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Double Exposure Technology for KrF Lithography

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Abstract

The application of Double Exposure Lithography (DEL) would enlarge the capability of 248 nm exposure technique to smaller pitch. We will use the DEL for the integration of critical layers for dedicated applications requiring resolution enhancement into 0.13 μm BiCMOS technology. In this paper we present the overlay precision and the focus difference of 1st and 2nd exposure as critical parameters of the DEL for $k_1 \leq 0.3$ lithography (100 nm half pitch) with binary masks (BIM). The realization of excellent overlay (OVL) accuracy is a main key of double exposure and double patterning techniques. We show the DEL requires primarily a good mask registration, when the wafer stays in the scanner for both exposures without alignment between 1st and 2nd exposure. The exposure tool overlay error is more a practical limit for double patterning lithography (DPL). Hence we prefer the DEL for the resolution enhancement, especially if we use the KrF high NA lithography tool for 130 nm generation.

Experimental and simulated results show that the critical dimension uniformity (CDU) depends strongly on the overlay precision. The DEL results show CDU is not only affected by the OVL but also by an optical proximity effect of 1st and 2nd exposure and the mask registration.

The CD uniformity of DEL demands a low focus difference between 1st and 2nd exposure and therefore requires a good focus repeatability of the exposure tool. The Depth of Focus (DOF) of 490 nm at stable CD of lines was achieved for DEL. If we change the focus of one of the exposures the CD-focus performance of spaces was reduced with simultaneous line position changing. CDU vs. focus difference between 1st and 2nd exposure demands a focus repeatability <100 nm for the exposure tool.

Summary, the results show DEL has the potential to be a practical lithography enhancement method for device fabrication using high NA KrF tool generation.

Keywords: double exposure lithography, double patterning lithography, KrF lithography

1. Introduction

Double exposure and double patterning techniques can help to push the lithography to lower resolution limits /1/. In special the Double Patterning Lithography (DPL) is driving the device shrinks below 40 nm half pitch with ArF immersion lithography /2-4/. The limit of the optical resolution (R) in lithography is defined by Rayleigh's equation:

$$R = k_1 \frac{\lambda}{NA}$$

λ = Wavelength
NA = Numerical aperture
 k_1 = Process factor

The idea of double processes is the reduction of the k_1 - factor due to layout splitting. The layout splitting offers the possibility to reduce the pitch in the overall layout. Therefore the k_1 - factor is reduced. The DPL limit for the k_1 - factor is $k_1 < 0.25$ and for DEL $k_1 \geq 0.25$ /3, 4/. Both techniques are shown in Fig. 1. The DPL uses a hardmask, which is

structured in two litho and two etch steps. After the structuring of the hardmask the complete layout is transferred in the substrate. In DEL the resist is structured in two litho steps. Afterwards the layout is etched in the substrate.

We show the improvement of the resolution from $k_1 = 0.43$ to $k_1 = 0.33$ by application of DEL with low cost binary masks (BIM) and high NA KrF lithography using double exposure. An example is given in Fig. 2. In Fig. 2a we show a single exposure with 240 nm pitch. The structures are not resolved. Fig. 2b shows resolved structures with 200 nm pitch, exposed with DEL. In contrast to DEL, the DPL has a practical limit due to the overlay error for the KrF high NA lithography tool for 130 nm generation. The key motivation for this work is the application of DEL, because of the possibility to achieve 100 nm half-pitch structures with the KrF lithography using binary masks.

2. Experimental

The DEL was carried out with a KrF Scanner (Nikon S207D, NA = 0.82, $\sigma = 0.4$) for a CD of 100 nm half pitch (Fig. 2). The chemical amplified positive resists SL4800 or UV2000 (Rohm & Haas) with a thickness of 325 nm was coated on a 70 nm AR10L (Rohm & Haas) bottom anti-reflective coating (BARC). With a single exposure it is not possible to resolve 100 nm half pitch with BIM application. Therefore, we studied the DEL technique. Alternatively to the DEL, we investigate the Double Patterning Lithography (DPL). For DPL we use an antireflective hard mask of 86 nm PECVD $\text{Si}_3\text{N}_4/\text{O}_2$ /5/. The ARC with optical constants of $n = 2.12$ and $k = 0.38$ have been adjusted for the DPL application /5/. For the overlay investigations we generate an overlay error by a shift of the 2nd exposure. The OVL was measured using KLA 5200. The process windows were analyzed by PRODATA software using KLA-Tencor's SEM eCD2 /6/ for the CD measurements.

