

Mix-and-Match: E-beam and Optical Lithography for Optical Gratings and Waveguides

Chia-Ming Chang

Department of Electrical Engineering, Stanford University

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Abstract: This report outlines mix-and-match of JEOL e-beam lithography and ASML stepper optical lithography. Optical gratings and waveguides are made using both machines. Systematic overlay testing is also conducted for both machines, which shows overlay offsets ranging from 400nm without process correction to 100nm with process correction per exposure.

Introduction

In SNF, different lithographic tools are used for different applications. For example, ASML stepper is used for devices that have feature size larger than 400nm. ASML stepper also has the advantage of large throughput. E-beam tool can be used for small feature size (<400nm), while the writing speed is limited. More and more applications require both large throughputs with critical feature size smaller than 400nm. Therefore, the motivation of this project is to develop a lithographic process in SNF for integrated devices with critical feature size smaller than 400nm, while most of the device sizes are larger than 400nm.

The organization of this project will be divided into two parts. First, integrated photonic devices that consist of optical waveguides and optical gratings will be fabricated by using ASML stepper in SNF and JEOL e-beam in SNC. Several process issues to mix-and-match two machines will be discussed. Second, to find out the overlay error systematically, test structures will be fabricated and measured using a standard testing method in ASML stepper.

Optical waveguides and gratings

1. Methods

Waveguide based grating coupler is a key component for integrated optics. Figure 1 shows the schematics of the grating coupler. The grating mesa is about $10\mu\text{m} \times 10\mu\text{m}$, which is about the same size as optical fiber mode. The grating pitch is about 200nm, depending on the wavelengths and materials. Since the feature size of gratings is smaller than 400nm, JEOL e-beam in SNC will be used to fabricate the grating. On the other hand, the width of the optical waveguide is 500nm, which can be made using ASML stepper. Therefore, in my grating coupler test structure, optical waveguides are defined by ASML stepper, and grating coupler and adiabatic tapers are defined by JEOL e-beam.

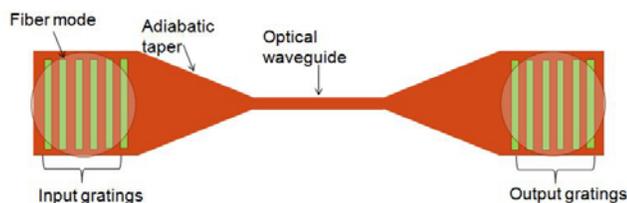


Figure 1. Schematics of waveguide based grating coupler for e-beam and optical lithography.

To simplify the process, “two litho” process was proposed. It is basically a JEOL e-beam first and ASML stepper second process. The reason for JEOL e-beam first is due to the consideration of alignment marks for JEOL e-beam, which will be discussed in detail later. The “two litho” process flow is summarized as follows.

1. E-beam layer

- Spin e-beam resist (ZEP): 330nm
- Expose gratings and ASML PM marks
- Develop
- Etch gratings and PM marks in P5000 and strip resist

2. ASML layer

- Spin photoresist (0.7 μm)
- Manual pre-alignment to find the coordinate offsets between JEOL and ASML
- Expose waveguides.
- Develop
- SEM inspection
- RIE

The first layer is JEOL e-beam. ZEP was tested for JEOL, and it showed better results compared to PMMA. ZEP was spin coated on standard silicon wafer using 5000RPM, resulting in 330nm thickness. The wafer was then sent into JEOL e-beam, in which both gratings and ASML PM marks were exposed. The layout of the gratings and PM marks is shown in Fig. 2. Although the writing speed in JEOL e-beam is faster than Raith e-beam due to higher dose, the overall writing time is still long compared to optical lithography. For a PM mark that is about $450\mu\text{m} \times 450\mu\text{m}$, the writing time is about 2 minutes. The wafer was developed using standard recipe, which uses Xylenes for 40 seconds, 1:3 MIBK:IPA for 30 seconds and IPA for 30 seconds. Finally, I used P5000 recipe polyetch PC in chamber C to etch the silicon substrate.

