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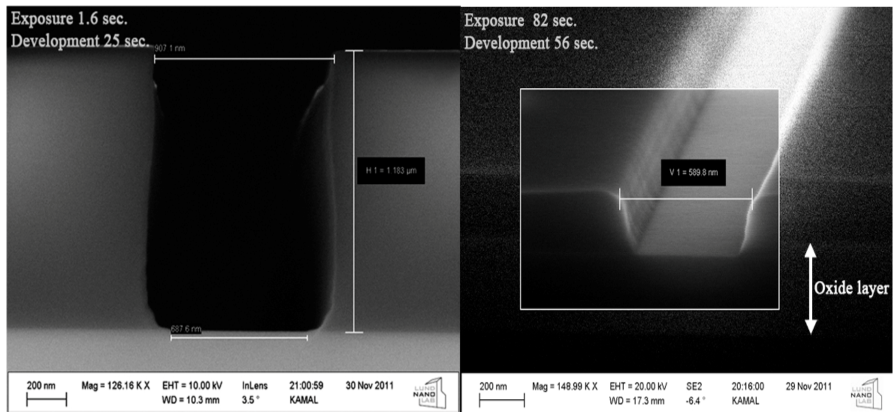
Master’s Programme in Microelectronics and Photonics, 60 credits

DEGREE THESIS



Optimization of Deep-UV Lithography Process

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Master’s thesis in Electrical Engineering, 15 credits

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Acknowledgement

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I am glad to have worked under supervision and in company of so many talented persons. I have learnt a lot from these helpful, hardworking people and enjoyed working together.

Finally I dedicate this work to my beloved parents, family members and friends whose encouragement and support helped me to be whatever I am today.

Abstract

This master's project report deals with the process development for patterning the sub-micron features using Deep-UV photolithography. Patterning of the sub-micron structures in the resists UV26 and ZEP520A-7 has been demonstrated successfully. Using the Karl Süss-MJB4 DUV mask aligner, trenches of width down to 535 nm have been obtained. Good results have been obtained in these experiments considering the development time and the exposure time, which are found to be shorter compared to previously published results. This provides a faster process and higher throughput. Experimental steps along with the further improvement areas are discussed.

Equipment used include a Karl Süss-MJB4 DUV mask aligner, an optical microscope and a Scanning Electron Microscope (SEM).

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1. Introduction

1.1 Lithography

Lithography is at the heart of IC fabrication technologies in micro and nano-electronics. It is a process of transferring patterns of geometric shapes on to a surface covered with the resist sensitive to the irradiation (photons) [1] and thus selectively removing either the exposed (in case of positive resist) or the unexposed (in case of negative resist) area of the resist. For nearly half of the century photolithography has overcome various challenges and undergone several phases of development to cope with Moore's Law. In most primitive form of lithography, visible light was used to pattern features of few micrometers [2]. But, with the shrinking circuit feature dimension, shorter wavelength irradiation light sources were used. In mid 1970s and 1980s, mercury lamps with UV wavelength emission at G–line (λ=436 nm) and I–line (λ=365 nm) were used to produce features dimension of 2 µm and 1 µm respectively [2, 3, 4]. The usage of the excimer laser at Deep UV (DUV) wavelength (λ= 248 nm and 193 nm) further extended the lower Critical Dimension (CD) to sub micrometer range. Today, DUV wavelength λ= 193 nm is capable of producing super small features of 22–20 nm [4, 5, 6]. Next-Generation Lithography will use extreme UV (EUV) at wavelength range λ=10–14 nm and X-ray at wavelength λ=1 nm [2, 7].

Although it may appear that changing the wavelength of the light source used has helped in lowering the CD over the years, advancement in numerous other areas like development of chemically amplified resists (CAR), increased numerical aperture(NA) of lenses, thinner resist, high quality lenses, well controlled process steps, etc. has helped in lowering the CD. But, that comes at an inevitable cost of increased complexities in lithographic process. This means that a careful refinement of both physical and the chemical effects is required to optimize the formation of the images and the resist profile [4].

1. 2 Motivation

Electron Beam Lithography (EBL) is a very slow and expensive technology and is generally used for sub 0.5µm ranges. Moreover writing time depends on the area being exposed. On the other hand, photolithography is characterized by its high throughput and low cost due to parallel processing. The Süss MicroTec-MJB4 DUV mask aligner is a photolithography exposure tool that uses DUV irradiation light source. It allows patterning feature in sub-micrometer range. So patterning standard structures like contact areas, nano-fluidic devices or other larger features, using DUV-mask aligner will have following advantages:

- Larger patterning area with hundreds of microns or even millimeter, which is very difficult and time consuming to produce using EBL,
- Efficient use of lithographic equipment,
- Reduced cost of operation,
- Extending life of existing equipment by reducing work load from expensive EBL machine.

1.3 Goal of the project

In this thesis work, we studied the Süss MicroTec-MJB4 DUV mask aligner thoroughly and stretched it to its limits. Aim of the project was to investigate the resolution limits of the Karl Süss-MJB4 DUV mask aligner for the resists UV26 and ZEP520A-7 with optimized exposure and development time. Hence, the project can be summarized as a development process for patterning sub-micron features using DUV photolithography.

1.4 Previous work

- Sub-micron resolution on 100 nm thick UV26 resist, diluted with Ethyl L-Lactate, has been presented [8].
- Sub-micron resolution patterning on 400 nm thick ZEP520A-7 resist has been achieved. It took 11 minutes of exposure time in vacuum contact mode, with Karl Süss MA6 mask aligner (λ=240 nm, exposure dose=6 $mWcm^{-2}$) and 2 minutes development by immersion in O-xylene followed by rinse with IPA [9]
- Resolution of 1 μm on 500 nm thick ZEP520 resist has been obtained with DUV exposure time of 2 minutes in constant power (500 W) mode. Exposed sample was developed for 150 seconds in N-amyl acetate and 30 seconds in MIBK/IPA (ratio 9:1) followed by 10 second rinse in IPA [10]

2. Background

2.1 DUV Lithography

As name indicates DUV lithography is a form of optical lithography that employs the DUV spectrum (157nm < λ < 300nm) [2, 11] of light irradiation for transferring the pattern(s) of a mask to the resist. There are three wavelengths that are used for the DUV lithography, 248 nm using KrF excimer laser or Hg arc, 193 nm using ArF excimer laser and 157 nm using F_2 excimer laser. DUV lithography allows formation of lithographic pattern in the sub-micrometer range. The DUV sensitive resist is required for DUV lithography which may be different from conventional photoresist.

