250nm Lithography with Step and Scan

HARRY SEWELL
SVG Lithography,
Wilton, CT 06897, USA.

This paper assesses the progress of Step and Scan systems towards "Production 250nm Lithography". Advantages of the Step and Scan technique are discussed.

The relationships between NA, wavelength, resolution, and depth of focus are examined. The lithographic performance of the new generation Deep-UV Step and Scan system with high-NA optics is presented. Data is provided from electrical probe linewidth metrology and SEM analysis. Linewidth control of 27nm (3 sigma) is demonstrated over a large field size of 650 mm² for 350nm features. A 250nm resolution capability is shown.

The family of Step and Scan systems, I-Line -- Deep-UV -- Very-Deep-UV, is reviewed in the context of progress towards 250nm lithography. The impact of Phase Shift Masks is highlighted. Particular attention is paid to the effect of partial coherence on the depth of focus achievable with Phase Shift Masks. Examples of 250nm lithography in a single level resist system are presented. It is indicated that optical lithography will continue to be the dominant lithographic technique down to sub-250nm lithography and that Step and Scan technique will be a critical factor in maintaining this dominance.

1. Introduction

The advanced semiconductor product is following the road map defined by Memory chip production (table 1).

Device	Chip Size (mm x mm)	Resolution	Total Overlay
16Mbit DRAM	7 x 14	600nm -- 450nm	120nm
64Mbit DRAM	9.5 x 19	450nm -- 350nm	100nm
256Mbit DRAM	13 x 26	350nm -- 250nm	80nm
1Gbit DRAM	18 x 36	250nm -- 200nm	60nm

Table 1. Estimated Lithographic Requirements of DRAM Production.

At present, production technology is moving down to 400nm linewidths. Step and Scan technique has been developed for 350nm lithography and pre-production systems are now under testing for both performance and reliability. The early production units for 350nm lithography will begin shipping very shortly, including wafer track systems. The debate on the prospects for 250nm lithography and 256MBit DRAMs has begun.

This paper will first discuss the advantages that the Step and Scan technology offers, and review the 350nm lithographic performance that is currently available. The approaches that are being investigated to implement 250nm Step and Scan lithography, including the impact of phase shift masks, are then discussed.

2. Advantages of Step and Scan

Step and Scan systems are optical systems and therefore obey the same rules of optics concerning the relationship of wavelength and NA. Step and Scan systems are available in both Deep-UV and I-Line versions. These systems allow companies with device processing running with I-Line resists to transfer to the large exposure field step and scan system before switching over to Deep-UV. Hence becoming familiar with the Step and Scan technology.

Step and Scan has the advantage over conventional stepper in four significant ways. First, a Step and Scan system scans a long narrow slot image field to produce the exposed field, this scanning action has the effect of averaging the residual distribution in the lens as the image points pass through each lens field point in turn. This produces low distortion over a large field. Second, the multi-target alignment capability allows for high overlay accuracy and distortion fitting over a large field. Third, the terrain following focus control significantly reduces focus variations over a large field. Fourth, uniformity of illumination allows tight linewidth control over a large scanned field.

2.1 Residual Field Distortion

Step and Scan achieves low field distortion because it scan averages the optical distortion over a small field to produce even lower distortion. Figure 1 shows the distortion over the illuminated optical slit 22mm by 5mm.

**Average of 3 Fields
Field 5mm by 21mm**

Statistics of Distortion

**Max. Vec. = 66 nm
Ave. Vec = 19 nm
X Std. Dev. = 16 nm
Y Std. Dev. = 14 nm**

Figure 1. Static Field Distortion.

Results for early optics indicate distortion of 66nm (max. vectors), including the metrology errors. This is typical of a good "stepper lens". When this optical field is effectively scanned, the distortion is averaged for all points along the scan direction, this produces a dynamic optical distortion shown in figure 2.

Static Distortion Averaged Along The Scan Direction (Computed)

Figure 2. Dynamic Optical Distortion.

The effective optical distortion is reduced, in this case to less than 22nm, a threefold improvement. Of coarse, the dynamic field distortion in the case of Step and Scan is actually a product of the optical distortion and the distortion contributed by the scanning stages. Figure 3 shows the results obtained from the prototype system for the dynamic field distortion.