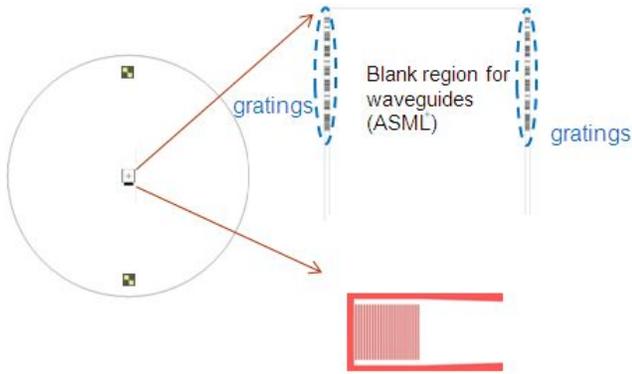


Figure 2. Layout of gratings and ASML PM marks for JEOL e-beam exposure.

The second layer is ASML stepper. SPR955 photoresist was used because the waveguide width is about $0.5\mu\text{m}$. The next step is to find out the coordinates of the alignment marks in ASML stepper. Since two global PM marks were defined in JEOL e-beam, there are coordinate system offsets between two machines. By using the manual pre-alignment function in ASML stepper, the coordinate system offsets can be found. The coordinate system offsets were found to be 1.242mm in x , 2.0643mm in y and 10.1629mrad in θ . After putting pre-alignment correction in ASML stepper, the waveguides were exposed and developed.

2. Results and discussion

Figure 3 shows the SEM pictures of the gratings and tapers before processing in ASML. Figure 4 shows the SEM pictures after developing the waveguides layer. It can be seen that there is a $-2.4\mu\text{m}$ offset in y . By stripping the photoresist, and putting $-2.4\mu\text{m}$ in process correction, the overlay between two layers (two machines) can be minimized (see Fig. 5). It can be seen in Fig. 5(b) that there is still some θ offset that need to be corrected.

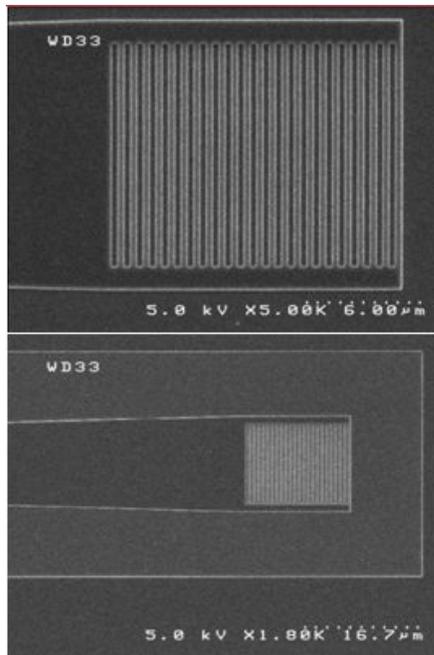


Figure 3. SEM photos of the gratings and tapers before processing in ASML.

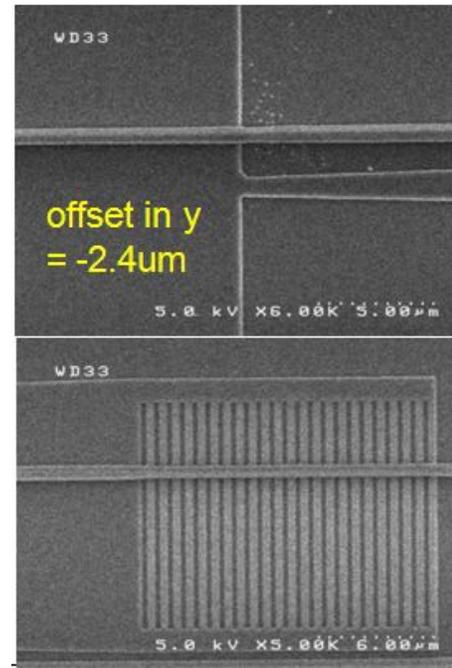


Figure 4. SEM photos of the gratings and waveguides after developing the waveguides layer.

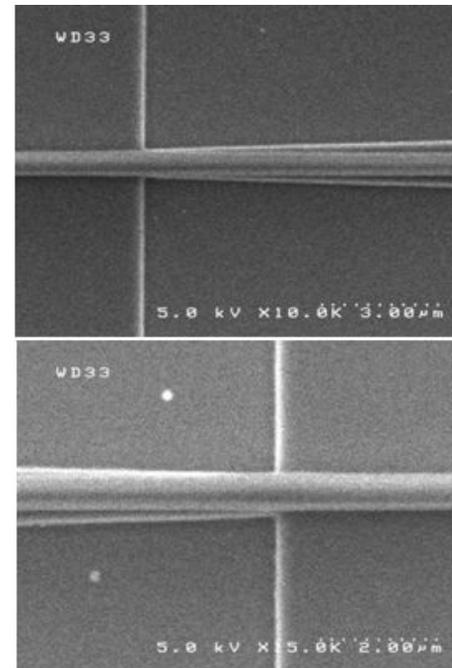


Figure 5. SEM photos of the gratings and waveguides after process correction.

