Wafer-Scale Fabrication of Single Domain Magnetic Nanostructures

2023 CNF REU Intern: Naomi Sharlotte Naranjo
Intern Affiliation: Mechanical Engineering, Cornell University

CNF REU Principal Investigator: Professor Itai Cohen; Physics, Cornell University

CNF REU Mentors: Melody Xuan Lim, Zexi Liang; Physics, Cornell University

Program & Primary Source of Research Funding: 2023 Cornell NanoScale Facility Research Experiences for Undergraduates (CNF REU) Program via the National Science Foundation under Grant No. NNCI-2025233

Contact: nsn25@cornell.edu, itai.cohen@cornell.edu, mxl3@cornell.edu, zl467@cornell.edu

Website(s): https://cnf.cornell.edu/education/reu/2023

Primary CNF Tools Used: ASML DUV Stepper, Oxford 82,
Gamma Automatic Coat-Develop Tool, SEM, AFM, P7 Profilometer

Abstract:

Single-domain magnets are critical to the development of untethered micromachines. To achieve single-domain behavior, these magnets must have a width of under 100 nanometers (nm). The current fabrication method of these magnets, electron-beam lithography, is both time and cost consuming. To address this, we developed a process to use Deep Ultraviolet (DUV) lithography as a more accessible alternative to the e-beam lithography process. Through precise etching of chromium on quartz photomasks, we can produce phase-shift photomasks with a 180-degree phase-shift, allowing for greater pitch density and depth of focus. Further improvements to the feature width in photoresist can be made by optimizing parameters on the ASML DUV Stepper. Our process successfully created features with a range of widths under the 100 nm threshold. Additionally, we characterized the optimal doses to achieve pitches ranging from 400 to 300 nm and control over the spacing between features.

Summary of Research:

Phase-shift photomasks are fully quartz masks with features etched to a specified depth such that there is a 180-degree phase shift of the light that passes through the etched area. This allows the light intensity to drop to zero at the boundary between the two different depth areas on the mask, leading to two features being defined on the wafer for each feature on the mask, increasing feature density and giving a larger process window.

The phase-shift mask fabrication process involved first using the Heidelberg Mask Writer DWL2000 to write a chrome on quartz mask and then using the CHF_3O_2 oxide etching recipe on the Oxford 82 etcher to etch the quartz on the mask to a desired depth of 248 nm. The etching process consisted of etching the mask for an initial five minutes and using the P7 Profilometer to calculate the chrome and quartz etching rates and remaining etch time. Once the final depth was reached, the chrome was etched off the mask and the final quartz depth was verified using an atomic force microscope (AFM).

Each image on the phase shift mask consisted of vertical alternating etched and unetched lines that were 100 µm long, with pitches ranging from 400 to 800 nm. Within each pitch, there were biases added to the width of the etched area, such that without bias the width of the etched and unetched lines were equal and with a positive bias the width of the etched line is greater than the unetched line while keeping the same pitch. This image was arranged into a 5 × 7 array on the mask, and S1813 photoresist was used to cover alignment marks and other features on the mask while etching one column of the array at a time.

The images were exposed on 4-inch wafers, that were coated with 62 nm of anti-reflective coating (ARC) and 300 nm of DUV210 photoresist using the Gamma Automatic Coat-Develop Tool. On the ASML DUV Stepper, the numerical aperture was set to 0.63, the illumination mode was set to partial coherent with an outer sigma of 0.302 and the focus was -0.1 µm, these parameters were shown to give the best results for phase-shift masks on a simulation software called Prolith. The cell size was set to 10 mm in order to fit multiple cells into a matrix on the wafer, which allowed a range of doses from 6 mJ/cm^2 to 21 mJ/cm^2 to be tested.

Scanning electron microscopy (SEM) was used to analyze the results of the exposures. SEM imaging showed that there was a range of line widths under the 100 nm target and that the line widths decreased as the dose increased (see Figure 1). Two distinct spacings between the lines were also observed, with one spacing being usually larger than the other. The ratio of these spacings was characterized at each of the biases tested on the mask (see Figure 2), which showed that as the unetched area becomes larger than the etched area, the spacing between the lines becomes more equal. This trend supports the hypothesis that the lines are falling onto the area that

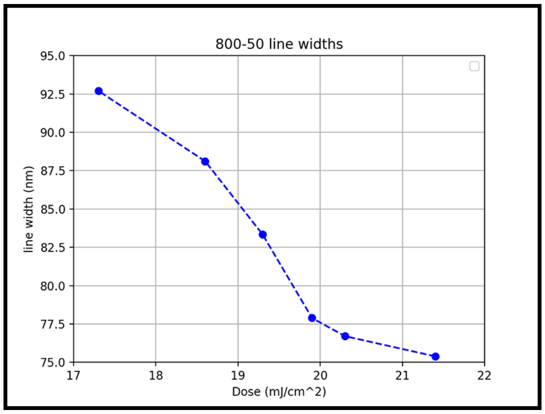


Figure 1: Line width of 800 pitch with a negative 50 bias across various doses.

