

Three-Dimensional Simulation of Anisotropic Wet Chemical Etching Process

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ABSTRACT

In this paper, we present result on the development of a simulation tool for the three-dimensional anisotropic wet chemical etching of bulk silicon etching or bulk micromaching. As a test of our simulation tool, we present several simulation results. Several simulation results demonstrate our simulation tool which is quite efficient for the design and development of MEMS device structure. The developed simulator demonstrates the applicability of complex three-dimensional MEMS device structures. We demonstrate the simulation of the anisotropic wet chemical etching process of basic exemplary structures featuring the virtual fabrication of an industrial MEMS structure manufactured by means of bulk micromaching.

Keywords: anisotropic etch simulator, wet etching, three-dimensional simulation, bulk micromaching

1 INTRODUCTION

Anisotropic wet chemical etching is still one of the fundamental techniques employed in silicon bulk micromaching technology. The bulk micromaching technology removes selectively significant amounts of silicon from a substrate. It constructs undercut structure that is required to form membranes on one side of wafer or to make a variety of trenches, holes. In the anisotropic wet chemical etching process, the etching procedure for bulk micromaching technology is commonly realized by using wet chemical etchants in order to obtain a significant underetching structure. The underetching structure is separated isotropic and anisotropic. These properties of etched geometries are the main responsible for the reactants and including the shapes of the masks used to define the etched regions. Although isotropic etching etchants is used to such bulk micromaching technology, usually anisotropic wet chemical etchants such as KOH, EDP and TMAH are used reasonable in MEMS single-crystal silicon-based process.

The recent growth in the number of MEMS devices that are being fabricated using bulk silicon etching technology has necessitated efficient design and development. But it is often difficult to predict the result of etching single-crystal silicon with typical wet etchants such as KOH, TMAH and EDP due to the anisotropic nature of the etching that is

taking place. Despite many research efforts have been made on the development of novel schemes which allows the designer to figure out the topographical evolution of the surface during fabrication process of the MEMS devices such as bulk silicon etching technology. And most of the available simulation software is specialized stand-alone programs, featuring no embedding in general-purpose topography simulation tools [1-4]. But the fabrication of progressively complex MEMS structures often requires additional processes for the three-dimensional structuring of bulk silicon.

In this paper, we present a simulation tool for the three-dimensional anisotropic wet etching of single-crystal silicon. Our simulation method and the cell representation of the etch body allows for an efficient three-dimensional simulation. Also, our simulation tool can easily be extended to incorporate different materials with various etching properties.

2 SIMULATION METHOD

In the anisotropic wet chemical etching process, anisotropic etchants etch attack certain crystal planes much faster in one direction than in another direction. For the case of silicon, $\langle 100 \rangle$ and $\langle 110 \rangle$ planes etch at much higher rate than $\langle 111 \rangle$ planes. This etch rate selectivity is used to create various cavity and groove structures. Etching at concave corners on (100) silicon stops at (111) intersections. But convex corners are undercut, allowing cantilevers rapidly undercut and released. This mechanism is explained as removing $\{111\}$ planes on the surface in lateral direction [5]. Our simulation method was adapted to the purpose of efficient topography simulation.

Our simulation method simulates movement of the surface through a list structure, so called the surface cell. The simulation region is divided into units of hexahedron-shaped cells. The material index information is assigned at each cell to be divided. Also, the location information is assigned by a location index indication which express location of inside or outside the etch body. The topography evolution information is assigned only at surface cells. The topography evolution information has etch properties according to its crystallographic position and cell volume value that evolves movement of the surface. The surface cells are constituted the list for the efficiency of the memory and computation. Figure 1 is a schematic diagram illustration the surface cell list composition for a surface

topography expression of the case of anisotropic wet chemical etching. The surface cell list is composed two lists. The surface cell list is composed the surface cells to be removing <110> planes and <111> planes (List1). The surface cell list is composed the surface cells to be removing <100> planes (List2).

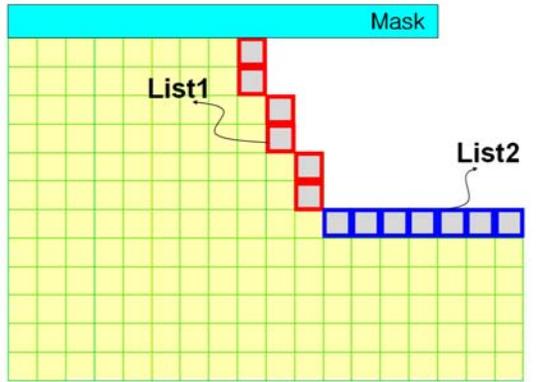


Figure 1: The cell list composition for a surface topography expression of the case of anisotropic wet chemical etching.

