Design of Compensation Structures for Anisotropic Etching

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ABSTRACT

Due to the highly anisotropic behavior of silicon bulk etching, there have been many publications on etch simulation and convex corner compensation for specific geometries. Our previous work introduced a general framework for algorithmically synthesizing mask layouts for wet etching. This paper extends that work to broader classes of corner compensation and demonstrates the encoding of a specific compensation structure such that it may be used with other orientations or process parameters.

Keywords: compensation structures, anisotropic etching, wet etching, bulk etching

INTRODUCTION

As silicon fabrication technologies gain broad exposure to micro-mechanical systems, new engineering tools are required that can automate routine design functions. As the systems become more complex there is an ever increasing need to automate routine fabrication steps thus allowing the non-specialist to design more complex devices and aid the efficiency of expert designers.

In our previous work [1] we described methods to algorithmically synthesizing mask layouts. This paper extends that work to provide more generalized and sophisticated compensation structures.

Recently, algorithms and procedures to model and simulate the etching process have been developed [2], [3]. While these simulators help reduce the number of design/fabrication iterations, current design procedures still rely heavily upon the designer's intuitive understanding of the etching process. Automated software tools should allow more intelligent and automatic choices of etch chemical, concentration, temperature, etc.

The problems of fabricating convex corners with certain crystal orientations using anisotropic bulk etching are well known [4]–[6]. Many articles have been written describing "compensation structures" for specific geometries and etchants [7]–[9]. Often these "point solutions" need to be modified to accommodate different process parameters, etchants, or changes in geometry.

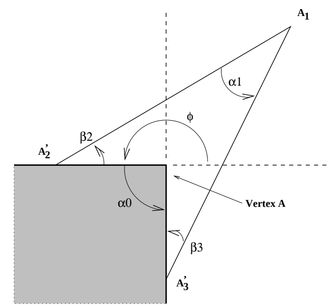

Figure 1: Parameterized Generic Vertex and 3-Point Compensation Structure.

Since these structures are often derived through many iterations, such modifications are difficult.

In additional to describing simple general approaches to compensation structures, this paper shows how these previous "point solutions" can be encoded by a system of equations that can then be solved to provide the desired compensation structure. In so doing, changes in etch profile and geometry can can be incorporated into the solution such that an appropriate compensation structure is computed.

SYNTHESIS METHOD

The shape of the desired etch outcome is decomposed into planes and vertices. The etch rate of the planes is determined by the etch rate diagram. The vertices are analyzed to determine if there are appearing planes during the etch [1]. If planes appear, the vertex is categorized as *compound*, otherwise it is *simple*. It is well know that convex compound vertices require compensation structures or sacrificial shapes in order to etch properly. In [1], methods were described to synthesize masks for *simple* vertices, further it was shown that compensation structures could be computed by replacing each single compound convex vertex with multiple simple vertices, each of which had a computable solution.

Figure 1 shows a generic compensation structure for a compound convex corner that consists of 3 vertices which is parameterized by the angles β_2 and β_3. The dark areas in Figure 2 correspond to values of β_2 and β_3