3. Results and Discussion

3.1 CD vs. overlay performance

Experimental and simulated results in Fig. 3 show the critical dimension uniformity (CDU) depends strongly on overlay precision. The overlay precision is divided into the stepping precision, the alignment accuracy and the mask registration. For DEL, we found the OVL error by mask changing for the 1st and 2nd exposure without changing the wafer (no wafer alignment between the exposures) to be small ($3\sigma \leq 6$ nm, excluding mask errors) in contrast to wafer changing and alignment ($3\sigma \leq 15$ nm).

We found a higher deviation from CD vs. OVL-curve of about:

$$\text{CD} \approx \text{CD}(\text{OVL}=0) \pm 1.2 \cdot \text{OVL}$$

The result for DEL (Fig. 4) show CDU is not only affected by the OVL error, but also by an optical proximity effect of 1st and 2nd exposure. The proximity effect is caused by the superposition of the intensities for the 1st and 2nd exposure. Therefore the mask registration is one of the critical quality parameters for the DEL. This effect requires improved mask registration quality for DEL by 20 %.

The proximity effect is slightly reduced using UV2000 resist (Fig. 4). The CD of the double exposure usually depends on stepping precision, lithography and mask registration error. The CD of double patterning technique is determined additionally by wafer alignment of 15 nm (mean + 3 σ) for the Nikon S207D. Fig. 5 shows the typical overlay problem and the practical limit for application of DPL using KrF lithography.

3.2 Process window investigations

For DEL we determined 390 nm Depth of Focus (DOF) at 3 % exposure latitude using SL4800 resist (Fig. 6 and 8). The better resist resolution of UV2000 results in a higher DOF = 490 nm. Compared to the process window of DPL (Fig. 7, first exposure for example), the process window of DEL (Fig. 6) is two times larger.

Second we investigate the focus repeatability of DEL technique. If we change the focus of one of the exposures the CD-focus performance of spaces becomes more sensitive, with an effect of simultaneous line position changing (line shift), as shown by the experimental (Fig. 9 and Fig. 10c) and simulated results using Synopsys-SOLID-E simulator /7/ (Fig. 9). CDU of spaces vs. focus difference between 1st and 2nd exposure demands a focus repeatability of < 100 nm (Fig. 10a). However, the CD variation of lines (Fig. 10b) caused by focus difference between 1st and 2nd exposure is small. In respect to the overlay budget the line shift (Fig. 10c) is not important. This indicates that the focus repeatability of the Nikon Scanner 207 of < 30 nm is sufficient for practical purposes of double exposure lithography. But this effect plays an important role in application of multi-layer reticles for two or more exposures especially at masks with 1st and 2nd layer positions not in the scan direction (x direction for Scanner S207). Multi layer reticles are common for reduction

of manufacturing costs for low- and medium-volume production and prototyping. Experimentally, we found that the focus difference between the 1st and 2nd exposure can occur, if the structures of the 2nd exposure are not in the scan direction. In this case the position of the wafer for the 2nd exposure is changed and other focus sensors are used to measure at the same position. The tool offers the possibility to use the same focus sensors for both exposures, but due to the wafer position change, they would measure at a different location for the 2nd exposure. Both possibilities can have an influence on the focus measurement of the exposure tool. The usage of different sensors can lead to different focus results and the measurement at other locations with fixed sensors, especially with topography on the wafer, is critical, too. In the case, that we use different sensors for 1st and 2nd exposure, we found a CDU 3 sigma of 10 nm - 15 nm. The problem is that the dynamic focus measurement results can be influenced by the wafer position and / or sensors and the wafer topography respectively. Obviously, this will have an impact to the CDU. Further investigations are ongoing to check focus enhanced methods for the DEL.

3.3 CD uniformity results

In order to check the practical wafer printing results the experimental data of CD's was measured across a wafer in 80 exposed fields (dimension x = 13 mm and y = 16 mm) for DEL. The measured pattern includes one 100 nm line and 100 nm space for 1st and 2nd exposure, respectively. The 1st and 2nd exposure for DEL were done without changing the wafer (no wafer alignment between the exposures) by pitch doubling of the same 100 nm grid (pitch 400 nm) by a shift of 200 nm between the 1st and 2nd exposure. The mask registration errors are excluded by wafer map measurements on the same structure. Furthermore, the same focus sensors are used for the 1st and 2nd exposure, due to the small shift of 200 nm of the mask. The resulting wafer position change for the focus measurement is negligible. This case is comparable to multi-layer reticle application with both exposure positions in the scan direction. Table 1 shows the CD and CDU results for the DEL.

