

Original Research Article

The etching rates of the anisotropic wet-chemical etching of silicon in KOH solutions

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ABSTRACT (ARIAL, BOLD, 11 FONT, LEFT ALIGNED, CAPS)

Chemical etching is employed as micromachining manufacturing process to produce micron-size components. As a semiconductor wafer is extremely expensive due to many processing steps involved in the making thereof, the need to critically control the etching end point in an etching process is highly desirable. It was found that not only the etchant and temperature determine the exact anisotropy of etched silicon. The angle between the silicon surface and the mask was also shown to play an important role. In this paper, angular dependence of the etching rate is calculated on the base of the silicon symmetry properties, by means of the interpolation technique using experimentally obtained values of the principal $\langle 100 \rangle$, $\langle 110 \rangle$, $\langle 111 \rangle$ directions in KOH solutions. The calculations are performed using an extension of the sparse field method for solving three dimensional (3D) level set equations that describe the morphological surface evolution during etching process. The analysis of the obtained results confirm that regardless of the initial shape the profile evolution ends with the crystal form composed of the fastest etching planes, $\{110\}$ in our model.

Keywords: Chemical etching, silicon, etchants, crystal, solution

1. INTRODUCTION (ARIAL, BOLD, 11 FONT, LEFT ALIGNED, CAPS)

Etch process is widely used in microfabrication to chemically remove layers from the surface of a wafer during manufacturing [1-5]. In order to form a functional MEMS structure on a substrate, it is necessary to etch the thin films previously deposited and/or the substrate itself. In general, there are two classes of etching processes. During the so called wet etching the material is dissolved when immersed in a chemical solution, while dry etching includes sputtering of the material by using reactive ions or a vapor phase etchant.

Chemical etching process has a long history and accepted one of the important nontraditional machining processes during the last half century [6]. The method is often applied to machine geometrically complex parts from thin and flat of any material. It is also used to reduce weight of the workpiece materials. Etching rates and etch end points need to be carefully monitored and controlled in order to end etching processes at the desired time [7, 8]. In semiconductor processing, for semiconductor devices having film layers or features in the micron and sub-micron range, an inadequate etch or an excess etch would lead to

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insufficient removal or the excess removal of a desired layer causing an undesired electrically open or short circuit connections. Additionally, if the etch is in excess, undercutting or punch through can occur resulting in poorly defined film patterning or total lift-off. Inadequate or excess etching time further leads to undesirable reliability problems in the subsequently fabricated semiconductor device.

Currently, most etch rate end point determination techniques depend on indirect measurement and estimation techniques. Some etch monitoring techniques have relied on external measurements of film thickness followed by etch rate estimation and an extrapolated etch end point prediction [9, 10]. However, etch rates may vary due to batch-to-batch differences in the chemical and physical characteristics of the film or the etchant. Therefore, these extrapolation methods are inadequate. Previous methods for measuring and minimizing overetch include scanning electron microscopy (SEM) of cross sections of fractured wafers [11]. Not only is the method of analysis destructive of the wafer, there can be significant imprecision in the resulting estimate of overetch when the number of sections is insufficient or when the sections are not representative of the whole. Other methods include optical measurements of fiducial regions or discrete test wafers [12]. However, such methods are expensive as portions of the wafer are occupied by non-product fiducial areas or require additional test wafers. Such optical methods are also subject to uncertainty resulting from turbidity of the etch bath and other optical effects and uncertainty resulting from non uniform films. Finally, such optical methods are subject to imprecision in the resulting estimate of overetch when the number of measured sites is insufficient or when the sections are not representative of the whole.

Recently, simulation techniques have evolved into very effective tools that complement laboratory experiments and analytic models [13,14]. Simulation codes have displayed a high level of sophistication and are routinely used in semiconductor industry for predicting various characteristics such as etch rate. In this paper we discuss the application of the level set method for the modelling of the three dimensional (3D) etching profile evolution during anisotropic wet etching of silicon with KOH etchant. Only etching rates along principal directions ($\langle 100 \rangle$, $\langle 110 \rangle$, $\langle 111 \rangle$) of silicon have been considered. Simulation results were achieved by using our simulation package (well documented in previous publication [14]) based on the level set method for the 3D simulation of the etching profile.

2. ANISOTROPIC ETCHING OF SILICON

Anisotropic wet-chemical etching of silicon in KOH solutions remains the most frequently used processing technique in silicon MEMS technology. Very complicated three-dimensional structures can be formed by this technique. In order to simulate the time evolution of three dimensional etching profiles it is essential that exact etch rates in all directions are known. The etching rates for only a few principal axes are known, but they can be used to determine rate value in an arbitrary direction $\mathbf{N} (N_x, N_y, N_z)$ by an interpolation procedure. It is supposed that N_x , N_y and N_z axes are aligned with $\langle 100 \rangle$, $\langle 010 \rangle$ and $\langle 001 \rangle$ crystal directions, respectively. In actual calculations we made use of measured etching rates in $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ crystal directions, for 30% KOH concentration at 70°C taken from ref. [13] ($R_{100} = 0.797 \mu\text{m}/\text{min}$; $R_{110} = 1.455 \mu\text{m}/\text{min}$; $R_{111} = 0.005 \mu\text{m}/\text{min}$).