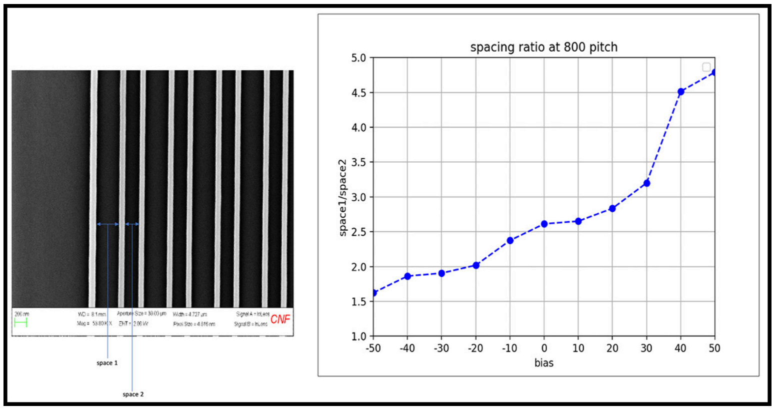
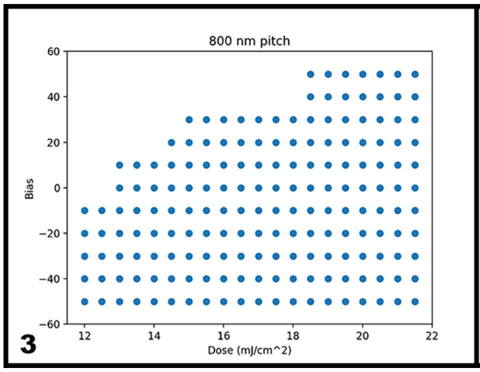
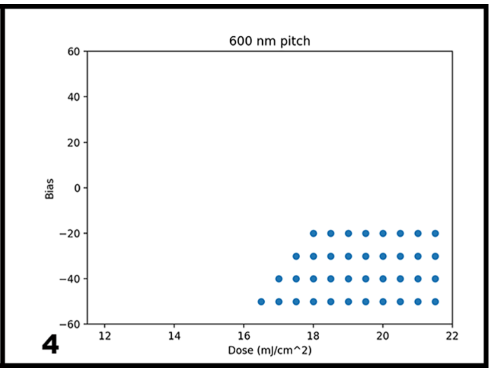


Figure 2: Ratio of line spacings at 800 nm pitch at 18.6 mJ/cm² dose across various biases.



3



4

Figure 3, left: Process window for 800 nm pitch. Figure 4, right: Process window for 600 nm pitch.

is unetched on the mask, so the unetched area must be greater than the etched area for the spacing to be uniform. The largest negative bias tested was 50 nm, which lead to a ratio of 1.5, so the ideal negative bias should be greater.

The highest pitch tested was 800 nm on the mask, which translates to 400 nm on the wafer. This pitch had the largest process window (see Figure 3), working at all the doses tested and all the biases. Pitches of 700 nm and 600 nm on the mask were also achieved, but as the pitch decreased, the process window shrunk to higher doses and greater negative biases (see Figure 4). Some pitch doubling was seen at 500 nm, but it was not uniform throughout the length of the lines. However, with a greater negative bias, the photoresist could possibly be fully exposed between the lines making the 500 nm pitch better defined.

Conclusions and Future Steps:

We demonstrated that we could fabricate a phase-shift mask completely at the CNF with an etch depth less than 10 nm away from our target of 248 nm. Using said mask, we achieved features with a range of widths less than 100 nm and were able to control the line width through changes in dose. We also were able to characterize the spacing between the lines and understand how to use bias on our mask to get uniform spacing.

Acknowledgements:

Special thanks to the Cornell NanoScale Facility Research Experiences for Undergraduates (CNF REU) Program for hosting this internship, and to the Cohen Research Group for their support and mentorship. This work was funded by the National Science Foundation via grant no. NNCI-2025233.