Alignment in Electron Beam Lithography

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Abstract— **Alignment was accomplished as the ultimate goal in the development of an electron beam lithography process. System was based on LEO EVO 50 scanning electron microscope at RIT's Semiconductor and Microsystems Fabrication Laboratory (SMFL) with external writing control software package NPGS v 9.0.160. Preliminary work included investigation of line- and area-pattern writing in negative tone AZ nLOF 2020 resist diluted 1:2 with PGMEA and pattern transfer into silicon substrate via plasma etch. Manual alignment with ±100 nm translational accuracy across a 100 μm writing field was demonstrated.**

Index Terms— **alignment, electron beam lithography.**

I. Introduction

ELECTRON beam lithography (EBL) is an attractive definition method for nano-scale device research due to the following qualities: naturally, its nano-scale resolution, flexibility in layout design, and the possibility of being performed in a standard scanning electron microscope (SEM). Field-emission SEMs have been shown to image lines as narrow as 20 nm [1]. Layout designs for EBL are stored and used electronically which makes them easily accessible for corrections and do not involve extra costs unlike conventional photo-masks. Finally the resources necessary to equip a standard SEM with writing capability are by orders of magnitude less than what a commercial EBL system is worth.

II. Theory

A. SEM Writing Methodology

To better understand the implications of various factors in EBL it is important to consider the method of pattern writing with an electron beam. Any design layout, independent of feature shape and size, is eventually broken down into discrete exposure elements (Fig. 1) which correspond to addressable locations in the writing field. These are visited by the beam in a programmed sequence and are given a programmed charge dose. If a number of such exposure elements are spaced closely enough in one dimension they will image as a thin line and similarly in two dimensions the result will be an area.

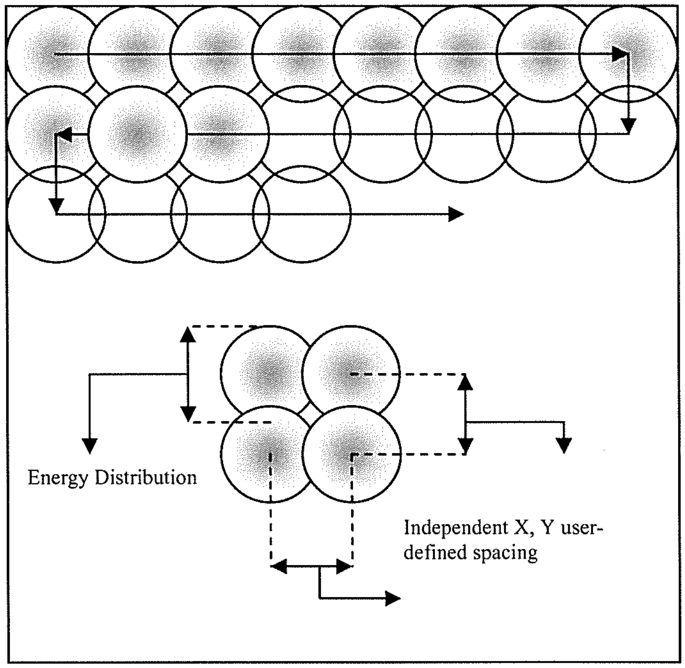

Fig. 1. SEM exposure of lines and areas. Energy distribution of exposure elements normally overlap to create a more complex energy distribution.

