Silicon Gratings with Different Profiles: Trapezoidal, Triangular, Rectangular, Arched

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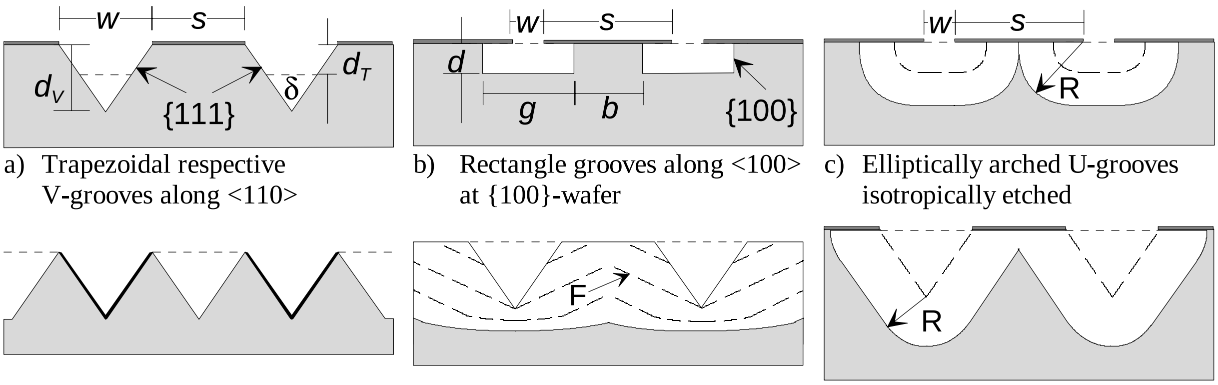
Introduction

By inspiration from the European Standard EN ISO 5436-1 [1] concerning material measures for the profile method for assessment of the surface texture some investigations are performed to find possibilities for the production of gratings with defined profiles by microtechnological processes using silicon. Silicon is a very suitable material for the realization of material measures because of its high thermomechanical stability [2] and because of the availability of the very precise processes for microstructuring. Different profiles of linear gratings can be etched depending on the used wafer orientation, the groove direction on the wafer and etching procedure. Unfortunately, the production of an unrestricted free shape is impossible or very difficult in any case. Of course, the gratings can also be used otherwise for example for the assessment of optical devices or as optical reflection gratings.

Types of profile and principles of their manufacture

The types of profiles capable of being produced by silicon etching can be divided into two groups: polygonal profiles and arched profiles, illustrated schematically in figure 1. Combinations of them are included. The horizontal parts of the polygonal and combined profiles correspond with the wafer surface or the etch ground.



a) Trapezoidal respective V-grooves along <110>
b) Rectangle grooves along <100> at {100}-wafer
c) Elliptically arched U-grooves isotropically etched
d) Triangular profile (typa a) modifyed by mask inversion
e) Parabolic arched profile (type a) modifyed by maskless etching
f) Elliptic arched profile (type a) modifyed by isotropical etching

Figure 1 Manufacturing principles of the profile types
w: width of a window; *s*: spacing between windows; d, d_T, d_V: etched depth
g: width of a groove; *b*: width of a barrier between grooves; *R*: isotropically etched depth
δ = 70.5° at {100}-wafer; δ = 109.5° at {110}-wafer

The straight and inclined sections of the polygonal types result from crystallographically defined planes arising from the orientation dependent etching processes (ODE). These planes are inclined by special angles which can be explained on the base of the pronounced anisotropy of the etch rates in basic solutions (e.g. KOH:H_2O-solutions). At windows along <110> the {111}-planes arise as sidewalls forming a trapeziodal profile, (figure 1a, dotted lines) or finally a series of V-grooves (“geometrical etch stop”). The angles of inclination of the {111}-planes relative to the wafer surface define the characteristical angles of the trapeziums and V-grooves along <110>. These angles have the following values:

$$\{100\}\text{-wafer: } \gamma = \arctan \sqrt{2} = 54.74°; \qquad \{110\}\text{-wafer: } \gamma = 90° - 54.74° = 35.26°.$$

A triangular profile can be made by modifying the V-groove type, figure 1a. Using silicon nitride as the 1st mask the V-grooves are etched followed by a selective thermal oxidation of the free silicon surface inside the grooves. Then the nitride is selectively removed. Now, the spacing is converted into a window suitable for etching a second series of V-grooves, figure 1d. In this way the period is halved.

Using an {112}-wafer the inclination of the opposite {111}-faces is different: 90° respective 19.48°. Consequently, the arising V-grooves have an asymmetric shape. The resulting periodic profile can be converted into an asymmetric triangular profile if $w = s$ analogous to the symmetric case, figure 1d.