Overlay testing

1. Methods

Although the fabrication of optical gratings and waveguides demonstrate good mix-and-match with process correction, it is desirable to know the overlay error for people who want to design their process flows using two machines. We collaborated with ASML staff to measure the offsets systematically. The standard overlay testing procedure is shown as follows.

- 3x3 array of PM marks per field were patterned in 1st layer by JEOL
- PM marks were etched into silicon substrate with 1200A etch depth
- Optical pre-alignment offset was determined by manual alignment in ASML
- 2nd layer of PM marks was exposed with images shifted 640um in Y by ASML
- Wafer development and marks readout
- Model the data and apply process correction
 - (1) without process correction, (2) process correction, (3) process correction per exposure

First, six 3x3 arrays of PM marks at specific positions were patterned in JEOL e-beam, shown in Fig. 6. Two additional PM marks were used for global alignment in ASML. The PM marks were etched 1200A deep into silicon substrate. Next, manual alignment was used to find out the pre-alignment offset. ASML staff exposed another arrays of PM marks in 2nd layer with image shifted in x or y by 640μm. Finally, by measuring the difference in position of the PM marks, ASML staff can model the data and find out the overlay error. In ASML, we can also apply process correction to reduce the overlay error.

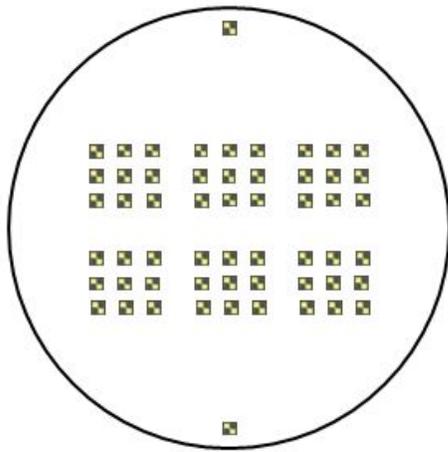


Figure 6. PM marks arrays for overlay testing.

2. Results and discussions

Figure 7 shows the testing results (1st layer to nominal, 2nd layer to nominal and 2nd layer to 1st layer) without process correction. It follows that the offset of 1st layer to nominal (1st to N), which corresponds to JEOL e-beam to nominal position, is large. The mean plus three sigma offset was 373nm, which might be due to the movement of the stages. On the other hand, the offset of 2nd layer to nominal (2nd to N), which corresponds to ASML stepper to nominal position, is much smaller. The mean plus three sigma offset was 60nm. Finally, the offset of 2nd layer to 1st layer (2nd to 1st) is large due to very different distribution of 1st to N and 2nd to N. The mean plus three sigma offset is 400nm.

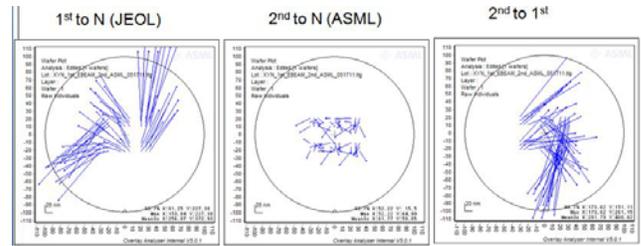


Figure 7. Overlay data without process correction. (From ASML)

From the results of 1st to N, ASML staff modeled and obtained data for process correction; that is, by applying process correction, 2nd to N can be distributed in a similar way to 1st to N, leading to a better overlay between 2nd layer and 1st layer. Furthermore, ASML staff can obtain process correction per exposure since the offsets are also different for each exposure. The data with process correction and process correction per exposure is shown in Fig. 8 and Fig. 9, respectively. It follows that the mean plus three sigma can be reduced to 200nm and 100nm with process correction and process correction per exposure, respectively.

