Pushing ArF Dry Scanner Beyond Limitation

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***Abstract*—ArF dry scanner contact hole printing capability was successfully driven down from 120nm to 100nm, exceeding Acceptance Test specification (ATP) contact printing capability. The improved 100nm printing capability showed good process margin, Critical Dimension (CD) uniformity and wafer-to-wafer repeatability. Phase Shifting Mask (PSM) showed better performance than binary mark. Larger mask bias demonstrated better printability. PSM with 40nm mask bias resulted in most rounded hole profiles with no formation of side-lobe. Conventional illumination with high partial coherence factor produced the least iso-dense bias. usable Depth of Focus (uDOF), Exposure Latitude (EL), CD Uniformity (CDU) and Wafer-to-Wafer (WTW) repeatability were quantified and established.**

***Index Terms*—contact hole, ArF, Lithography, printability, uniformity**

I. Introduction

Optical lithography has been one of the major driving forces behind the remarkable advances in semiconductor research and industry over the past decades. The advance in reduction of the minimum resolvable feature size printed onto a silicon wafer has led to smaller, faster and cheaper transistors that are connected together into ever more powerful integrated circuits. As lithography moves into the low k1-region, it becomes increasingly challenging to reduce the feature size while keep sufficient process window. To improve the process margins, it is inevitable to apply the Resolution Enhancement Techniques (RETs), such as Off-Axis Illumination (OAI), Phase Shifting Mask (PSM), high numerical aperture (NA) and sub-resolution assist features (SRAF). While RETs provide the essential benefit of allowing printability of the Critical Dimension (CD) at a given node, the side effects such as localized non-linear pattern distortions due to mutual interaction of all the optical conditions (e.g., wavelength, mask, illumination, optical tools, photoresist, etc.) and the specific mask layout shapes are essential [1]. Therefore, Optical Proximity Correction (OPC) has been extensively developed and applied in combination of RETs for 45nm, 28nm, 20nm technology nodes and beyond.

In resolution limited lithography process, the contact hole pattern is one of the most challenging features to be printed on wafers. A lot of studies were carried out to make robust hole patterns under 45nm node and beyond, especially for those layouts including both dense array contact holes and isolated contact holes simultaneously. The strong OAI such as dipole is a very useful technique to enhance resolution for specific features. However, the contact hole formed by dipole illumination usually has elliptical shape and the asymmetric feature leads to increment of chip size [2]. Based on the Acceptance Test specification (ATP), ArF dry scanner contact hole printing capability is 120nm. To further drive contact hole resolution beyond ATP limit, a creative way was used to stretch printing capability down to 100nm, by establishing process parameters with consideration from materials, scanner and reticle in this study.

For materials, an appropriate photoresist candidate was selected based on supplier's material data. For reticle, a suitable contact reticle was used to test the effect of different mask bias on contact hole profile. For scanner, CD profile and iso-dense bias were characterized in terms of different exposure illumination settings. A process margin study was also conducted in this study to determine the optimum exposure dose and focus, usable Depth of Focus (uDOF), Exposure Latitude (EL), CD Uniformity (CDU) and Wafer-to-Wafer (WTW) repeatability.

TABLE I. Parameters Consideration in Establishing ArF Dry 100nm Contact Process

Parameters	Conditions
Photoresist	Resist Candidates: • Type_1 • Type_2 • Type_3
Scanner	Illumination Type: • Conventional (NA/PC:0.78/0.9) • 2/3 Annular (NA/PC: 0.78/0.85) • 1/2 Annular (NA/PC: 0.78/0.9)
Reticle	100 nm Contact Hole: • Phase Shift vs Binary • +20nm/+30nm/+40nm Reticle Bias • 4/6/8holes per um^2 hole density

II. Experimental

In this study, experiments were carried out on oxide substrates with 600A bottom anti-reflective coating (BARC). The start point was from the selection of the best photoresist for ArF dry contact hole printing. Three different types of photoresist (Type_1, Type_2 and Type_3) were chosen to be the appropriate candidates as recommendations from materials vendor. Three different