Table 1: Wafer CD and CD uniformity for 100 nm lines and spaces.

DEL	Line 1	Line 2	Line 1+2	Space 1	Space 2	Space 1+2
Average CD	102 nm	103 nm	102 nm	97 nm	100 nm	99 nm
CDU 3σ	7.1 nm	6.8 nm	7.2 nm	5 nm	4.4 nm	6.3 nm

The wafer map results for the DEL show a $3\sigma = 7.2$ nm for the lines and a $3\sigma = 6.3$ nm for the spaces in respect to the CDU. First results for the DPL technique for spaces show a $3\sigma \sim 10$ nm. The higher CDU deviation can be explained by the higher DOF of the DEL in comparison to the DPL (Fig. 6-7). Furthermore the overlay error ($3\sigma \sim 15$ nm) of the exposure tool degrades the CDU results for lines using DPL technique. The achieved results for the DEL fulfill the 100 nm half-pitch requirements according the SIA roadmap /8/.

4. Summary

In summary, our initial results show that double exposure lithography has the potential to be a practical lithography enhancement method for device fabrication using high NA KrF tool generation. The results of double exposure lithography of KrF lithography (NA = 0.82) applying binary masks confirm the achievement of 100 nm pattern resolution at 200 nm pitch with an acceptable process window with depth of focus of 490 nm. The practical wafer printing results show a CD uniformity of 7.2 nm (3σ) for lines and for spaces of 6.3 nm (3σ) without mask errors. The CD uniformity of lines is caused by exposure tool precision errors like stepping precision, which is ≤ 6 nm (3σ).

Nevertheless, the advantage of lower overlay errors and larger process windows of double exposure technique in comparison with the double patterning technique play a very decisive role in the performance of high NA KrF lithography for 130 nm tool generation.

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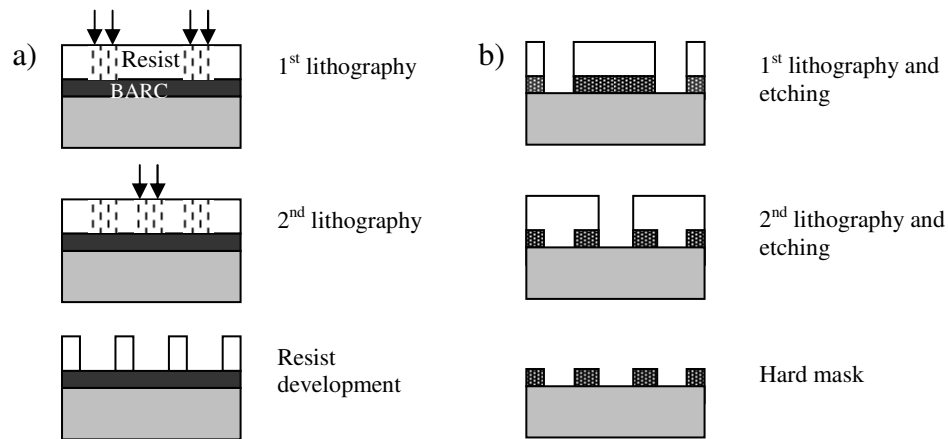


Fig. 1: a) Double exposure technique and b) double patterning by double expose/double etch process with positive resist

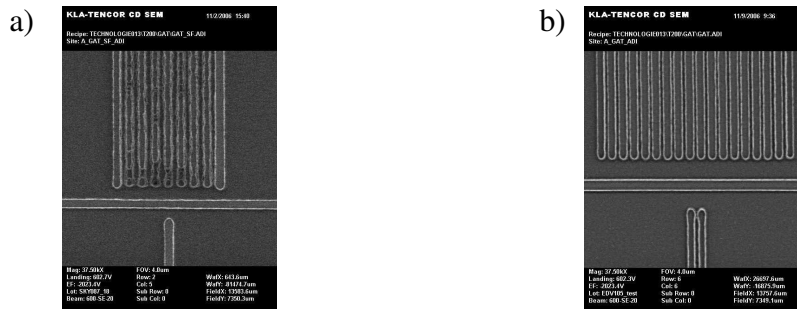


Fig. 2: SEM of resist (UV2000) structures of CD = 100 nm. a) Single exposure with pitch = 240 nm, which shows the resolution limit and b) Double Exposure Lithography (DEL) with pitch = 200 nm.

