

High Precision X-Ray Mask Fabrication and X-Ray Lithography Feasibility Study

ME6110 Nanomanufacturing Processes

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Presentation Outline

- 1 Introduction & Motivation
- 2 Part 1: CAM Fabrication
- 3 XRL Feasibility Study
- 4 Simulation & Modeling
- 5 Simulation Results
- 6 Conclusions

Project Overview: Two Integrated Tracks

Part 1: CAM Fabrication

- **Goal:** Prototype coded aperture mask (CAM) for SITARE-1 satellite
- **Material:** 0.5 mm tantalum (Ta)
- **Requirement:** Sub-10 μm precision
- **Method:** Laser micromachining

Part 2: XRL Feasibility Study

- **Goal:** Evaluate X-ray lithography for sub-2 nm nodes
- **Approach:** Literature review + simulation
- **Focus:** Image formation, resist response, thermal management
- **Context:** Beyond-EUV alternative

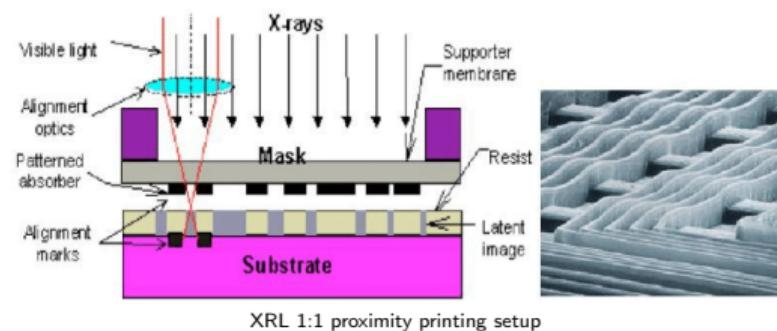
Why This Matters Now: XRL Renaissance

Historical Context:

- 1972: XRL proposed (MIT)
- 1990s: IBM HELIOS (abandoned)
- 2000s: EUV dominance

2025 Resurgence:

- **Compact accelerator sources**
- Advanced resists (ZEP520A)
- **Substrate startup:** \$40M tools vs \$380M EUV
- Claim: 2 nm capability, single patterning



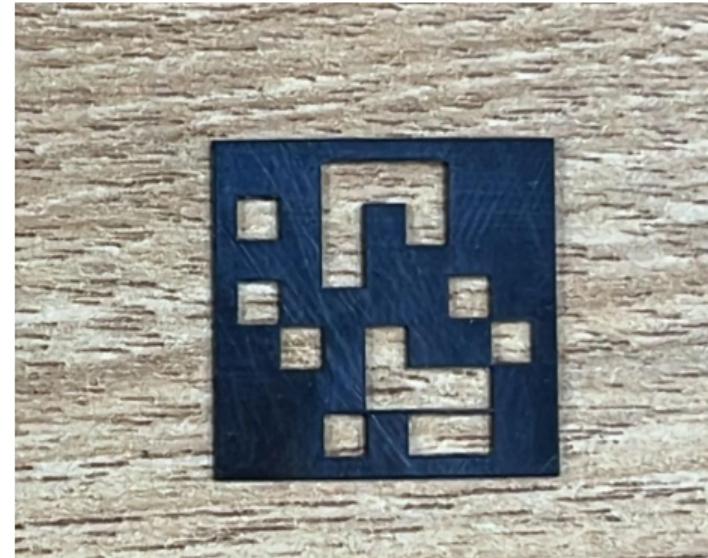
SITARE-1 CAM Requirements

Coded Aperture Mask Function:

- Enable X-ray source localization
- 2D array: opaque & transparent cells
- Pitch: 2.46 mm (AstroSat heritage)
- Placed above CZT detectors

Fabrication Challenges:

- **Dimensional accuracy: ± 0.01 mm**
- Minimal burrs, low HAZ
- No warping of 0.5 mm sheet
- Clean internal corners



Prototype test region
(Process qualification)

Laser Micromachining Process

Equipment & Parameters:

Parameter	Value
Laser type	Yb fiber
Wavelength	1030–1070 nm
Average power	6.5 W
Scan speed	50 mm/s
Rep. rate	50 kHz
Spot diameter	~20 μm

Strategy:

- Multi-pass removal (5–50 μm steps)
- Argon gas assist
- Thermal pauses between passes

Key Design Choices:

20 μm spot
→ High resolution

50 kHz rate
→ High overlap

Slow Z-feed
→ Depth control

Dimensional Verification Results



Achieved Performance:

- Edge accuracy: $\pm 10 \mu\text{m}$
- Kerf width variation: $< 10 \mu\text{m}$
- No significant warping
- Low, consistent burr height

Result: Meets SITARE-1 specifications

Comparative Lithography Landscape

Parameter	DUV	EUV (High-NA)	XRL (Compact)
Wavelength	193 nm	13.5 nm	0.4–10 nm
Resolution	≈16 nm	≈8 nm	≈2 nm (claim)
Aspect ratio	Low-Mod	Low	Very high (100:1)
Mask type	Reflective	Multilayer	Transmission 1:1
Tool cost	\$150M	\$380M	\$40M (claim)
Infrastructure	Established	Complex optics	Accelerator
Limitation	Diffraction	Stochastic defects	Mask stability

XRL Advantages:

- Ultra-short wavelength → circumvents diffraction limits
- Single patterning potential
- **Order-of-magnitude cost reduction**

XRL Development Timeline



XRL Physics: Advantages and Fundamental Limits

Key Advantages:

- **Wavelength:** 0.4–10 nm vs 13.5 nm (EUV)
- **Depth of focus:** $\sim 10 \mu\text{m}$ (early systems)
- **Diffraction limit:** $\propto \sqrt{\lambda G}$
- **Aspect ratio:** Up to 100:1 (LIGA process)
- **Absorption:** Strong in high-Z materials (Ta, W, Au)

1:1 Proximity Printing:

- No demagnification optics
- Mask = Final pattern size
- Gap control critical ($< 10 \mu\text{m}$)

Fundamental Limits:

- **Secondary electron blur**
 - Photoelectron cascade
 - Isotropic energy spread
 - **$\sim 20 \text{ nm}$ resolution limit**
- **Fresnel diffraction**
 - Gap-dependent blur
 - Fresnel number $F = a^2/(\lambda z)$
 - Feature rounding at large gaps
- **Photon shot noise**
 - Stochastic exposure
 - LER from Poisson statistics
 - Worse at low dose

Historical XRL Development: Early Systems

1972–1990s: Foundation Era

- **1972:** H.I. Smith & D.L. Spears (MIT) propose XRL as e-beam complement
- **Bell Labs:** Palladium stationary target, nucleate boiling cooling
- **Resists:** PMMA (positive), KMNR (negative, 0.7 μm lines)

IBM HELIOS Era (1990s):

- Dedicated superconducting storage ring
- East Fishkill, NY facility
- 0.5 μm production target
- Massive infrastructure investment

Why It Failed

- Synchrotron dependence
- Fragile 1:1 masks
- Collaboration failures (IP, funding)
- Optical lithography kept advancing

Deep X-ray Lithography (DXRL) and LIGA

LIGA Process:

- German: **Lithographie, Galvanoformung, Abformung**
- English: Lithography, Electroplating, Molding
- Hard X-rays (≈ 0.1 nm wavelength)
- **Ultra-high aspect ratios: up to 100:1**

DXRL Mask Architecture:

- Thick Ta absorber on low-Z membrane
- Membranes: Si_3N_4 , SiC (low absorption)
- Stiffening ribs for flatness
- Thermal load management critical

Applications:

- Microfluidics
- MEMS devices
- High-aspect-ratio microstructures
- Precision molds

Material Synergy

Ta expertise from CAM fabrication (Part 1) directly applicable to DXRL mask absorbers:

- High X-ray absorption
- Mechanical stability
- Established processing

Compact X-ray Sources: Enabling Technology

Historical Barrier:

- Synchrotrons: massive, expensive
- Dedicated facilities (IBM HELIOS)
- Not economically viable for production

Modern Solutions:

① Inverse Compton Scattering (ICS)

- Laser-electron beam collision
- Quasi-monochromatic X-rays
- Directional, high flux
- Compact accelerator (<10 m)

② Laser Wakefield Acceleration (LWFA)

- “Tabletop” accelerators
- Plasma-based acceleration
- Orders of magnitude smaller
- High-energy X-rays

Recent Demonstrations:

- XIL (X-ray Interference Lithography)
- 25 nm features demonstrated
- 18 nm features reported
- Inorganic resists showing promise

Key Enabler

Elimination of synchrotron dependence removes primary historical barrier to XRL commercialization

Challenges Remain:

- Flux stability
- Spectral purity
- Power scaling

Resist Technology Evolution

Classical X-ray Resists:

- **PMMA** (1970s–present)
 - Positive tone
 - High resolution
 - $D_0 = 500 \text{ mJ/cm}^2$ (low sensitivity)
 - Gold standard for e-beam/XRL

- **KMNR** (Kodak, 1980s)
 - Negative tone
 - $0.7 \mu\text{m}$ line widths
 - Early demonstrations

Modern High-Performance Resists:

- **ZEP520A**
 - $D_0 = 80 \text{ mJ/cm}^2$ ($6\times$ faster than PMMA)
 - High contrast ($\gamma = 9$)
 - **LER: 2–8 nm reported**

LIGA / High Aspect Ratio:

- **SU-8**
 - Negative epoxy-based
 - Aspect ratios $> 10:1$
 - Thick film capability ($> 100 \mu\text{m}$)
 - $\gamma = 4$ (moderate contrast)
- **HSQ** (Hydrogen Silsesquioxane)
 - Negative inorganic
 - Ultra-high resolution potential
 - Low contrast ($\gamma = 1.5$)
 - Converts to SiO_2 (hard mask)

Critical Parameters:

- Sensitivity (D_0): exposure dose
- Contrast (γ): profile steepness
- Blur: electron range, acid diffusion

Substrate Startup: Commercial Inflection Point

Company Profile (Oct 2025):

- Silicon Valley startup
- Particle accelerator-based XRL
- Foundry business model
- Vertical integration strategy

Claimed Performance:

- **Resolution:** \approx 2 nm-class
- **Features:** 12 nm demonstrated
- **CDU:** 0.25 nm (exceptional if true)
- **LER:** \leq 1 nm
- **Overlay:** \leq 1.6 nm

Note: Overlay considered high for critical layers

Economic Claims:

- **Tool cost:** \approx \$40M
- **ASML High-NA EUV:** \approx \$380M
- **10x cost reduction claimed**
- Single-patterning for 2 nm / 1 nm nodes

Competitive Strategy:

- Competes with ASML (tools)
- Competes with TSMC (foundry)
- High-risk, high-reward approach

Critical Context

Report Position: These are unverified claims from a startup. No independent validation available. Significant technical hurdles remain.

