A Strategic Optical Lithography for Below 0.25 Micron Design Rules

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Semiconductor device fabrication costs are dramatically escalating each year. Almost lithographers suffer from a paradox; "Which lithography will best meet the technical and economic needs of VLSI manufacturing in the drive toward below 0.25 micron design rules?". This paper gives an outline of the possibility and strategy of optical lithography with productivity and cost efficiency for the development and production of 0.25 micron design rule devices and beyond on the basis of our recent development results.

To control costs, lithography will continue to push the extension of optical lithography as far as it can go. In the lithography for 256MbDRAMs production, a capability of 0.20 micron lithography resolution is required. We have developed a new chemically amplified positive resist with high stability and an excimer laser based stepper with high alignment accuracy and off-axis illumination for KrF excimer laser lithography as a state-of-the-art on shorter wavelength. The solution of 256MbDRAMs lithography is a complementary strategy employing both i-line for non-critical layers and KrF excimer laser for critical layers in order to achieve the lowest manufacturing cost.

Sub-quarter micron feature size is required to lithography for the development of 1Gbit DRAMs. In order to break-through below 0.20 micron barrier of optical lithography, ArF excimer laser lithography, which is a super state-of-the-art, has been challenged and developed. The challenges are constructed of the projection system installing a refractive achromatic aspherical 4X lens and a suitable resist material with high transparency. It is expected not only as the next significant technology but also as the final
optical lithography to produce next generation VLSI. The strategy of optical lithography will be an endless development for semiconductor industries.

1. Introduction

The research and development of lithography is not staying and energetically challenging in spite of the semiconductor depletion and the enlarging investment cost. However, the strategy of lithography will be innovated to the investigating thoroughly a limitation of optical lithography with the saving costs. It is very difficult to separate the cost and the technology of lithography. This problem is a paradox and a headache for lithographers. This paper describes a strategic optical lithography for below 0.25 micron design rules VLSI on the basis of our recent development results of excimer laser lithography.

2. Lithography Trend and Scenario

Recently, optical lithography has been pushing its limits down to sub-half micron resolution. Figure 1 shows the technology history of lithography and DRAM developments. Optical lithography is facing major limitations in the resolution and the depth of focus (DOF). The most significant trend in lithography over the last decade has been the gradual transition in exposure wavelength from g-line (436nm) to i-line (365nm) and shorter wavelength, such as KrF (248nm) and ArF (193nm) excimer laser. In this stage, the transition from g-line to i-line has been done on 16MbDRAM and 64MbDRAM production. The trend of lithography development has crossed over the R&D trend of DRAM development in recent year. The lithography for 64MbDRAMs development delayed for over few years to the previous trend. The significant issue is a maintenance of DOF range of over 1.2 micron. The fabrication of a second generation of 0.30 micron feature size 64MbDRAMs by optical lithography has to be selected by two approaches that first is the extension of higher and variable numerical aperture (NA) and coherency i-line lithography for a saving costs, other is KrF excimer laser lithography in order to lead a future scenario. However, NA value of i-line is almost facing to the limit [1]. Therefore, i-line lithography combined with lithography improvement such as a phase shifting mask [2] and an off-axis illumination [3] techniques are growing as a promising candidate. However, phase shifting mask and off-axis illumination have the restriction of pattern layout and cannot be difficulty applied for various real LSI pattern such as microprocessor and LSI logic[4]. Accordingly, from the area of a second generation 64MbDRAM is painful development for optical lithography.

KrF excimer laser lithography [5] is the most exciting technology for quarter micron VLSIs such as 256MbDRAMs. The technology has a resolution capability below 0.25 micron. The introduction of KrF excimer laser lithography for mass-production is being accelerated by resolved
several technical barriers. These are two main barriers. First is the stability and CD (Critical Dimension) controllability of positive resist. Second is the power and life of the narrow band excimer laser based stepper with high alignment accuracy. This paper describes a new positive resist with high sensitivity and stability named ASKA, Alkaline Soluble Kinematics using Acid generator positive resist; a KrF excimer laser with a high laser power, high repetition rate and more than $10^9$ pulses named PCR, Polarization Coupled Resonator; and the result of KrF excimer laser lithography for 0.25 micron VLSI using this combination of ASKA and PCR technologies indicates improved throughput over conventional i-line lithography. The development of a KrF excimer laser lithography system with wide projection field and high alignment accuracy will start a challenge for KrF excimer laser lithography to be used in mass-production. The system newly employed a low distortion quartz lens with high NA and a new heterodyne holographic TTR (Through The Reticle) alignment system. This technology was successfully applied to the fabrication of 256MbDRAM[6]. The solution of 256MbDRAMs lithography is a complementary strategy employing both i-line for non-critical layers and KrF excimer laser for critical layers in order to achieve the lowest manufacturing cost.

