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Blazed and Slanted Grating Mastering using Crystallography-based Silicon Etching

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Blazed and Slanted Grating Mastering using Crystallography-based Silicon Etching

ABSTRACT

This disclosure describes crystallographic etching techniques to manufacture blazed or slanted silicon gratings such that their characteristic angles are defined by the facet angles of the silicon crystal substrate. The techniques enable the manufacture of precisely formed and uniform gratings with smooth surfaces over large areas. The grating pattern is achieved by using anisotropic, potassium hydroxide based, crystallographic etching of a silicon wafer along selected crystal planes. The grating structures manufactured by the described techniques can be used as master molds for replicated fabrication of nano-imprint optical devices such as waveguides.

KEYWORDS

- Blazed grating
- Slanted grating
- Master grating
- Facet angle
- Crystallography
- Miller index
- Wet etching
- Silicon etching
- Photoresist layer
- Hard-mask layer
- Face-centered cubic
- Anisotropic etching
- Crystallographic etching
- Crystallographic direction
- Potassium hydroxide
- Waveguide

BACKGROUND

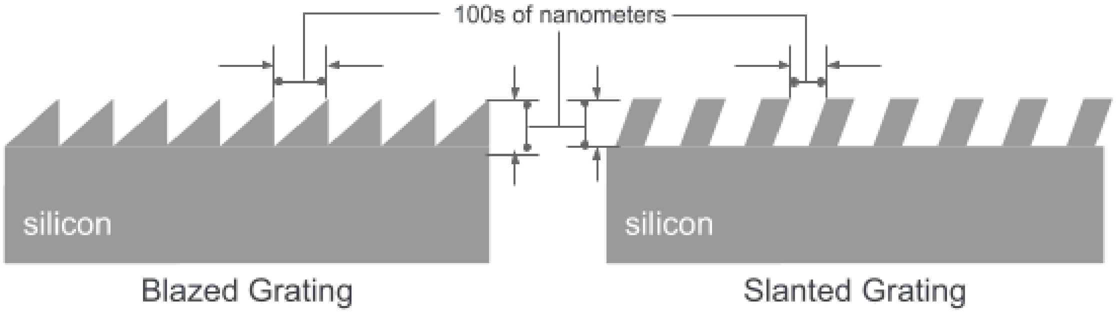

Fig. 1: Blazed and slanted silicon gratings

Fig. 1 illustrates two types of gratings on a silicon surface. Seen from the side, a blazed grating comprises periodic, triangular, tooth-like structures hundreds of nanometers in depth and pitch. A slanted grating comprises periodic, parallelogram-shaped, tooth-like structures hundreds of nanometers in depth and pitch. Seen from the top, both blazed and slanted gratings are parallel lines on a silicon surface.

Silicon gratings can serve as a master mold for manufacturing diffraction gratings in transparent resin. Silicon gratings can be used to fabricate diffraction gratings in transparent resin by pressing them against the resin. Diffraction gratings in transparent resin (e.g., used in lenses of smart glasses) have a variety of optical properties - they can split light, they can redirect light to particular directions, they can serve as an optical waveguide, etc. These optical properties find application in augmented reality and other domains.

Being the imprint of the silicon (master) grating, the optical properties of the resin grating depend on the geometry of the silicon grating, e.g., the angle of the triangle in the blazed grating or the slope of the slant in the slanted grating. Blazed grating is presently made using mechanical ruling, e.g., by lithography patterning followed by an ion-milling procedure (replicated using a master, as necessary). Slanted grating is presently made using lithography patterning followed by angled plasma etching or ion milling. Both approaches have limitations on angle control, large-area pattern uniformity, etched surface roughness, etc. A periodic error in the groove of a mechanical ruling can cause stray light in a blazed grating. Plasma etching produces slanted gratings with rough surfaces which can reduce diffractive efficiency and lower optical performance.

Facet Angle (º)		(hkl)					
		100	**110**	**010**	**001**	**101**	**111**
(HKL)	**100**	0.0	45.0	90.0	90.0	0.0	54.7
	011	90.0	60.0	45.0	45.0	60.0	35.3
	111	54.7	35.3	54.7	54.7	35.3	0.0
	211	35.2	30.0	65.9	65.9	30.0	19.5
	311	25.2	31.4	72.4	72.4	31.4	29.5
	511	15.8	35.2	78.9	78.9	35.2	38.9
	711	11.4	37.6	81.9	81.9	37.6	43.3

Table 1: Facet angles of crystalline silicon

Silicon is a face-centered cubic (FCC) crystal. The lattice planes and lattice directions of the crystal can be described using Miller indices. For a cubic lattice, the normal to a surface direction is denoted by Miller indices [hkl]; the surface of a particular lattice plane is denoted by Miller indices (hkl). Table 1 illustrates some facet angles of silicon. For example, as seen in Table 1, the facet angle between the 711 and the 111 crystal planes is 43.3°.