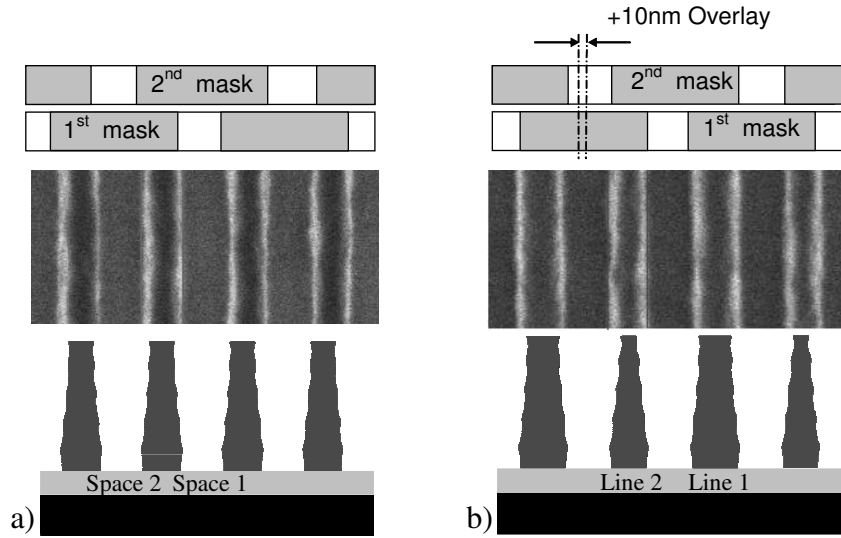


Fig. 3: SEM pictures and simulated resist profiles of double exposed 100 nm resist patterns with optimized alignment (a) and a misalignment of +10 nm between the two exposures (b). Exposure were performed using resist SL4800 (Rohm & Haas) on bottom antireflective thin film of AR10L (Rohm & Haas) and an exposure dose of 50 mJ/cm².

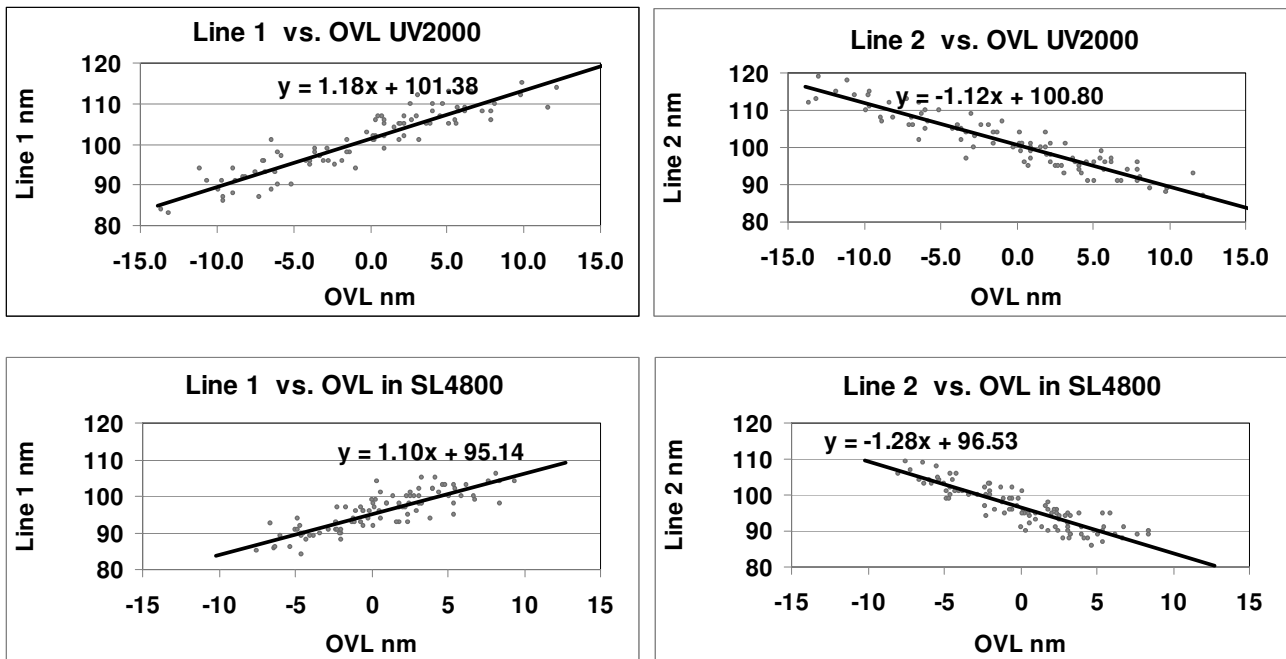


Fig. 4: CD vs. overlay for SL4800 and UV2000 resist (definition of line1 and line 2 see Fig. 3).