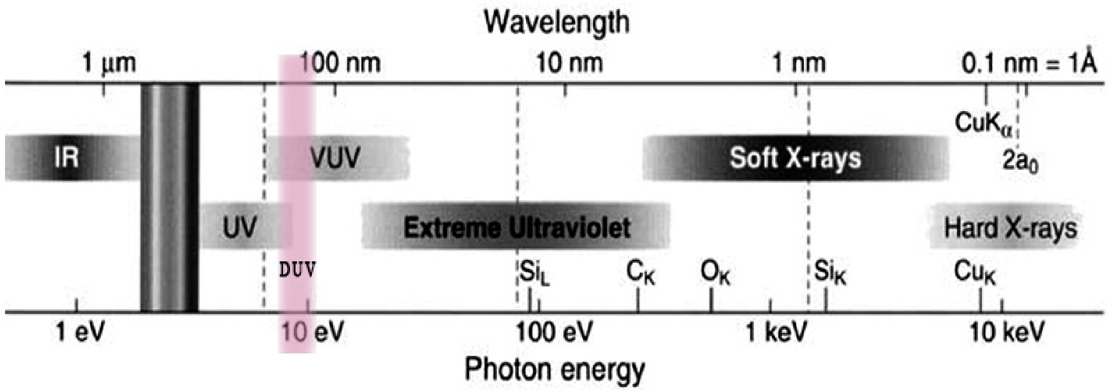


Figure 1: ***Complete spectrum of photon wavelength [2].***

2.2 Photoresist

The photoresist is a chemical compound that is sensitive to radiation. Photoresist can be either positive or negative depending upon their response to the radiation. A positive resist removes the exposed area while negative resists preserves it.

For positive photoresists, the chemical structure in the exposed area becomes more soluble in the development solution, hence removing the exposed area in the process. On the contrary, when a negative photoresist is used a cross-linked/polymerized with higher molecular weight are formed in the exposed areas, which makes the exposed area more difficult to dissolve in the developer and hence removing the unexposed areas in the process. In this thesis research positive photoresists UV26 and ZEP520A-7 were used.

2.2.1 UV26 photoresist

UV26 is a positive tone, chemically amplified DUV photoresist from Microchem Corporation [12]. Chemically amplified resists (CAR) are more sensitive to the exposure dose. Increased sensitivity is due to the fact that in CAR, a single photon triggers the deprotection of hundreds of acid-catalyzed deprotection reactions and hence fewer photons are required.

Advantages:

- Suitable for deep implantation application.
- Compatible with a wide range of substrates.
- Has low viscosity so quantity of resist per dispense is reduced. This also improves the coating uniformity.
- Allows patterning features in sub-micron resolution.

Disadvantages:

- Poor adhesion, requires hexamethyldisilazane (HMDS)-based MICROPOSIT™ Primer to promote adhesion.

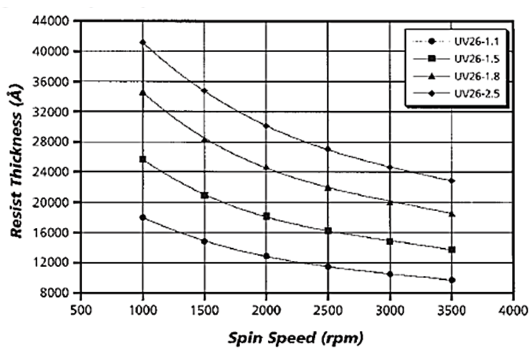


Figure 2: ***UV26 resist spin curve [12].***

2.2.2 *ZEP520A-7 photoresist*

ZEP520A-7 belongs to the ZEP520 series of resists from Zeon Corporation. It is a high performance positive tone EB (Electron beam) resist with molecular weight 57000 Da and viscosity 7 mPas [13].

Advantages:

* High resolution and contrast
* High sensitivity
* High dry etch resistance
* Sensitive to DUV light (key to use for DUV lithography).

Disadvantages:

* Poor adhesion
* Expensive

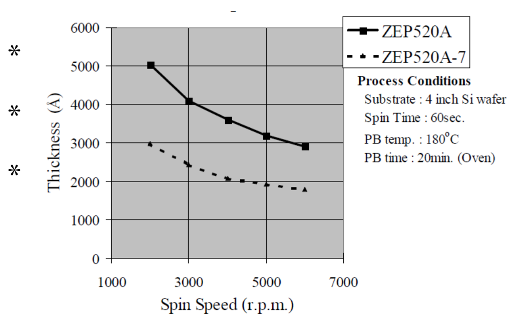


Figure 4: ***ZEP520 A spin curve [13].***

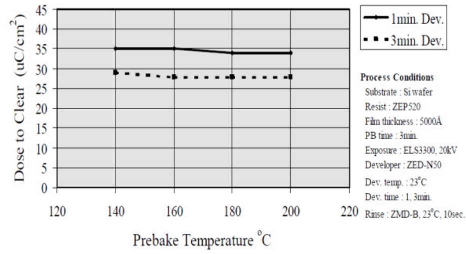


Figure 3: ***Clearing dose of ZEP520A-7 vs pre-bake temperature [13].***

2.3 Exposure Tool

MJB4 is a reliable, high precision and high performance DUV mask aligner from Süss MicroTec. It offers three different contact exposure modes namely soft contact, hard contact and vacuum contact, and a proximity exposer mode called gap exposer. In contact exposure mode, wafer and the mask are in contact with each other whereas proximity exposure mode allows the exposure at a pre-set gap between wafer and the mask. Depending upon the type of substrate used and the resolution requirements, exposure mode is selected. For all the experiments in this research project the vacuum contact mode was used as it provides the highest achievable resolution of the machine. In this mode, mask is brought in closed contact with wafer by creating a vacuum between mask and the wafer, while applying mechanical pressure and purging nitrogen underneath the wafer simultaneously.

