EBL tricks:

Improving EBL performance for writing nanostructure arrays over large areas

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Initial considerations

The electron beam lithography equipment at NTNU NanoLab consists of a Raith Quantum pattern generator and stage, integrated into a Hitachi S-4300 Schottky Field Emission SEM. Each user has their own application, but optimizations probably are common for many users. In the following report a few tips tricks and optimization are described [1]. The optimizations are performed with the goal of writing 100 nm features with SU-8 as the resist, over large areas at high writing speeds, but the results are likely transferable to other feature types and resist types.

The NTNU NanoLab EBL system employs a refurbished SEM, and thus the EBL capabilities are closely tied with the capabilities of the SEM, and partly the Raith stage. Below, in Table 1 and Table 2, general specifications and the typical trade-offs involved in the system are listed, forming a basis for the more detailed investigations below.

[1] Some of the information in this text is taken from the excellent Q&A section here: `http://www.jcnabity.com/q_a.htm`

Table 1: Rough guides to some of the instrument capabilities

Stage size	40x40 mm
Working distance	6-23 mm
Voltage	1 kV - 30 kV
Beam current	5pA-3nA
Current stability	Very good
Magnification	~50X to 300kX
Probe size	1.5 nm at 30 kV, 5 mm WD
Pattern generator	6 MHz
Blanker rise time	~ tens of ns

Table 2: Trade-offs involved in optimizing the EBL

Feature	**Effect** ↑	**Effect** ↓
Working distance	Increased DOF	Less aberrations, better resolution
Beam current	Increased write speed	Reduced probe size and increased DOF
Write field size	Increased write speed	Increased precision
Beam speed	Increased write speed	Increased precision

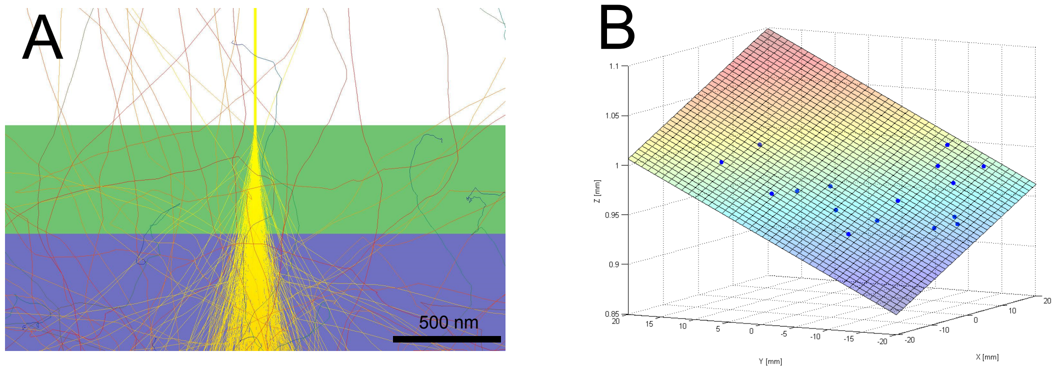

Figure 1: (A) CASINO scattering simulation of 30 kV electron beam interacting with 500 nm SU-8 on a silicon wafer, displaying a certain degree of forward scattering. (B) An example of possible stage tilt in the NanoLab EBL system. The stage height necessary to maintain good focus was measured at several locations (blue dots) and fitted to a plane.

Sample preparation and SEM preparation

Although sample preparation is not a major part of the EBL process, mistakes here can propagate. It is important to ensure that:

- Your sample is conductive. It is possible to use non-conductive samples, but focusing is more of a challenge and charging artifacts might occur. If focusing on a charging sample without a charging reduction layer, brightness and contrast needs to be readjusted (typically much lower than usual), and scan rates need to be high (e.g. TV mode).
- Your sample is completely clean underneath, free of photoresist residues that might imbalance the sample.
- You make a small scratch in your sample, preferable in at least three corners, before inserting into the EBL.
- You focus the SEM well at your desired acceleration voltage. CASINO [2] can be used to simulate electron scattering in the resist to help determine an appropriate acceleration voltage. More scattering means increased exposure, but also broadening of the exposed area, as shown in Figure 1A.
- To adjust astigmatism correctly, a tip is to use either some small feature on the Faraday cup or introduce a sample with small features. This is simpler than doing it in on a resist-coated sample.
- Finally, focus on the sample, aided by one of your scratches, and burn a couple of contamination dots to ensure perfect focus and astigmatism.

[2] `http://www.gel.usherbrooke.ca/casino/index.html`

Reducing stage tilt effects on large samples

Stage tilt can be significant on large samples, spanning over 200 µm across the stage in one test (Figure 1B). However, stage tilt depends on the sample, how it is clamped, small specks of debris, etc. This can lead to severe reduction in feature resolution (see Figure 2A) or even complete disappearance of features. There are several ways around this.