DESCRIPTION

This disclosure describes crystallographic etching techniques to manufacture blazed or slanted silicon gratings such that their characteristic angles are defined by facet angles of the silicon crystal substrate. Since the facet angles are crystallographically defined by the FCC structure of silicon, the techniques enable the manufacture of precisely formed and uniform gratings with smooth surfaces over large areas. The grating pattern is achieved by using anisotropic, potassium hydroxide (KOH) based, crystallographic etching of a silicon wafer along selected crystal planes. The grating structures manufactured by the described techniques can be used as master molds for replicated fabrication of nano-imprint optical devices such as waveguides.

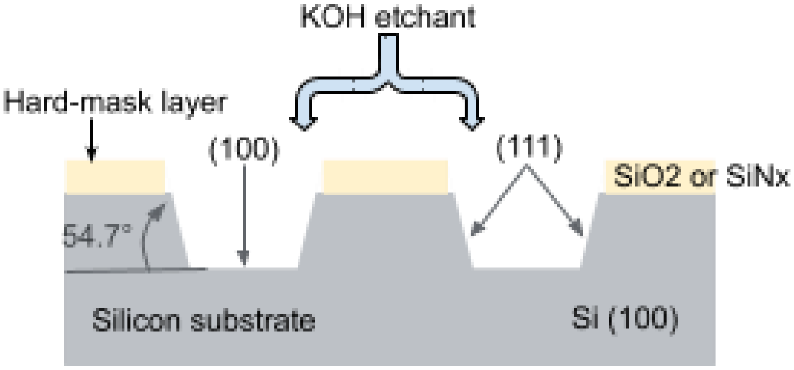

Fig. 2: Potassium hydroxide etches the 100 silicon plane at a much faster rate than the 111 silicon plane, resulting in deep, pyramidal pits or trenches with 111-plane facets

The techniques leverage the observation that wet etching by certain chemicals is anisotropic with respect to crystal planes. For example, at certain temperatures and concentrations, potassium hydroxide (KOH) attacks the 111 silicon plane at a rate six hundred times slower than 100 silicon planes. Illustrated in Fig. 2, when KOH etchant at a certain concentration and temperature enters a silicon substrate oriented along the 100 plane and covered with a patterned hard-mask layer, the etchant flows into the gaps in the hard-mask layer and creates pits or trenches much deeper than they are wide, corresponding to the fact that the 100 crystal plane corrodes much faster than the 111 plane. The sides of the trench correspond to the 111-plane facet; the slope of the sides corresponds precisely to the facet angle between the 100 and the 111 planes - 54.7°.

