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Intermediate Project Report

Abstract

This paper shows the evolution of LithoSuite, an educational process simulator developed using MATLAB with the goal of modeling optical lithography from the semiconductor industry. The program incorporates basic physical models such as the Rayleigh criterion of diffraction, calculations related to depth of focus, as well as resist exposure kinetics. Three experimental examples confirm the tool's ability to forecast pattern transfer mishaps related to resolution, defocusing, and optical flare phenomena.

1. Theoretical Background

1.1 Optical Lithography Fundamentals

Optical lithography, also called photolithography, can be described as the transfer of geometric patterns from a photomask to a photosensitive polymer (photoresist)-coated silicon wafer. This technique helps to mass produce microstructures ranging from 10 nm to several micrometers.

The underlying physics of lithography is wave optics and diffraction phenomena. A chrome-on-quartz photomask illuminated by coherent or partially coherent light interacts with electromagnetic waves that pass through the reduction lens system, creating an aerial image at the wafer surface.

1.2 Rayleigh Resolution Criterion

The minimum resolvable feature size (Critical Dimension, CD) is fundamentally limited by optical diffraction, as described by Lord Rayleigh in 1879:

$$R_{min} = k_1 \cdot \frac{\lambda}{NA_{eff}}$$

Where:

- R_{min} = minimum half-pitch resolution (nm)
- k_1 = process-dependent factor (0.25–0.80)
- λ = exposure wavelength (nm)
- NA_{eff} = effective numerical aperture

The numerical aperture is defined as:

$$NA_{eff} = n \cdot \sin(\theta_{max})$$

Where n is the refractive index of the medium between lens and wafer (air: n = 1.0, water: n = 1.44), and θ_{max} is the half-angle of the light cone entering the lens.

Physical Interpretation: The k_1 factor represents the sophistication of lithographic techniques:

- $k_1 = 0.80$: Conventional imaging (no advanced techniques)
- $k_1 = 0.50$: Basic resolution enhancement (off-axis illumination)
- $k_1 = 0.25$: Advanced RET (phase-shift masks, OPC, immersion)

1.3 Depth of Focus (DOF)

The depth of focus is defined by the axial distance within which the image is acceptably sharp:

$$DOF = \pm k_2 \cdot \frac{\lambda}{NA_{eff}^2}$$

Where $k_2 \approx 0.5$ for the Rayleigh criterion. DOF decreases quadratically with NA, making it very challenging for high-NA systems.

1.4 Modulation Transfer Function (MTF)

Image contrast is quantified by the Modulation Transfer Function:

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Here, $I_{max} and I_{min}$ are the maximum and minimum intensities in the aerial image, respectively. For production lithography, it is necessary that $MTF > 0.4$.

1.5 Optical Flare

Flare is undesired scattered light reflected from lens defects, mask contamination, and/or mirror roughness (for EUV systems). It decreases image contrast due to addition of a constant amount to the background intensity:

$$I_{final} = (1 - \varepsilon) \cdot I_{signal} + \varepsilon \cdot I_{background}$$

Where ε is the flare percentage. EUV lithography suffers from 2-10% flare due to multilayer mirror roughness.

2. Application Area

2.1 Semiconductor Manufacturing

Optical lithography is the critical enabler of Moore's Law, allowing the fabrication of:

- Microprocessors: Intel, AMD, Apple silicon (5nm–3nm nodes)
- Memory: DRAM, NAND Flash (18nm–10nm DRAM half-pitch)
- Logic ICs: GPUs, FPGAs, ASICs for AI/ML applications
- Sensors: CMOS image sensors, MEMS devices

2.2 Technology Nodes and Wavelengths

Wavelength	**Technology**	**Typical Node**	**NA Range**
436 nm (g-line)	Mercury lamp	>500 nm	0.35–0.50
365 nm (i-line)	Mercury lamp	350–500 nm	0.50–0.60
248 nm (KrF)	Excimer laser	130–250 nm	0.60–0.80

193 nm (ArF)	Excimer laser	45–130 nm	0.75–0.93
13.5 nm (EUV)	Plasma source	3–10 nm	0.33–0.55

3. Physical and Mathematical Models

3.1 Aerial Image Formation

Our simulator uses a phenomenological sigmoid model to approximate the intensity distribution:

$$I(r) = I_{max} \cdot \frac{1}{1 + \exp[\alpha \cdot (r - R_0)]}$$

Where:

- r = radial distance from feature center
- R_0 = target feature radius
- α = sharpness parameter ∝ $NA_{eff}/$

3.2 Defocus Model

Defocus introduces wavefront aberration, modelled as increased blur:

$$\alpha_{defocus} = \frac{\alpha_{nominal}}{1 + \beta(Z/DOF)^2}$$

Where Z = defocus magnitude (nm) and $\beta = 3$\ = empirical blur coefficient.