In the lithography for 1GbDRAMs, the extension of KrF excimer laser lithography with combination of lithography improvement has to overcome the resolution capability. ArF excimer laser lithography has a capability to realize sub-quarter micron pattern fabrication [7]. In order to study the feasibility of ArF excimer laser lithography, we developed the projection system installing a refractive achromatic 4X reduction aspherical lens. To realize ArF excimer laser lithography, the development of wider exposure field lens and high transparency resist are needed. The future lithography trend and scenario is summarized in Figure 2. Our opinion is that the extension of optical lithography will be continued to be more economical than X-ray or electron beam lithographies.

Figure 1, The trend and history of lithography technology and DRAM developments.

Figure 2, The future lithography trend and scenario.
3. KrF Excimer Laser Lithography Performance

KrF excimer laser lithography is a state-of-the-art candidate to fabricate sub-half micron patterns in combination with high performance positive resist using chemical amplification concept. The remaining problems of KrF excimer laser lithography in the sub-half micron device fabrication are the CD change due to multiple interference effect and the stability of the chemical amplification resist.

This paragraph describes our recent progress of the stepper and the resist in KrF excimer laser lithography for sub-half micron device manufacturing and reports on the approaches to overcome the problems such as multiple interference effect and halation when the developed resist was applied for an experimental 256MbDRAM production. Also, we introduce the increasing DOF margin using excimer laser lithography combined with off-axis illumination and in-house developed chemically amplified positive resist.

3.1 KrF Excimer Laser Stepper

Main problems of KrF excimer laser stepper are the power and the life of narrow band excimer laser and the high accuracy alignment system to achieve 1/4 alignment budget (below 100nm). We have developed the in-house excimer laser stepper[8] with PCR laser[9] and the TTR alignment system[10] to overcome these problems.

Typical features of the in-house developed excimer laser stepper are given in Table 1. Wide field lens having NA 0.48 with 20X20mm square is adopted. Figure 3 illustrates the schematic view of the conventional and the PCR laser. To reduce the laser load on the etalon and increase the output power, the P polarized laser beam and the S polarized laser beam are separated by the polarizing beam splitter. P polarized spectra narrowed seed light oscillates weakly and partially converted to S polarized light. Then S polarized light is amplified to intense light in the same cavity and extracted by the polarizing beam splitter. At the output power level of 8W at 500Hz, the etalon-load power was reduced to 0.75W and the etalon life is drastically extended to over $10^9$ pulses. Figure 4 shows the schematic diagram of the developed TTR alignment system. This alignment system employs a heterodyne holographic method[11] using Zeemann type He-Ne laser that detects the wafer position error as the phase difference between a reference beat signal and the detected signal from wafer alignment mark. Figure 5 shows the overlay results for various substrate of processed wafers. Overlay accuracy within 100nm was successfully obtained using the TTR alignment system.

3.2 Chemically Amplified Positive Resist

Resolution of KrF excimer laser resist is the most exciting issue because there had been no positive resist which could achieve quarter micron resolution. We have successfully developed a
new chemically amplified positive resist, named ASKA[12], which is composed of an alkaline-soluble protected polyvinyl phenol based polymer, photo acid generator and surface-inhibition reducing reagent [13]. The surface-inhibition reducing reagent prevents the insoluble surface skin (T-top) formation of the exposed resist, which leads to the high resolution and the stable pattern fabrication in a time delay between the exposure and the following post exposure bake. Lithographic performance was evaluated using in-house developed KrF excimer laser system. The post exposure bake was performed for 90sec at 95 C. The dipping development was done for 60 sec using TMAH solution.

