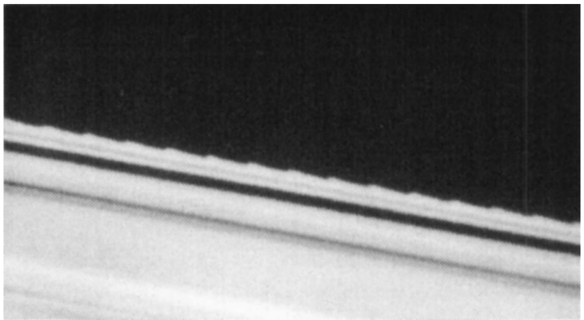

Fig. 5 (111) silicon grating surface at 1000× magnification.

produce stray lights and degrade the diffraction efficiency of the grating. The width of flat-tops can be controlled by the period of the HF etching time.

The optical and scanning electron microscope can provide the general picture of the shape of the groove, but are not applicable to precisely quantitative measurements. To study the profile with atomic resolution, we can use an atomic force microscope to measure the topography of the gratings. Figure 7 is the AFM image for the blazed silicon grating with a period of 8 μm. The scanning range of the AFM is 30×30 μm. In this picture, we can see the 3-D topography of the grating. The period of grating measured by the AFM is 7.942 μm, and the error to the designed value is only 58 nm. The result indicates that the grating blazed facet formed by {111} crystallographic planes is very smooth by the wet etching method. So, the process to fabricate blazed gratings through the anisotropic etching method using a deflecting crystallographic direction (111) silicon wafer is quite effective to obtain a groove shape with an exact groove angle and with smooth and flat facets.

4 Conclusion

Silicon grating, which is fabricated on a silicon wafer by using microfabrication techniques such as ultraviolet lithography and anisotropic etching, is a principal kind of dispersing element to fabricate microspectrometers. We design a method to fabricate gratings with a small blazed angle using a deflecting crystallographic direction (111) silicon wafer. The topographies of the silicon gratings are measured by AFM and SEM.

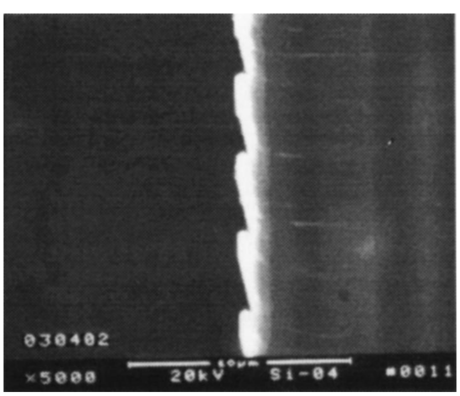

Fig. 6 The SEM image of (111) silicon grating at 5000× magnification.

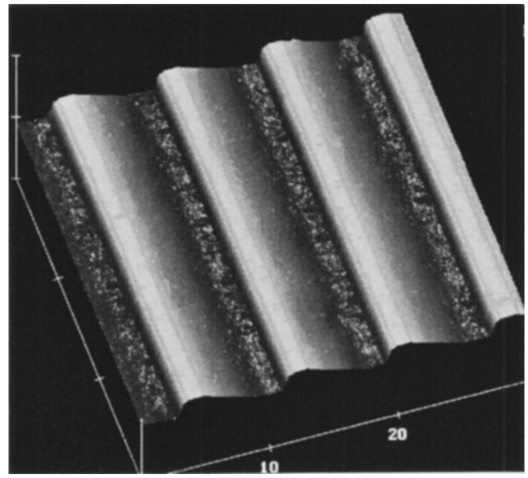

Fig. 7 The AFM image of (111) silicon blazed grating (8 μm).

The results exhibit that the silicon (111) crystal planes of a silicon wafer are very smooth after the wet etching. Thus, the anisotropic etching method using a (111) silicon wafer for fabricating blazed gratings is quite effective to obtain groove shapes with an exact groove angle and with smooth and flat facets. The gratings can be used for reflecting dispersion, if it is deposited as a layer material of reflection. Gratings fabricated by an (111) silicon wafer can be used in integrated spectrometers.

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Hui Ju received the MS degree in mechanical engineering from Jilin University of Technology, China. He was awarded a PhD in mechanical and electrical engineering from Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences (CIOMP,CAS). He spent several years working at CIOMP, where he studied microspectrometers used for chemical and biochemical analysis and MEMS silicon gratings. He is now on the faculty in the Department of System Engineering at Wakayama University, Japan. His research is focused on micro-optics and developing optical MEMS devices for temperature detection and plasma diagnoses.