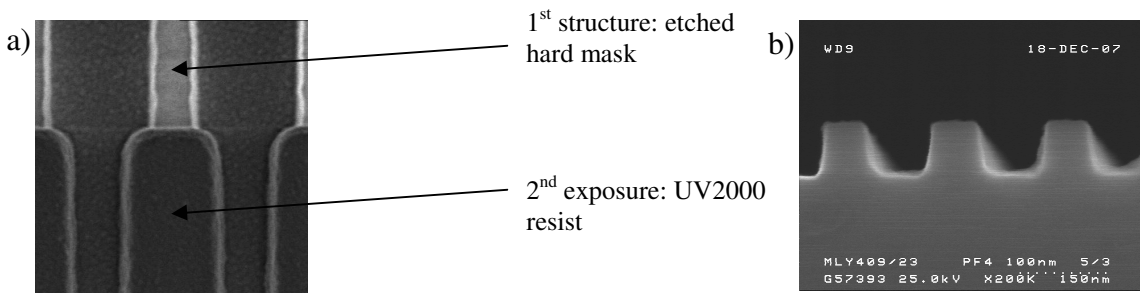


Fig. 5: Double Patterning Lithography (DPL): a) SEM top view after 1st lithography and etching and 2nd lithography and b) cross section view after 2nd lithography and etching of ARC hard mask.

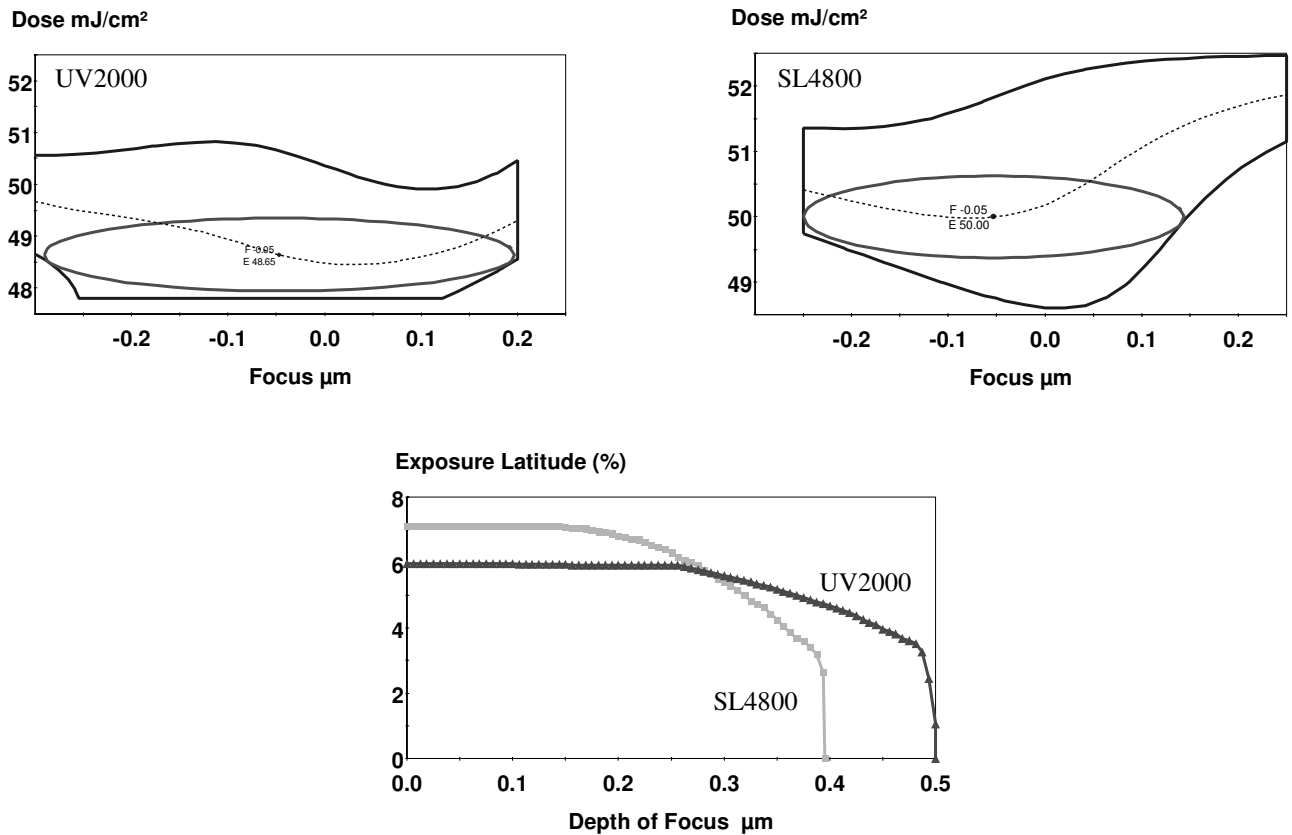


Fig. 6: Process windows (exposure latitude = 3 % and process latitude for line CD = 100 nm \pm 5 %) for double exposure of 100 nm L&S using UV2000 and SL4800 resist. The depth of focus is 490 nm for UV2000 and 390 nm for SL4800.