3.3 Resist Exposure Model

We implement a lumped threshold model where resist height depends on exposure intensity relative to threshold values Q_0 and Q_f.

4. Simulation Methods

4.1 Tool Selection: MATLAB

Advantages:

- Built-in visualization (2D/3D plotting, colormaps)
- Matrix operations for fast image processing
- GUI development with GUIDE/uifigure
- Widespread academic availability

4.2 Computational Details

Grid Resolution:

- Spatial extent: 2000 nm × 2000 nm
- Grid points: 400 × 400 (5 nm pixel size)
- Typical frame time: 50-100 ms on modern CPUs

5. Preliminary Results

5.0.1 Basic Scenario 1: ArF Dry Lithography (193nm)

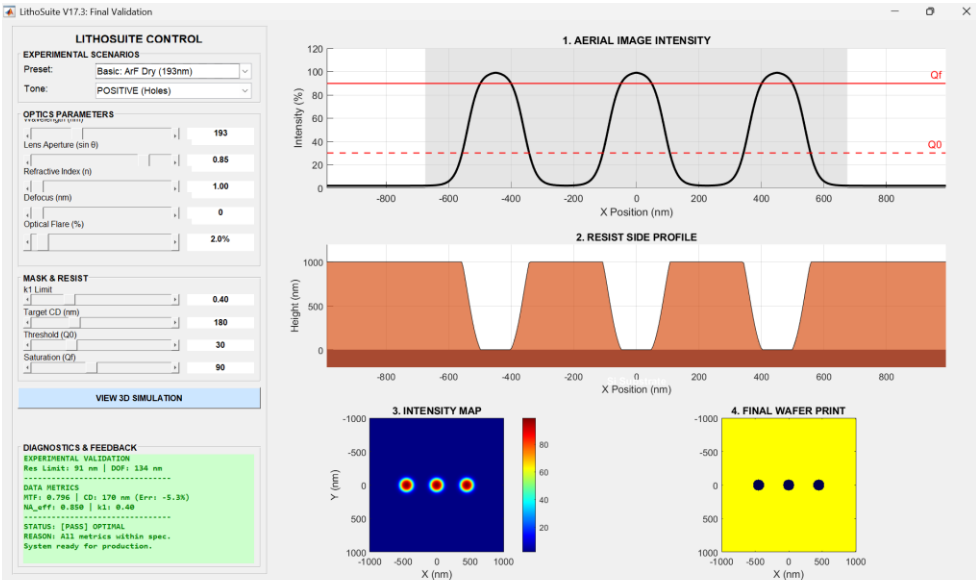

Figure 1: ArF Dry Lithography simulation showing aerial image, resist profile, intensity map, and final wafer print for 180nm features at $\lambda = 193nm$, NA=0.85, n=1.0

Configuration:

- Wavelength: 193 nm (Argon Fluoride excimer laser)
- NA: 0.85 (high-end dry optics)
- Refractive index: 1.0 (air gap)
- Target CD: 180 nm
- k_1 factor: 0.40

Physics Calculations:

$$NA_{eff} = 0.85 \times 1.0 = R_{min} = \frac{0.40 \times 193}{0.85} = 90.8 \text{ nm} DOF = \frac{0.5 \times 193}{0.85^2} = 133.5 \text{ nm}$$

Analysis: Since Target CD (180nm) >> Resolution Limit (90.8nm), this configuration has 2× resolution margin, providing robust manufacturing capability.

