Patterning of 100 nm Features Using X-ray Lithography

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Patterning of 100 nm critical dimension features using X-ray proximity lithography is discussed. Lithographic performance is shown using photoresists APEX-E, UV-4 and an experimental formulation of ESCAP photoresist. Conditions to pattern isolated and nested lines at maximum permissible gap is discussed.

Keywords: X-ray Lithography, chemically amplified resists, nanolithography

1. Introduction

Extension of the traditional optical projection lithographic techniques from current 248 nm DUV to 193 nm will support VLSI production of 175 nm critical dimension (CD) patterns. For the 130 nm CD generation and beyond, non-traditional lithography solutions need to be explored. Several technologies are considered as candidates for VLSI mass production at 130 nm CD and below: electron beam projection lithography [1], reflective projection lithography at 13 nm wavelength (Extreme Ultraviolet Lithography, or EUV) [2], and X-ray proximity lithography [3].

Resolution capability of proximity X-ray lithography below 100 nm CD has been demonstrated in the early years of the technology development [4]. In the present, various manufacturability issues of the technology must be taken into account. One of the concerns is that ≤ 100 nm CD will require a gap between the mask and the wafer so small that it will be difficult to use in manufacturing.

The requirement to print at a small gap complicates the proximity technology since it imposes tight tolerances on the wafer and mask flatness, gap control in the stepper, and particle-free mask and wafer surfaces. The resolution limit in proximity lithography is determined by the gap between the mask and the wafer (G) and the wavelength of the radiation (λ). Due to diffraction, the maximum permissible gap to print CD using a radiation of wavelength λ , is

$$G = (CD)^2 / (k * \lambda) \quad (1),$$

where k is a factor that depends on the feature type, the material and the process. X-ray proximity lithography uses synchrotron radiation with maximum intensity at $\lambda = 0.7 - 0.8$ nm determined by beamline and mask membrane transmission properties. According to (1), 12 - 15 μ m gap is required for 100 nm resolution if k is equal to 1. Resolution capabilities of existing resist materials and their contribution to the k factor and the overall performance at 100 nm CD printing need to be evaluated.

In this paper, conditions to print various features of 100 nm CD in several resists systems are evaluated. The photoresists used were chemically amplified positive tone resists built on different concepts: APEX-E, UV-4 and an experimental formulation of ESCAP.

2. Experimental

X-ray exposures were performed at the IBM Advanced Lithography Facility. Wafers were exposed on Suss XRS-200 and SVGL steppers installed on the Helios synchrotron storage ring. Synchrotron radiation had a soft x-ray spectrum with the maximum intensity at 0.8 nm. Several X-ray masks have been used in this study. All masks were fabricated at IBM Thomas Watson Research Center on a vector scan 100 keV e-beam tool VS-5 [5]. The masks had a boron doped silicon membrane of 2.2 μm thickness and a gold absorber. A mask having 420 nm absorber thickness with smallest features of 100 nm isolated lines and 110 nm nested lines in 250 nm pitch was used for exposures on Suss XRS-200. X-ray masks for a gate level of advanced CMOS logic devices (isolated 100 nm lines) and for semi-isolated 100 nm lines nested in 400 nm pitch have also been used on a Suss stepper. A high resolution mask with 380 nm absorber thickness (smallest features of 75 nm) was used on a SVGL stepper. Several positive chemically amplified resists have been used in this study. APEX-E was coated to a thickness from 300 nm to 450 nm and post-apply baked at 105°C for 105 s. Exposed wafers were baked at 85°C for 120 s and developed in 0.21 N TMAH developer for 40 s. Experimental resists formulations of the ESCAP family have been evaluated for 100 nm resolution. The photoresists were coated to 500 nm thickness, post-apply baked at 140°C for 60 s, post-exposure baked at 140°C for 90 s and developed in 0.263 N TMAH. Similar conditions have been used for photoresist UV-4. SEM measurements were done on an OPAL 7830i SEM and a S-806C Hitachi SEM, and cross-section views were taken on an Amray 3300 SEM.

3. Results and Discussions

3.1. Patterning of 100 nm isolated lines

Isolated and semi-isolated (lines separated by larger spaces) features have applications to gate conductor levels of logic devices in CMOS (Complementary Metal Oxide Semiconductor) technology.

The gate level of an advanced CMOS logic device has been printed on a Suss XRS-200 stepper at 25 μm gap. Figure 1 shows the linewidth variation with the exposure dose of 100 nm isolated lines in 350 nm thick APEX-E photoresist.