Exposure Mode	UV400	UV300	UV250
Vacuum Contact	< 0.8 µm	< 0.6 µm	< 0.5 µm
Hard Contact	1.0 µm	< 1.0 µm	-
Soft Contact	2.0 µm	< 2.0 µm	-
Gap Exposure	> 3.0 µm		

Line, space resolution achieved in 1µm thick resist AZ 4110 (UV400, UV300) and 0.5µm thick resist (UV6, UV250) respectively. Achievable resolution depends on wafer size, wafer flatness, resist type, clean room condition and therefore, might vary for different processes.

Figure 5: ***Different exposure modes in MJB4 mask Aligner [14].***

3. Experimental Procedures

Experiments were conducted in three phases. First phase involved working with the resist UV26. Second phase involved inspection of patterns, mainly width of the trenches and negative lines on the mask using SEM (scanning electron microscope). Third phase involved working with the resist ZEP520A-7. Some of the conditions used in these experiments are listed below:

- Only exposure and development time were optimized in the experiments conducted in this project.
- All experiments were performed on 2” Silicon wafer.
- First step in all the experiments was to treat silicon wafer with acetone and isopropanole on spinner to remove any organic contamination.
- All samples were exposed using vacuum contact mode of the mask aligner to obtain the highest possible resolution (where 1 second of exposure = 8.6 mJ/cm^2 exposure dose)
- Although many different patterns were present on the mask, only trenches in the range of 400 nm to 1µm (in some cases to 1.5 µm) were considered in the experiments conducted in this project.

3.1 Experiment with UV26 resist (Phase 1)

3.1.1 Resist coating

At first the adhesion promoter, MicroChem (MCC) primer 80/20, was applied on an acetone and IPA treated silicon wafer followed by a 2 minutes bake on a hotplate (HP) with vacuum suction. The MCC primer 80/20 is a mixture of 80% acetate and 20% Hexamethyldisilazane (HMDS). After that, resist UV26 was spun on at 8000 rpm for 60 seconds and edge bead remover (EBR) was used to remove edge bead. Soft bake was performed at 130°C for 1 minute on hotplate with vacuum suction.

3.1.2 Exposure and Development

Samples were exposed for different exposure time, maximum of 2.5 seconds to minimum of 1.2 seconds. After a waiting time of about 2 minutes, post exposure bake (PEB) was performed at 110°C for 1 minute on hotplate in vacuum.

Although UV26 is optimized for 0.20N developers [12], developer MF-26A was used in these experiments. Samples were developed by immersion in the developer for a development time of maximum 40 seconds to minimum of 25 seconds. Samples were stirred while immersed in the developer. This step appeared important for proper removal of residues from the pattern for short development times. Developed samples were then cleaved through the middle of the trenches and examined in the SEM. Depending upon the profile and the trench width obtained, exposure and the development time were varied.

Table 2: *Experimental steps for UV26*

Steps	Description
Sample cleaning	Acetone and isopropanol on spinner
Prime	MCC 80/20 at 4000 rpm for 30 seconds
Bake	110°C, 2 minutes on HP
Spin-on resist (with EBR)	UV26–2.0 at 8000 rpm for 60 seconds(20 seconds at 4000 rpm for EBR)
Soft bake	130°C,1 minute on HP
Exposure	1.2–2.5 seconds vacuum contact mode, pre vacuum 5 seconds, full vacuum 5 seconds
PBE	110°C, 1 minute on HP
Development	MF-26A, immersion
Drying	N_2 blower

3.2 Mask features inspection (Phase 2)

In order to verify if the actual width of the trenches and the negative lines patterned on the mask are same as those of the designed/printed values, it was examined in the SEM. Since the mask was made up of quartz, which is non-conducting, it could not be imaged in the SEM due to charging effects. It was therefore coated with the conducting polymer ESPACER 300Z (Showa Denko) so that it can dissipate charge. ESPACER 300Z worked very fine and the mask was imaged in the SEM. After the inspection, ESPACER 300Z was removed in water.

3.3 Experiment with ZEP520A-7(Phase 3)

3.3.1 Resist Coating

After dispensing a few drops of ZEP520A-7 resist over an acetone- and IPA-treated sample, it was spun at 3000 rpm for 60 seconds. As per the spin curve of the resist, this resulted in a resist coating thickness of about 250 nm. The actual thickness of the resist was not measured. Soft bake at 180 ^{o} C for 3 minutes on a hotplate was performed to remove any excess solvent content from the resist. After the soft bake, a waiting time of about 3 minutes was used before the exposure.

3.3.2 Exposure and Development

ZEP520A-7 is a EBL resist with low sensitivity in the DUV region [12] [8], so the experiment was started with highest exposure time of 8 minutes and later reduced to 82 seconds only. Exposed samples were first cleaved into 2 or 4 pieces, then each piece was developed for different development time, minimum of 28 seconds to maximum of 120 seconds, by immersion in O-xylene followed by rinse with IPA for 40 seconds. Samples were stirred while immersed in the developer. N_2 stream was used to dry samples. Finally the developed sample was cleaved through the middle of the trenches and examined using SEM. Depending upon the profile and the trench width obtained, exposure and the development time were varied.

Table 3: ***Experimental steps for ZEP520A-7 processing***

Steps	Description
Sample cleaning	Acetone and isopropanol on spinner
Spin-on resist (with EBR)	ZEP520A-7 at 3000 rpm for 60 seconds
Soft bake	180 ^{o}C, 3 minutes on HP
Exposure	Vacuum contact mode, pre vacuum 5 seconds, full vacuum 5 seconds
Development	O-xylene, immersion
Rinse	IPA, 40seconds
Drying	N_2 Gas

4. Measurements and Results

4.1. Mask

Figure 6, shows the layout of different features present in a block on the mask. Lines which are obtained by removing of the resist from the exposed area are called ***positive lines or trenches*** whereas ***negative lines*** are those obtained by leftover resist after the development.