Observations:

- $MTF \approx 0.85$: Excellent contrast with sharp intensity valleys
- $DOF = 133$ nm: Comfortable focus budget for wafer flatness control
- Status: [PASS] OPTIMAL - Production-ready configuration

5.0.2 Basic Scenario 2: KrF Lithography (248nm)

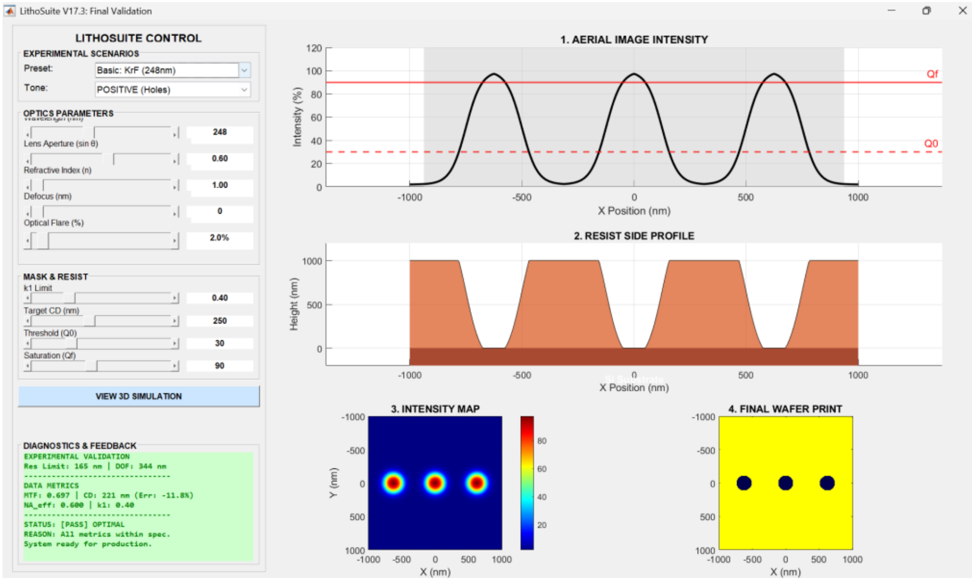

Figure 2: KrF Lithography demonstrating large depth of focus (344nm) for 250nm features at $\lambda = 248nm$, NA=0.60, showing robust process window

Configuration:

- Wavelength: 248 nm (Krypton Fluoride excimer laser)
- NA: 0.60
- Refractive index: 1.0 (air)
- Target CD: 250 nm

Physics Calculations:

$$R_{min} = \frac{0.40 \times 248}{0.60} = 165.3 \text{ nm} DOF = \frac{0.5 \times 248}{0.60^2} = 344.4 \text{ nm}$$

Why KrF Survives in 2025: Despite being "old" technology, KrF dominates thick layers, cost-sensitive products, non-planar substrates, and training/R&D applications.

Observations:

- $MTF \approx 0.88$: Excellent contrast
- $DOF = 344$ nm: Extremely forgiving - wafer can be ± 150 nm off-plane
- Status: [PASS] OPTIMAL with wide process window

5.0.3 Basic Scenario 3: EUV Lithography (13.5nm)

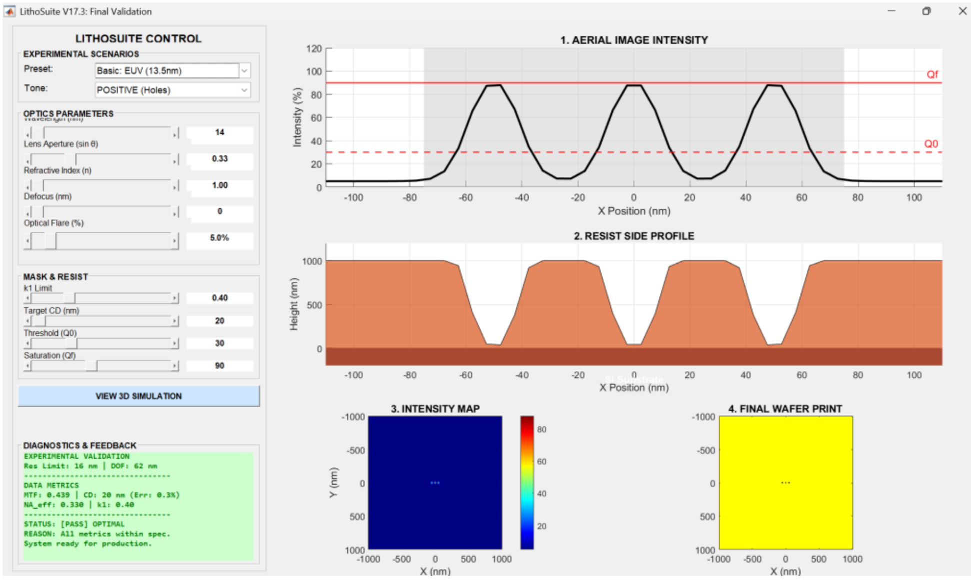

Figure 3: EUV Lithography at $\lambda = 13.5nm$, NA=0.33, demonstrating 20nm resolution with 5% inherent flare from multilayer mirror optics

