A Framework for Mask-Layout Synthesis Implementing a Level Set Method Simulator

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Abstract

Recently, evolutionary methods have been developed to automate MEMS mask-layout synthesis [3]–[6]. These design synthesis methods are iterative searches in which each iteration consists of mask-layout modification, determination of etched shape via an *arbitrary* 3-D etch simulator, and similarity evaluations between the etched shape and the desired shape, which is used to guide modification. The work described here differs from previous work in that a framework is developed for mask-layout synthesis that implements level set methods as the 3-D etch simulator.

Keywords: mask-layout synthesis, evolutionary algorithms, level sets

1 Introduction

Automation of MEMS mask-layout synthesis allows the MEMS designer to focus on device shape and function, rather than on device fabrication, resulting in shorter design cycles and more robust designs, analogous to the benefits accrued in VLSI design where circuit layout is automated. To this end, a tool, based on evolutionary algorithms, has been developed to automate mask-layout synthesis [3]–[6]. The evolutionary algorithm is a search technique that repeatedly modifies a set of candidate solutions depending on each candidate's relative 'performance'. In this case, performance is taken as the similarity between the desired shape and the shape that results after etching the candidate mask. Hence, a robust and accurate forward simulator is required to simulate the etching process. Previous work has implemented SEGS, a geometrically accurate 3-D bulk etch simulator, as reported in [2]. However, there are two notable drawbacks of using SEGS. First, it is difficult to implement multiple etchant processes and, second, SEGS is unable to simulate growth/deposition processes. These drawbacks result in a much smaller set of feasible shapes, thereby reducing the potential utility of automated mask-layout synthesis. Level set methods, as compared to SEGS, do not have these drawbacks; albeit, at the expense of longer running times.

In adopting level set methods as the 3-D etch simulator, a new framework for the search process is developed and reported here. The paper is organized to: (i) briefly introduce level set methods, (ii) develop a general n-D etch rate modeller, (iii) discuss a level set evolutionary algorithm, (iv) present preliminary results, and (v) conclude with a summary and discussion of future work.

2 Brief Introduction to Level Set Methods

Level set methods are algorithms for tracking the evolution of interfaces [7]. The approach taken is to represent the interface as the zero level set, or contour, of a scalar, higher dimensional function, $\phi(x(t), t)$, where $x(t)$ represents the coordinate space and t is time. Given the speed in the normal direction, F, the evolution of ϕ takes the form of the following initial value problem

$$\phi_t + F|\nabla(\phi)| = 0, \text{ given } \phi(x, t = 0).$$

The level sets for the initial condition can be generated from the initial, zero level set, or interface, which is known at $t = 0$. Since the PDE cannot be solved analytically, a numerical finite difference scheme is implemented. In a finite difference scheme, spatial and time coordinates are discretized into grid points such that, through difference calculations between grid points, the necessary gradients can be approximated. From here, the evolution of $\phi(t)$ is approximated and the movement of the interface can be found by extracting the zero level set at any time. Due to the required discretization of space and time, the accuracy of the level set method depends on the resolution of discretization. Furthermore, the number of grid points required scales according to the dimension of the interface. Thus, level set methods are often slow in higher dimensions, since the number of operations scales with number of grid points. For a more detailed discussion of level set methods see Sethian [7].

3 Etch Rate Modelling

Level set methods, along with all etch simulators, require accurate knowledge of the etch rate diagram. In most instances, however, only a few etch rates and directions are known for any given etchant and substrate. To complete the etch rate diagram, an etch rate model is needed. For accuracy, the etch rate model must interpolate through the given etch rates and directions while maintaining C_0 continuity (C_1 is too high, as empirical studies have shown cusps in etch rate diagrams). A simple etch rate model having these properties is developed here for the 2-D case, then is extended to the 3-D case. Moreover, results of the developed etch rate model show good agreement with empirical results and other, less general, etch rate models [2]. Note, that the problem of etch rate modelling is equivalent to function interpolation over a circle in 2-D and a sphere in 3-D if the directions are normalized to equal magnitude.