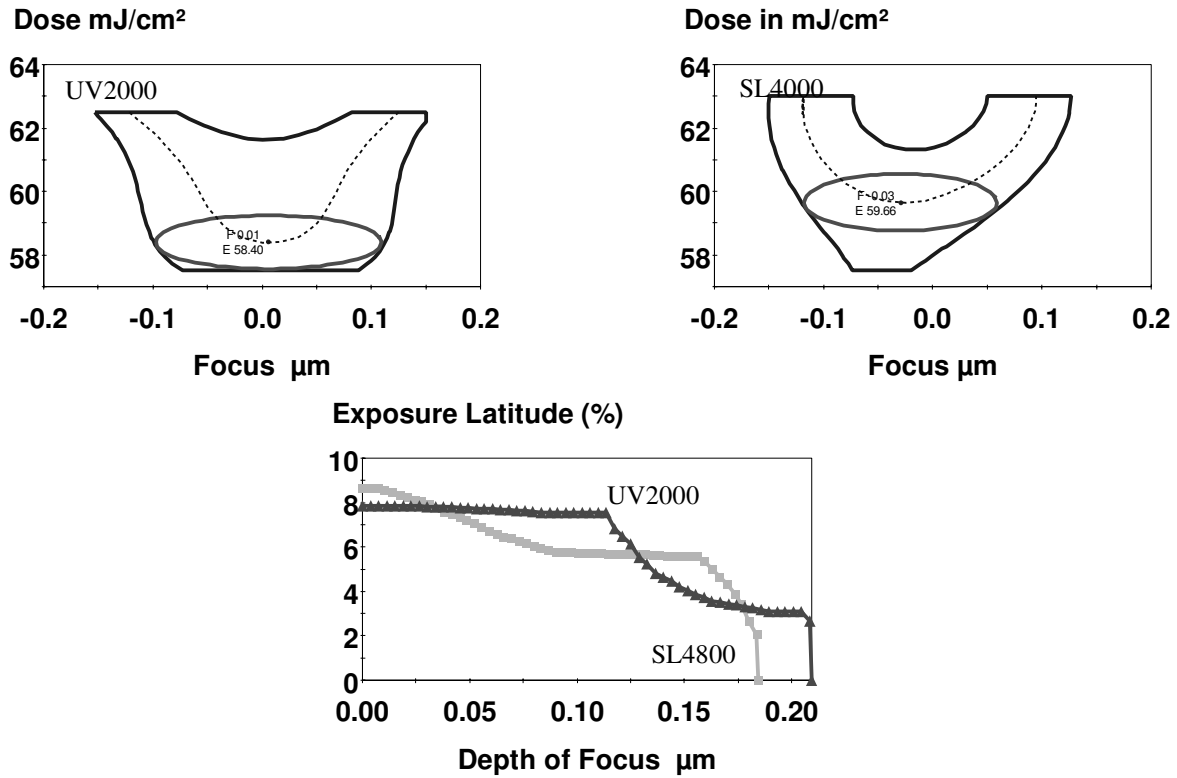


Fig. 7: Lithography process windows (exposure latitude = 3% and process latitude for space CD = 100 nm \pm 5 %) for single exposure of 100 nm spaces with pitch of 400 nm on 86 nm PECVD Si_xN_yO_z /5/ using UV2000 and SL4800 resist for DPL. The depth of focus is 180 nm for SL4800 and 210 nm for UV2000.