B. Electron Beam-Resist Interaction

If an instant of point exposure is taken into consideration one can realize the complexity of the exposure process. Figure 2 shows a simple scenario of resist film on substrate with a stationary electron beam of normal incidence. Note that the purpose of this diagram is to only illustrate concepts and not to model any particular observations since quantification of the latter is beyond the scope of this paper. First phenomenon to be expected in this situation is electron scattering leading to beam dispersion inside the resist-substrate system. This causes the energy dose to be effectively delivered to a larger area than the beam cross-section which further implies that a line of exposure elements will generally be wider than the diameter of the beam used to write it. The line-width may be partly dependent on the exact dispersion profile which must be a function of electron energy and resist material. On the other hand the 3-D region defined by scattered electrons has at least two important energy characteristics: net spatial distribution and quanta distribution. It is certainly important how energy is distributed but it also makes sense to consider the portions or quanta in which it is delivered over the 3-D electron dissipation region. It is very likely that certain quanta are consumed in resist transformation and others are useless. Another source of side-effects that may influence the quality of imaging is the resist-substrate interface. Depending on the substrate material it may come to electron backscattering or X-ray emission into the resist.

Considering the complexity of resist exposure with electron beam it is often more practical to optimize the process through experimentation using the above principles merely as guidelines.

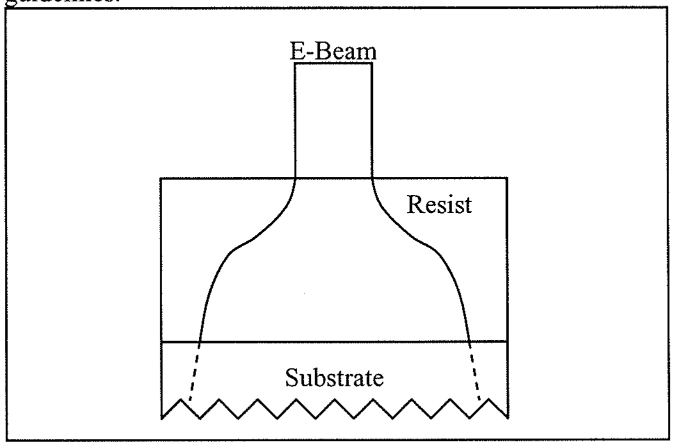

Fig. 2 Diagram of electron beam dispersion in resist.

C. SEM System Performance

Besides the technicalities of writing and exposure there is another important aspect of EBL and it is the system used to generate and control the beam. A standard SEM, being similar to an optical system, suffers from aberrations as well. For ideal imaging and writing performance the beam should focus in a perfect cylindrical shape that would move in a perfect plane when the beam is deflected. In practice however this is not the case and great effort is invested in tuning the system as close to these conditions as possible for best writing results. Small features such as lines of single exposure elements are very sensitive to the beam cross-section shape. Two most common aberrations are astigmatism which causes the beam to focus in a complex elliptical cylinder and spherical aberration of the focus field which causes defocus away from the centre of the writing field. Astigmatism is normally correctible to a great extent while spherical distortion naturally becomes an issue when larger writing fields are used; in SEM terms this would mean from approximately 500 µm and up to maximum depending on the tool's capability.

III. Experimental Procedures

A. Sample Preparation

Samples were prepared by cleaving approximately 1 cm^2 pieces from 4" bare silicon (100) wafers. Any dust was blown off with compressed nitrogen and pieces were baked several minutes at 150°C to dehydrate surface. Once cooled, they were primed with HMDS at 4000 rpm for 50 s immediately followed by application of resist at same settings. The resist was a 2:1 mixture of PGMEA and AZ nLOF 2020 that yielded 300 nm films – thin enough for electron beam exposure. Resist was soft baked at 90°C for 60 s.

B. System Preparation

Before each writing session the SEM was thoroughly prepared for optimal performance. The following procedure was used:

1. Degauss lenses.
2. Adjust electron gun shift/tilt for maximum specimen current.
3. Using golden standard alternately zoom in and focus until 200KX magnification is reached.
4. Alternate adjustment of astigmatism/focus wobble until best image is achieved.
5. Measure and record specimen current using faraday cup on sample holder.
6. Enter current value in NPGS job-file(s) to be executed.