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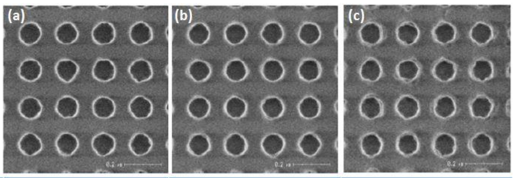
illumination modes were selected to determine the best illumination parameters for the OAI scanner settings: Conventional (NA/PC:0.78/0.9), 2/3 Annular (NA/PC: 0.78/0.85) and 1/2 Annular (NA/PC:0.78/0.9). PSM and binary mask were both used and compared. Patterns with nominal CD +20nm/+30nm/+40nm reticle bias were written at the same mask. The examination of contact holes were with density of 4/6/8 holes per um^2 respectively. The details of the parameter consideration in establishing ArF dry 100nm contact process are listed in Table I.

III. Results and Discussion

A. Materials Selection

Through the comparison of the top down images of three types of photoresist printed at 100nm contact hole, it was found Type_2 resist had the most rounded top down profile and clear sidewall images (as shown in Fig. 1), thus was selected as the candidate for further process optimization.



Resist	Type_1	Type_2	Type_3
circularity	3.36	2.64	4.41

Figure 1. The top down profiles and the circularity data of different types of photoresist for ArF dry contact hole process: (a) Type_1 photoresist; (b) Type_2 photoresist; and (c) Type_3 photoresist.

B. PSM vs Binary Mark

100nm contact hole CD printed from 6% attenuated PSM and Binary mask were compared. It can be seen that 6% att. PSM resulted in a more rounded hole CD profile, as shown in Fig. 2. PSM has been widely applied in modern lithography industry to improve the resolution limits of scanners. A phase-shifting mask usually has a phase-shifting portion for shifting the phase of a transmission light on both of one surface and another surface of a transparent substrate. Thus destructive interference between optical waves from adjacent apertures cancels some diffraction effects and increases the spatial resolution with which such patterns can be projected [3]. Different from binary mask which is composed of quartz (clear) and chrome (opaque) features, Att-PSM forms the patterns through adjacent areas of quart and, for example, molybdenum silicide (MoSi). One distinct optical feature of MoSi is that it only allows a small percentage of the light to pass through (e.g., 6%). By concisely control the thickness of the MoSi layer, the weak light passes through is 180^o out of phase with the light that passes through the neighboring clear quartz areas. The phase delta results in a sharper intensity profile and thus allows smaller features to be printed on the wafers. Our investigations showed the limitations of binary mask in printing small features, especially when it approaches the tool resolution limits.

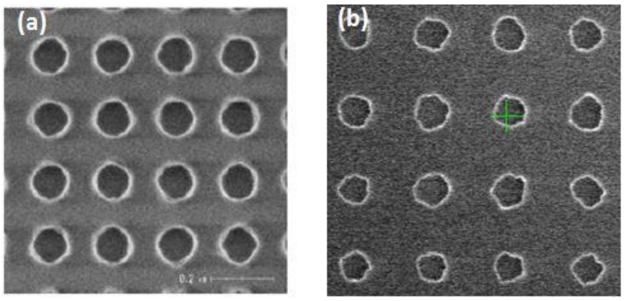


Figure 2. The SEM images of contact holes printed by different types of masks: (a) 6% PSM, and (b) binary mask.

C. Mask Bias Effect

A major disadvantage of PSM is the printability of side-lobes due to the light that is transmitted through the conventionally chrome areas. This effect is more serious when wafer printed at defocus. To solve this issue, mask bias is often used in simple OPC evaluations to eliminate the side-lobe erosions and improve the process window [4]. In this study, 100nm contact hole with CD +20nm, +30nm and +40nm mask bias were placed in the same mask and exposed using nominal exposure dose (mJ/cm^2). With a smaller mask bias, a higher exposure dose was required to define the hole (e.g., 90 mJ/cm^2 was required for CD+20nm bias mask compared to 68 mJ/cm^2 for CD+30nm bias mask). It is clear that CD printed using +40 nm mask bias gave the most rounded top down profile and no formation of side-lobe (as shown in Fig. 3).