Stage alignment

Due to certain limitations in the software and hardware, the stage alignment is somewhat tedious, although it can be done with some practice. The method relies on the built-in 3-point alignment of the Raith software:

- Make a scratch in three corners of your sample
- In the UV-alignment tab, set the origin and angle as usual
- In the 3-point alignment tab, press the little edit box in the top right, go to options, and activate automatic focus compensation, with stage selected. A red text reading Focus! will now be displayed at the bottom of the 3-point alignment box.
- Focus as normal on your first scratch, and press the dropper tool to sample the stage height at this point. Do not alter the UV or XY values.
- *Without touching the focus*, move to your second scratch, then press the z-axis button on the joystick. Then, get your scratch in focus again, but this time by altering the z-height with the joystick. Press the dropper on the second point when in focus to sample the height.
- Change back to XY movement, and repeat the above for the third scratch and third dropper. Now, during exposure, the stage height will automatically compensate for systematic height deviation of the sample or stage.
- Note that when changing the z-height, small shifts in the beam might occur. Thus, if correct write field alignment over large areas is critical, other methods might be better.

Working distance

The working distance and the depth of field scale linearly, so by increasing the working distance from e.g. 6 mm to 22 mm (Z=13 to Z=1 mm), the depth of field is increased by a factor of 3.5. This helps reduce the effects of stage tilt. The trade-off is reduced resolution due to increased spherical aberrations, but no significant effects of this have been observed in practice. A simple test to see if resolution is significantly reduced is by sputter coating a thin (e.g. 5 nm) gold layer on a Si wafer, and attempting to image the small grains of a few nm in the layer.

Beam current

As the beam current is limited by the size of the condenser aperture, increased beam current will cause a large beam convergence angle, which reduces the depth of field. Thus smallest possible beam currents should be used if sample tilt is an issue.

Optimizing writing speeds

Increasing the beam current, write field size and beam speed all will improve writing times, but typically at the cost of writing precision and resolution. For each type of features the optimal

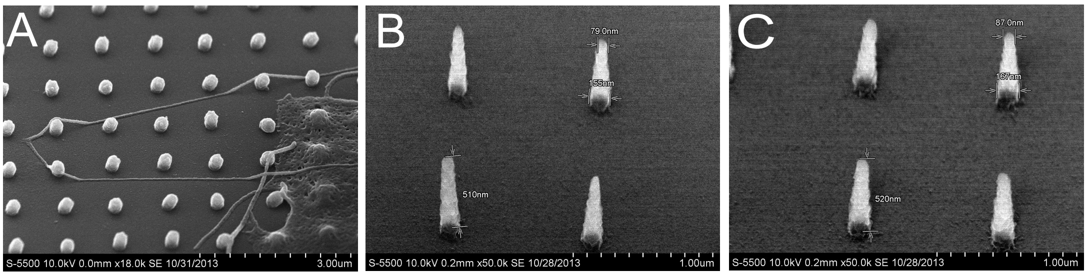

Figure 2: (A) Features written out of focus will be less well defined or not defined at all, as in this where the pillars become short and wide. By chance, cells were grown on this sample. (B) and (C) Comparison between (B) 10 pA and (C) 200 pA beam current, with otherwise identical EBL parameters. No significant differences are observed, indicating the current itself is not a decisive parameter for feature quality in this example. The settling time was 500 µs.

values must be found, but here are some examples.

Beam current

At a constant exposure dose, increasing the beam current will decrease the writing time correspondingly. The theoretical trade-off is lower depth of field (see above), and reduced resolution resolution due to increased electron-electron repulsion and larger spherical aberrations. Roughly, the beam current I and the probe size d are related by $d_{beam} \propto \sqrt{I_{beam}}$. [3] For very high resolution requirements this might matter, e.g. increasing the beam current from 10 pA to 1 nA will increase the optimal probe size from roughly 1.5 to 15 nm. However, for features in the 100 nm range, this is not a significant effect, as shown in Figure 2.

Write field size

For writing large areas with sparse features, stage movement and stage settling is a significant contribution to the total writing time. Increasing the write field size is a way around this, each doubling of write field size decreases the number of stage moves by a factor of 4. Contrary to what might initially be expected, resolution and magnification are not really related in an SEM. The magnification is only determined by the scanning field size, while the probe size remains unaltered by changing the magnification. The write field size is determined by the magnification, so large write fields should in theory be usable without a loss of resolution.