The data structure to perform the above surface cell list is shown Figure 2. Referring to Fig. 1, surface cell list has list1 and list2, respectively.

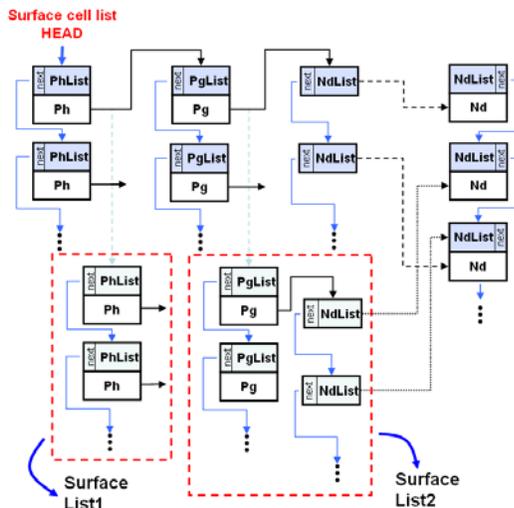


Figure 2: The data structure of surface cell list

As above mentioned, the composed surface cell list is used to do the simulation for the movement of the surface. The surface cell list is composed two lists according to normal vector of crystallographic planes. We perform the list construction such as following steps: a) Extract normal vector formed by crystallographic plane with surface cell, which the material index of cells is same. b) Separate lists with each crystallographic plane into surface cell list. The

exposed direction of surface cell is same, or the angle between normal vectors of each surface cell is within critical angle. c) Find common list with crystallographic plane. Finally, d) Couple list with same crystallographic plane.

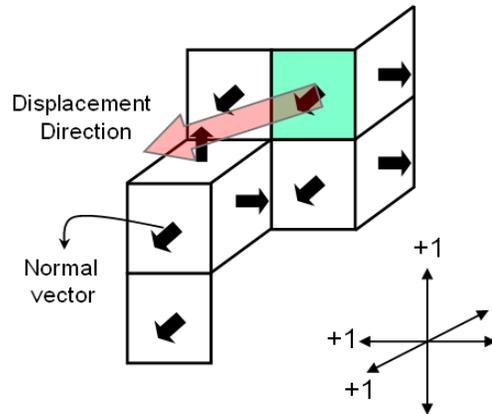


Figure 3: A normal vector of surface cell with crystallographic plane.

Each surface cells are moved according to the etch properties. The etch properties is different according to its crystallographic direction. Our simulation tool uses etch properties to determine displacement direction of surface cells through the normal vector of crystallographic planes. Figure 3 is a schematic view illustrating the method defining displacement direction according to a normal vector of surface cells with crystallographic plane. The displacement direction is calculated by summing up the normal vectors of surface cells.

Our simulation tool uses the mathematical method. During the time evolution of the etch front, which is represented by the change of the material index information of each cell. The topography evolution information are assigned to surface cells to determine the etch properties according to its crystallographic position.

During the simulation, an equation (1) is used to express movement of the surface cells.

$$\vec{P}_i(t + \Delta t) = [\vec{P}_i(t) + e_i \cdot \Delta t \cdot \vec{c}_i] \cdot g_i \quad (1)$$

The plane displacement direction \vec{c}_i is determined by the crystallographic properties of the surface cell. The g_i is used to determine whether cell has been etched away, the position vector \vec{P}_i from t to $t + \Delta t$ is calculated. The position of new surface cells that exposed by the proceeding of the etch front. The etch rate e_i is determined from experimental data.

Etch rates for a given temperature and concentration of the etchant is not the same for the different silicon crystal planes. Figure 4 shows a graphical representation of the silicon etches rate dependence on the crystalline plane, etchant temperature, and etchant concentration.