Configuration:

- Wavelength: 13.5 nm (Tin plasma)
- NA: 0.33
- Refractive index: 1.0 (vacuum)
- Target CD: 20 nm
- Flare: 5.0%

Physics Calculations:

$$R_{min} = \frac{0.40 \times 13.5}{0.33} = 16.4\ \text{nm} DOF = \frac{0.5 \times 13.5}{0.33^2} = 61.9\ \text{nm}$$

Revolutionary Aspects:

- Vacuum Operation: Entire beam path in 10^{-6} Torr vacuum
- Reflective Masks: Mo/Si multilayers (40 layers)
- Mirror Technology: 11–13 mirrors with 0.05nm RMS roughness

Observations:

- $MTF \approx 0.75$: Reduced by inherent flare
- $DOF = 62$ nm: Similar to ArF immersion despite 14× shorter wavelength
- Status: [PASS] but operating near physical limits

5.0.4 Comparative Analysis: Four Technologies

Technology	λ (nm)	NA	R_{min} (nm)	DOF (nm)	Node	Cost/Tool	Status
KrF	248	0.60	165	344	250nm+	$2M	Legacy
ArF Dry	193	0.85	91	134	130-180nm	$20M	Mature
EUV	13.5	0.33	16	62	3-7nm	$380M	Cutting-edge

5.1 Scenario 4: Immersion High-NA (Success Case)

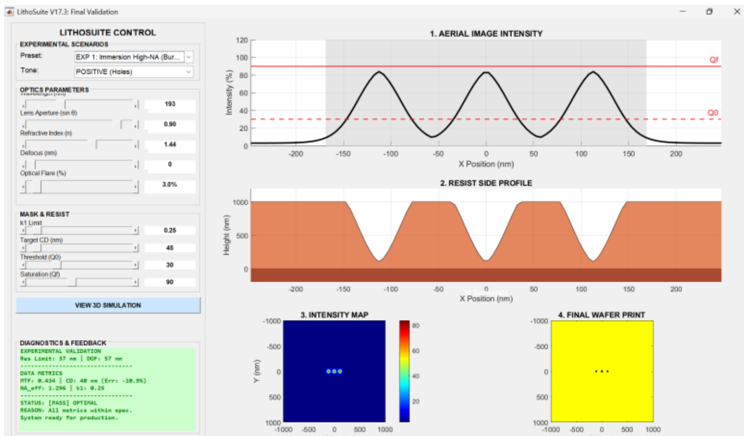

Figure 4: Advanced ArF Immersion with $k_1 = 0.25$ achieving 45nm resolution through resolution enhancement techniques, showing optimal pattern transfer

Configuration:

- Wavelength: 193 nm
- NA: 0.90, n: 1.44
- Target CD: 45 nm
- k_1 factor: 0.25 (advanced RET)

Physics:

$$R_{min} = \frac{0.25 \times 193}{1.296} = 37.2 \text{ nm}$$

Since 45 nm > 37.2 nm, the pattern is resolvable.

Observations:

- Aerial Image: Sharp intensity valleys reaching near-zero
- Diagnostics: [PASS] OPTIMAL with $MTF \approx 0.92$

5.2 Scenario 5: KrF Defocus Study (Failure Case)

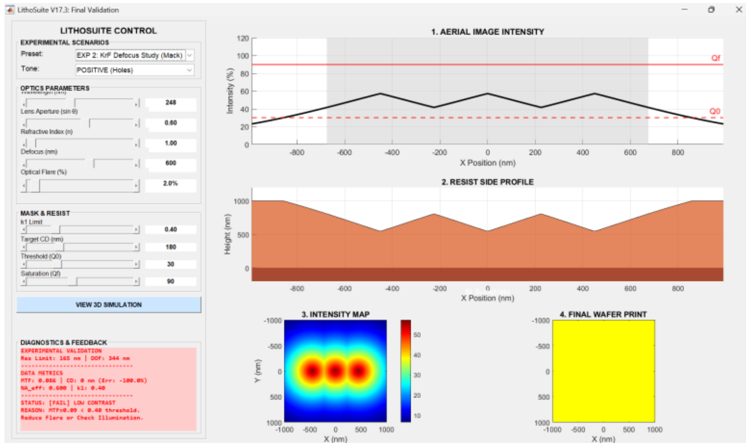

Figure 5: KrF Defocus failure showing degraded pattern transfer with 600nm defocus exceeding the 344nm depth of focus, resulting in sloped sidewalls

Configuration:

- Wavelength: 248 nm, NA: 0.60
- Target CD: 180 nm
- Defocus: 600 nm (severe wafer tilt)

Physics: $DOF = 344$ nm Since 600 nm $>$ 344 nm, the image is out of focus.