The point group of silicon's symmetry $m\bar{3}m$ (subgroup of $Fd\bar{3}m$ space group) contains 48 elements. Since it is not possible to assemble angular section using 3 principal directions with which the whole space can be covered by the symmetry operations, only 16 out of 48 symmetry elements can be used for that purpose. Even more, it is necessary to observe only at 1/16th of the full angular extent, that is actually the union of three sections defined by

the principal vectors A[100, 111, 110], B[100, 111, 101] and C[001, 111, 101], as depicted in Fig. 1.

The etching rate R in an arbitrary direction defined by vector $\mathbf{N}$ is given by an interpolation relation [16]:

$$R(\mathbf{N}) = \begin{cases} \left[R_{100}(N_x - N_y) + R_{110}(N_y - N_z) + R_{111}N_z \right] / N_x; & \mathbf{N} \in A \\ \left[R_{100}(N_x - N_z) + R_{110}(N_z - N_y) + R_{111}N_y \right] / N_x; & \mathbf{N} \in B. \\ \left[R_{100}(N_z - N_x) + R_{110}(N_x - N_y) + R_{111}N_y \right] / N_z; & \mathbf{N} \in C \end{cases} \quad (1)$$

Etching rate angular dependence can be obtained by introducing spherical angular coordinates ϕ and θ instead of Cartesian (N_x, N_y, N_z) :

$$N_x = \sin \theta \cos \phi; N_y = \sin \theta \sin \phi; N_z = \cos \theta. \quad (2)$$

The angular dependence of the etching rate $R(\theta, \phi)$ can be written in the form:

$$R(\theta, \phi) = \begin{cases} R_{100} - (R_{110} - R_{111}) \cot \theta / \cos \phi + (R_{110} - R_{100}) \tan \phi, & (\theta, \phi) \in A \\ R_{100} + (R_{110} - R_{100}) \cot \theta / \cos \phi + (R_{111} - R_{110}) \tan \phi, & (\theta, \phi) \in B, \\ R_{100} + [(R_{110} - R_{100}) \cos \phi + (R_{110} - R_{100}) \sin \phi] \tan \theta, & (\theta, \phi) \in C \end{cases} \quad (3)$$

and shown in Fig. 2.

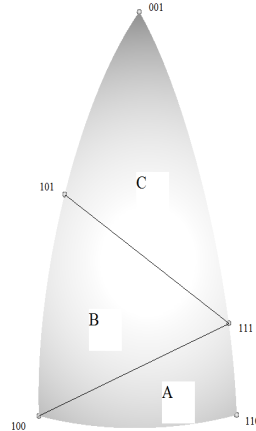


Fig. 1. Etching rate model regions used in our 3D simulations.

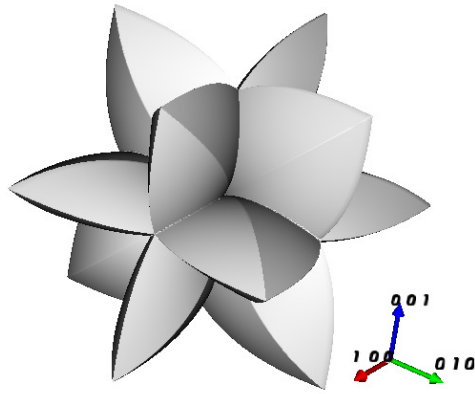


Fig. 2. The angular dependence of the etching rate.

3. RESULTS AND DISCUSSION

Figure 3 shows the etch rates versus the temperature (in degrees Celcius) for various KOH solution concentrations: 20% (open circles), 40% (solid squares), 50% (open triangles) and 60 % (solid circles). It was found that addition of KOH solutions leads to decreasing of the etch rate by approximately 20%.

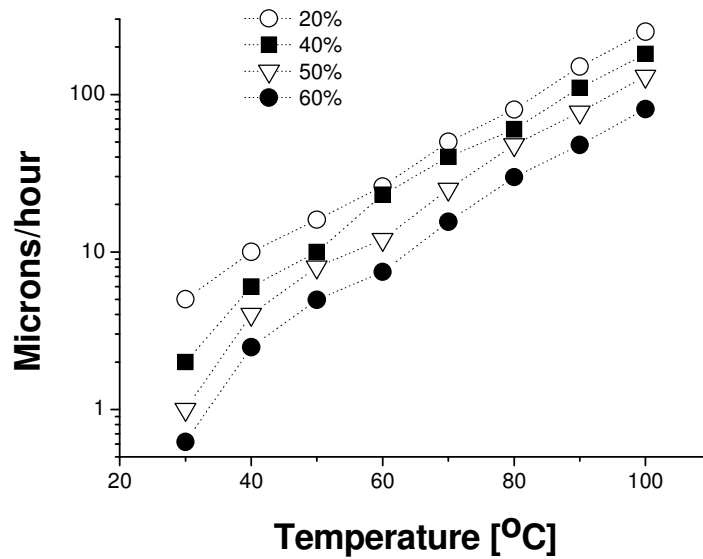


Fig. 3. Dependences of the etch rate on the temperature (expressed in °C) and concentration of the KOH solution.

4. CONCLUSION

In this paper the angular dependence of the etch rates for 30% KOH concentration at 70°C has been determined. The influence of the temperature as well as concentration of the KOH solution on the etch rates are presented and discussed. The analysis of the obtained results confirm that regardless of the initial shape the profile evolution ends with the crystal form composed of the fastest etching planes, {110} in our model. Results presented here indicate that the sparse field level set method can be used as an effective tool for wet etching process modeling, and that it is a viable alternative to the cellular automata method, which is today widely used in for that purpose.

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