Figure 1. Linewidth dependence on exposure dose at 25 μm gap (100 nm isolated lines)

The nominal CD has been printed at the exposure dose of 180 mJ/cm^2 , and the exposure latitude in the region around the nominal CD was $\pm 16\%$. The linewidth change with the exposure dose in the over-exposure region is slower than it is around the nominal CD. It is possible to shrink the line size in resist by 10 nm compared to the mask feature size. Beyond that, the small lines pattern would lose its integrity. For high doses, resist thickness loss in the large pattern elements is also observed.

SEM cross-sections of isolated 100 nm lines printed in APEX-E at 25 μm gap are shown on Figure 2. The line has vertical wall profile with rounded top surface and a small distinctive undercut at the bottom. Effects of the mask contrast, exposure gap and resist contrast that may contribute to the roughness of the resist top surface need to be further investigated. The small undercut that is clearly resolved on Figure 2 was not

observed on larger lines printed in APEX-E. An additional exposure of the bottom resist layer by photoelectrons emitted from the silicon substrate may be one of possible interpretations.

Figure 2. 100 nm isolated line printed at 25 μm gap in resist APEX-E

3.2. Patterning of semi-isolated 100 nm lines

100 nm lines with 300 nm spaces have been printed in resist APEX-E on a Suss XRS-200 stepper. At 25 μm gap, the exposure latitude was $\pm 13\%$. At 40 μm gap, nominal CD was still attainable but the exposure latitude was reduced to $\pm 9\%$ (Figure 3).

Figure 3. Dose dependence of 100 nm lines in a 1:3 line/space pattern. Δ - at 25 μm gap, $\square$ - at 40 μm gap

SEM photograph of the 1:3 line / space 100 nm pattern printed in APEX-E at 25 μm gap is shown on Figure 4.

Figure 4. SEM cross-section of 100 nm lines in 400 nm pitch printed at 25 μm gap

The linearity plot of 1:3 line / space pattern printed at 25 μm gap has a slope of 0.95 (Figure 5).

Figure 5. Linearity of 100 nm 1:3 line / space pattern printed at 25 μm gap in APEX-E; Exposure dose 140 mJ/cm^2

3.3 Dense nested lines

Printing dense patterns with 1:1 line/space ratio is important for DRAM applications that are driven by pitch size. At 25 μm gap, the smallest nested lines printed had 250 nm pitch size (the pattern on the mask had 115 nm line and 135 nm space). Figure 6 shows a cross-section of this pattern with printed equal 125 nm lines and spaces in the experimental formulation of resist ESCAP. Thickness of the resist was 5000 Å, producing an aspect ratio of 4 for this lines. Similar results have been obtained with APEX-E and UV-4 resists.

Figure 6. 250 nm pitch pattern (115 nm line and 135 nm space on the mask) printed in the experimental formulation of ESCAP resist. Dose=80 mJ/cm²; Gap=25 µm

CD linearity of the ESCAP resist printed at 25 µm gap is shown in Figure 7. For CD < 175 nm, nonlinearity is observed. The CD bias between nested and isolated lines is about 20 nm for CD=175 nm and increases rapidly for smaller CD. At small CD, both isolated and nested lines exhibit deviations from linearity and contribute to the bias. For CD=125 nm, the nested-to-isolated bias of 60 nm has been observed.

Figure 7. Linearity plot for the experimental formulation of ESCAP resist at 25 µm gap
◆ - isolated, ■ - nested lines

The image quality of small dense lines (Figure 6) is not acceptable, and the exposure window to print CD ≤ 125 nm dense lines at G=25 µm is narrow.

Because nested-to-isolated lines bias scales with the exposure gap [6], exposures at small gaps have been performed on a SVGL stepper. Figure 8 shows linewidth dependence on the exposure dose for isolated and nested 100 nm features for the exposure gaps of 15, 20 and 25 µm.

Figure 8. Nested and isolated 100 nm lines in resist APEX-E printed at different gaps: ■ - isolated at 25 µm gap, ● - isolated at 20 µm gap, ○ - nested at 20 µm gap, ▲ - isolated at 15 µm gap and △ - nested at 15 µm gap.

