Gray-Scale Electron-Beam Lithography

Yin Ian Yang, Electrical Engineering, University of Virginia
NNIN REU Site: Microelectronics Research Center, Georgia Institute of Technology

NNIN REU Principal Investigator: Dr. Kevin Martin,
Microelectronics Research Center, Georgia Institute of Technology
NNIN REU Mentor: Dr. Raghunath Murali, Microelectronics Research Center, Georgia Tech
Contact: kevin.martin@mirc.gatech.edu, yy2c@virginia.edu

Abstract:

Gray-scale lithography is the patterning of 3-D surface topographies. Its relevance is a result of a demand for applications in optics and micro/nano-electromechanical systems (M/NEMS). In optics, various geometries for gratings or lenses require a gradient or sloped profile. In M/NEMS, 3-D structures allow for flexibility in mechanical motion.

Our goal, through the JEOL JBX-9300FS e-beam lithography (EBL) system, is to produce a blazed grating. The characteristic of such a grating is high sensitivity to a peak wavelength of light upon incident polychromatic light. Our specifications require a blazed angle of 1.1°, groove period of 11 μm, and a depth of 220 nm. With these specifications, the device will be used in a spectrometer in the very-near infrared (VNIR) range [1].

Introduction:

The key notion behind gray-scale lithography is having control over the incident energy. Varying this energy across the resist produces differential solubility rates and, therefore, differences in resist depth. In EBL, incident energy is indicated by dose (charge per unit area). The EBL system features a serial, direct-write beam that pixilates the pattern; the entire pattern is exposed one pixel at a time. This allows for direct control over the dose applied to each pixel, a concept known as *shot modulation*.

Limitations of EBL arise out of electron scattering within the resist (forward scattering) and substrate (backscattering) layers. The deposited energy profile is approximated by the point spread function [2]:

$$f(r) = \frac{1}{1+\eta}\left(\frac{1}{\pi\alpha^2}\exp(-\frac{r^2}{\alpha^2}) + \frac{\eta}{\pi\beta^2}\exp(-\frac{r^2}{\beta^2})\right)$$

Equation 1: Beam energy profile, termed proximity function in context of EBL.

Here, r is the radial distance from the point of beam incidence, α is the forward scattering parameter (typically small), β is the backscattering parameter (typically large), and η is the ratio of total backscattered to forward scattered electron energies. This energy spread leads to *proximity effects*: the incident pixel is underexposed while the remaining energy is distributed to surrounding pixels (Figure 1). Proximity effect correction is utilized to counteract these effects.

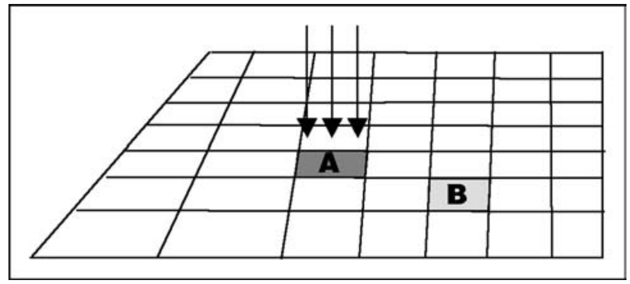

Figure 1: Exposure at pixel A affects pixel B, illustrating proximity effect.

Experimental Procedure:

To design the gratings, we took a single groove and divided its entire area into many, very thin rectangles. Along individual rectangles, dose was kept constant, while from rectangle to rectangle dose was varied (Figure 2). Essentially, we approximated each slope by a staircase pattern. The distance between pixels was denoted the shot pitch.

PMMA was the preferred resist because it exhibits low contrast. We obtained the contrast curve for 220 nm

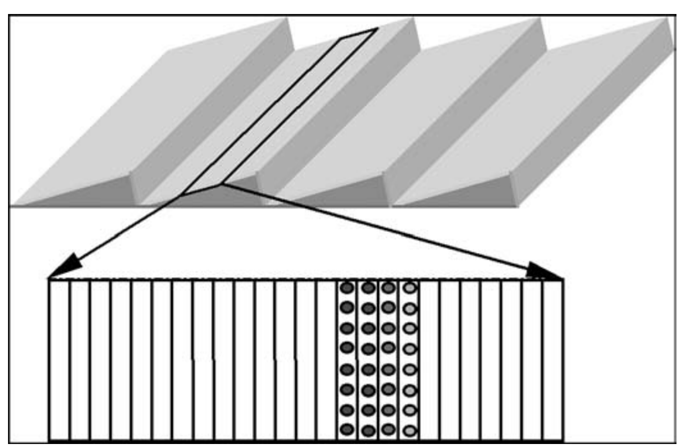

Figure 2: CAD file preparation.