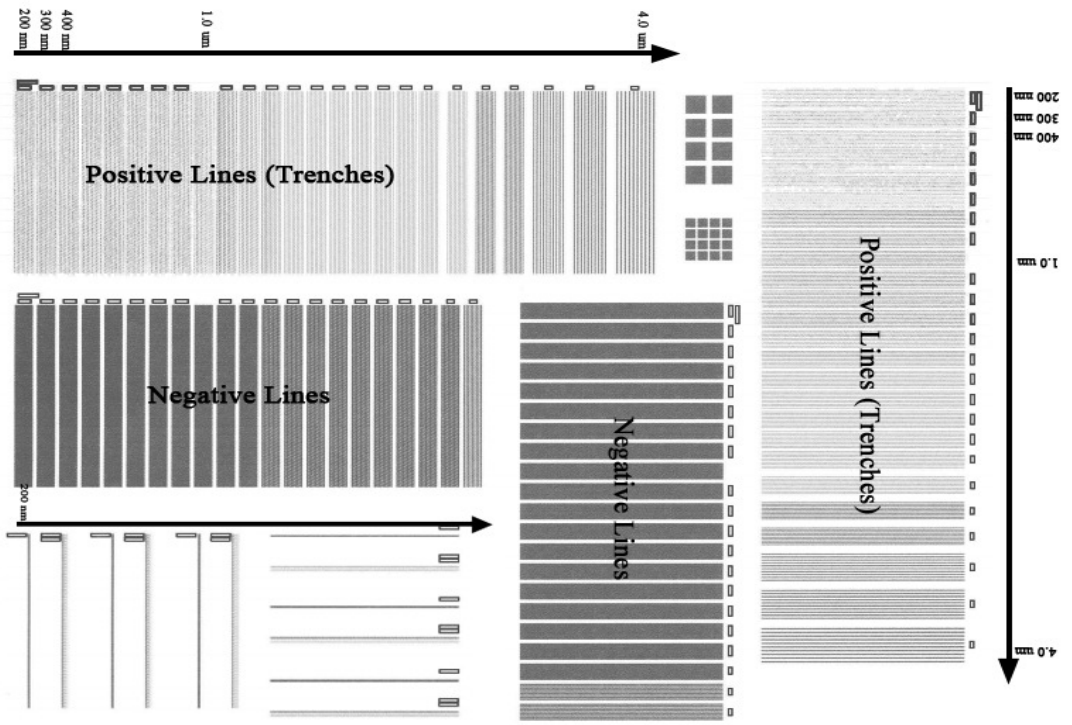


Figure 6: ***Top view SEM image of the mask layout showing different features present in a block on the mask.***

Although a very good lithography profile was obtained in the UV26 experiments, the width of the produced patterns in the resist did not match those of the mask data (designed width). For example, a 0.4 µm wide trench on the mask produced an about 1 µm wide trench in the resist. Likewise, the produced patterns for negative lines (not included in this report) were by far away from the mask data. Therefore, it seemed necessary to inspect the mask data which was later added to the project plan. To examine the mask, average measured widths of trenches and negative lines from five different locations (A, B, C, D, and E in *Figure 7*) were chosen.

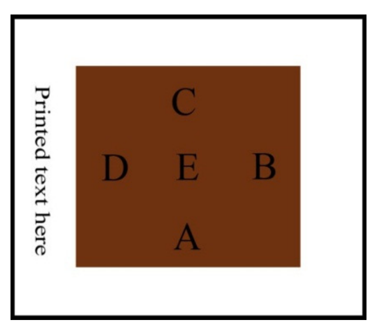


Figure 7: ***Locations on the mask where sample data was collected.***

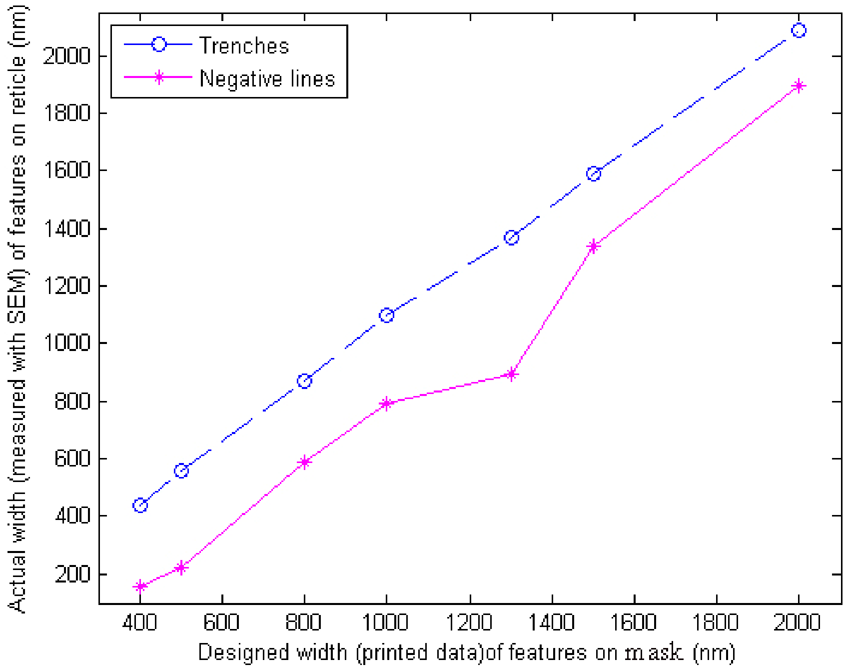


Figure 8: ***Measured average width vs designed width of features on the mask for trenches and negative lines. Measured width of tranches is comparatively much closer to the designed width than the negative lines.***

It is clear from the graphs in *Figure 8* that the designed widths on the mask differ from the actual width of the features on the mask. For the trenches, the measured width is about 37–95 nm wider compared to the designed width on the mask. This discrepancy might seem small, but must be taken into account for sub-micron processing. In case of negative lines, the actual width in the range 0.20–1.3 µm is much smaller than the designed width. Comparable data can be considered only after 2µm.

