# Comprehensive Simulation of E-beam Lithography Processes Using PROLITH/3D and TEMPTATION Software Tools

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## *Abstract*

Because of the complexity of physical mechanisms and chemical reactions involved in e-beam patterning, there is no single software tool that is capable of modeling all processes. A comprehensive simulation approach for the entire e-beam lithography process is presented. This is possible by combining the simulation strengths of the TEMPTATION (Temperature Simulation) and PROLITH/3D software tools. Compatibility of the two software tools was developed by matching internal formats of intermediate simulation data. Monte Carlo simulation of a single point energy distribution, proximity effects, local temperature rise and corresponding change of resist sensitivity, absorbed energy in exposure of a pattern at given condition, post-exposure bake, acid diffusion in the resist, and resist development were simulated. The simulation was followed by analysis of resulting resist profile, including critical dimensions, wall slope, and residual resist thickness. Examples of simulations demonstrated use of this comprehensive simulation approach.

**Keywords:** Electron Beam Lithography Simulation, PROLITH/3D, TEMPTATION

## 1. INTRODUCTION

Simulation of Electron Beam Lithography (EBL) is a complex task that includes precise modeling of physical and chemical effects like electron scattering in multilayer solids, resulting proximity effects, resist heating, chemical exposure of the resist, post-exposure bake including acid diffusion and reaction (for a chemically amplified resist), resist development, etc. At this moment, there is no single software tool that is capable of modeling all these processes. In this paper we present a comprehensive simulation approach for the entire e-beam lithography process. This is possible by combining the simulation strengths of the TEMPTATION (Temperature Simulation) and PROLITH/3D software tools.

The TEMPTATION software was originally developed for simulation of the temperature rise in EBL and was upgraded to simulate also the Monte-Carlo point spread function of electron scattering and dose variation due to the combined influence of proximity effects and resist heating. It has been experimentally verified and has demonstrated good accuracy and high speed of simulation.[1] By inputting an exposure pattern (a series of flashes for vector scan e-beam lithography), current, dose, and material properties of the resist and substrate, the temporal variation of temperature can be determined, as well as an "effective" exposure dose including the effect of changing resist sensitivity with temperature.

PROLITH/3D is an industry standard tool for simulation of optical lithography including light propagation in the resist, diffusion and reaction during resist baking, and resist development. It is also capable of providing detailed analysis of the resulting resist profiles in two and three dimensions.[2]

The compatibility of these two software tools involved matching internal formats of data that are the results of intermediate steps of simulation. Example simulations presented here demonstrate the successful approach of the use of this combined simulation tool.

20th Annual BACUS Symposium on Photomask Technology, Brian J. Grenon, Giang T. Dao, Editors,
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## 2. SIMULATION PROCEDURE

In this work, TEMPTATION was used to simulate vector scan electron beam lithography through exposure to produce and effective absorbed dose in the resist, including:

- point spread function using Monte Carlo module;
- flash-by-flash exposure of a pattern;
- energy distribution over the pattern due to proximity effects;
- temperature rise during E-beam exposure;
- resist sensitivity change due to local resist heating;
- effective absorbed energy in the resist as a result of proximity effects and resist heating.

The resulting file of effective absorbed energy was transformed to the format identical to that needed for input into the PROLITH/3D exposure module. PROLITH/3D accepted the file as an intermediate result of simulation of energy deposited in the resist. PROLITH/3D was used then to simulate:

- resist development using one of the embedded models;
- analysis of resist profile including critical dimensions, residual resist thickness, wall slopes, etc.

Optionally, the post-exposure bake step for conventional or chemically amplified resists can also be simulated in PROLITH/3D.

This approach allowed for simulation of a complete e-beam lithography process following by metrology of the resulting resist image including the critical dimension (CD). Thus, the combination of TEMPTATION and PROLITH/3D allows the investigation of the effects of resist heating, including the impact of flash order, on the final resist profile.

## 3. RESULTS OF SIMULATIONS

### A. "Frame" pattern

For the first simulation example, 20 kV variably shaped flashes at 20 A/cm$^2$ current density and 10 $\mu$C/cm$^2$ exposure dose were used. A photomask substrate was used in all simulations consisting of 400 nm resist on 80 nm chrome on bulk glass. The test pattern was a 0.5 $\mu$m dark square inside 1 $\mu$m thick frame. The order of exposure is shown in Figure 1a. The temperature rise due to exposure of the pattern is presented in Figure 1b, with the bar on the right showing values of the temperature in degrees C. These values are the averaged temperature rise over the exposure time of each flash. An effective absorbed energy in the resist as a result of the combined influence of proximity effects and resist heating is shown in Fig. 1c, and the resist image after development is shown in Fig. 1d.