Figure 6 shows SEM photographs of the line and space patterns ranging from 0.4micron down to 0.25 micron. Quarter micron pattern with rectangular profile was successfully delineated. Figure 7 shows the DOF characteristics of 0.25 micron line and space patterns. DOF tolerance over 1.0 micron was obtained at 0.25 micron line and space, which is enough for sub-half micron device fabrication. The stability of the resist after exposure is shown in Figure 8. The CD change due to the
time delay between exposure and PEB was much reduced as compared to our former formulation [14].

Although the resolution of KrF excimer laser positive resist was successfully improved down to quarter micron, the most serious problems of KrF excimer laser lithography are the multiple interference effect and the halation from the high reflective substrate in actual device fabrication. To overcome the multiple interference effect and the halation, we investigated the Overcoat resist process (OC) and Anti-Reflective Coating (ARC) processes [15].

3.3. KrF Excimer Laser Process

3.3.1 OC process

OC material composed of polyvinyl alcohol was spin coated to a thickness of 42nm (Lambda/4n) on ASKA. Refractive index (n) of OC material is 1.48. OC film works as anti-reflective layer which prevents the reflection light from resist top surface. Figure 9 shows the CD change due to multiple interference effect when the resist thickness of ASKA was changed from 0.95micron to 1.05micron. CD control within +/- 0.02micron was achieved using OC, while that without OC became over +/-0.08 micron.
To confirm the advantage of OC process, we applied it to 256MbDRAM process. Figure 10 shows the 0.25 micron storage node contact hole pattern. Contact hole size variation due to multiple interference effect was observed on chip corner without OC film. On the contrary, CD uniformity of contact hole within +/-0.02 micron was achieved on a whole chip area by using OC process.

3.3.2 ARC process

Although OC film can reduce multiple interference effect, it is difficult to suppress the linewidth shrinkage (halation) caused by the reflection light from the inclined sidewall such as LOCOS as shown in Fig. 11. ARC process is able to reduce multiple interference effect and halation simultaneously as shown in Fig. 11. However, there remains the problem of the linewidth variation caused by the removal of ARC. To minimize the linewidth variation, we examined the etching condition and the material of ARC. ARC material and substrate film was continuously dry etched on the same etching condition, or on the 2 step etching condition for each films. PMMA with the introduced dye was chosen as an ARC material for its poor etching resistance because it is easy to remove ARC material on the same etching condition with substrate. ARC film was spin coated to the thickness of 0.2 micron on the Si wafer and then ASKA with the thickness of 1 micron was spin-coated on it.

CD loss within 0.03 micron was achieved in case of 2 step etching condition and CD variation within +/-0.03 micron was obtained for ARC process.

From the results, it has been confirmed that the pattern fabrication of a experimental 256MbDRAM with 0.25 micron design rule can be successfully achieved by KrF excimer laser lithography combined with OC and ARC process for various processes.

Figure 9. The CD change due to the interference effect with and without OC process.

Figure 10. 0.25 micron storage node contact hole patterns with and without OC process.
However, an additional cost consideration for KrF excimer laser lithography is requirement for OC and ARC processes along with process complexity compared with i-line. All require some tradeoffs between performance and complexity. For the decreasing cost of ownership of KrF excimer laser lithography, a suitable dyed resist material should be urgently developed with a bleaching effect.