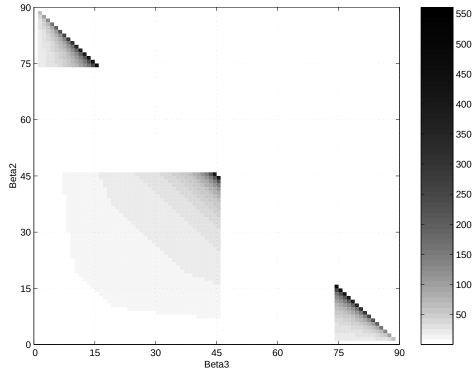

Figure 2: $\beta_2\beta_3$ Plot, Colorbar Indicates Distance from A to A_1

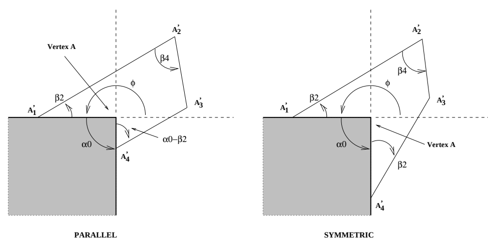

Figure 3: Four Simple Vertex Compensation Structure Parameterizations

that form a valid compensation structure with 3 *simple* vertices [1]. The grayscale in the plot corresponds to the distance between the the desired vertex, A, and the tip of the compensation structure, A_1. Once a point in the plot is chosen, the values of β_2 and β_3 are specified. The single convex compound vertex is thus replaced by three simple vertices with intra-vertex distances of infinitesimal length. As the simulation for these simple vertices is run in reverse time the size of these planes grow forming the necessary compensation structure [1].

This basic approach is extended to compensation structures that have four vertices and are parameterized by two scalar values. Figure 3 shows subclasses of a generic four vertex compensation structure that have parallel and symmetric side angles. The values of β_2 and β_4 corresponding to valid compensation structures is shown in Figure 4, where the dark areas correspond to compensation structures with 4 simple vertices [10].

TIMING MODEL

The compensation structures in the previous section contained 3 or 4 vertices that were all of type *simple*. This section explores methods to derive compensation structures that may have *compound* vertices. By definition, a *compound* vertex has has appearing planes as the etch begins. Therefore, a *compound* vertex formed by a

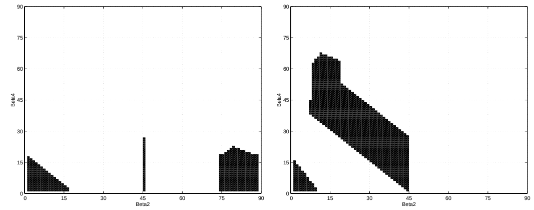

Figure 4: $\beta_2\beta_4$ Plots for Four Simple Vertex Compensation Structures

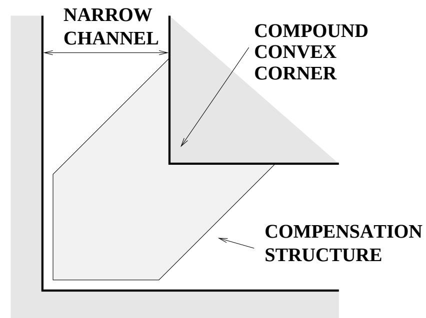

Figure 5: Compensation Structure, after ref:zhang96

synthesis method must have those appearing planes disappear exactly at the end of the "reverse simulation". As discussed in [1], [10], the topological evolution of the "reverse simulation" can be altered by inserting appropriate planes during the synthesis procedure.

The timing model proposed in this section parameterizes these topology bifurcations and encodes the shape of a compensation structure in a system of equations. Once the precise orientation of the geometry and etch process parameters are known, the equations are solved to determine the time and location of the topology changes in order that *compound* vertices are formed appropriately.

In [11], [7], compensation structures are discussed for use in narrow channels, Figure 5. While a formulation is provided to modify the structure for different etch rates, the guidelines are very application specific. That is, the formulation does not allow for changes in the principle rate directions (eg. $\langle 410\rangle$ to $\langle 310\rangle$), or tradeoffs in structure width and length.

What follows encodes the compensation structure found in [7] in a general formulation that can be optimized based on the designers needs. Further, the process demonstrates how any compensation structure can be generalized.

First the method of the previous section is used to choose a starting point. Figure 2 shows the selection of simple 3 point structures available for this vertex. Since the timing model relies on topology modification and ultimately on the structure of appearing and disappearing planes, no planes can be added to the reverse simula-

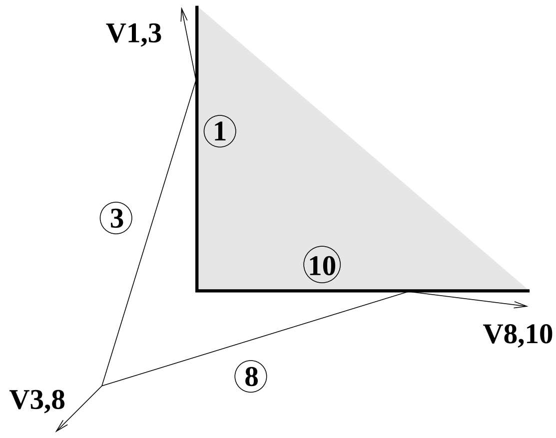

Figure 6: Basic 3 Point Compensation Structure.