Note that although the original pattern is symmetric, the temperature distribution, energy distribution, and corresponding resist profile are highly asymmetric due to resist heating. The writing history and non-uniform temperature rise result in this kind of pattern distortion. Also, pictures of the temperature distribution and absorbed energy are not similar because of the complicated contribution of backscattered electrons to the total exposure dose. Backscattered electrons from different flashes reach the resist when it is of different temperature. This makes their contribution to absorbed dose a complicated function. TEMPTATION handles this problem using a heat function that was described in Ref. 3.

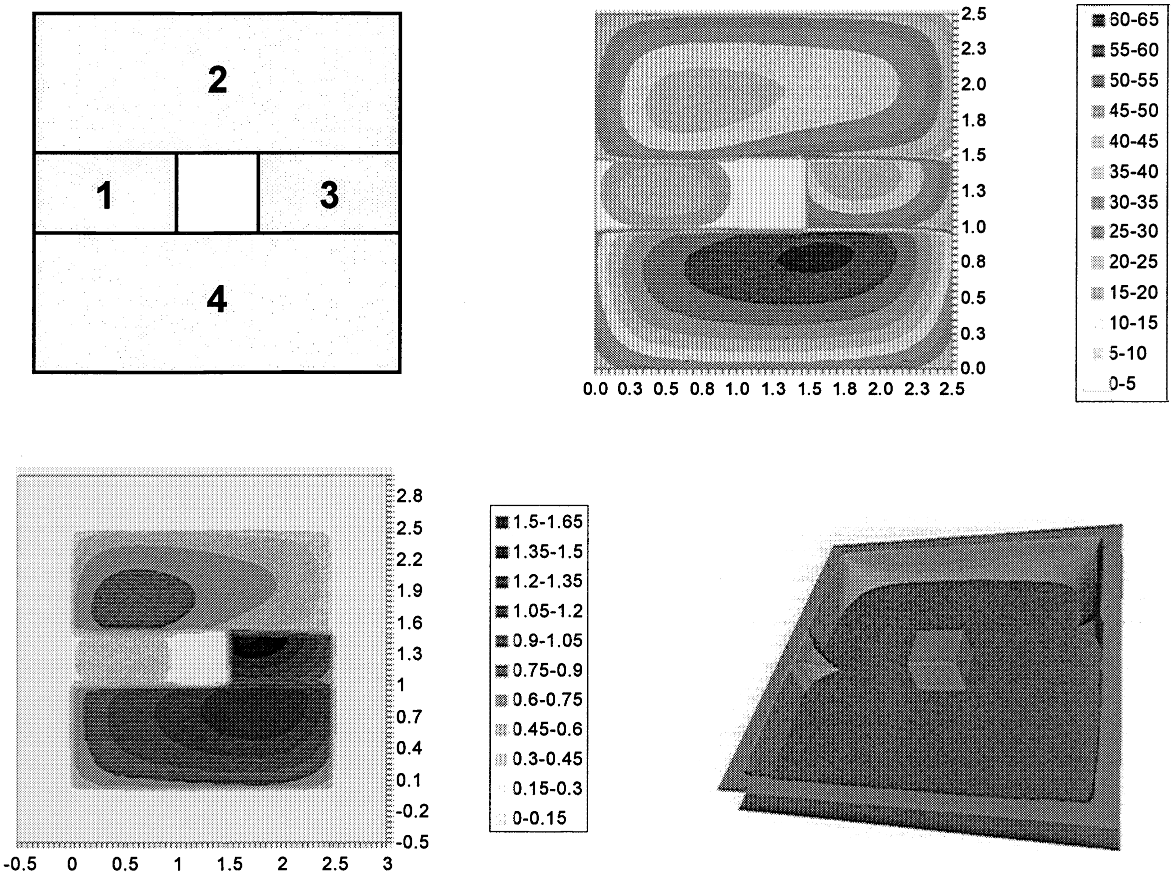

Figure 1. Test pattern: 0.5 μm square inside 1 μm thick frame. a) e-flashes and order of their exposure; b) temperature rise in exposure of the pattern; c) absorbed energy due to proximity effect and resist heating; the energy is highly non-uniform due to local heating which depends on writing history; d) developed resist - asymmetric distortion.