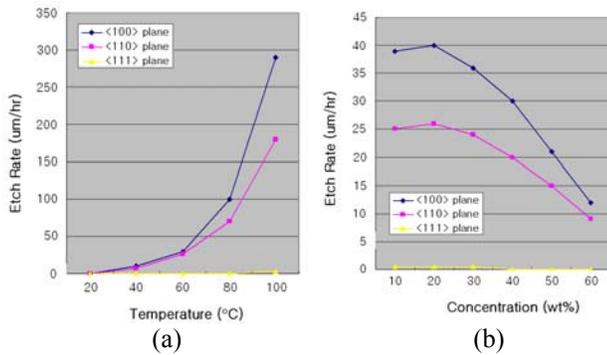


Figure 4: (a) Etch rate of single-crystal silicon according to a temperature at fixed concentration of 35wt%, (b) Etch rate of single-crystal silicon according to a concentration at fixed temperature of 60°C.

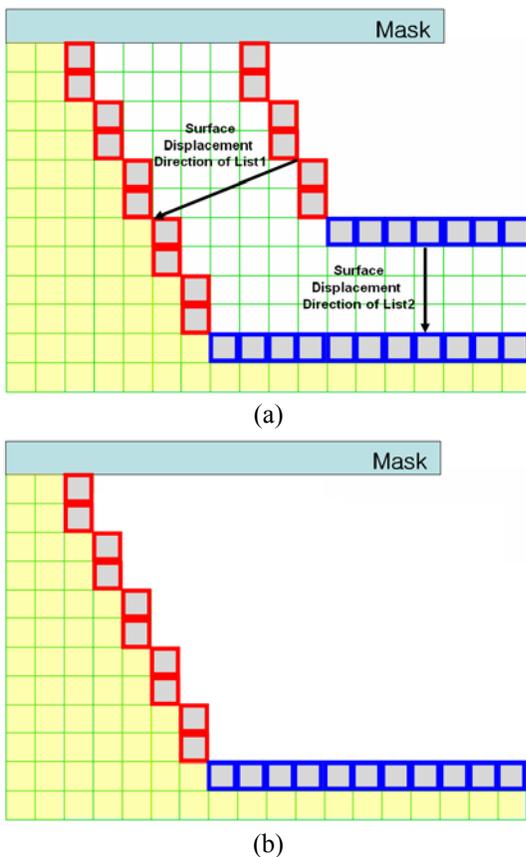


Figure 5: (a) Motion of surface cells along displacement direction and generation of new etch front during the time step, (b) The final etched shape after removing the etched cells.

The surface cell is removed according to the following procedure as the simulation method illustrated in figure 5. At single time step, the list of surface cell is searched. The surface cell list is composed two lists according to normal vector of crystallographic planes. The movement of surface cell is determined displacement direction according to a normal vector of surface cells with crystallographic plane.

During the next time step, the surface cells moves position exposed by the proceeding of the etch front along the vector of displacement direction. The information of the surface cells of initial position were transferred to the new surface cells exposed by the proceeding of the etch front. The time step is updated. Finally, newly exposed cell is added surface cell list, before the next time step may begin. The surface cells are removed until time T is reached. Time (T) is defined according to the user's selection. The final etched shape is obtained, as shown in figure 5(b).

3 SIMULATION RESULT AND DISCUSSIONS

As a test of our simulation method, we presented several simulation results. Our simulation method was applied to the cases anisotropic wet chemical etching process such as the construction of comb driver resonator and spring-mass system. Also, our simulation method is applied to predict etched shape for isotropic wet chemical etching process. Several simulation results demonstrate our simulation tool which is quite efficient for the design and development of MEMS device structure.

Figure 6 shows result of wet etching a simulation which predicts the etched shape for isotropic etchants. According to our simulation method, simulation region is divided into units of hexahedron-shaped cells. The simulation region is used the size $200 \mu\text{m} \times 150 \mu\text{m} \times 30 \mu\text{m}$. This structure has total 900,000 ($200 \times 150 \times 30$) cells. This resulting is a final profile structure on the wafer after simulation in accordance with the user-defined layout and the processing of isotropic wet chemical etching procedure. The generated structure shows that, by means of our simulation method, fully isotropic topographical shape.

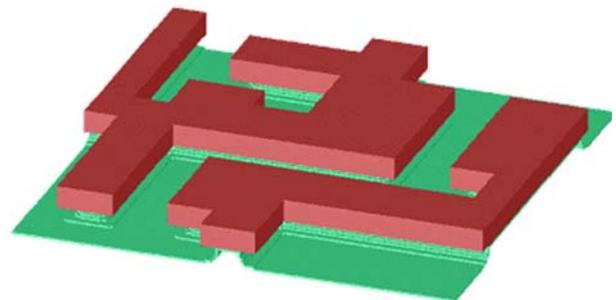


Figure 6: A schematic diagrams illustrating the result of wet etching a simulation which predicts the etched shape for isotropic etchants.