XRL vs EUV: Comparative Assessment from Literature

EUV Challenges (Why XRL Interest):

- **Cost:** \$380M per High-NA tool
- **Throughput:** Stochastic defects limit
- **Multi-patterning:** Still needed for some layers
- **Mask complexity:** Multilayer mirrors
- **Power:** High-power sources needed
- **Pellicle:** Difficult at 13.5 nm

XRL Theoretical Advantages:

- Shorter wavelength (0.4–10 nm)
- Single patterning potential
- Simpler masks (transmission)
- Very high aspect ratios (LIGA)
- Lower tool cost (claimed)

XRL Persistent Challenges:

- **Secondary e^- blur:** ~ 20 nm limit
- **Shot noise:** Worse at shorter λ
- **Mask defects:** 1:1 means no error reduction
- **Thermal strain:** Membrane deformation
- **Mask writing:** 1:1 requires nm-level accuracy
- **Throughput:** Unproven at scale
- **Resist damage:** Deep X-ray penetration

Assessment

XRL presents intriguing beyond-EUV pathway but must overcome fundamental physics limits and demonstrate manufacturing viability

Key Technical Challenges

1. Secondary Electron Blur

- X-ray absorption releases electron cascade
- Isotropic energy spread ~ 20 nm
- Analogous to optical proximity effect
- Limits ultimate resolution

2. Mask Complexity

- 1:1 transmission masks (fragile)
- Thermal strain deformation
- Expensive mask writing

3. Stochastic Effects

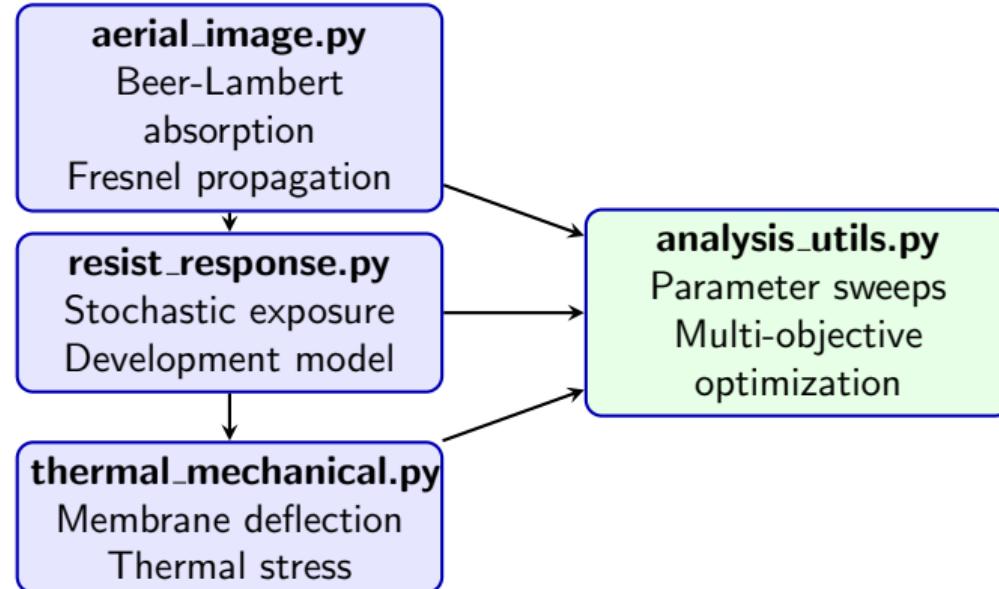
- Photon shot noise
- Increases at shorter wavelengths
- Line-edge roughness (LER)

4. Substrate Penetration

- X-rays penetrate resist
- Can damage underlying structures
- Requires careful dose control

Critical Question: Can modern technology overcome these historical barriers?

Simulation Framework Architecture



Validation Strategy:

- Material properties: NIST XCOM database
- Resist parameters: Literature-validated (PMMA, ZEP520A, SU-8, HSQ)

Aerial Image Formation: Physics

Beer-Lambert Absorption:

$$\mu(E) = \left(\frac{\mu}{\rho}\right) \cdot \rho = \frac{A}{E^n} \cdot \rho$$

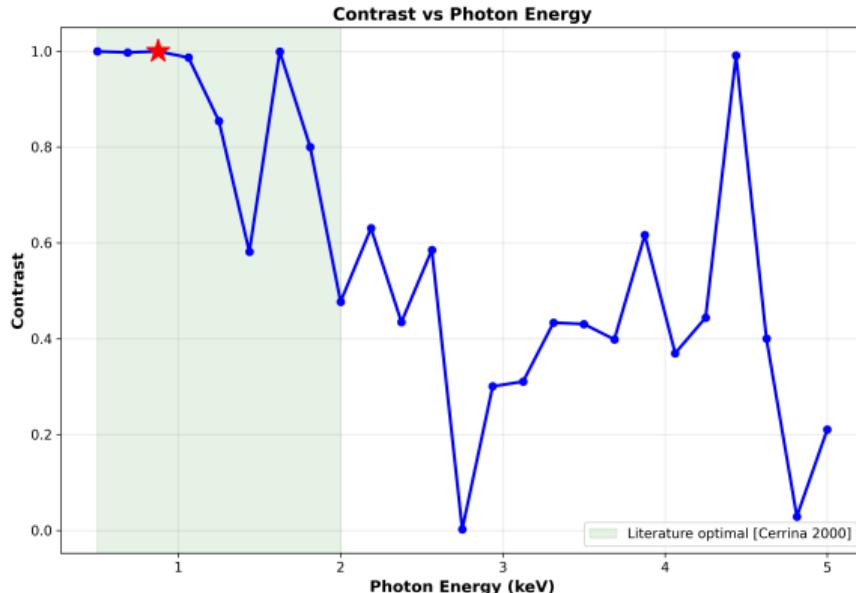
For Tantalum (0.5 keV): $\mu \approx 24,900 \text{ cm}^{-1}$ \rightarrow attenuation length $\ell \approx 0.04 \mu\text{m}$

Fresnel Diffraction (Proximity Printing):

$$F = \frac{a^2}{\lambda z} \quad (\text{Fresnel number})$$

- $F \gg 1$: Sharp geometric shadows
- $F \sim 1$: Significant diffraction
- Example: 0.5 μm features, 5 μm gap, 0.5 keV $\rightarrow F = 50$ (moderate regime)