C. Writing

Prior to writing on a sample special marking was applied in order to define locations for writing so that the images could be easily found. Such marking would normally consist of a straight scratch across the sample with a few tick-marks near the centre. After system preparation the end of the large scratch was found at the edge of the sample and used as a guide to the tick-marks. The tip of each mark could then be used as a starting point of a writing job; there would usually be many small particles to focus the beam on. For better accuracy focusing was done at magnification about ten times higher than the job was to be carried out at. Once focusing was done SEM control was transferred to NPGS and writing was initiated.

D. Developing

Developing was done in MF CD-26 for 60 s followed by DI water rinse and drying with compressed nitrogen. The scratch-marks remained clearly visible and greatly facilitated looking up the image for inspection.

E. Etching

Prior to etching samples were hard-baked at 140°C for 90 s. Etching was carried out at 75 mTorr in SF_6(4 sccm)/CHF_3(16 sccm) plasma with RF power input of 185 W for 3.5 min. For the process samples were placed on a bare Si wafer to minimize contamination.

F. Alignment

The only way for NPGS to make use of the alignment marks is through SEM imaging. In order to avoid exposing device area while doing this the software allows for selective scanning in user-defined areas also known as alignment windows. These windows are normally twice the size of the marks and are centered at the same coordinates in layout. In order to make use of them the device area must already be pre-aligned accurately enough so that the marks are at least partially visible within the windows when the latter turned on (Fig. 3).

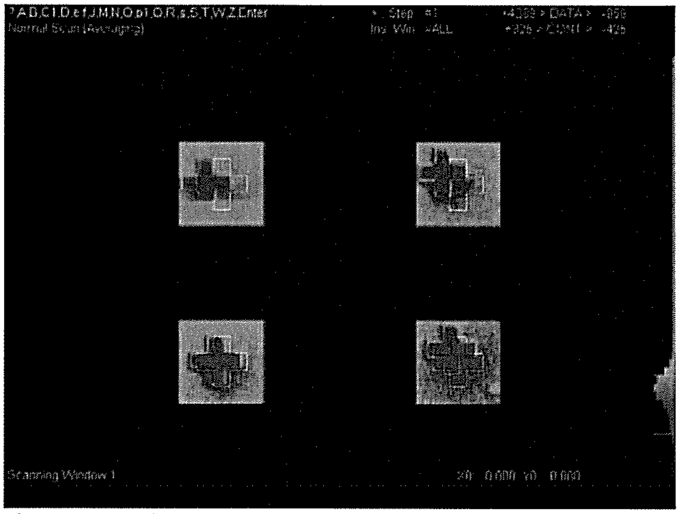

Fig. 3 Images of alignment marks in alignment windows. Top-left window currently being scanned

What complicates pre-alignment of the device area is the fact that SEM imaging is the only accurate feedback of its location however it cannot be used because this will expose the entire resist over it. For this purpose a sacrificial pre-alignment feature was introduced. This feature is written along with the first lithography level and therefore naturally shares the same orientation; in addition the distance between them is well known. Prior to alignment this feature was found and used to properly orient the sample by aligning the feature with the SEM field of view (Fig. 4). Once this was accomplished the beam was blanked and the sample stage moved a distance equal to the separation between the pre-alignment feature and the device area thus accurately centering the latter in the writing field.

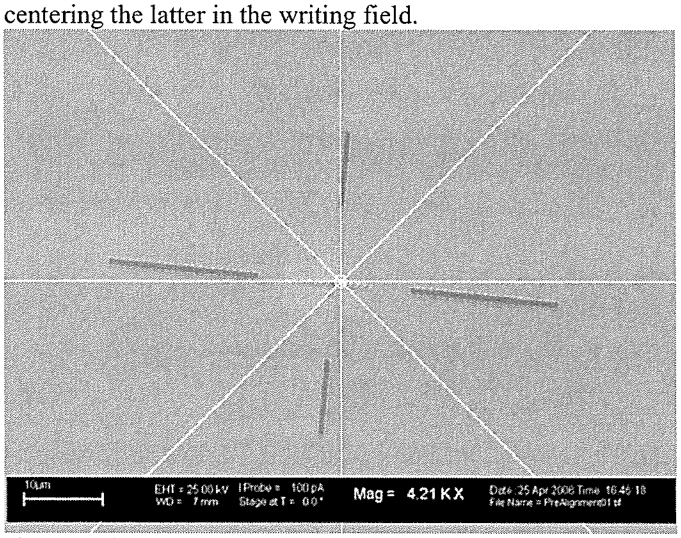

Fig. 4 Pre-alignment mark in SEM field of view.