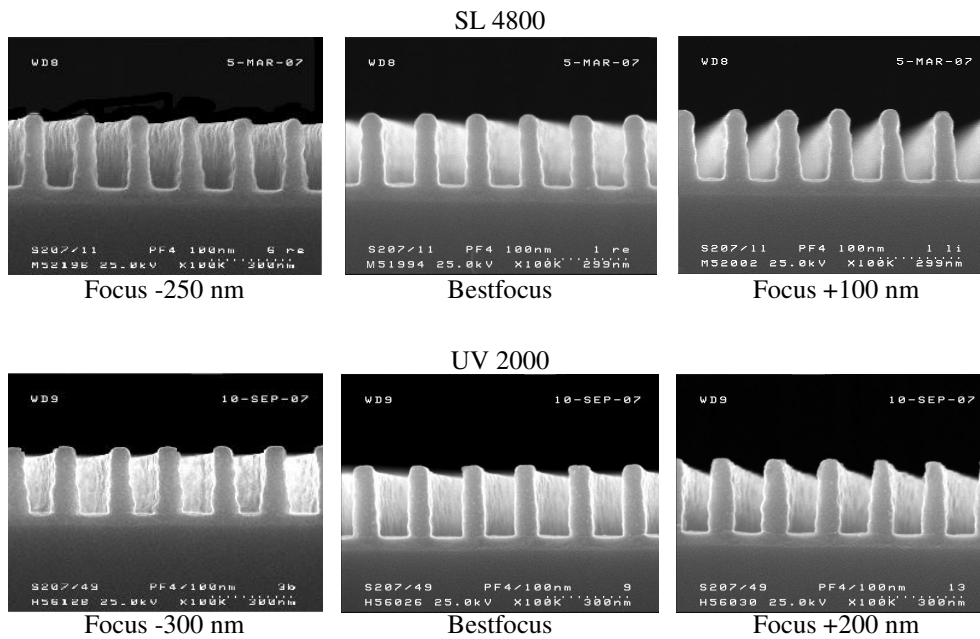


Fig. 8: Focus latitude of double exposure lithography (DEL) with 100 nm half pitch SL4800 and UV2000 resist structures.

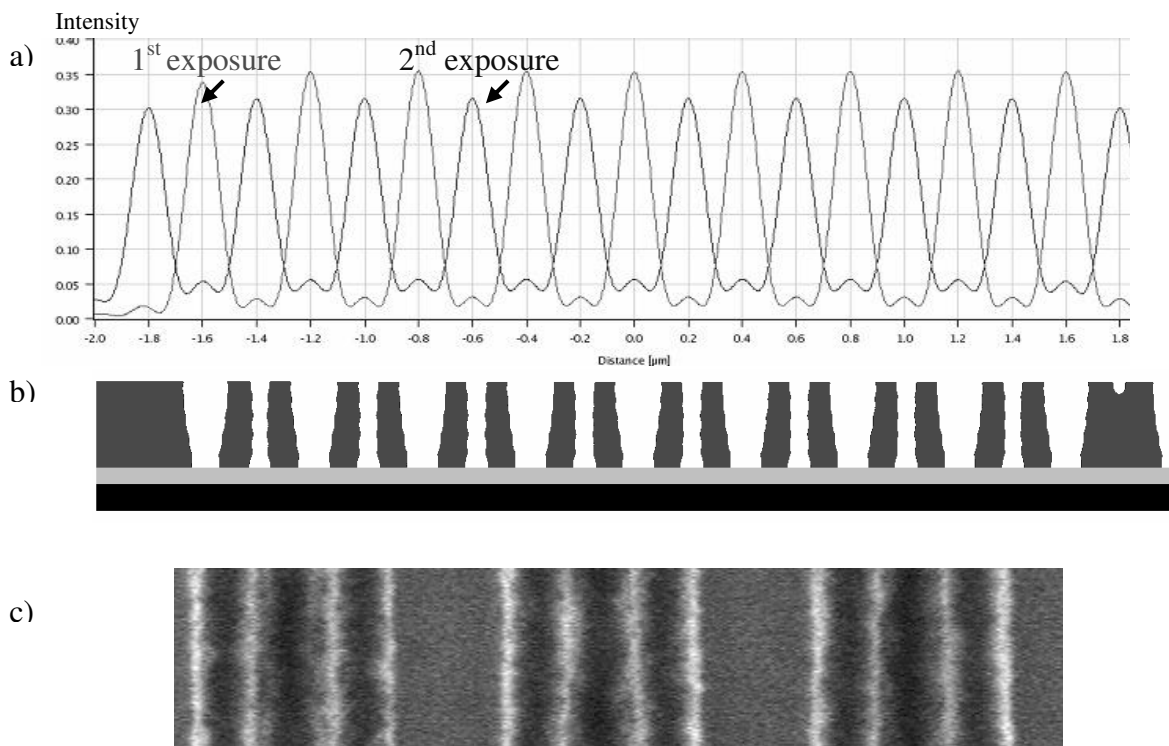


Fig. 9: Intensity (a), and profile SOLID-E simulations (b) of Double Exposure Lithography (DEL) with SL4800 resist (pitch = 200 nm) at best focus of 1st and -0.2 μm defocus of 2nd exposure. (c) shows a corresponding SEM image of resist structures for the defocus of 2nd exposure.