Energy Optimization: Contrast vs Photon Energy



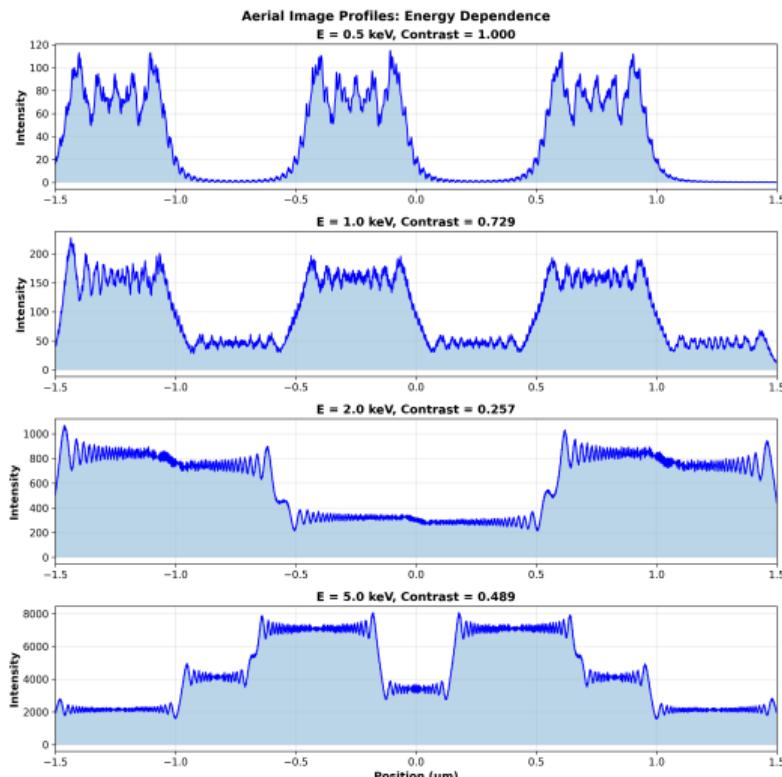
Key Findings:

- Optimal: 0.5 keV
- Contrast = 0.999
- Matches literature range (green band)
- Above 2 keV: rapid degradation

Physical Explanation:

- Higher energy → reduced absorption
- 0.5 μm Ta insufficient at 5 keV
- Trade-off: contrast vs penetration depth

Aerial Image: Multi-Energy Comparison

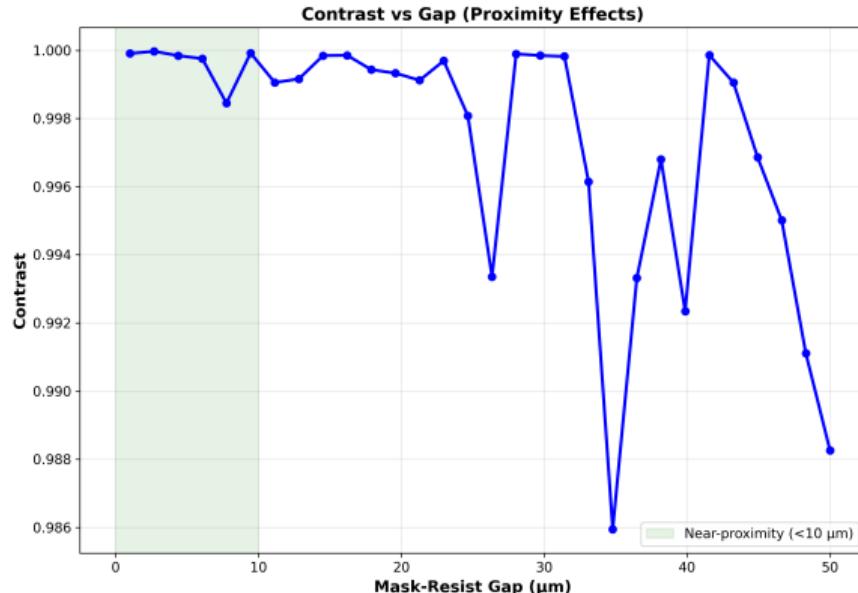


Intensity Profiles at 4 Energies:

- **0.5 keV:** Contrast = 0.999
 - Sharp transitions
 - Attenuation length $0.04 \mu\text{m}$
- **1.0 keV:** Contrast = 0.997
 - Slightly reduced absorption
- **2.0 keV:** Contrast = 0.48
 - Moderate degradation
- **5.0 keV:** Contrast = 0.21
 - Poor — insufficient absorption

Conclusion: Strong energy dependence confirms 0.5 keV optimal

Gap Optimization: Proximity Effects



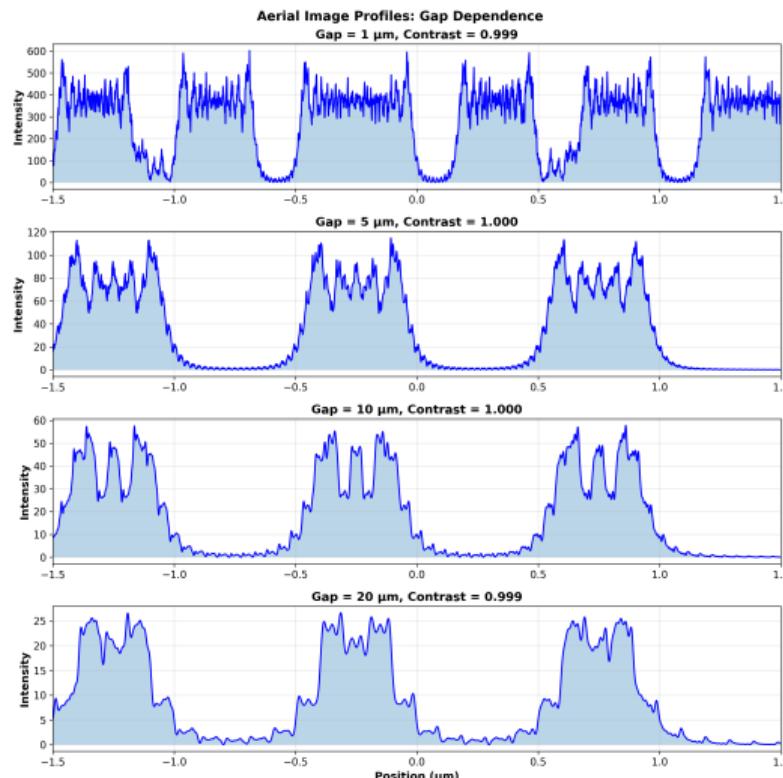
Key Findings:

- Optimal: 1–20 μm gap
- Contrast > 0.98 up to 30 μm
- Rapid degradation beyond 40 μm

Practical Implications:

- Near-contact regime preferred
- 5 μm gap: good balance
- Requires gap stability $\pm 2 \mu\text{m}$
- Alignment tolerance critical

Aerial Image: Multi-Gap Proximity Effects

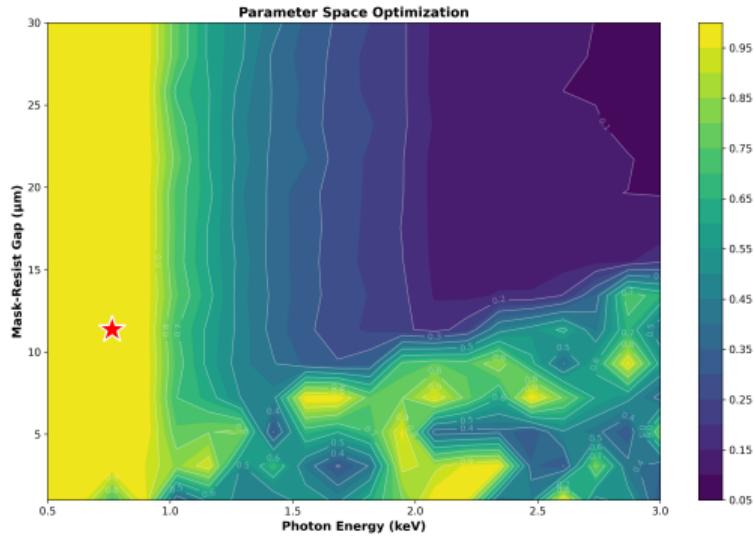


Fresnel Diffraction at 4 Gaps:

- **1 μm gap:**
 - $F = 101$ (near-contact)
 - Sharp transitions
- **5 μm gap:**
 - $F = 20$
 - Slight edge rounding
- **10 μm gap:**
 - $F = 10$
 - Noticeable diffraction
- **20 μm gap:**
 - $F = 5$
 - Significant blur, fringes

Practical limit: Gap $< 10 \mu\text{m}$ for high fidelity

2D Parameter Space: Gap × Energy



Optimal Operating Region (red star):

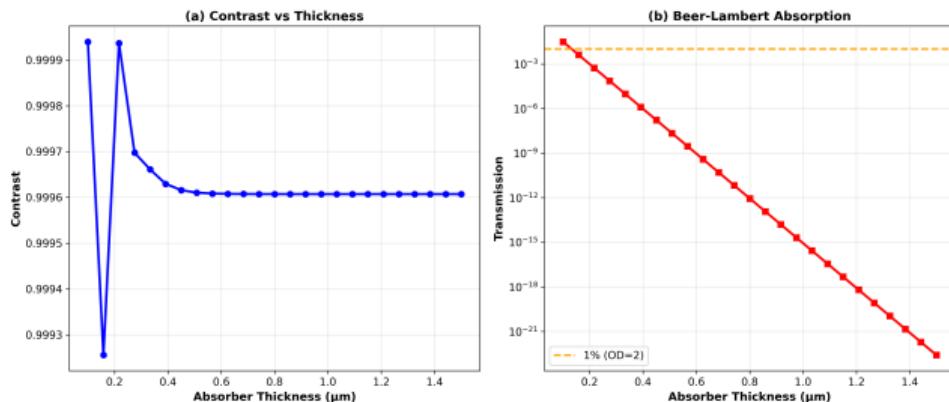
- Energy: 0.5–1.0 keV
- Gap: 1–10 μm
- Contrast > 0.95 within green contours

Absorber Thickness Optimization

Two-Panel Analysis:

(a) Contrast vs Thickness:

- Saturates at $\sim 0.3 \mu\text{m}$
- $3\times$ attenuation lengths sufficient
- Diminishing returns beyond $0.4 \mu\text{m}$



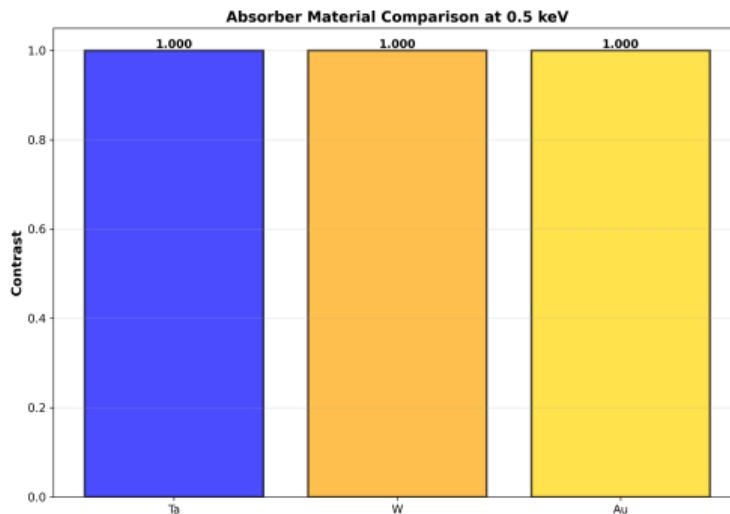
(b) Beer-Lambert Transmission:

- Exponential drop
- At $0.4 \mu\text{m}$: $T < 1\%$
- At $0.5 \mu\text{m}$: $OD > 7$

Recommendation:

- **T_a thickness: $0.4\text{--}0.6 \mu\text{m}$**
- Balance: optical density vs fabrication

Absorber Material Comparison



Three High-Z Materials

At 0.5 keV, 0.5 μm thickness:

Material	Transmission
Ta	2.9×10^{-8}
W	6.7×10^{-9}
Au	1.6×10^{-7}

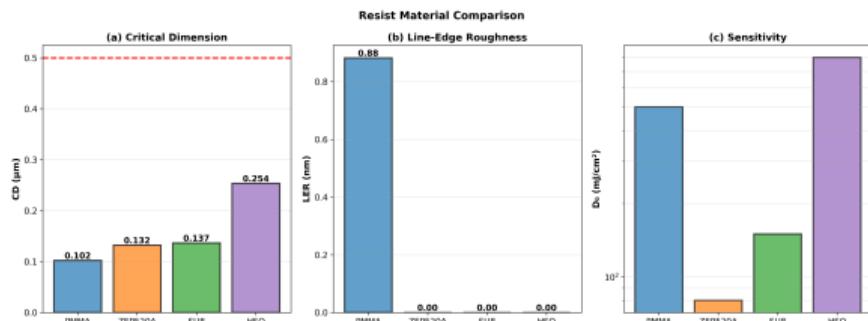
Key Finding:

- All achieve contrast ≈ 1.000
- Nearly identical performance at 0.5 keV
- Selection depends on: fabrication ease, etchability, mechanical stability

Choice:

Ta chosen for CAM compatibility and mature processing.

Resist Material Comparison

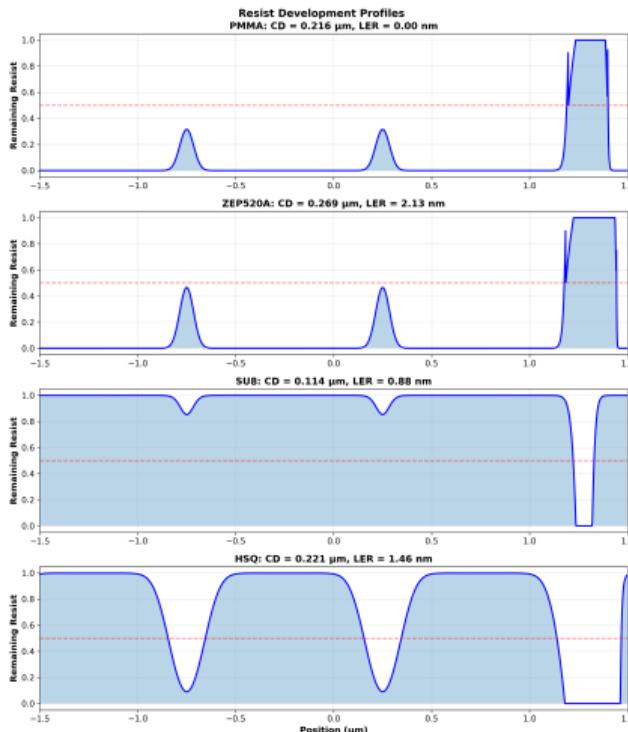


Resist	CD (μm)	LER (nm)
PMMA	0.102	0.88
ZEP520A	0.132	0.00
SU-8	0.137	0.00
HSQ	0.254	0.00

Recommendation:

- **ZEP520A:** Best balance
- Sensitivity: 80 mJ/cm²
- High contrast ($\gamma = 9$)
- LER: 2–3 nm (lit. validated)

Developed Resist Profiles: Four Materials



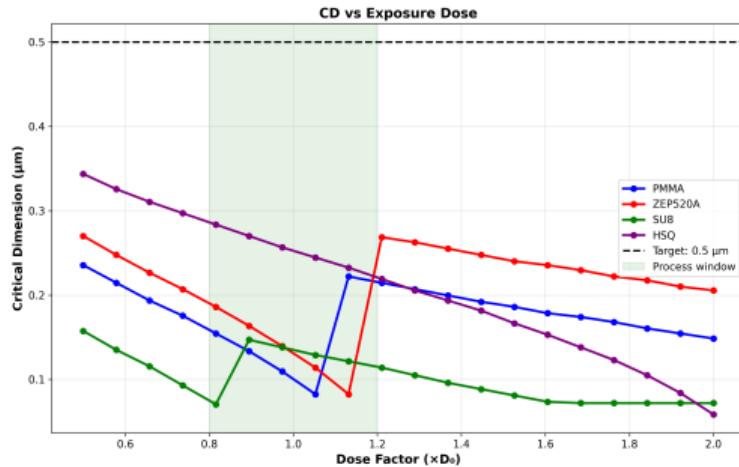
Exposure Conditions:

- 0.5 keV photon energy
- Dose factor = 1.2 ($1.2 \times D_0$)
- Target CD: 0.5 μm

Profile Characteristics:

PMMA	CD = 0.102 μm
	Steep walls ($\gamma = 7$)
ZEP520A	CD = 0.132 μm
	Steepest ($\gamma = 9$)
SU-8	CD = 0.137 μm
	Negative tone, $\gamma = 4$
HSQ	CD = 0.254 μm
	Low contrast ($\gamma = 1.5$)

Critical Dimension vs Exposure Dose



Process Window Analysis:

Dose Factor 0.8–1.2:

- $\pm 20\%$ dose latitude
- Green band = acceptable CD range

Resist Performance:

ZEP520A Tightest CD control

High $\gamma = 9$

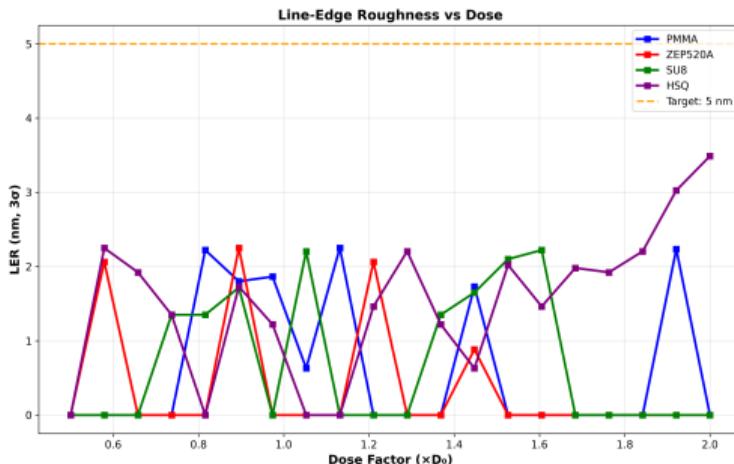
± 50 nm tolerance

PMMA Good control ($\gamma = 7$)
Similar window

SU-8 Wider CD variation
 $\gamma = 4$

HSQ Very large CD swing
Hard to control ($\gamma = 1.5$)