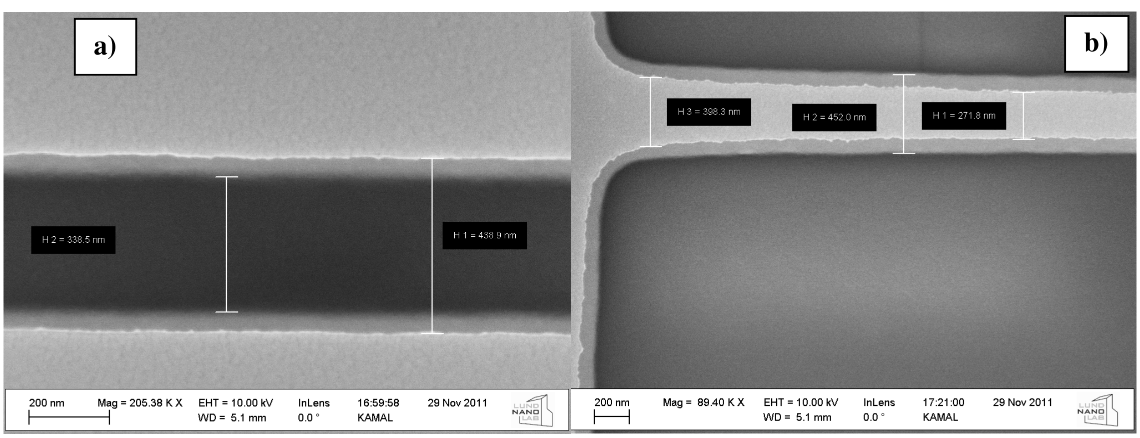


Figure 9: ***Top view SEM image of 400 nm a) trench b) negative line on mask .Trenches have good contrast and uniform trench width whereas negative lines have non-uniform width, wider at the ends and narrower towards the center.***

The profile pattern of the trenches on the mask were found to be very satisfactory apart from some deviation in dimension in width size. The corresponding profile pattern of the negative lines on the mask were found to be very unreliable for smaller dimensions and could not be considered for the experiments. Good quality patterns for the negative lines were observed only after 2000 nm.

4.2 UV26

After the samples were exposed and developed, they were first examined in an optical microscope. If the optical microscope inspection was acceptable, then selected samples were cleaved through the middle of the trenches and examined in the SEM. For a sample with exposure time of 1.2 seconds and development time of 25 seconds, 400 nm and 500 nm trenches did not develop completely see *Figure 8(a)*. For all other samples, all patterns were developed completely. *Figure 8(b)* shows the sample with the exposure and the development time of 1.6 seconds and 25 seconds, respectively, which was found to have the best resist profile with comparable straight side wall. In few samples the side walls had a small curvature which may be a sign of over-developed patterns as shown in *Figure 8(c).*

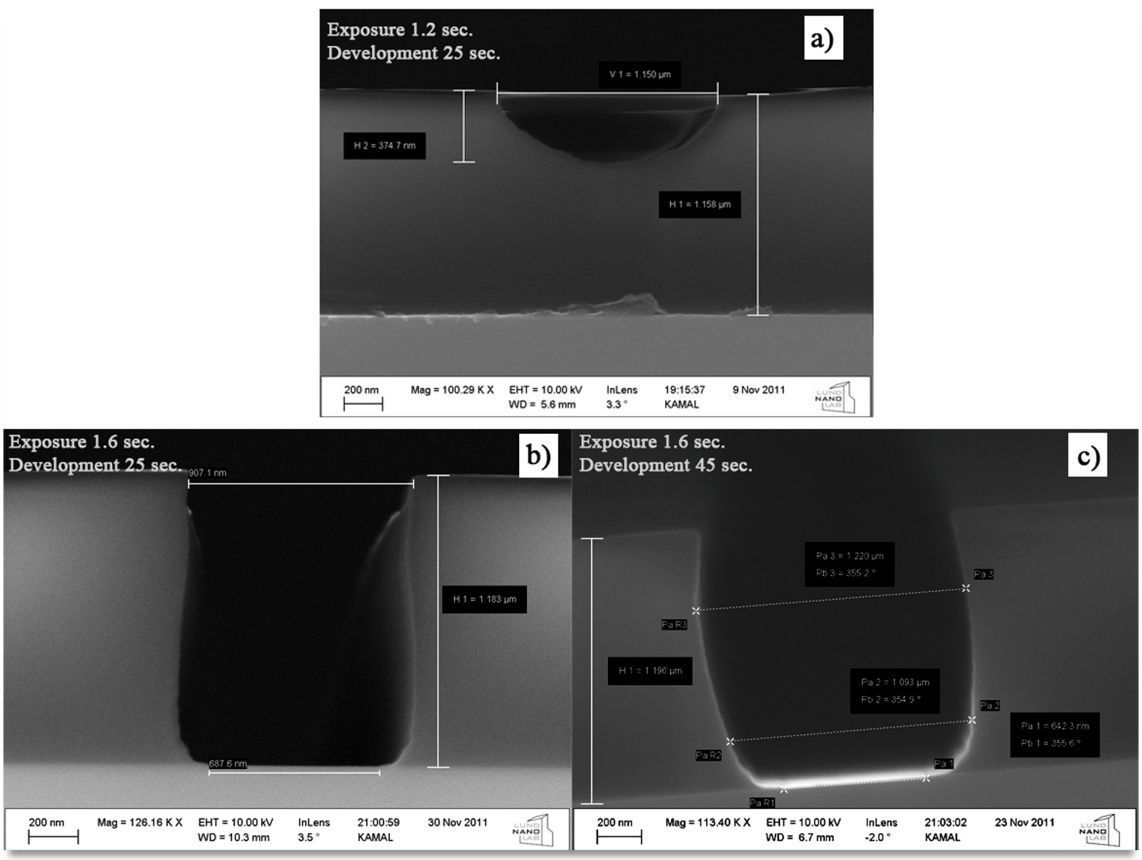


Figure 7: ***Side view of 400 nm trenches obtained in UV26 resist.***
a) Pattern that could not be developed completely due to insufficient DUV dose (under exposure).
b) Good profile with straight side walls (optimum exposure and development time).
c) Slightly curved side walls possibly because of over-development.