Once alignment procedure was initiated NPGS started scanning the alignment windows and large portions of the alignment marks appeared in them. The fine alignment was accomplished by using the alignment overlays - graphical outlines of the alignment marks displayed within the alignment windows. These outlines were dragged and dropped over their corresponding alignment mark images by using the computer mouse and the software was commanded to read their locations. After performing the necessary shift/rotate correction to the writing field the alignment marks were scanned again and their images appeared almost perfectly centered. After a few iterations of the previously described process the software was commanded to do final recalculation and start writing the second level. This was a manual alignment procedure with NPGS. Automatic alignment functions in a similar manner only the positioning of the overlays is done by the software.

IV. Results and Analysis

A. *Exposure Element Lines*

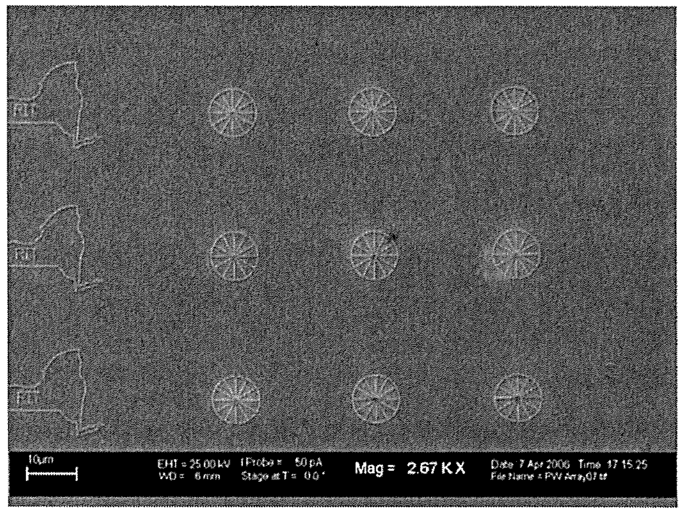

Fig. 5 The pinwheel array.

The pinwheel array (Fig. 5) was the first pattern written due to short writing time and excellent characterization capabilities. It is entirely composed of single exposure element line segments and therefore very sensitive to beam tuning; in addition the spokes are oriented in six different directions which makes them excellent detectors of distortion in beam cross-section. Smallest reproducible line-width observed was 48 nm (Fig. 6) imaged with line dose of 50 nC/cm and 7.18 nm spacing between exposure elements. Figure X also displays unequal spoke width, an imperfection that persisted in all pinwheel arrays written in spite of meticulous astigmatism correction. It is suspected that the source of this aberration was the irregular emission source image of the LaB_6 crystal. The gravity of the effect was not large enough to impede this work's progress.