4. Challenge of KrF Excimer Laser Lithography

There were many works which reported that off-axis illumination (super resolution) improved the resolution and DOF in i-line. We here investigated the possibility of sub-quarter micron patterning using KrF excimer laser lithography combined with off-axis illumination and ASKA. Figure 12 shows SEM photographs of 0.2 micron line and space patterns, the 0.2micron space storage node patterns in case of conventional and off-axis illumination. The focus latitude of 0.25 micron line and space patterns was enlarged from 0.9 micron to 2.1 micron as shown in Figure 12 by means of off-axis illumination, which eliminates the-0th order diffracted light and improves the optical contrast. The developed exposure system could also attain 0.2 micron resolution using off-axis illumination combined with ASKA. It is possible that sub-quarter micron pattern required for a second generation 256MbDRAM will be fabricated using KrF excimer laser lithography combined with super resolution optics and ASKA.
However, we have not yet overcome two problems which decrease process latitude for quarter micron complex actual device circuit pattern fabrication such as a peripheral circuit of DRAM and random logic LSIs. The first problem is that the process latitude by off-axis illumination is not improved for whole voluntary patterns. The another problem is that the developed resist is not enough obtained thermal stability due to use a high transparency and a low glass-temperature polivinylphenyl derivative polymer. As a conventional DUV hardening method, the resist is occurred CD loss in a actual device. For complex pattern variant CD loss is occurred. We have developed new technologies in order to break-through two above-mentioned problems on quarter micron actual device fabrication. First break-through technology is higher NA KrF excimer laser lithography system with new off-axis illumination technology in order to improve the resolution for voluntary patterns. Second technology is the new DUV hardening technique which prevents shrinkage of resist pattern to obtain excellent CD control for quarter micron KrF excimer laser resist [16].

5. ArF Excimer Laser Lithography for 1GbDRAMs

ArF excimer laser lithography has been considered to be one of break-throughs to achieve quarter-micron pattern for a production of 1GbDRAMs, although KrF excimer laser lithography combined with phase shifting mask technique is growing an another candidate. Main difficulties of ArF excimer laser lithography are the optical absorption of resist material and lens material (the resultant lens design), and the optical projection exposure system [17]. The resolution of ArF excimer lithography was compared with many types [18] of phase shifting mask, (alternating, edge enhancement, unattenated, etc.). Alternating and unattenated phase shifting mask only provide the enhancement of the image contrast, but these give rise to the restriction of pattern layout and cannot be applied for various real LSI pattern[4]. On the other hand, the image contrast of ArF excimer laser was enough high to realize 0.25 micron line and space patterns without the restriction of pattern.

To reduce the total lens thickness and improve the transmittance of projection lens, we proposed a new projection achromatic lens type having aspherical lens. Figure 13 shows the newly designed aspherical projection lens. The lens system is composed of 7 elements having three aspherical faces with 22.5X22.5 mm square field size and NA 0.42 although there remains the lens distortion a little bit over 0.01micron. Total quartz thickness of the aspherical lens system was successfully decreased to 10.3 cm. To achieve the lens distortion below 0.01 micron, we must make the OID (distance between mask and wafer) longer or NA. reduced. The transmittance of the projection lens improved over 60%. designed lens. MTF value greater than 40% is obtained at the spatial frequency of 2000 line pair.
As for 193nm resist, the large photo absorption is the most important problem. To prevent the optical absorption, we evaluated the 193nm resist which is composed of the aromatic group excluded in both of the polymer and photo acid generator as shown in Figure 14. The transmittance exceeded to 70% and 0.2micron line and space patterns was obtained as shown in Figure 15.

Figure 13, The newly designed aspherical lens system with 22.5X22.5mm$^2$ and NA0.42.

Figure 14, The chemical structure of the developed chemically amplified resist for ArF excimer laser lithography.

Figure 15, SEM photographs of 0.2 micron line and space patterns by exposed the developed ArF excimer laser system.
6. Conclusion

We have developed high performance KrF excimer laser resist, laser and lithography system. The positive chemically amplified resist, ASKA, long life excimer laser, PCR, and lithography system showed excellent lithographic characteristics, which meet the requirements for the fabrication of 256MbDRAM. A experimental 0.25 micron-rule 256MbDRAM was successfully fabricated on KrF excimer laser lithography. We verified KrF excimer laser lithography is very promising for 256MbDRAM production.

ArF excimer laser lithography has been proved to be more attractive below 0.20 micron lithography tool for 1GbDRAMs. And also, it has been confirmed that a aspherical projection lens system and a transparency resist could be designed and manufactured for ArF excimer laser lithography. We will corroborate 1GbDRAMs with the extension of this optical lithography.

From the results and the progress, the possibility and strategy of optical lithography with productivity and cost efficiency for the development and production of 0.25 micron design rule devices and beyond has been proved. We believe that 0.1 micron generation VLSIs will be delineated by super-optical lithography in the late 20th century.

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References


