Computational Performance of Level Set Methods for Etching, Deposition, and Lithography Development

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Overview

The application of level set techniques to problems two and three dimensional surface evolution in etching, deposition, and lithography development have been described in a series of papers, see [1,6]. The techniques are robust, accurate, unbreakable, and extremely fast, and can be applied to highly complex two and three dimensional surface topography evolutions in [1,6]), including sensitive flux/visibility integration laws, simultaneous etching and deposition, effects of non-convex sputter laws demonstrating faceting, as well as ion-sputtered re-deposition and re-emission with low sticking coefficients, and surface diffusion.

In this paper, we will focus on efficient algorithms for some of the most complex problems, and discuss the computational requirements and performance of these techniques.

Level Set Techniques

Level set techniques [5] numerically approximate the equations of motion for a propagating front by transforming them into an initial value partial differential equation, whose unique solution gives the position of the front. Corners and cusps are naturally handled, and topological change occurs in a straightforward and rigorous manner with no special user intervention. More precisely, level set methods take the perspective of viewing the moving interface as the zero level set of a function $\phi(x, t = 0)$. An evolution equation for the interface moving with speed F in its normal direction is given by [5,6].

$$\phi_t + F|\nabla\phi| = 0, \qquad \phi(x, t = 0) = given. \tag{0.1}$$

The surface $\phi = 0$ corresponding to the propagating hypersurface may change topology, as well as form sharp corners, Upwind finite differences lead to a numerical scheme to approximate the solution, and intrinsic geometric properties (normal vectors and curvature) are easily determined from the level set function. The formulation is unchanged for propagating interfaces in three dimensions. Two additional enhancements bring speed to this approach; (1) a *narrow band* implementation, which confines the labor to thin band, making the technique the same work as string and cell methods, [1], and (2) a *fast marching method*, applicable to problems in lithography development and isotropic etching/deposition based on a fast heap sort algorithm [7].

In this paper, we will discuss details of

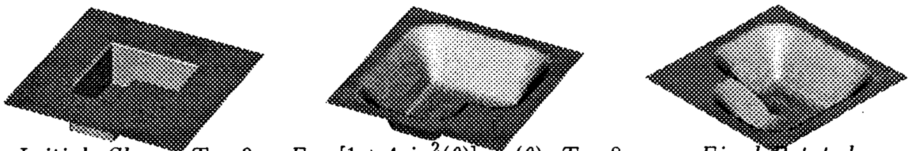
- Fast algorithms for computing visibility of three-dimensional surfaces.
- Fast techniques for computing the matrices in the integral equations for the total flux.
- Adaptive meshing to efficiently represent the surface and build the interaction matrix.

Examples: Deposition and Etching

We provide two examples of the application of level set techniques:

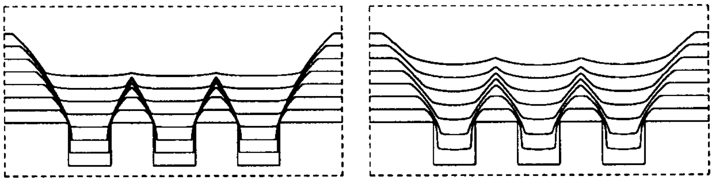
First, we show the effects of ion-milling of a saddle surface; showing the effects of a non-convex speed law, where θ is the angle of the surface normal with the vertical. Note the sharp faceting in the profile.

Next, in Figure 0.2 we show a combination of ion-milling (using a non-convex sputter law), and ion-induced sputtered re-deposition, together with conformal deposition and direct deposition. In both calculations, the direct deposition term includes the effect of visibility, and the conformal deposition is isotropic; the goal is to model experimental evidence in [2,3,4]. In Figure 0.2a, the ion-induced sputter re-deposition coefficient is set to zero. In Figure 0.2b, which requires the solution of the matrix integral equation, re-deposition occurs during the etching process, resulting in considerable rounding of the sharp corners.



Initial Shape : $T = 0$ $F = [1 + 4\sin^2(\theta)]\cos(\theta)$ $T = 8$ *Final Rotated*

Figure 0.1: Downward Saddle Under Ion Milling



$Fig.0.2a$, No re-deposition $Fig.0.2b$, With re-deposition

Figure 0.2: Combination of ion-milling, direct deposition and re-deposition

Timings and Computational Requirements

Below, we provide current timings of our techniques; all calculations are for a Sparc 10. As can be seen, the fast marching method for photolithography development is extremely fast; 3D development on a 80 × 80 × 80 grid is less than 3 seconds; almost all two-dimensional problems are on the order of one minute for complex problems; the three-dimensional problems involving re-deposition and re-emission require considerably more effort. (The figures marked "N.A." are currently being computed.).

Grid Size	50^2(2D)	100^2(2D)	40^3(3D)	80^3(3D)
Lithography	.0016 secs	.060 secs	.37 secs	3.0 secs
Etching with Visibility	1.7 secs	10.9 secs	66 secs	17 min.
Etching + Re-deposition (Visibility between all points of surface)	6.2 secs	64 secs	36 min	120 min
Etching + Deposition + Re-deposition + Re-emission (Solving Integral Eqn. for Total Flux)	10.2 secs	110 secs	N.A.	N.A

We will discuss our work on fast multipole and adaptive meshing for efficient three-dimensional algorithms.

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