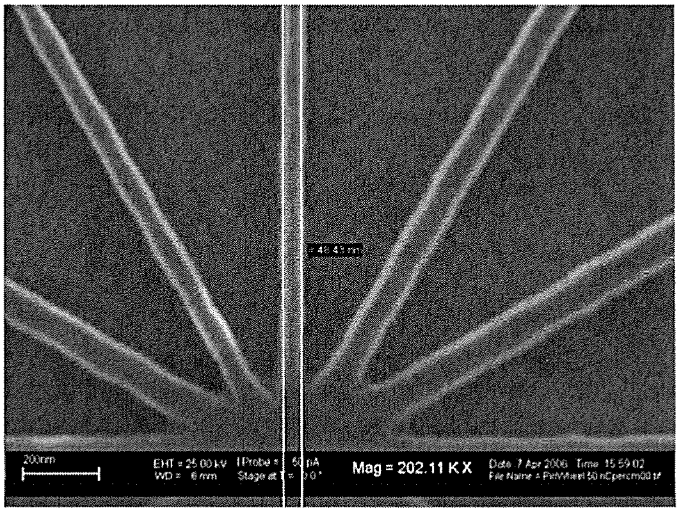

Fig. 6 Pinwheel exposed with 50 nC/cm dose and 7.18 nm exposure element spacing. Vertical line width is 48.43 nm.

B. Area Patterns

Area patterns are generally less sensitive to beam distortion since it only affects the outline and the amount of error is usually much smaller than their gross dimensions. For instance if the beam has an elliptical cross-section that is oriented along one of the sides of a square feature it will technically image as a rectangle (Fig. 7) however this is barely noticeable. The real problem with area patterns is writing time due to the generally greater number of exposure elements involved. Whereas optimization of line imaging may tolerate trading of time for dose this may not be acceptable when large areas are in question. With the working resist an area dose of 2600 $\mu C/cm^2$, 31 nm exposure element separation with 25 fC per element a 4.6 μm square was imaged with target side length of 5 μm. At such settings it would take 14.5 minutes to expose a 50 μm square with specimen current of 75 pA. Even though experimental results showed that lower doses were possible the reported setting was found to be acceptable for the purposes of this work.

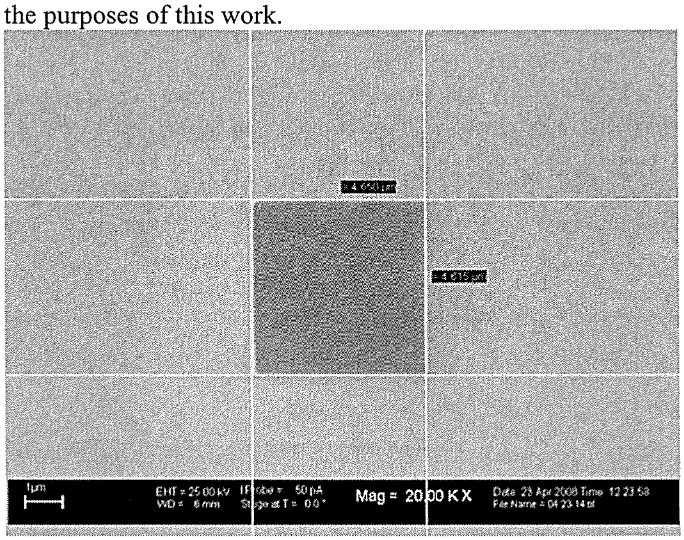

Fig. 7 Target square of 5 μm side-length exposed with 2600 μC/cm2 area dose and 31 nm exposure element separation images as a 4.615×4.650 μm rectangle.

C. Dry Etch

AZ nLOF 2020 showed sufficient masking properties. Silicon to resist etch selectivity was calculated to be 1.33. A nearly anisotropic 200 nm deep etch (Fig. 8) was observed after 3.5 min of etch time. Such depth was sufficient to create a relief image in silicon that would be easily seen with the SEM even when covered with resist. This meant that it was possible to create high contrast alignment marks.

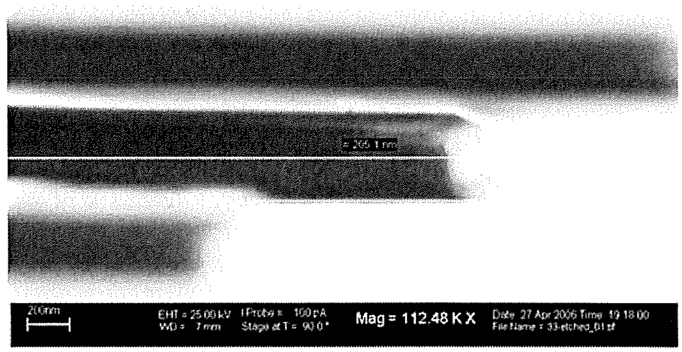

Fig. 8 AZ nLOF 2020 etch mask on top of a 200 nm feature in Si.