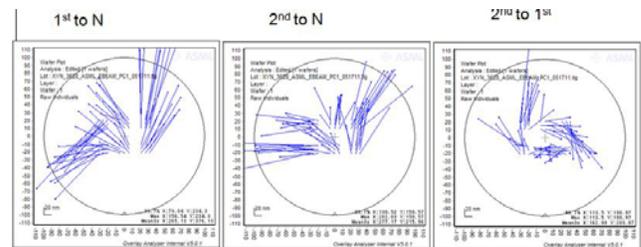


Figure 8. Overlay data with process correction. (From ASML)

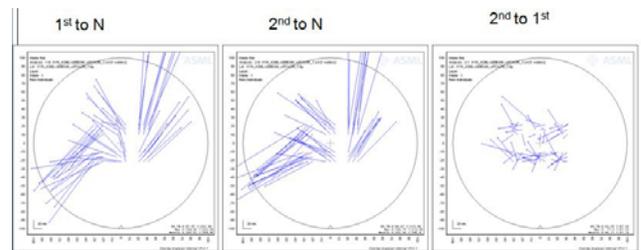


Figure 9. Overlay data with process correction per exposure. (From ASML)

In summary, the overlay errors between JEOL e-beam and ASML stepper vary from 400nm without process correction to 100nm with process correction per exposure. The use of different model and process corrections depends on applications.

In addition to JEOL e-beam first and ASML stepper second methodology, ASML stepper first and JEOL e-beam second is another option. However, the requirements for JEOL e-beam alignment marks need to be considered. In JEOL e-beam, cross alignment marks are preferred, as shown in Fig. 10. The size of the cross alignment marks should be designed to be about 1mm x 1mm, and the width of the cross is about 1μm. Unlike ASML alignment marks that should be etched 1200A into silicon, the JEOL cross

marks should be etched at least 500nm into silicon (1 μ m preferred) to provide enough contrast for JEOL e-beam machine. As a result, the process flow for both alignment marks can be described as follows (see Fig. 11). The ASML PM marks with 1200A etch depth are defined in the 0th layer by ASML stepper, followed by the JEOL cross marks with 1 μ m etch depth defined in the 1st layer by ASML stepper aligned to the 0th layer PM marks.

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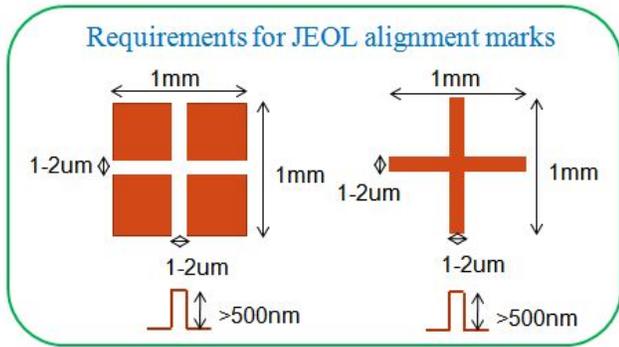


Figure 10. Requirements for JEOL e-beam alignment marks

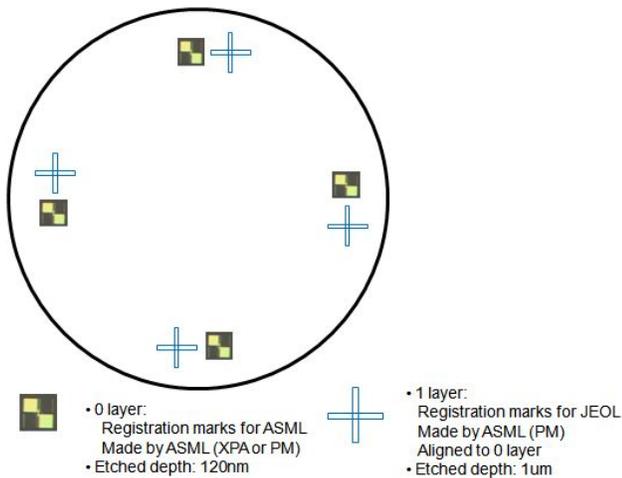


Figure 11. Process flow for both ASML and JEOL e-beam alignment marks for ASML stepper first and JEOL e-beam second process

Conclusion

In conclusion, mix-and-match of JEOL e-beam and ASML stepper depends on the applications and requirements, such as tolerance of alignment errors and process flow designs. I demonstrated JEOL e-beam first and ASML stepper second by using optical gratings and waveguides as test structures. Pre-alignment correction and process correction may be needed due to the overlay errors between two machines. The systematic overlay testing shows that the mean plus three sigma offsets range from 400nm without process correction to 100nm with process correction per exposure. For the ASML stepper first and JEOL e-beam case, the JEOL e-beam alignment marks need to be designed so that it can satisfy the requirements for JEOL e-beam alignment marks.