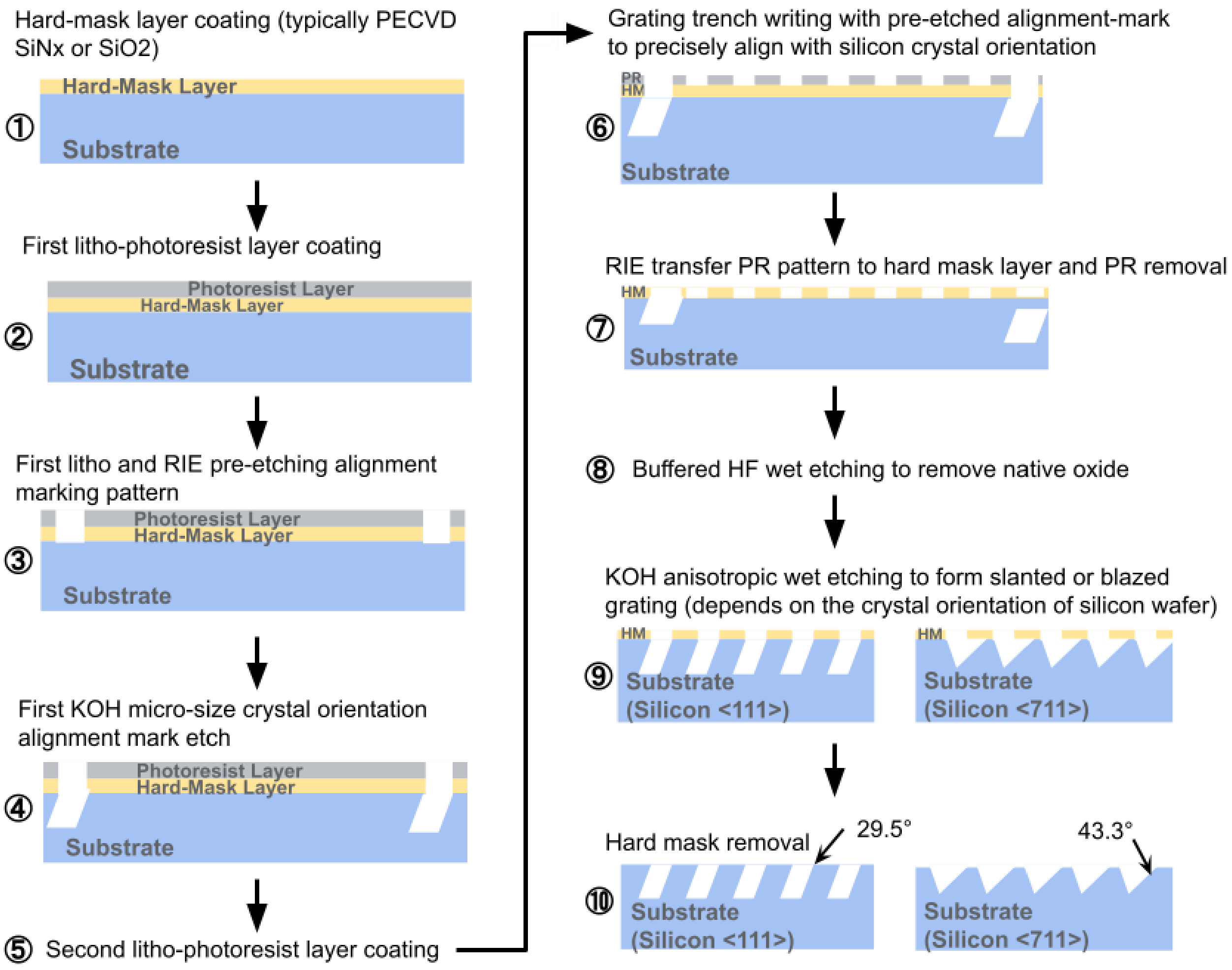

Fig. 3: Workflow for the manufacture of blazed or slanted silicon master grating using crystallography-based etching

Fig. 3 illustrates an example workflow for the manufacture of blazed and slanted silicon master grating using crystallography-based etching. A silicon substrate is coated with a hard-mask (HM) layer, typically, using a plasma-enhanced chemical vapor deposition technique ①.

The HM layer is typically a silicon nitride or silicon dioxide. A first litho-photoresist (PR) layer coating is applied ②. The HM and PR layers are pre-etched ③ to establish an alignment marking pattern. The pre-etching can be done using reactive ion etching (RIE). A first potassium hydroxide wet-etching is carried out to establish a micrometer-level crystal orientation between the alignment etches ④. A second litho-photoresist coat is applied ⑤.

The PR layer is etched such that the resulting grating trenches align precisely with the previously established alignment marks in the silicon substrate, which in turn align with the orientation of the silicon crystal ⑥. The pattern on the PR layer is transferred to the HM layer using RIE and the PR layer removed ⑦. Crystalline alignment of the hard-mask pattern is an essential lever of control to ensure well-defined etching structures. Rather than using conventional choices (e.g., wafer major flat or minor flat) as guidelines, pre-etched micrometer-sized alignment marks improve the hard-mask pattern alignment and result in precise crystallographic etching of grating structures.

Wet etching using buffered, e.g., diluted, hydrogen fluoride is carried out to remove native oxides ⑧. Anisotropic wet etching is carried out using potassium hydroxide at a particular concentration and temperature to form slanted or blazed grating at a designed slant or angle ⑨. The hard mask layer is removed ⑩. For example, if the silicon substrate is aligned along its 311 plane and KOH of the right temperature and concentration is used for wet etching, a slanted grating forms with slant angle 29.5°, which is the facet angle between the 111 and the 311 crystal planes (see Table 1). As another example, if the silicon substrate is aligned along its 711 plane and KOH of the right temperature and concentration is used for wet etching, a blazed grating forms with angle 43.3°, which is the facet angle between the 111 and the 711 crystal planes (see Table 1).

The etching solution can be prepared by diluting potassium oxide with deionized water until it reaches an appropriate concentration. The temperature of the etching solution is selected for different crystal facets. Surface roughness can be minimized by adding isopropyl alcohol (IPA) as appropriate. After etching, the grating is rinsed with deionized water and blow-dried with nitrogen.

As explained earlier, the direction of the anisotropic etch depends on the orientation of the silicon substrate with reference to its crystal planes. Etching occurs along natural and well-defined crystalline facet angles, resulting in smooth surfaces and precisely shaped angles or slants to the gratings. The sidewall angles of the grating patterns are not arbitrary; rather, they are selected from Table 1 (and extensions thereto). However, while not admitting to arbitrary angles, Table 1 provides a wide range of angle selections.

The blazed or slanted silicon master gratings manufactured using the described techniques can be used to mold diffractive optical elements in waveguide devices with high uniformity and dimensional definition over large areas. The techniques can also be used to manufacture other types of nanometer or micrometer-sized structures on crystalline structures such as gallium nitride, gallium arsenide, germanium, etc.

CONCLUSION

This disclosure describes crystallographic etching techniques to manufacture blazed or slanted silicon gratings such that their characteristic angles are defined by the facet angles of the silicon crystal substrate. The techniques enable the manufacture of precisely formed and uniform gratings with smooth surfaces over large areas. The grating pattern is achieved by using anisotropic, potassium hydroxide based, crystallographic etching of a silicon wafer along selected crystal planes. The grating structures manufactured by the described techniques can be used as master molds for replicated fabrication of nano-imprint optical devices such as waveguides.

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