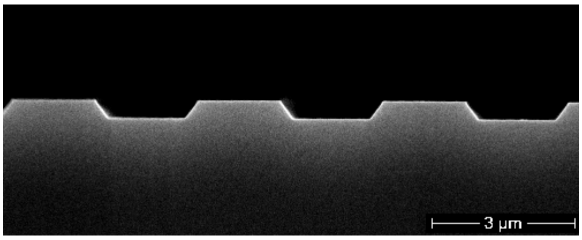
A groove with vertical {100}-sidewalls can be realized along the <100>-directions on the {100}-wafer resulting in a rectangular profile, figure 1b. In this case the sidewall face has the same etch rate as the etch ground because of the crystallographic equivalence of both faces.
Grooves with approximately vertical bounding planes necessary for rectangular profiles arise also by anisotropical dry reactive ion etching (RIE). In this case the sidewall planes are not crystallographically defined resulting in deviations from a vertical even shape.
The deep profiles with arched sections result directly from an isotropical etching process (figure 1c) or from isotropical etching of the polygonal V-groove (figure 1f).
A 2nd orientation dependent etching of the V-groove after a complete removing of the mask at first produces very fast etching faces (F) flattening the profile. If the fast etching faces arrive the vertex line of the V-groove the geometrical etch stop is dissolved and a new slightly curved etch ground arises resulting in a shallow arched profile, figure 1e.

Preparation of gratings

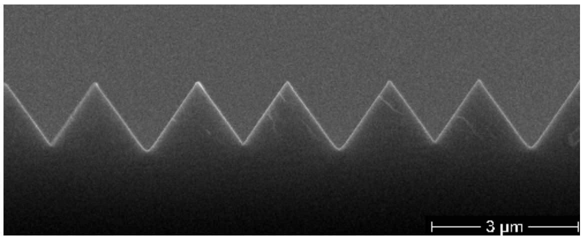
The gratings were produced by etching of different series of long but narrow mask windows of the width w with narrow spacings of the width s in between resulting in grooves of the width g with barriers of the width b in between. The length of the period p is defined by $p = w + s = g + b$. Mask patterns of the grating fields with periods between 1,6 – 50 µm are realized inside a chip size of 10 mm x 10 mm together with additional guiding grooves.
The used technologies for the realization of the passivation layers (thermal SiO_2 and Si_3N_4) and for the transfer of structures into these films depend on the magnitude of the period of the gratings. The use of the projection and step and repeat techniques of lithography was necessary to achieve the extreme precision for the small periods. Especially, by varying of the exposure time the ratio w/s can be adjusted. As mentioned above a special kind of two-step etch process with intermediate oxidation is used to realize the triangular gratings [3].
The choice of the used etchant depends on the wished shape of the grating and was related to the target depth: etchants with low rate for low depth (TMAH 25% - 60 °C: rate = 0.11 µm/min; KOH 30% - 80 °C: rate = 1.1µm/min). The rate of the isotropical etchant HNO_3:HF:CH_3COOH at room temperature is about 3.3 µm/min.
After the wafer preparation the chips were diced by sawing. For the investigation of the profiles of the gratings the chips were broken to achieve cross sections for the obversation by SEM. The determination of the radii of edges was performed by TEM.

Results

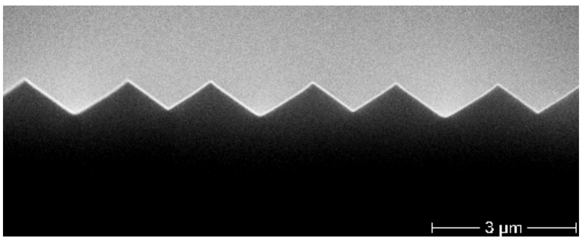
The SEM-pictures figures 2, 3 and 4 give an overview about the cross sections of the prepared gratings. Some preparations result in good aproximation with the expected profiles as the trapezoidal types, the V-groove types and the isotropically etched arched types shown in figures 2a and 3a,b. Other preparations reveal deviations from the target profile as the triangular and the deep or shallow arched profiles, figure 2b, c, d and 3c, d.
The neighboured V-grooves of the triangular profiles have a different width because the oxidation of the V-grooves reaches into the interface between the nitride and the silicon.



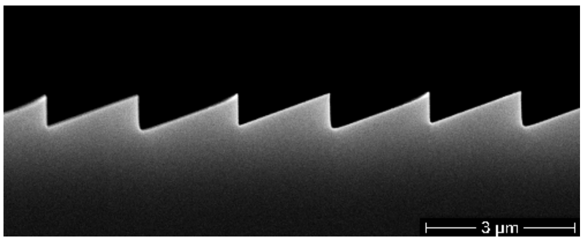
a) Trapezoidal profile $\gamma = 54.7°$



b) Triangular profile $\delta = 70.5°$



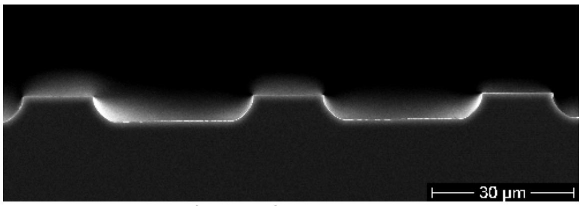
c) Triangular profile $\delta = 109.5°$



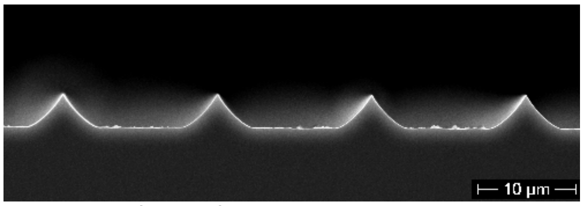
d) Asymmetric triangular profile $\delta = 70.5°$