However, in practice the write field size does effect the writing precision. The reason is that the SEM uses different sets of scanning coils depending on the magnification (and the working distance). The higher magnification scanning coils are more precise, but naturally have a smaller scan field area. A small click can be heard due to relay switching when the magnification passes certain points, this click indicates a change of scanning coils. At which magnification this occurs depends on the working distance. At about 6 mm (Z=13mm), the relevant change occurs between 500X and 600X, while at 22 mm (Z=1mm), the same change occurs between 200X and 300X. Thus, depending on the working distance, a write field size of 200 µm at 300X could be written with higher precision than a write field size of 100 µm at 500X.

A second consideration are artifacts due to scanning at the extremes of the scanning coil range, which can cause distortions at the edges of write fields. (Note: In general one should always avoid placing critical features at the edges of write fields.) Thus, when choosing a write

[3] `http://dx.doi.org/10.1116/1.2907780`

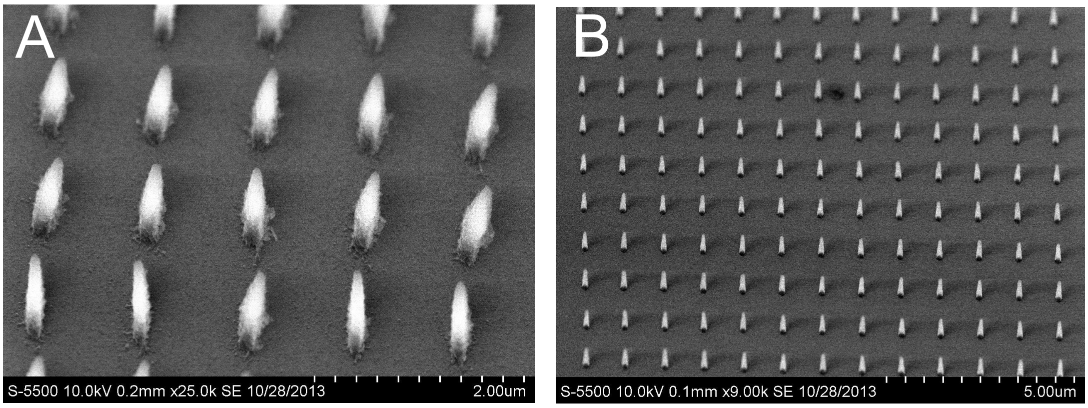

Figure 3: (A) When settling time is reduced below about 50 µs, such as to 10 µs in this example, features can be severely distorted due to beam instability. (B) With optimized parameters, large arrays of features can be written reliably, practically defect free at acceptable writing times.

field size a trade-off between higher precision at the lower range of a scanning coil and reduced edge artifacts at the higher range of the scanning coil must be considered, in addition to the writing time aspect.

For writing SU-8 nanopillars a 200 µm write field at 300X (working distance 22 mm) was chosen as the optimal size, but this will vary by application.

Beam speed

The total beam speed is determined by the sum of exposure time, the beam movement time to the next feature, and (optional) waiting time at the feature before exposure (called settling time). Exposure time is limited to 167 ns (1/6MHz) by the pattern generator, and this value is obtainable in practice, if the current is high enough. However, the scanning coils are significantly more limiting and require a certain time to stabilize after each move. The necessary settling time depends on how large the spacing is and how small the sparse features are. A value of 50 µs for the settling time has been found to not induce artifacts for e.g. 100 nm features separated by up to 10 µm, while 10 µs induces significant artifacts (see Figure 3A). Settling time is set in advanced exposure parameters in the exposure tab.

An alternative method of writing e.g. sparse arrays, instead of using single dot arrays, is writing areas with a large step size. In this case there is no inherent settling time, so here the exposure time must be so high that small deviations in the start of the exposure do not matter, or not very high precision is needed.

In general it is recommended by the manufacturer that the beam speed be limited to <10mm/s, with improved performance at 5 mm/s and best performance at 1 mm/s. With e.g. sparse features spaced at 1 µm, 10 mm/s corresponds to 100 µs per feature, including settling time and exposure time. Thus, in practice we see that it is the SEM and not the pattern generator that is the major factor in determining possible writing speeds, and that large gains could likely be achieved for less critical writing applications.

Conclusion

An overview of many relevant parameters to achieve optimal electron beam writing speed, precision and feature quality has been given. Although these parameters have been optimized for SU-8 nanopillar writing in this work, the general trends in deciding appropriate instrument settings are relevant for many other EBL processes as well.

As an application example, well-defined, defect free arrays of SU-8 nanopillars were produced on glass by optimizing all of the above parameters (Figure 3B). The arrays were produced over large areas of several cm, and written at a rate of about 6 minutes per square mm.