The resist profiles for different combinations of exposure and development times were found to be similar except for exposure and the development times of 2 seconds and 45 seconds, respectively, which appeared to have suffered from diffraction, see *Figure 9.* This could stem from improper (not parallel with mask) alignment of the wafer, wedge error correction, or presence of dust preventing proper contact between mask and wafer.

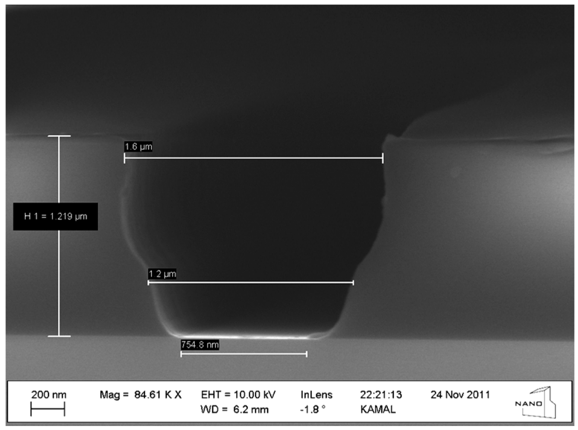


Figure 8: ***Side view of 400 nm trenches obtained in UV26 resist. The non-optimal resist profile may be the result of diffraction effects.***

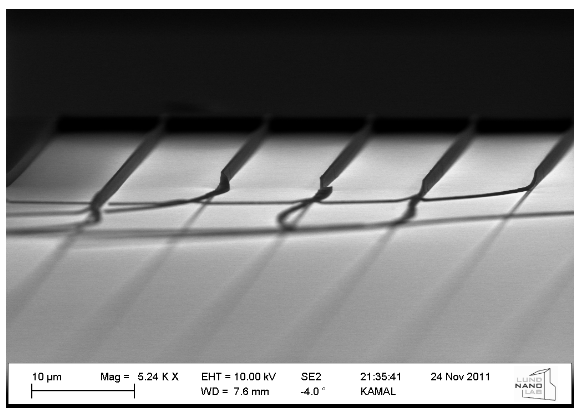
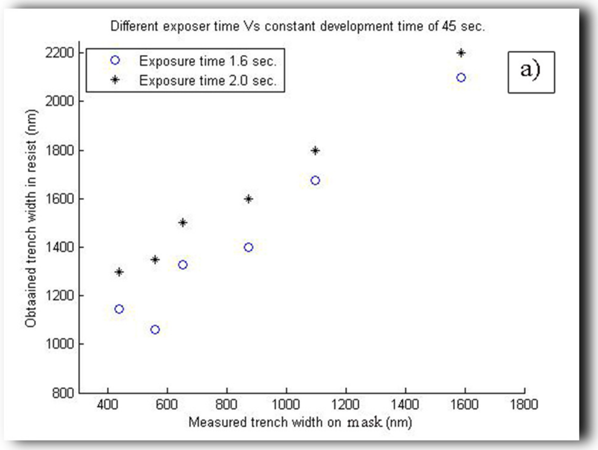


Figure 9: ***Washed away negative lines-UV26 resist after development due to poor adhesion.***

In these experiments the adhesion promoter MCC Primer 80/20 was used to promote better adhesion of the resist to the wafer. Nevertheless the resist in a few samples was washed away as shown in *Figure 10.* This may be due to some process variation like wait time between steps, or insufficient cleaning of the wafer.

Although good resist profiles and contrast were obtained, the widths of the trenches obtained in the resist were much wider compared to the measured width on the mask. A minimum trench width of 907 nm was obtained in the resist for 437 nm wide trench on the mask. *Figure 11,* shows a comparison of the trench width obtained for different combinations of the exposure and the development times.



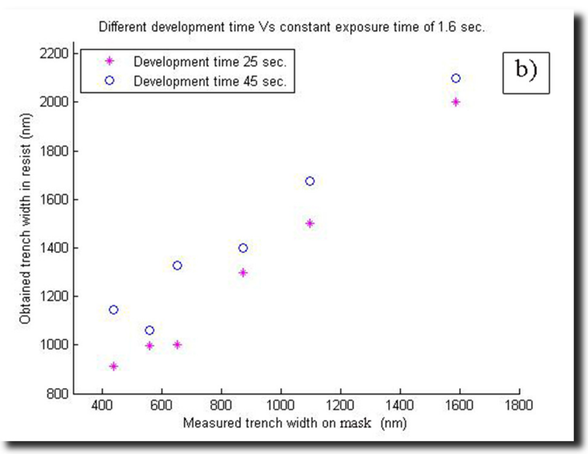


Figure 10: ***Obtained trench width in resist vs measured trench width on the mask - UV26.***

a) Constant development time and different exposure time.

b) Constant exposure time and different development.

The width of the trenches approach the actual width for shorter exposure and development times. The sample with the exposure time of 1.6 seconds and the development time of 25 seconds shows the best result among all the developed samples. The sample with the exposure time of 1.2 seconds could not be developed completely due to insufficient dose. Further reduction in the development time was not tried as it may not be sufficient for proper removal of residues from the pattern.

The initial project plan included experiments with diluted UV26 resist with a thickness of 100 nm. But due to lack of time this plan was dropped, also few more experiments with shorter exposure time between 1.6–1.2 seconds could not be performed. The resist thickness plays a very important role in submicron lithography, discussed later in the report under title "*Future Work and Improvement Areas*".