Figure 2 Prepared polygonal profiles

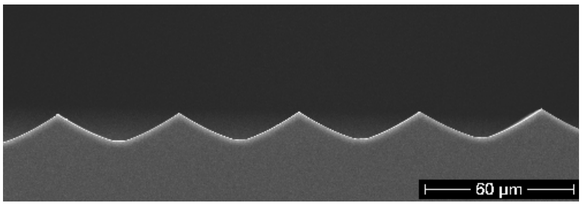
The “so called” isotropical etchant produced a week anisotropy which is large enough to miss the ideal target profile [4]. Etching a V-groove the rate is obviously diminished at the vertex which is conserved over a certain time. Later a flat face arises along the vertex, figure 3c.



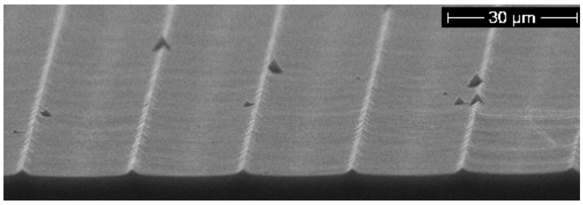
a) Flat / arched / flat profile



b) Arched / flat profile

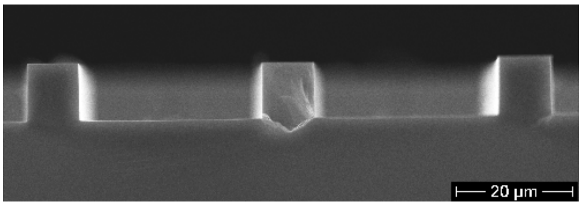


c) Deep arched profile

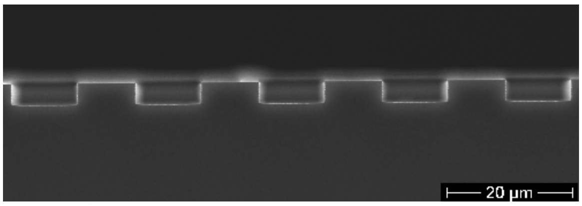


d) Shallow arched profile

Figure 3 Prepared arched profiles



a) anisotropically wet etched



b) dry reactive ion etched

Figure 4 Rectangular profiles

The profile depth of the shallow arched profile is very low. Consequently a small roughness inside the grooves must be supposed. Unfortunately the fast etching faces (leaving the curved etch ground, figure 1e) are very irregular for a certain time after their generation and they transfer the irregularities into the etch ground. Using TMAH the irregularities can be largely avoided but the curvature of the etch ground is smaller resulting in a lower profile depth.

A characteristical feature of the gratings are the radii of the occuring edges. Large radii (> 50 nm) can be measured by SEM. Smaller radii must be observed by TEM. The concave vertex of the V-grooves of the prepared gratings shows a minimum radius of < 5 nm which is of the order of the native oxide. All the top edges, but especially at the rectangular profile, are very sharp (15 - 50 nm) suitable for the assessment of the stylus tips of tactile profiling instruments.

Conclusions

Wet etching of mask patterns with long windows spaced by small distances on silicon wafers can produce gratings with a variety of groove profiles. The profile type depends on the used wafer orientation, the groove direction on the wafer and the used etching technique. Trapezoidal, triangular, rectangular and arched profiles are realizable by orientation dependent or isotropical etching. The realized gratings have edges with very small radii between < 5 up to 60 nm.

In particular the arched profiles miss the ideal target shape because of a weak anisotropy of the "so called" isotropical etchants. Further investigations are necessary for the improvement of the arched profiles and for the realization of special shapes of trapezoidal and rectangular profiles suitable for the assessment of profiling instruments.

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References

[1] DIN EN ISO 5436-1:2000-11 Geometrische Produktspezifikation (GPS) – Oberflächen-beschaffenheit: Tastschnittverfahren; Normale – Teil 1: Maßverkörperungen; Deutsche Fassung EN ISO 5436-1:2000

[2] Frühauf, J., Trumpold, H.: Silicon Standards for Assessment and Calibration of Stylus Probes. Annals of the CIRP, 51(2002)1, P. 475-478

[3] Neuzil, P.; Serry, F. M.; Maclay, G. J.: Fabrication of sharp ridges on single crystal silicon wafers. The Electrochemical Society. Extendet Abstracts 95-2, 975 (1995), P. 1534-1535

[4] Schwesinger, N.: The anisotropic etching behaviour of so-called isotropic etchants. Proc. of the 5th International Conference on Micro Electro, Opto, Mechanical Systems and Components, Potsdam, Germany, P. 481-486