### 3.2. Mask with OPC features

This pattern was an array of 1 x 2.5 $\mu m^2$ bars that involves optical proximity correction. Serifs, 0.3 x 0.3 $\mu m^2$ squares, were added at the corners, as shown in Fig. 2a. A subfield of 32 x 32 $\mu m^2$ was filled with these features. A 50 kV beam at 50 A/cm$^2$ delivered a dose of 40 μC/cm$^2$.

The temperature rise is highly nonuniform. The developed resist is shown in Fig. 2c as a resist on chrome and as a 3-D image of the resist, Fig. 2d. Considerable distortion of the pattern was found in both linewidth and size of OPC features. By varying beam current density or other conditions, it is possible to find regimes of exposure when distortions will be reduced to an acceptable level.

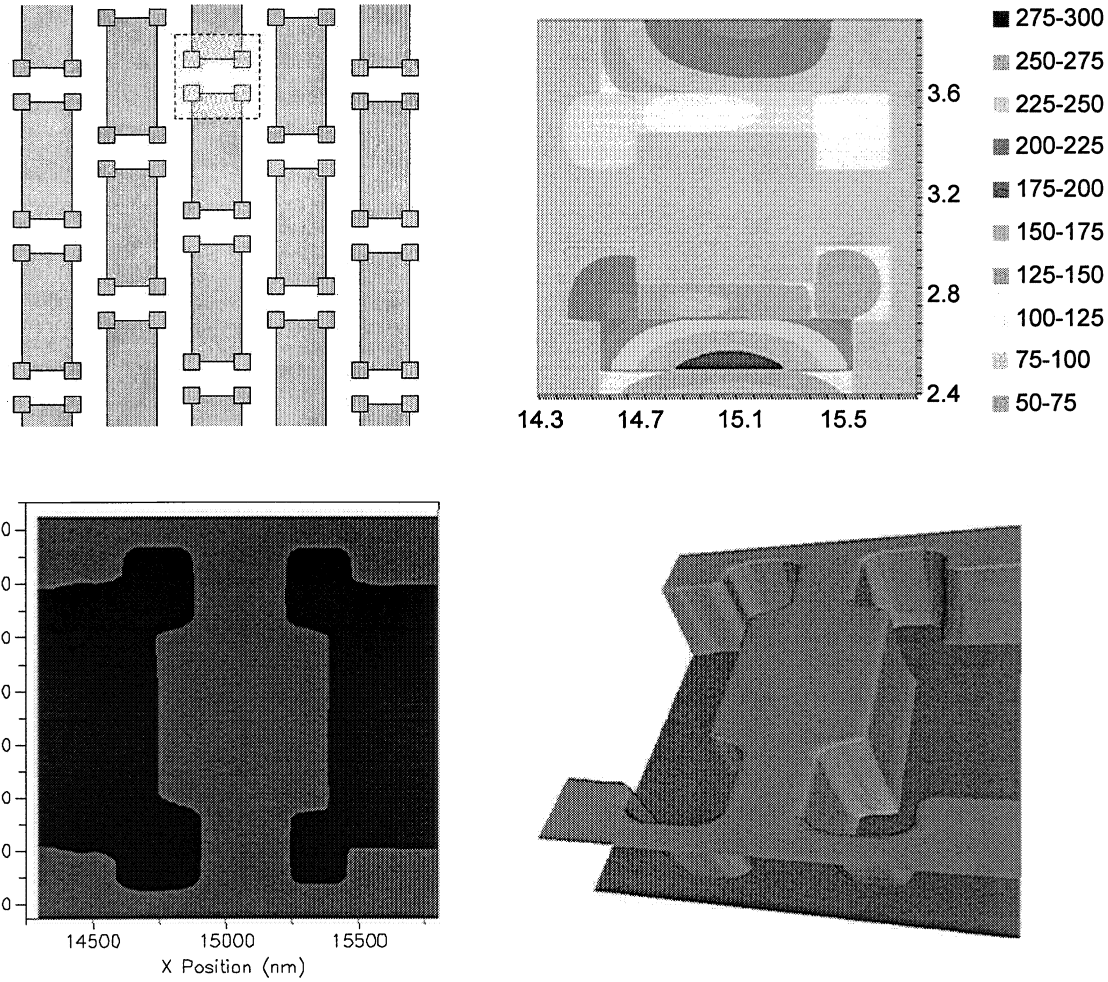

Figure 2. Simulation of OPC features on photomask. a) pattern with 0.3 μm OPC features; area of simulation is shown; b) temperature rise over the area regarding decomposition by flashes; c) 2-D picture of resist left on chrome; d) 3-D resist profile. Distortions of linewidth and size of OPC features are significant.