8 Field Average
Field 29mm by 20mm
Prototype System
Reticle Errors Included

Statistics of Distortion

Max. Vec. = 41 nm
Ave. Vec = 12 nm
X Std. Dev. = 6 nm
Y Std. Dev. = 13 nm

Figure 3. Dynamic Field Distortion.

Even on the prototype, 40nm was achieved with the X-axis distortion being less than 20nm. Indications are that this can be further reduced to less than 30nm with the correction of the slight bow distortion. These distortion results demonstrate the unique property of Step and Scan to produce large exposure fields with low levels of distortion. This performance will support a 60nm total overlay budget on a 250nm tool.

2.2 Overlay

Figure 4 shows the typical exposure layout used for overlay testing. 36 fields are used each 22mm by 32.5mm.

Figure 4. 36 Field 6-Term Global Layout for 8" Wafers.

These fields are produced by scanning the wafer and reticle through an illuminated optical field 5mm by 22mm. Scan directions are shown. For Global Alignment three or more fields are pre-scanned and six alignment terms fitted: X-Offset; Y Offset; Skew; Rotation; X-Mag; Y-Mag. From the position of these die the grid is calculated. Results for total overlay accuracy on etched oxide wafers from the prototype testing are shown in figure 5.

Figure 5. Step and Scan Overlay (Prototype System).

Approximately 100nm (mean plus 3 sigma) is indicated. Further testing on pre-production units, in which wafer and reticle stage laser mirror mapping has been introduced indicates that approximately 85nm (mean plus 3 sigma) is achieved. 60nm (mean plus 3 sigma) is expected to be achieved on production units which have improved stage control algorithms. The success in meeting this 60nm goal will be a major success in the realization of a 250nm Step and Scan system.

2.3 Dynamic Focus

The Step and Scan system focuses on the fly. Typical focus contours over a field are shown in figure 6.

Figure 6. Dynamic Focus Uniformity on a Silicon Wafer.

Focus is very tightly controlled in the scan direction, better than 100nm. The predominant focus variation is in the cross-scan direction, in this case approximately 200nm and represents some field curvature in the prototype optics. This cross-scan field curvature is being progressively reduced and is expected to eventually be less than 100nm in production units. The total focus budget for the current pre-production units is less than $\pm 0.4\mu\text{m}$, including edge fields. Improvements in optical field curvature to 100nm will allow the total focus budget to be reduced to $<200\text{nm}$. This will be important advantage for the realization of a 250nm exposure tool using Step and Scan.

2.4 Linewidth Control

The current step and Scan tools are 0.50 NA and both Deep-UV and I-line versions are available. The specified resolution for the I-line tool is 500nm and the Deep-UV tool is 350nm. We are using electrical probe metrology to assess both resolution and linewidth control performance. We measure both grouped and isolated lines. Results shown in figure 7 from the prototype system indicate a depth of focus of over one micron for grouped lines with good linewidth control.

350 nm Lines Using 2208 Positive Resist Resist.

Figure 7. Linewidth through Focus for Grouped Lines

Analysis of the linewidth control through a focus range of $\pm 0.4 \mu\text{m}$ indicates remarkable results for the prototype system. Histograms of linewidth control shown in Figure 8 and 9 indicate that better than 35nm (3 sigma) values were obtained in etched polysilicon for isolated or grouped lines, this includes metrology and reticle errors.

Over $\pm 0.4 \mu\text{m}$ Focus Range, 2208 Positive Resist

Wafer pti-72. Exposed 2-12-91. Lines <100 nm or >600 nm weeded after probe.

Figure 8. 350nm Linewidth Control Histograms -- Isolated Lines.

Over $\pm 0.4 \mu\text{m}$ Focus Range, 2208 Positive Resist

Wafer ptl-72. Exposed 2-12-91. Lines <100 nm or >600 nm weeded after probe.

Figure 9. 350nm Linewidth Control Histograms -- Grouped Lines.

The high degree of linewidth control demonstrated by Step and Scan is in part due to the tight control of focus and illumination that a Step and Scan system can achieve. The illumination along the scanning slit is controlled to better than $\pm 1\%$. We did note an offset between the grouped and isolated average linewidths of 28nm. We have investigated this phenomena and concluded that it is predicted by the theory of optics. It is an important effect that we are studying for 250nm lithography.