4.3 ZEP520A-7

In total ten silicon samples were exposed, six of them were oxidized (253 nm thick SiO_2) to have better resist adhesion. Exposed and developed samples were first inspected in an optical microscope and then imaged in top view using SEM. Later on, selected samples were cleaved through the middle of the trenches for side view inspection with SEM.

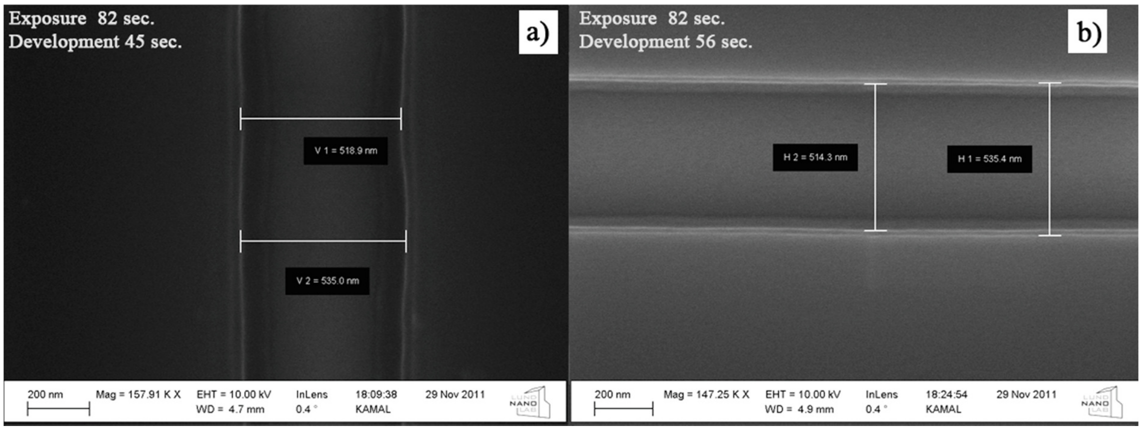


Figure 11: ***Top view SEM images of 400 nm trenches in ZEP520A-7 resist.***
a) Under-developed sample.
b) Developed and exposed using optimal time.

Both the samples shown in *Figure 12* were exposed for 82 seconds, but developed for different time. The sample with development time of 56 seconds is completely developed, whereas a development time of 45 seconds appeared to be insufficient as it has some resist left.

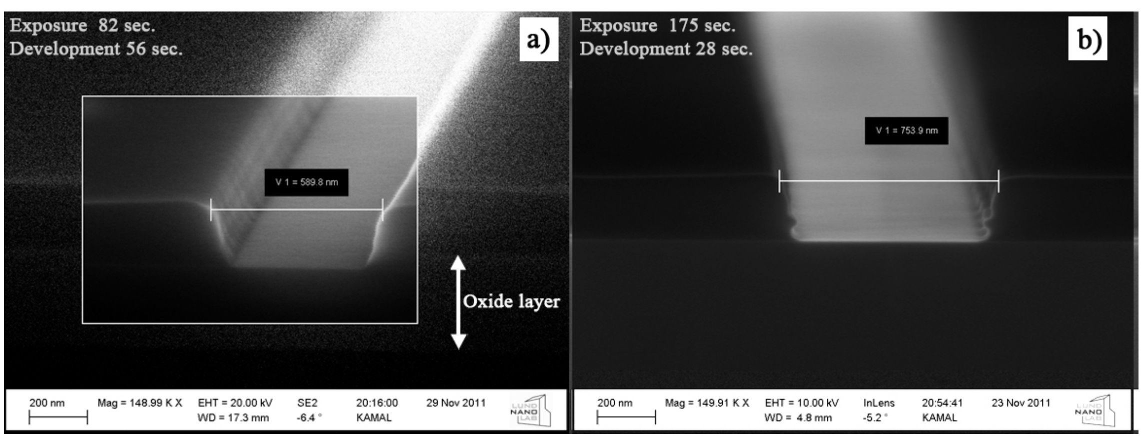


Figure 12: ***Side view of 400 nm trenches obtained in ZEP520-A resist. a) Sample with oxide layer in between substrate Si and ZEP520A-7 resist, showing smooth side walls. b) Sample without oxide layer in between substrate and resist, showing some unwanted notch or roughness on side walls.***

Figure 13, shows the effect of oxidization of silicon wafer before resist coating. The samples with oxide layers showed a smooth resist profile compared to the samples without oxide layer. It may be concluded that the oxide layer not only provides better adhesion to the resist, but also prevents reflection of UV radiation from the silicon wafer.