### 3.3. "Gate" type pattern

The "gate" pattern was a 0.5 μm bright line surrounded by large bars at 0.5 μm distance. The order of exposure was varied: the gate was exposed either the first or the second after the pad, see Fig. 3a. An area of resist development simulation using PROLITH/3D is shown by the dashed square. This simulation used a 20 kV exposure at 7.5 $\mu C/cm^2$ exposure dose, 3.75 $A/cm^2$ current density, with a maximum flash size of 2 μm. The temperature rise for the two orders of exposure is shown in Fig. 3b and 3c. When the pad was exposed first (3b), the gate was exposed over a preheated area. The effect on CD was measured: for equal development, the CD variation between the two orders of exposure was found to be 38 nm.

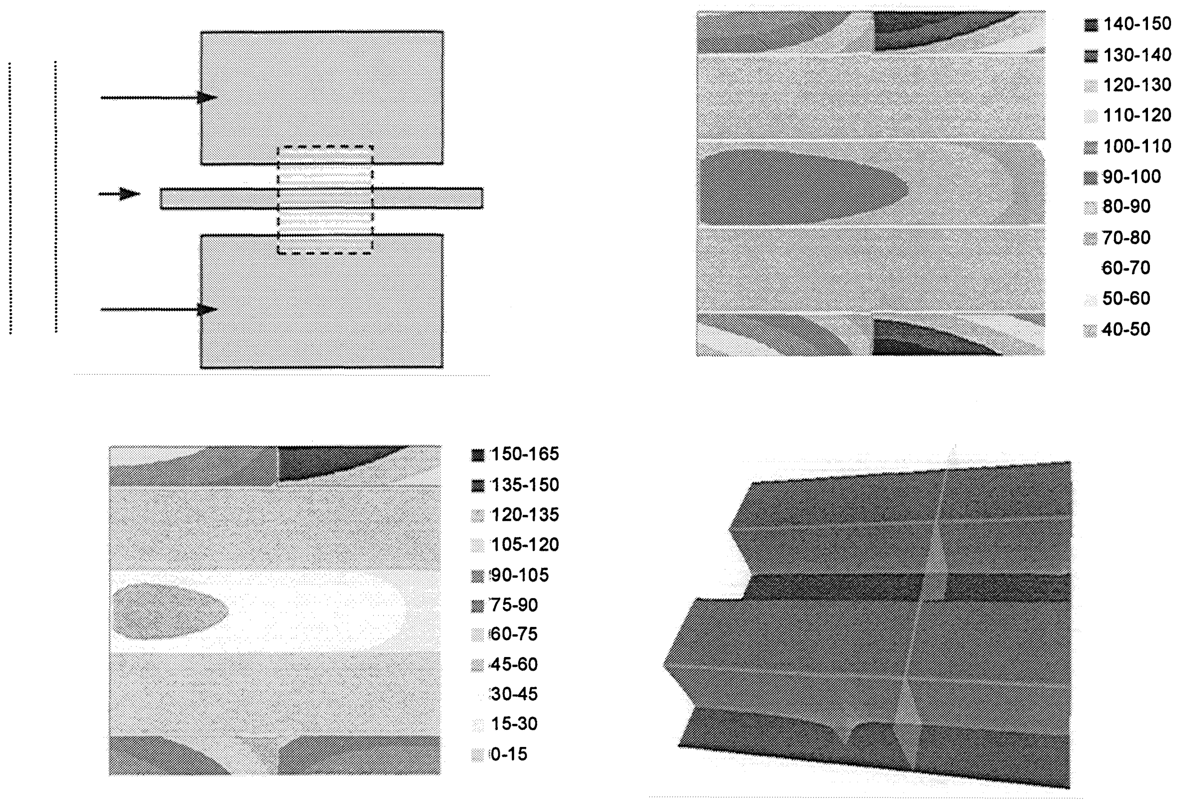

Figure 3. a)"Gate" test pattern and two orders of its exposure. Temperature rise when the gate was exposed first b), second c). Resist image and metrology plane to determine CD, residual thickness, and edge slope d).

## 4. CONCLUSIONS

Compatibility of the PROLITH/3D and TEMPTATION software tools was developed. The combination of the two software tools allowed for detailed, comprehensive modeling of EBL exposure and resist processing and prediction of CD error at chosen parameters of EBL.

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