D. Alignment

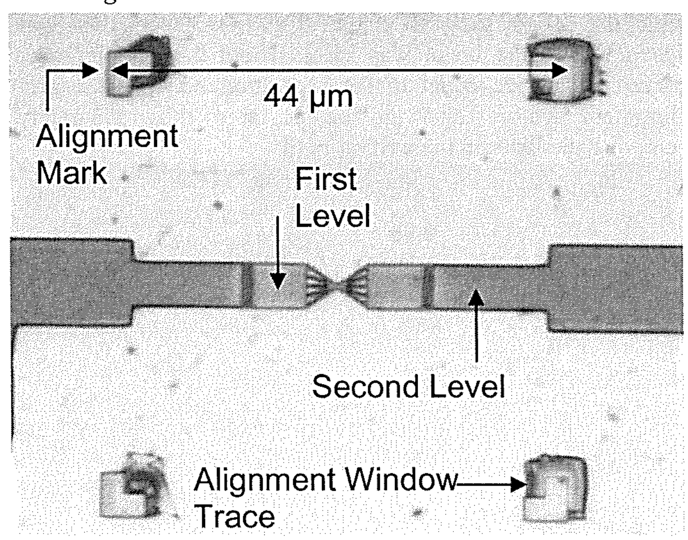

Fig. 9 First results in alignment.

First alignment attempt was done on a two level sample design available with NPGS. Results were encouraging (Fig. 9); no noticeable error in *y* and a slight offset in positive *x*. For the sake of better evaluation a 10×10 array of overlay verniers of 100 nm resolution was designed to span a 100 μm square field. The two layers of this test pattern were manually aligned with a ± 100 nm accuracy tolerance. By visual inspection 100 nm offset in *x* and 0 nm in *y* were observed (Fig. 10). In general the vernier array provides enough data for a thorough overlay error analysis however this procedure was not included in the scope of this work.

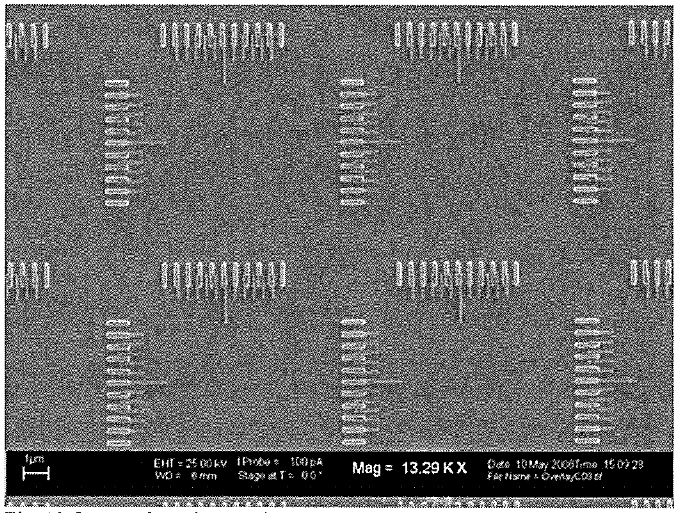

Fig. 10 Centre of overlay vernier array. Nearly perfect alignment in *y* and approximately 100 nm displacement in *x* can be noticed.

V. CONCLUSION

With such promising first results in alignment and all preliminary processes a solid foundation has been laid for a functional electron beam lithography process at SMFL. The ultimate goal of this development will be to adjust, optimize, and apply this process in the fabrication of a variety of classic and novel nano-scale devices.

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