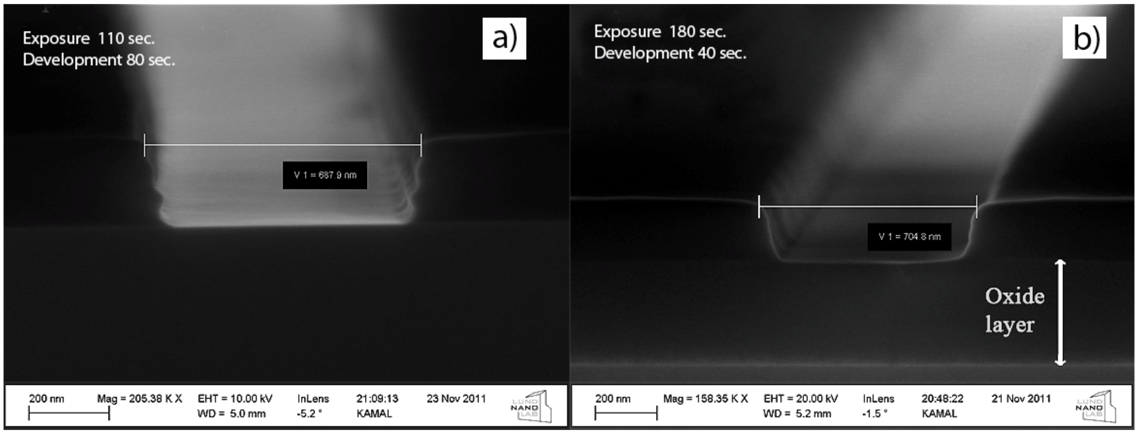
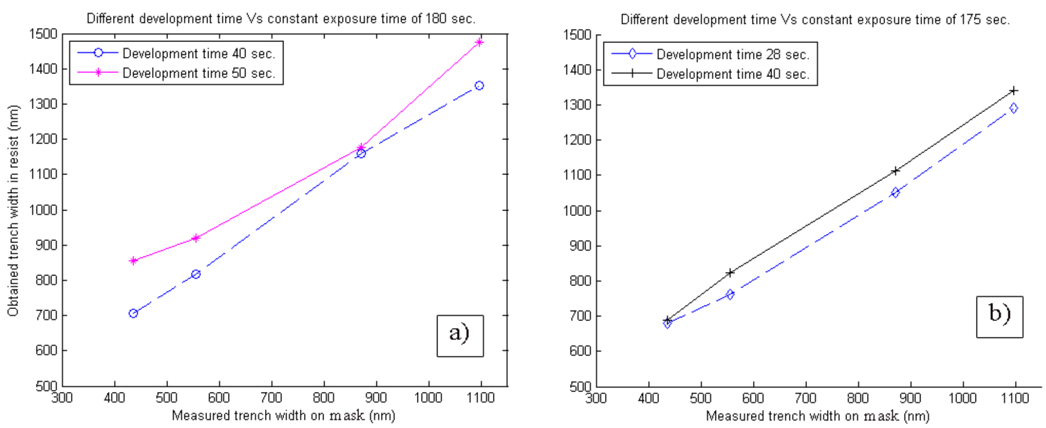


Figure 13: ***Side view of 400 nm trenches obtained in ZEP520A-7 resist. a) Sample with shorter exposure time but longer development time. b) Sample with longer exposure time but shorter development time. Both the samples have equal trench width of 704 nm although different exposure and development time.***

Figure 14 shows SEM images of two samples with the same trench width of 704 nm. The exposure time of the sample in *Figure 14(a)* is shorter than of the sample in *Figure 14(b),* whereas the development time of the sample in *Figure 14(b)* is shorter than that of the sample in *Figure 14(a).* From this we can conclude that the exposure time can compensate for the development time and vice versa. This can be proved very useful for mix-match lithography techniques where a single development is preferred to ease the process.



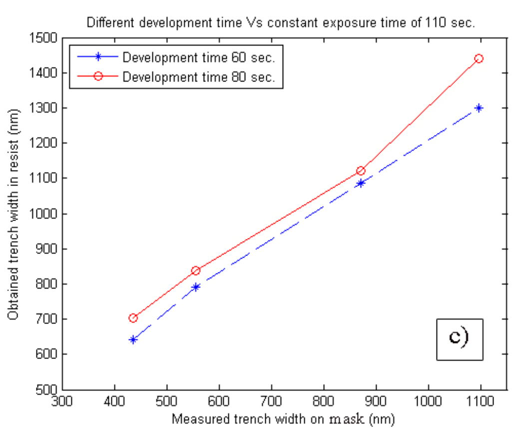


Figure 14 a-c: ***Obtained trench widths in resist vs measured trench width on mask - ZEP520A-7 with constant exposure time of 180 seconds, 175 seconds and 110 seconds respectively for different development time from 28 - 80 seconds.***

Figure 15 a−c, show a comparison of the trench width obtained in the resist for different combinations of exposure and the development time. The shortest trench width of 519 nm was obtained for the exposure time of 82 seconds and the development time of 45 seconds, but it was not developed completely (*Figure 12.a*). The sample exposed and developed for 82 seconds and 56 seconds, respectively, gave the best result (*Figure 12.b*) with a trench width of 535 nm for 437 nm wide trench on the mask. These two results are not included in graphs, *Figure 15.*

5. Conclusion

The research done in this thesis work shows that it is possible to pattern sub-micron features using the Karl Süss-MJB4 DUV mask aligner using the resists UV26 and ZEP520A-7. Optimum exposure and the development time was found to be shorter than previously published results and hence resulted in improved throughput. It was also shown that the exposure time and the development time for the ZEP520A-7 resist can compensate each other to some extent, which is useful for processes like e.g. mix-match lithography where the exposure time can be compensated to achieve a single development time for differently exposed patterns.

Table 3: *Final results*

Resist	UV26	ZEP520A-7
Optimum exposure time (s)	1.6	82
Optimum development time (s)	25	56
Minimum obtained trench width in resist for 437 nm trench on mask (nm)	911	535

6. Future Work and Improvement Areas

No matter how perfect an experiment is performed, there is always space for improvement.

6.1 For UV26

- Critical Dimension (CD) for contact printing is given as

  $$CD \cong \sqrt{\lambda g},$$

  Here,
  g = gap between the mask and the wafer including thickness of the resist
  λ = wavelength of exposure radiation.

  Experiments in this work were performed on about 1 μm thick resist layers. From the above relation, it is clear that the thickness of the resist can be a limiting factor for sub-micron lithography. There is thus a possibility to obtain better results with thinner resists.
- The exposure time of 1.2 seconds was found to be insufficient, whereas a successful result was obtained for 1.6 s of exposure. So there is still space left for optimization of exposure time (or dose) between 1.2–1.6 seconds
- UV26 is a chemically amplified resist (CAR). The performance of a CAR is strongly dependent on the temperature, especially PEB. In these experiments both waiting time between steps and baking temperature were not optimized.
- Some adhesion problems with the resist were faced, so maybe a different type of primer can provide better results.

6.2 For ZEP520A-7

- The obtained profile lacks good contrast, steepness of the side walls, and smoothness. The ZEP 520 is sensitive to temperature; it has been proved that lower temperature development gives better profile [13, 15].
- Diluted developer is another option which can improve the result.
- Finally thinner resist layer can be used.

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