3.1 2-D Etch Rate Modelling

The developed etch rate model can be thought of as a 'mixture of experts' approach in which each expert is only responsible for interpolation of etch rates over a range of directions. These 'experts' are formed in the following manner. First, given a set of etch rates and directions, the directions are normalized to unit length. The directions are then connected in such a way that a convex polygon inscribes the unit circle. Each edge of the polygon constitutes an expert and interpolates only for the directions lying within the boundaries of its endpoints. A simple method of determining which expert is active is to normalize the desired direction to unit length and find the polygon edge that is intersected by the ray emanating from the origin to the normalized direction. The point of intersection is then used in a linear interpolation to determine the etch rate. This process is shown graphically in Figures 1–3 for etch rates of 5 for the (10) family of directions and etch rates of 1 for the (11) family of directions.

3.2 3-D Etch Rate Modelling

The 3-D case is a simple extension of the 2-D case. For example, the directions are normalized to the unit sphere rather than the unit circle. These directions are triangulated in such a way that the unit sphere is inscribed by a convex polyhedron. Each triangular facet of the polyhedron then constitutes a expert whose active range consists of those directions that intersect it. The etch rate is determined by linear interpolation over the expert, which ensures C_0 continuity.

4 Level Set Evolutionary Algorithm

Since a mask is the zero level set of a 2-D scalar function and only the initial 2-D scalar function is required, each candidate solution is encoded as a 2-D grid of real values ranging from -1.5 to +1.5. Initial population members are generated by randomly assigning each grid point a value within this range.

The search operators are mutation and crossover. Mutation, which is similar to a gradient descent opera-

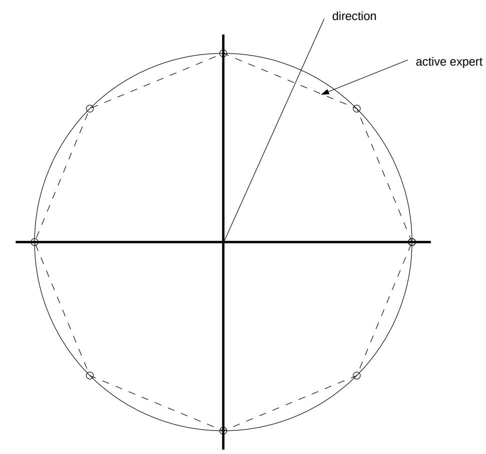

Figure 1: Expert generation and determination of active expert.

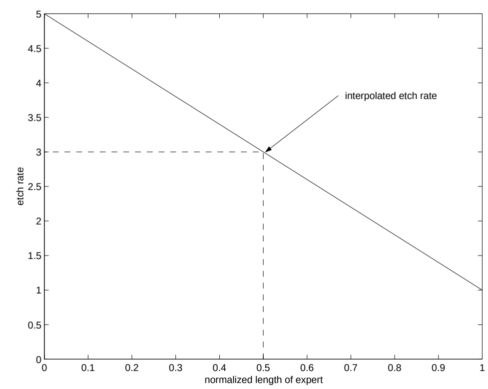

Figure 2: Linear interpolation of etch rate.

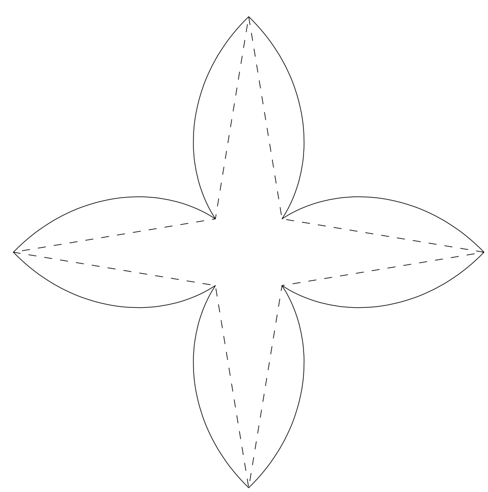

Figure 3: The complete etch rate model (–) and a naive etch rate model(- -).

tor, perturbs each grid point with some small probability. Crossover, which seeks to preserve common features between two candidate solutions, compares two candidate solutions and modifies grid points only if the same grid points of the two candidates have different signs. Also, a regularization operator is included to remove isolated grid points whose neighbors are all of opposite sign. A standard roulette wheel selection strategy is imposed [1].