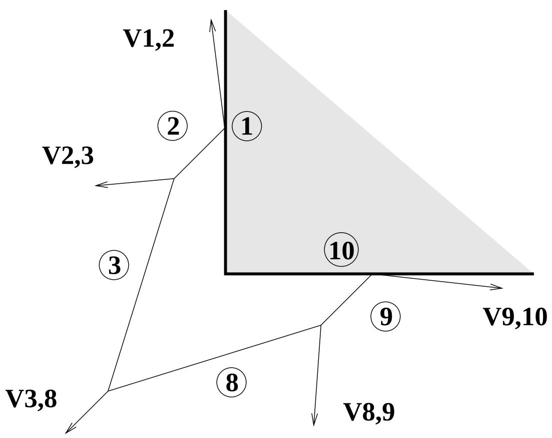

Figure 7: Insert ⟨100⟩ planes at time, $-t_1$

tion that will not reappear during etching. Therefore, the selection of points from Figure 2 is restricted to the dominant etch planes. Here, the ⟨310⟩ planes are chosen and inserted into the topology, Figure 6. Moving along the reverse simulation in time, ⟨100⟩ planes are inserted at time t_1, Figure 7, (planes 2 & 9).

Similarly at time $-(t_1 + t_2)$, ⟨310⟩ planes 5 & 6 are inserted in the topology, Figure 8. Note that each of these planes is selected because of it's local dominance in the etch rate diagram [10]. Therefore, in reverse time the plane will grow, but during the forward etch the plane will shrink, disappearing at time, $-(t_1 + t_2)$.

The last step is to insert ⟨110⟩ planes at time $-(t_1 + t_2 + t_3)$, Figure 9. The digram shows that as the reverse etch proceeds for an additional time t_4, $V_{4,5}$, $V_{5,6}$, and $V_{6,7}$ intersect to form a the *compound* corner of the compensation structure. For the method to be valid, the total desired etch time, T, must equal the sum of the increments, $t_1 + t_2 + t_3 + t_4$.

To solve for each of the intermediate times, each of

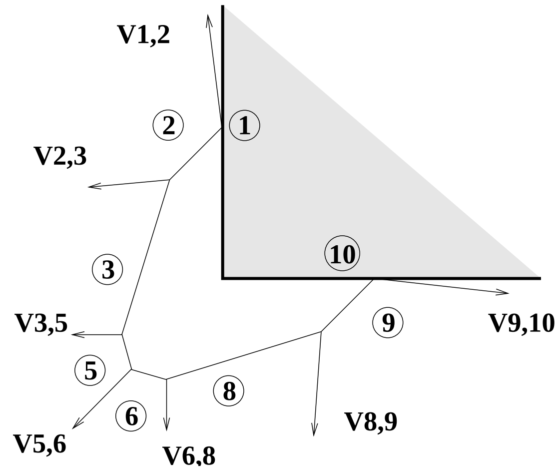

Figure 8: Insert ⟨310⟩ planes at time, $-t_2$.

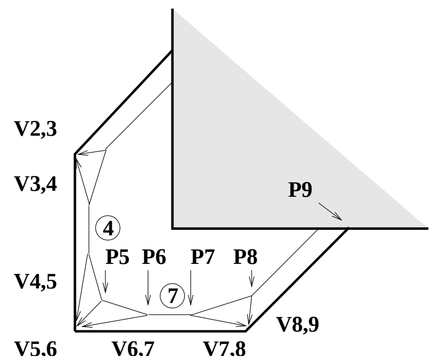

Figure 9: Insert ⟨110⟩ planes at time, $-t_3$.

the vertex velocities is first derived [10].

$$V_i = r_i \cdot \hat{n}_i + [\frac{r_{i+1} - r_i \hat{n}_i \cdot \hat{n}_{i+1}}{\hat{\tau}_i \cdot \hat{n}_{i+1}}] \cdot \hat{\tau}_i \qquad (1)$$

where r_1', $\hat{n}_1'$, and $\hat{\tau}_1'$ are the etch rate, normal, and tangent unit vectors of the appearing plane at vertex i.