Figure 7 shows the simulation result for structure of comb drive resonator. This resulting is a final profile structure on the wafer after simulation in accordance with the user-defined layout and process procedure. The simulation region is used the size $257 \mu\text{m} \times 234 \mu\text{m} \times 2 \mu\text{m}$. This structure has total 120,276 ($257 \times 234 \times 2$) cells. This structure is constructed moving comb, anchor, folded beam and stationary comb. The comb drive resonator is

suspended by two folded beam flexures to form a mechanical mass-spring damper system.

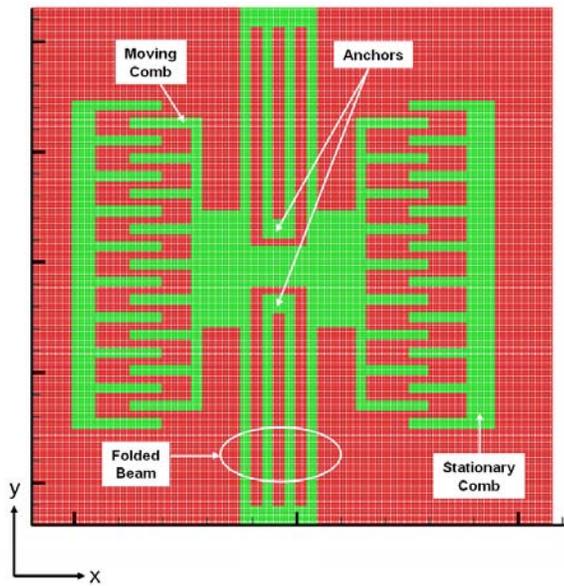


Figure 7: The simulation result of a comb drive resonator.

Figure 8 shows three-dimensional simulation results of the typical spring-mass system. This resulting is simulated with our simulation tool. The simulation parameter of typical spring-mass system is used <100>-oriented wafer surface and KOH of 35 wt% and 60 °C. The simulation region is used the size $200\ \mu\text{m} \times 200\ \mu\text{m} \times 25\ \mu\text{m}$. This structure has total 1,000,000 ($200 \times 200 \times 25$) cells.

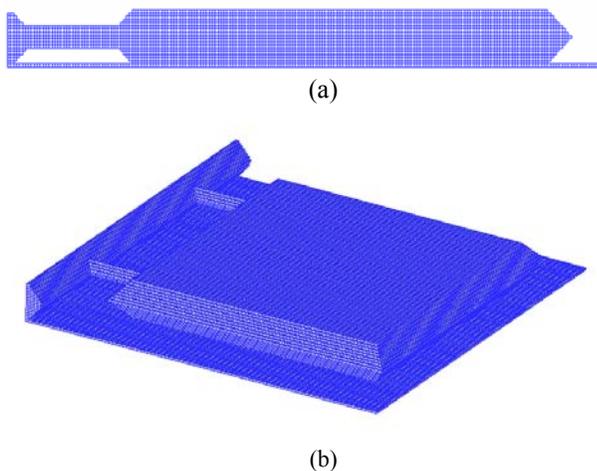


Figure 8: Simulation result of a spring-mass system (part of an acceleration sensor): (a) Side view of x-y plane direction, (b) Bird-eye's view.

The processing of anisotropic wet chemical etching which is the typical application of bulk micromachining technology of silicon. But bulk micromachining of silicon processing requires long etching times, since the substrate

has to be etched in its whole thickness. Also, the geometric of MEMS device is required an accurate predictive simulation due to the anisotropic nature of the etching that is taking place. The accurately designed MEMS device structures derived from realistic simulations, which play an essential role to avoid waste of device development time and costs.

4 CONCLUSION

In conclusion, we develop a simulation tool for the three-dimensional anisotropic wet etching of single-crystal silicon. Our simulation tool provides the capability of considering the etching properties of various materials and structuring techniques. And the developed simulation tool guarantees for the detailed analysis of complex three dimensional MEMS structures. Several simulation results demonstrate our simulation tool which is quite efficient for the design and development of bulk micromachining technology. Thus, it is considered that our simulation tool is very suitable to figure out the profile during the anisotropic wet chemical etching process.

5 ACKNOWLEDGEMENT

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