The fitness function is a shape similarity measure for 2-D level sets. Since the interface is determined by the zero level set, grid points can be denoted as being inside or outside of the interface (*i.e.*, > 0 or < 0). The shape similarity measure is taken as the intersection of the inside grid points divided by the union of the inside grid points. Thus, values closer to 1 are more similar. To extend this to the 3-D case, the fitness is the sum of shape similarities for different depths.

There are two advantages of using a level set representation in the evolutionary algorithm as compared to the vector-type representation used in previous work. First, there is no intermediary step required to implement the level set simulator and, second and perhaps more importantly, mask-layouts consisting of multiple polygons and enclosed polygons can be synthesized.

5 Preliminary Results

Preliminary results are presented for 2-D shape synthesis. This is equivalent to a mask-layout synthesis that has no etch step. The level set is a 64x64 grid and the algorithm is allowed to run for 500 generations. Convergence of the algorithm is shown in Figure 4, while Figure 5 shows the best initial population member. The target shape and best evolved shape are displayed in Figure 6. Note that the best evolved shape can be improved by passing the level sets through a smoothing filter.

Results for mask-layout synthesis having etch steps have yet to be completed. The reason for this is that the current level set simulator is not fast enough. A 64x64x64 level set simulation with 50 time steps requires roughly 5 minutes of computing time on a Sun Sparc10. Considering that the evolutionary algorithm has a population of 15 and requires roughly 200 generations to obtain reasonable results implies that synthesis would take around 250 hours or 10 days. Work is currently being done on improving the efficiency of the level set simulator.

6 Summary and Future Work

The groundwork for an automated mask-layout synthesis tool implementing a level set method for 3-D etch simulation has been developed in this paper. An accurate etch rate modeler is also developed, as it is essential for use in any accurate bulk etching simulator.

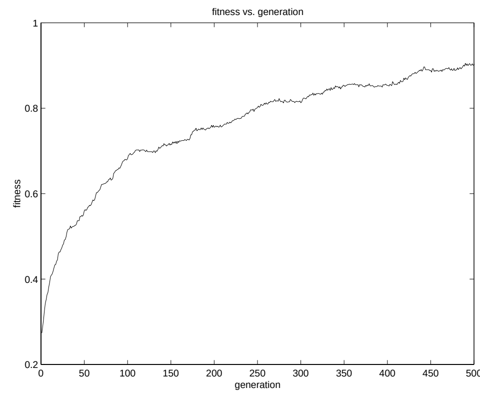

Figure 4: Fitness vs. generation

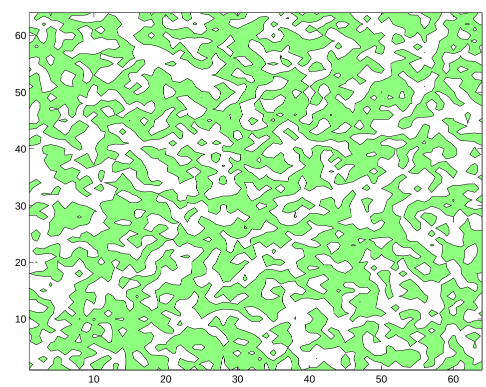

Figure 5: Best shape for initial population

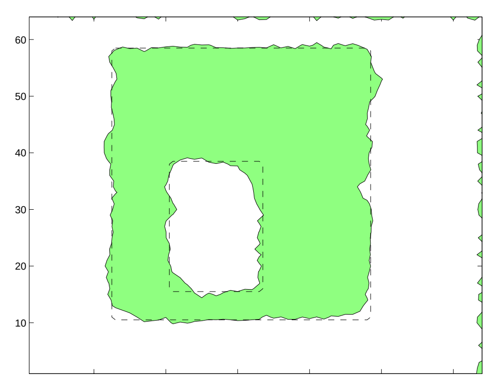

Figure 6: Best shape for generation 500 and desired shape (- -)

Preliminary results utilizing the developed framework are promising with good 2-D shape synthesis. However, mask-layout synthesis in which etch processes exist are currently infeasible due to running time of the level set engine. Work is currently being done on improving the efficiency of the engine and in alternative search procedures such as simulated annealing.

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