3. Progress towards production 250nm Lithography

Two optical approaches are available for a 250nm resolution tool: High NA or Very-Deep-UV (193nm). Both approaches are being pursued. Depth of focus is the issue. Figure 10 indicates the estimated depth of focus for current and future systems.

Grouped Lines Just Opened in Positive Resist

■ MS92(DUV), NA=0.50 ♦ MS94(193), NA=0.50 ▲ MS94(DUV), NA=0.68

Figure 10. Resolution and Depth of Focus.

It is expected that the nominal depth of focus for either a 193nm system or a Very-High-NA system at 250nm will be approximately 0.8 μ m, but this is subject to processing. Technologies such as surface imaging, bi-level resist, annular illumination, and phase-shift masks will increase this depth of focus. Phase shift techniques will be the prime technique as annular illumination produces some degradation in the quality of the aerial image which may be critical at 250nm resolution. Combination of phase shifting and annular illumination may be more effective. Using the etched phase shifter technology and the Levenson alternating phase shifter technique the depth of focus can be significantly enhanced when highly coherent illumination is used. The depth of focus at 250nm resolution using a 0.50NA Deep-UV Step and Scan system is enhanced from 0.4 μ m two to threefold depending upon the partial coherence used. Figure 11 shows that for a partial coherence < 0.3 , over 1.25 μ m depth of focus is expected (note, for partial coherence > 0.6 there is little improvement in depth of focus because the phase shift effect is derived from the interference of out of phase adjacent coherent images).

Figure 11. Depth of Focus for Grouped Lines using a Phase-shift Mask (NA=0.50)

The effect of phase shift masks on resolution can be clearly observed if we plot the the clear line intensity and the opaque line intensity for grouped line patterns of various linewidths. Figure 12 is plotted for a standard mask used on a 0.50NA Step and Scan systems at I-line, DUV, and VDUV. It is clear to see that the 60% process point indicates the resolution capabilities of the I-line, DUV, and VDUV systems to be 400nm, 280nm and 230nm respectively. This shows that an I-line system will not be able to achieve 250nm resolution in production, unless the NA is substantially higher than 0.50 or phase shift masks are used.

If phase shift masks are used then a 0.50 NA Step and Scan I-line system will be able to achieve 250nm resolution (Figure 13). 200nm will be achieved on the DUV Step and Scan system and 160nm on the Very-Deep-UV system. Early testing of phase Shift masks on the DUV 0.50 NA prototype system indicate that 250nm is readily achieved as shown in figure 14. The available depth of focus was over 0.8 μ m using a partial coherence of 0.3.

NA=0.50, SIGMA=0.5, FOCUS=0.0 μ m, Standard Mask

■ Clear Line Ints. (I-Line) ◆ Opaque Line Ints. (I-Line) ▲ Clear Line Ints. (DUV)
 X Opaque Line Ints. (DUV) + Clear Line Ints. (VDUV) ▾ Opaque Line Ints. (VDUV)

Figure 12. Image Contrast (I-line, DUV, VDUV) using a Standard Mask.

NA=0.50, SIGMA=0.3, FOCUS=0.0 μ m, Phase Mask

■ Clear Line Ints. (I-Line) ◆ Opaque Line Ints. (I-Line) ▲ Clear Line Ints. (DUV)
 X Opaque Line Ints. (DUV) + Clear Line Ints. (VDUV) ▾ Opaque Line Ints. (VDUV)

Figure 13. Image Contrast (I-line, DUV, VDUV) using a Phase-shift Mask.

Figure 14. SEM Photograph of 250nm Grouped Lines Exposed on DUV Step and Scan using a Phase-shift Mask. (NA=0.50, Sigma=0.3)

4. Conclusions.

250nm resolution will be achieved with Step and Scan using Very-High-NA optics or 193nm illumination on a Step and Scan system. The first of the 193nm systems will begin testing within six months. The availability of production quality phase shift masks will enhance the depth of focus of these systems for periodic patterns and allow current 0.50 NA I-line and DUV Step and Scan systems to achieve 250nm resolution.