The position of each vertex during the etch evolution is expressed as:

$$\begin{aligned} P_5 &= V_{3,8}\ t_1 + V_{3,8}\ t_2 + V_{5,6}\ t_3 + V_{5,6}\ t_4 && (2) \\ P_6 &= V_{3,8}\ t_1 + V_{3,8}\ t_2 + V_{6,8}\ t_3 + V_{6,7}\ t_4 && (3) \\ P_7 &= V_{3,8}\ t_1 + V_{3,8}\ t_2 + V_{6,8}\ t_3 + V_{7,8}\ t_4 && (4) \\ P_8 &= V_{8,10}\ t_1 + V_{8,9}\ t_2 + V_{8,9}\ t_3 + V_{8,9}\ t_4 && (5) \\ T &= t_1 + t_2 + t_3 + t_4 && (6) \end{aligned}$$

where P_k is the position of vertex k, $V_{i,j}$ is the velocity of the vertex formed by planes i & j, and t_n is the etch time, Figure 5 - 9.

For this example, the compensation structure is symmetric, therefore only $P_5 \rightarrow P_8$ are examined. The relation to determine the etch time are given by: $P_5 = P_6$

(plane 6 disappearing) and $P_7 = P_8$ (plane 8 disappearing). Note that since planes 6 & 8 are locally dominate planes for convex vertices, they will appearing immediately as the etch commences. From eqs. 2 & 3:

$$P_5 = P_6 \rightarrow t_3 = \alpha\ t_4 \tag{7}$$

where α is a function of the etch rates. The second relation ($P_7 = P_8$) with eqs. 6 gives:

$$[A] \begin{pmatrix} t_1 \\ t_2 \end{pmatrix} = \vec{B}(T) \tag{8}$$

Due to the symmetries involved, matrix $[A]$ is singular which allows another degree of freedom in the specification. Since the channel width is to be minimized, $\min(P_8 \cdot \hat{y})$ will be used to resolve the extra parameter. Eq. 5 can be rewritten using eqs. 6 & 7 as $P_8(t_1, t_2)$. The minimum corresponds to $t_2 = 0$, thus planes 2,5,6, & 9 are inserted at the same time. Eq. 8 can then be solved for t_1 as a function of the etch Time T.

For Rate $\langle 110 \rangle = 1 \mu m/\mathrm{hr}$, Rate $\langle 310 \rangle = 60 \mu m/\mathrm{hr}$, and Rate $\langle 100 \rangle = 50 \mu m/\mathrm{hr}$: $t_1 = 0.1856\ T$, $t_2 = 0$, $t_3 = 0.6076\ T$, $t_4 = 0.2069\ T$.

SIMULATION

The above compensation structure was verified in [7], and Figure 10 shows a simulation of the etching using the SEGS simulator (http://micron.me.tuns.ca) [3], [12].

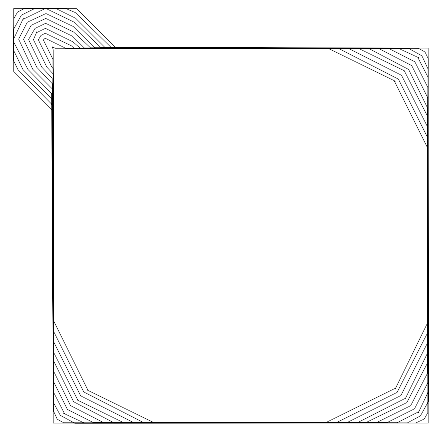

Figure 10: Simulation Results of Computed Compensation Structure, Other 3 Corners Uncompensated

CONCLUSIONS

The μCAM synthesis method for photolithographic mask layout for bulk etching has been extended to allow compenstation strucutures that contain *compound* vertices. The method is general an has been demonstrated to encode existing point solutions and allow for their modifications.

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