thick PMMA resist on silicon, and map doses to our grating profile. The proximity correction algorithm determined the resultant physical profile from this dose profile. To achieve the desired profile, the algorithm adjusted doses accordingly. Optimization of the algorithm was accomplished by fine-tuning the three proximity function parameters. We held α and β constant and varied η. After exposure, PMMA was developed by a 1:1 solution of MIBK:IPA; characterization was performed using an atomic force microscope (AFM).

Initially, each groove was fabricated by a 100-step staircase pattern without proximity correction. This caused a groove at the edge to be underexposed in comparison to a groove in the middle. This was consistent with the proximity model because proximity effects are lower for a groove at the edge. This non-uniformity ultimately required us to utilize proximity correction.

Results and Conclusions:

The first few iterations with proximity correction produced overexposed grooves. We achieved the desired profile by settling on a negative η, but this was unphysical and led to even greater uniformity problems. We identified the fault as an oversight in our method for obtaining data for our contrast curve. This curve assumes an ideal energy distribution. If pixel A were to receive a dose of X, the measured depth corresponding to a dose of X should be measured at a location where exactly that amount of dose is applied. We cannot obtain this ideality but reproduce the situation by exposing a sufficiently large region (box) to include the full effects of backscattered electrons. Now, depth is measured at the center of the box rather than at the edge.

With a new contrast curve, we settled on a positive η. However, we also discovered that beam fluctuations affect exposure: a larger beam current leads to underexposure (all proximity effect parameters constant). The beam diameter and, as a result, α, is directly linked to beam current. Thus proximity correction is sensitive to beam fluctuations. The final iteration (Figure 3) used a 40 nm shot pitch, 1.3 nA current, and an η of 0.2. The grooves had a depth of 210 nm.

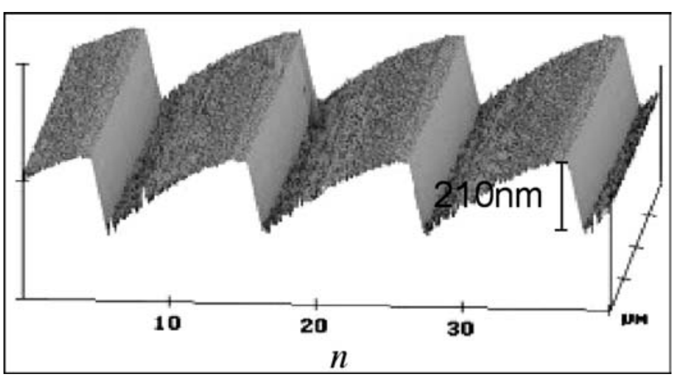

Figure 3: AFM image of final patter.

Preliminary roughness measurements were taken. Roughness was found to increase with increasing groove depth and increasing shot pitch. The best and worst case numbers were about 3 nm and 9 nm, respectively. As for pattern uniformity, there was a 15% difference between the middle and edge grooves when proximity correction was used; this is a drastic improvement over the 60% error in the uncorrected design. These characterizations reveal the importance of proximity correction.

Future Work:

For a given beam condition, there was good control over the design and the final profile could be predicted well by the proximity correction models. Once the beam fluctuated, proximity effect parameters had to be extracted for the new beam conditions. Therefore, finding the optimal proximity effect parameters for different beam settings would be a valuable addition to the project.

Acknowledgements:

I would like to thank my mentor Dr. Raghunath Murali for his support and guidance, my PI, Dr. Kevin Martin, our site coordinator Jennifer Tatham, Dr. James Meindl, NNIN and NSF for funding the research, the GSI group, and the clean room and administrative staff at MiRC.

References:

[1] J. Fisher, J. Antoniades, "A Hyperspectral Imaging Sensor for the Coastal Environment", Naval Research Laboratory.

[2] A. van de Kraats, N. Kikuchi, "Electron Scattering Effect in Electron Beam Lithography".