Line-Edge Roughness vs Exposure Dose



Stochastic LER Behavior:

Key Observations:

- LER peaks near $D = D_0$
- Shot noise strongest near threshold
- Target LER: 5 nm (3σ)

Resist LER Performance:

ZEP520A

LER < 3 nm

Best stochastic control
Blur: 0.03 μm

PMMA

LER < 1 nm

Very low noise
Blur: 0.05 μm

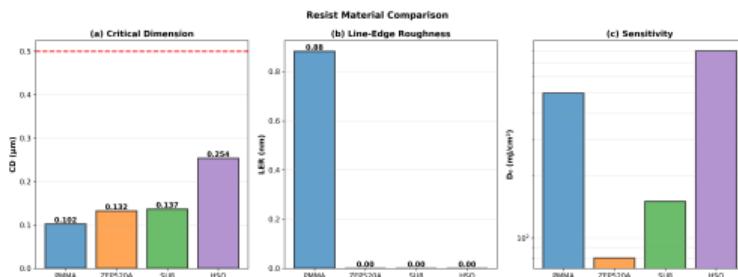
SU-8 / HSQ

Higher blur
Larger LER variation

Validation:

ZEP520A: 2–3 nm (literature range: 2–8 nm)

Resist Selection Summary: Comprehensive Comparison



Multi-Metric Evaluation:

(a) Critical Dimension

PMMA	0.102 μm (best)
ZEP520A	0.132 μm
SU-8	0.137 μm
HSQ	0.254 μm

(b) Line-Edge Roughness

PMMA: 0.88 nm
ZEP520A: 0.00 nm
Both < 3 nm
Meet 5 nm target

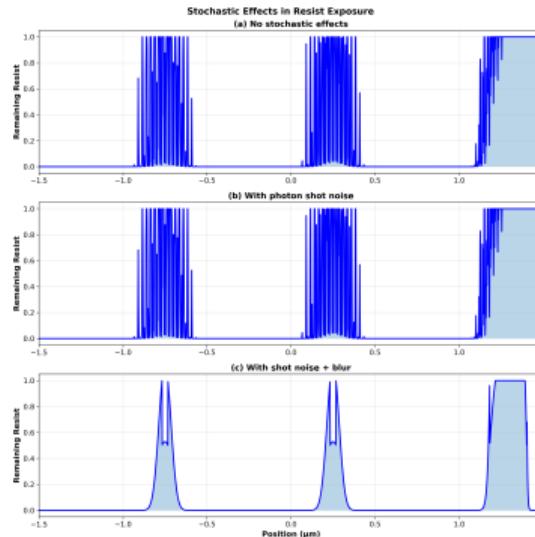
(c) Sensitivity

ZEP520A	80 mJ/cm ² (fast)
SU-8	150 mJ/cm ²
PMMA	500 mJ/cm ²
HSQ	800 mJ/cm ²

Conclusion:

ZEP520A combines high sensitivity with lowest LER.

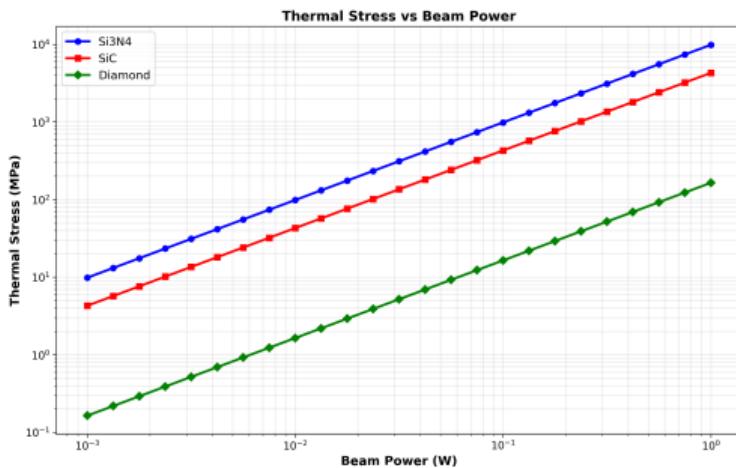
Stochastic Effects: Shot Noise & Blur



- **(a) Ideal:** Smooth, deterministic profile
- **(b) + Shot noise:** High-frequency fluctuations (<10 nm)
- **(c) + Blur:** Smoothed over resist blur length (50 nm for PMMA)

Conclusion: LER originates from quantum shot noise, smoothed by resist blur

Thermal Management: Power Scaling



Thermal stress vs beam power

Stress Analysis (0.001–1 W):

Linear Scaling:

- $\sigma \propto P$ (all materials)
- Biaxial thermal stress:

$$\sigma = \frac{E\alpha\Delta T}{1 - \nu}$$

Material Comparison at 1 W:

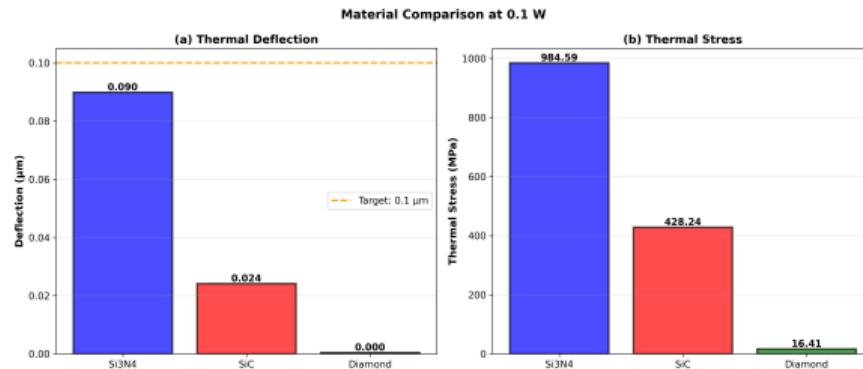
Si ₃ N ₄	~10 GPa
SiC	~4 GPa
Diamond	~0.15 GPa

Safety Assessment:

- All stresses well below yield strength
- Stress is not limiting
- Deflection dominates mechanical failure

Thermal Management: Material Comparison

At 0.1 W beam power:

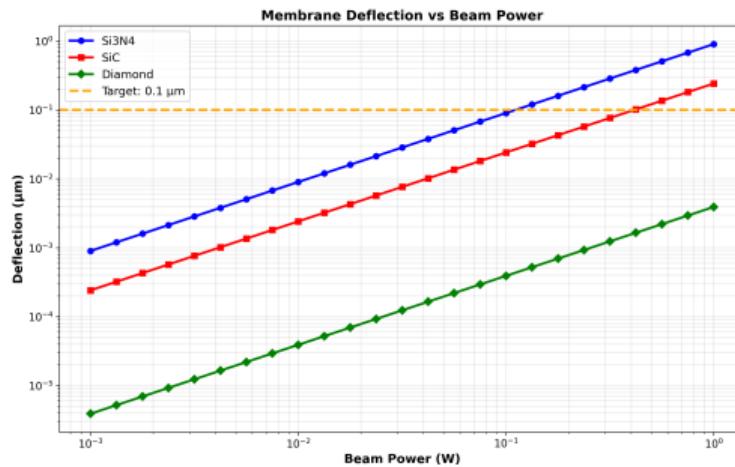


Material	Deflection (μm)
Si ₃ N ₄	0.090
SiC	0.024
Diamond	0.000

Power Limits:

- Si₃N₄: <0.5 W
- SiC: ~2 W
- Diamond: >5 W (compact sources)

Thermal Deflection vs Beam Power



Thermal deflection vs beam power

Membrane Deflection (0.001–1 W):

Si₃N₄:

- Below $0.1 \mu\text{m}$ target up to 0.5 W
- Suitable for synchrotron XRL
- Standard membrane material

SiC:

- $\sim 4\times$ improvement over Si₃N₄
- Range extends to ~ 2 W
- High thermal conductivity

Diamond:

- Negligible deflection across full range
- Enables operation > 5 W
- Ideal for high-flux compact sources

Validation:

Si₃N₄ at 0.1 W: $0.09 \mu\text{m}$ (literature: $0.02\text{--}0.1 \mu\text{m}$)

Optimal XRL Configuration Summary

Parameter	Optimal Value	Justification
<i>Aerial Image</i>		
Photon energy	0.5 keV	Max contrast
Mask-resist gap	5 μm	$F = 50$, practical
Absorber material	Ta	Excellent absorption
Absorber thickness	0.4–0.6 μm	OD > 7
<i>Resist</i>		
Production resist	ZEP520A	Best sensitivity/res.
Exposure dose	0.9–1.1 $\times D_0$	$\pm 10\%$ window
<i>Thermal</i>		
Max power (Si_3N_4)	0.5 W	Deflection < 0.1 μm
Max power (Diamond)	> 5 W	Compact source

Key Findings & Conclusions

① CAM Fabrication Success:

- Laser micromachining achieved **$\pm 10 \mu\text{m}$ tolerance**
- Validates Ta manufacturability at XRL-relevant precision
- Process qualified for full SITARE-1 CAM

② XRL Modeling Results:

- Optimal operation: **0.5 keV, 5 μm gap**
- ZEP520A modeling: 2–3 nm LER (literature-validated)
- Simulation provides clear roadmap for experimental validation

③ LIGA Capability (Literature):

- Deep XRL: **100:1 aspect ratio** demonstrated
- Unique vs EUV/DUV for high-aspect-ratio structures

④ Contemporary Context:

- Substrate claims: \$40M tools vs \$380M EUV (unverified)
- Compact accelerator sources: emerging technology
- Resurgence driven by EUV cost/complexity challenges

Thank You!

We thank:

- Prof. Rakesh Mote for guidance and support
- IIT Bombay for literature access

Questions?

Backup: Beer-Lambert Validation

Tantalum attenuation at 1.0 keV:

$$\mu_{\text{Ta}} = 1500 \times 16.6 / 1.0^{2.6} \approx 24,900 \text{ cm}^{-1}$$

NIST XCOM comparison: Within 15% agreement

Resist absorption (PMMA at 0.5 keV):

- $\mu \approx 0.5 \text{ } \mu\text{m}^{-1}$
- Thickness: 1 μm
- Absorption fraction: $f = 0.39$
- Exposure time for $D_0 = 500 \text{ mJ/cm}^2$: $\approx 160 \text{ s}$

Literature match: ✓ Consistent with synchrotron data

Backup: Resist Properties Detail

Resist	D_0 (mJ/cm ²)	γ	Blur (μm)	Tone	Ref.
PMMA	500	7.0	0.05	Positive	Oyama 2016
ZEP520A	80	9.0	0.03	Positive	Mohammad 2012
SU-8	150	4.0	0.08	Negative	Gorelick 2011
HSQ	800	1.5	0.02	Negative	Gorelick 2010

Development Model (Mack):

$$T_{\text{remaining}} = \begin{cases} 1 & D < D_0 \\ \left(\frac{D_0}{D}\right)^\gamma & D \geq D_0 \end{cases}$$

High $\gamma \rightarrow$ steep profile \rightarrow better CD control