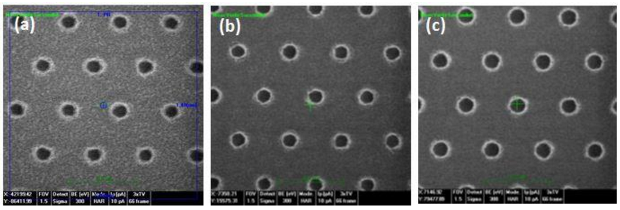


Figure 3. The top down images of contact holes printed at different mask bias: (a) CD+20nm bias; (b) CD+30nm bias; and (c) CD+ 40nm bias. Holes with 40nm mask bias give the most rounded top down profile and no formation of side-lobe.

D. Impact of Illumination Setting on Iso-Dense Bias

In general, off-axis illumination can demonstrate wider process latitudes when combined with att-PSM. The partial coherence factor (σ) also plays an important role in determining the EL and DOF of one process. With larger mask bias, the iso-dense bias can become smaller. However, the selection of mask bias, illumination mode and the partial coherence factor have to be optimized in terms of the specific applications [5].

To evaluate the iso-dense bias performance, the CD+40nm mask bias was selected. The iso-dense bias was computed from 100nm contact CD exposed using three high Lens Numerical Aperture (LNA) illuminations: Conventional, 2/3 Annular and 1/2 Annular (Table I). As shown in Fig. 4, conventional illumination was found to produce the least iso-dense bias. Good sidewalls and top down profiles could be achieved for both dense and iso holes (images not shown here) by the conventional illumination. The partial coherence factor (σ =0.9) adopted was high enough thus the light intensity of the dark field was reduced and the iso-dense bias was also improved.

Illumination Condition	8 holes/um^2	6 holes/um^2	4 holes/um^2
Conventional	104.2	97	93.7
2/3 Annular	103.9	50 (Bad profile)	20 (Bad profile)
1/2 Annular	103	60 (Bad profile)	30 (Bad profile)

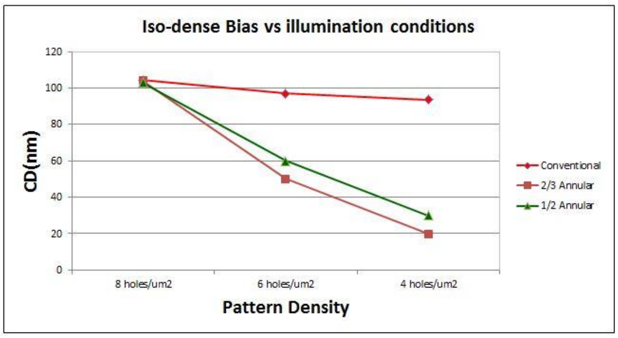


Figure 4. The relationship of iso-dense bias vs the illumination settings. Conventional illumination produced the least iso-dense bias compared to annular illuminations.

Annular illumination showed its limitation to print iso contact holes at the energy dose for dense holes. Although good dense holes can be obtained for both 2/3 and 1/2 annular illumination, the iso holes shrunk dramatically and irregular holes with severe scum occurred simultaneously (images not shown here). By further reduction of the inner partial coherence factor (σ_{in}) of annular illumination, the side-lobe effect may become evident again [5]. Different from previous studies, our study showed conventional illumination demonstrated better iso-dense bias performance for contact holes than that of annular illumination.

E. Process Window Verification

With photoresist, mask bias and illumination condition determined, a Focus Exposure Matrix (FEM) print down was conducted. Process window and EL plots for different pattern density are plotted in Fig. 5. From the plots, the optimum exposure dose and best focus are 48 mJ/cm^2 and -0.35um respectively. The uDOF is 0.12um and EL is 9%. Good process margin, DOF and EL were observed.