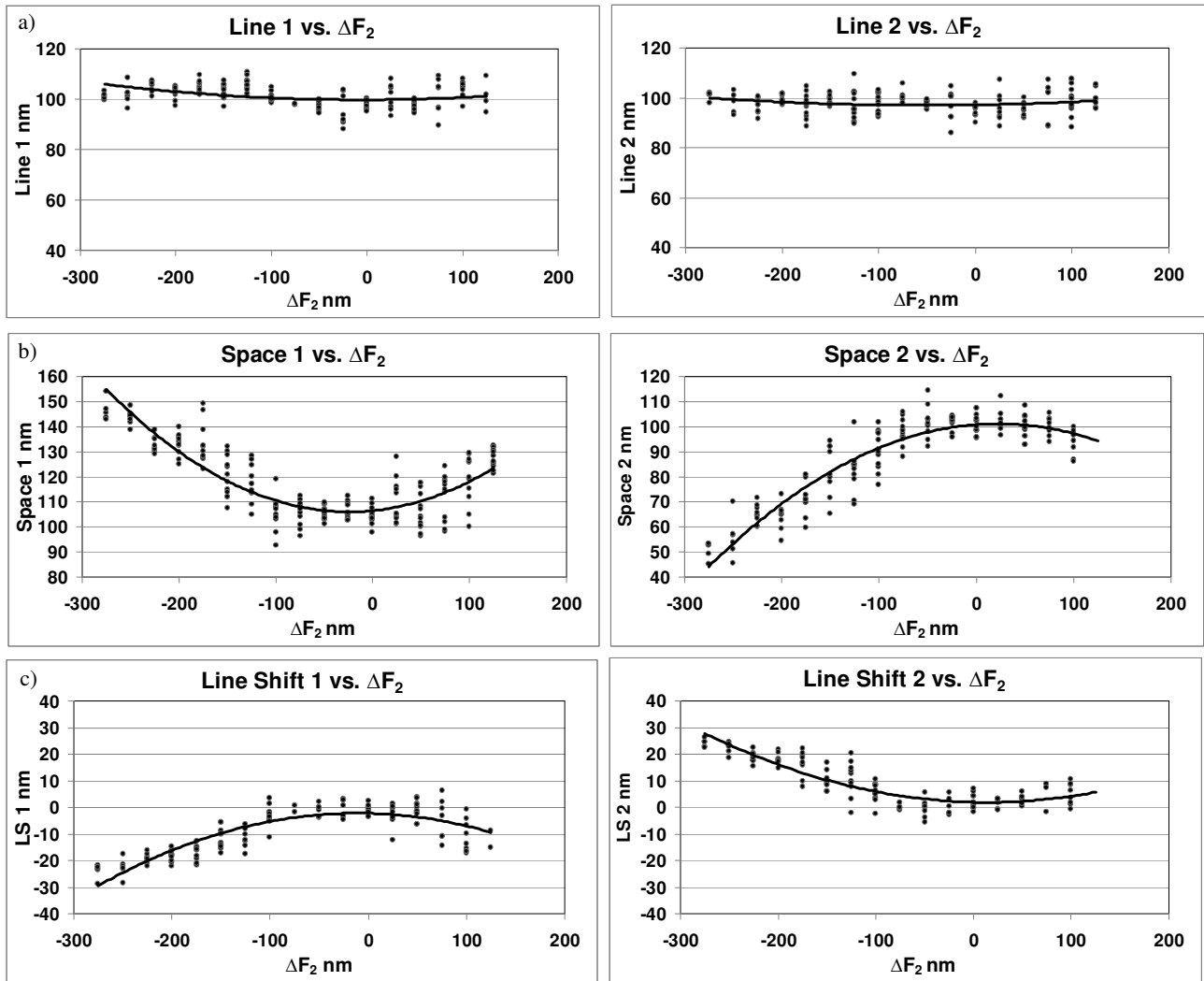


Fig. 10: Lithography performance of double exposure technique vs. difference of focus between 1st and 2nd exposure by using SL4800 resist: a) CD uniformity of spaces, b) CD uniformity of lines measured by SEM top view images, and c) the line shift error analogous Fig. 6 (Line Shift = 100 nm - Space / 2 - Line / 2). One of the exposure works in the best focus, the focus of the other exposure is the x axis.