Exposure gaps of 25 µm did not produce an exposure window to print 100 nm lines with 1:1 lines/ space ratio. A small exposure window for nested lines appears at 20 µm gap, and it increases to 35 mJ/cm² at 15 µm gap. The boundaries of the exposure window are determined by the unresolved, under-exposed pattern at 75 mJ/cm² and the disintegrated, over-exposed pattern at 110 mJ/cm² that results in 37 % of exposure margin around the nominal dose of 82 mJ/cm². At 15 µm gap, exposure latitudes for nested and isolated lines were ± 9% and ± 10%, respectively. At the nominal CD for nested lines, the print bias between isolated and nested lines printed in APEX-E was 25 nm. Resist UV-4 has shown similar to APEX-E gap dependence. At 15 µm gap, exposure margin to print 100 nm nested lines in UV-4 was 34%, nested-to-isolated bias was 25 nm and exposure latitudes for nested and isolated lines were ± 9% and ± 8.5%, respectively.

The linearity plot for resist UV-4 is shown on Figure 9. The value of observed nested-to-isolated lines bias for printing at 15 μm gap (25 nm) is in excellent agreement with the aerial image simulations [5].

Figure 9. Linearity of isolated (Δ) and nested (O) (1:1 line/space ratio) lines printed in UV-4 at 15 μm gap.

The slope of the linearity plot for isolated lines was 1.02, while for nested lines it was 1.17. Figure 9 shows that, similar to exposures at larger gaps, contribution of nested lines to the loss of linearity is significant. Linearity of APEX-E was similar to the UV-4 linearity, with the slope values of 1.05 and 1.1 for isolated and nested lines, respectively. A SEM photo of 100 nm nested lines printed in UV-4 is shown in Figure 10.

Figure 10. 100 nm nested lines printed at 15 μm gap in UV-4 resist

3.4. Material aspects

Many of imaging characteristics of APEX-E and UV-4 for CD=100 nm are quite similar. Nested-to-isolated lines biases are the same, linearity characteristics are similar, and exposure latitudes are only slightly different: $\pm(9-10)\%$ vs. $\pm(8.5-9)\%$ for APEX-E and UV-4. This comparison indicates that the resolution capabilities of those positive tone chemically amplified resists are well below 100 nm, and the performance is dominated by the exposure conditions and the aerial image. There are issues however that need to be addressed in the design of a resist material for 100 nm CD. Figure 8 shows that the nominal CD for 100 nm nested lines is printed too close to the lower exposure margin: the overall exposure window consists of 20% for under-exposed margin and 80% for over-exposure margin. Similar effects have been observed for UV-4 resist. Nominal CD for nested 100 nm lines is achieved at the exposure doses that exceed E_0 by 19% and 37% for UV-4 and APEX-E, respectively. For a robust resist process, it is desired that the nominal CD is achieved at higher exposure dose relative to E_0 . At the same time, image quality of 100 nm nested lines was much higher for resist UV-4 than for APEX-E. Compared to well defined smooth vertical walls and clean developed spaces in UV-4 (Figure 10), 100 nm line / space pattern in APEX-E suffered from scum (resist residuals in spaces) and rough resist sidewalls. Similar effects observed earlier for experimental ESCAP formulations have been related to the resist contrast and the level of dissolution inhibition [7]. While having superior resolution characteristics and good environmental stability, ESCAP and UV-4 resists do not have X-ray photospeed adequate for manufacturing [7,8]. In order to support production of VLSI devices with 100 nm CD by synchrotron based X-ray lithography, threefold increase in resist photospeed from current 155 mJ/cm² for UV-4 must to be achieved. Another issue of patterning 100 nm CD that requires a resist material improvement is top surface roughness noticeable both on isolated and nested 100 nm lines in APEX-E and UV-4. The role of photoresist contrast and photoacid diffusion in formation of top surface roughness as well as the extent of its transfer to the etched structures need to be investigated.

4. Conclusions

Proximity X-ray lithography printing of 100 nm isolated and semi-isolated (space larger than line) features provides large exposure latitudes and can be easily achieved at 20-25 μm gap. 100 nm dense pattern (with 1:1 line/space ratio) can be printed at 15 μm gap with good exposure latitudes and exposure windows. $\pm(9-10)\%$ exposure latitude and 33% exposure window has been achieved in APEX-E and UV-4 photoresists at the exposure gap of 15 μm using processes that were not optimized specifically for such small CD. Printing simultaneously nested and isolated 100 nm pattern can also be achieved at 15 μm exposure gap with proper biasing of the X-ray mask by about 25 nm. Positive chemically amplified resists studied have resolution capabilities for 100 nm CD, and UV-4 resist produces better 100 nm CD image quality than APEX-E. Further improvements and optimization of resist material for X-rays are desirable: increase of exposure latitude from current $\pm(8.5-9)\%$ (UV-4) to about $\pm(10-13\%)$, center the process for nested lines in the exposure window, reduce resist top surface roughness, and increase resist speed.

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