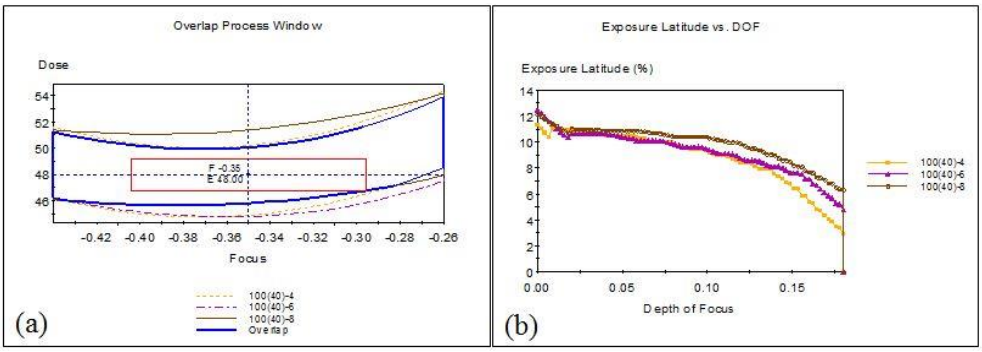


Figure 5. The improved 100nm printing process has good process window, DOF and EL, with common DOF around 0.12um and EL of 9%.

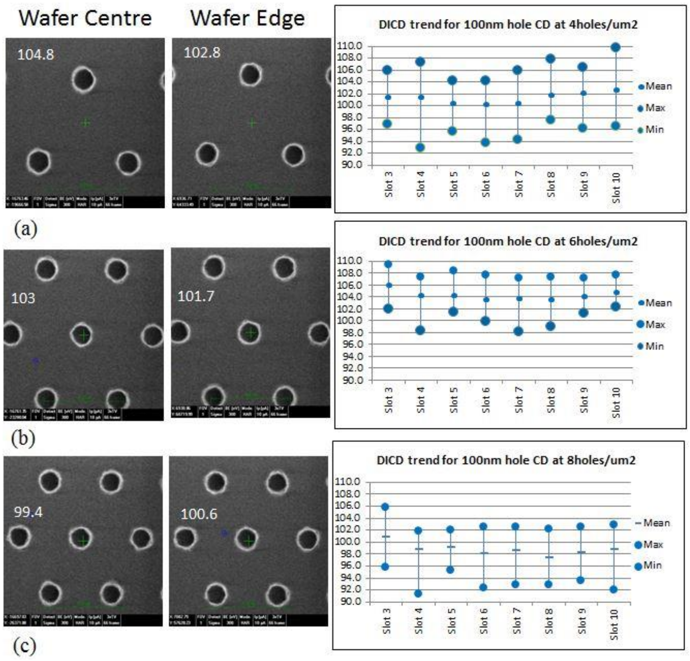
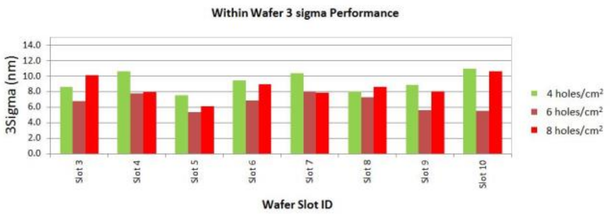


Figure 6. The top down images of nominal printing wafers with Type_2 resist, 40nm Mask Bias and conventional illumination at E/F: 48mJ/-0.35um with different hole densities: (a) 4 holes/cm^2; (b) 6 holes/cm^2 and (c) 8 holes/cm^2. Relevant wafer to wafer DICD uniformity data statistics are shown in the right.



Figture 7. The within wafer DICD uniformity performance of contact holes with different hole densities.

Using nominal exposure dose and focus, 8 wafers were printed and measured for CDU and WTW repeatability performance evaluation. As shown in Fig. 6, all wafers demonstrated stable CD performance within the wafers. The printed profiles were rounded and clear at both the wafer center and the wafer edge, and for both iso and dense holes. The within wafer average CDU (3sigma) is 10.8nm and WTW repeatability is 2.72nm, respectively. Good CDU and WTW repeatability were observed (as shown in Fig. 7).

IV. Conclusions

In this study, we pushed ArF dry scanner beyond limitation. The ArF dry scanner contact hole printing capability was successfully driven down from 120nm to 100nm, exceeding ATP contact printing capability. The improved 100nm printing capability showed good process margin, CD uniformity and wafer-to-wafer repeatability. Photoresist, illumination mode and reticle are the main contributing factors to be considered during our investigations. PSM showed better performance than binary mark. Larger mask bias demonstrated better printability. PSM with 40nm mask bias resulted in most rounded hole profiles with no formation of side-lobe. Conventional illumination with high partial coherence factor produced the least iso-dense bias. The established process conditions showed large process margin and good CD performance on silicon wafers.

Acknowledgment

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