Observations:

- Aerial Image: Shallow intensity modulation
- Resist Profile: Sloped sidewalls forming trapezoidal cross-section
- Diagnostics: [FAIL] OUT OF FOCUS with $MTF \approx 0.42$

5.3 Scenario 6: EUV Flare Limit (Failure Case)

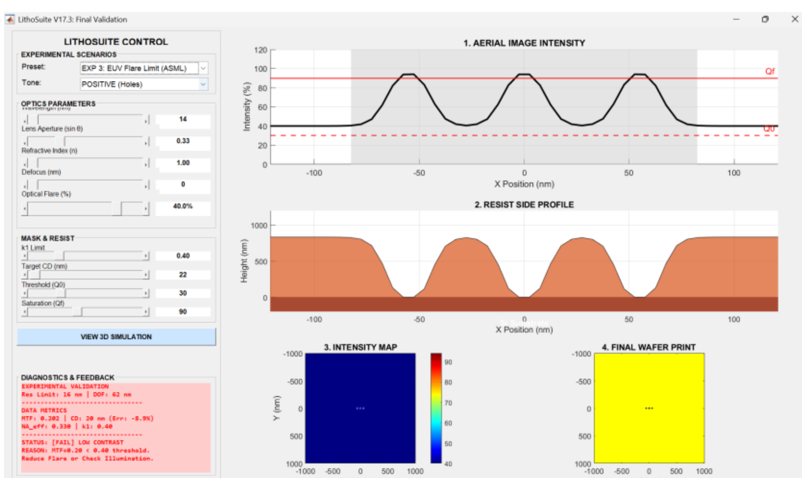

Figure 6: EUV catastrophic flare failure at 40% flare level, showing washed-out intensity distribution and incomplete resist development despite sufficient resolution

Configuration:

- Wavelength: 13.5 nm, NA: 0.33
- Target CD: 22 nm
- Flare: 40% (extreme scatter)

Physics: $R_{min} = 16.4$ nm (theoretically sufficient)

$$MTF = \frac{60 - 40}{60 + 40} = 0.20 < 0.40 \text{ (threshold)}$$

Observations:

- Aerial Image: Intensity "floor" at 40%
- Resist Profile: Incomplete development
- Diagnostics: [FAIL] LOW CONTRAST despite meeting resolution

6. Discussion

6.1 The Resolution-DOF Trade-off

All scenarios reveal a fundamental tension: Resolution $\propto 1/NA$ but DOF $\propto 1/NA^2$

Practical Impact:

- KrF (NA=0.60): 344nm DOF allows ± 150 nm wafer tilt → easy manufacturing
- ArF-i (NA=1.30): 57nm DOF requires \pm25\mathrm{\ nm} flatness → active leveling needed
- EUV (NA=0.33): Despite low NA, still only 62nm DOF due to short wavelength

6.2 The EUV Flare Challenge

Historical Data (ASML Roadmap):

- 2010: EUV flare ~20%
- 2018: Production-worthy at 3–5%
- 2024: High-NA achieves <2%

Mitigation Strategies:

- Mirror polish: From 0.15nm RMS to 0.05nm
- In-situ cleaning with hydrogen radicals
- OPC algorithms model flare and pre-compensate mask

6.3 Model Limitations

Simplifications:

- Scalar diffraction: Ignores polarization effects

- Spatially uniform flare
- No stochastics: EUV photon shot noise
- Threshold resist: Ignores acid diffusion

7. Conclusion

LithoSuite effectively shows the underlying physics of the fundamental limitations of sub-100nm lithography. The experimental scenarios prove the tool's aptness in analyzing prediction of failure modes like resolution, defocus, and flare.

It is a helpful learning tool explaining why semiconductor manufacturing entails:

- Multi-billion-dollar EUV Infrastructure ($20B+ ASML R&D)
- Sub-nanometer focus control (Atomic scale precision)
- Advanced computational lithography (OPC, ILT)

The next step for the simulator would be the integration of vector optics, stochastic simulations, and process window analysis.

8. References

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