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

Project Plan (Nov 2025)

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Overview

This project integrates two complementary efforts:

Part 1: Fabrication of High-Precision Tantalum X-ray Masks (CAM Project)
Development and characterization of 0.5 mm tantalum coded aperture masks (CAMs) for satellite X-ray payloads, targeting sub-10 µm precision and robust manufacturability.

Part 2: Exploration of X-ray Lithography (XRL) for Advanced Microfabrication
A comprehensive investigation of modern XRL—combining literature review, modeling, simulation, and preliminary process design—to evaluate its technological feasibility and commercialization potential in the 2020s context.

The timeline for the combined project runs from **8 Nov – 28 Nov 2025** with intensive daily engagement in modeling, analysis, and experimental planning.

1 Part 1: X-ray Mask (CAM) Fabrication

Objectives

- Fabricate a Coded Aperture Mask (CAM) in tantalum with cell accuracy better than 10 µm.
- Evaluate and benchmark fabrication routes—laser micromachining, micro-EDM, and chemical etching.
- Characterize dimensional tolerance, surface finish, warpage, and burr formation.
- Develop a manufacturability protocol and parameter optimization guide.

Implementation Workflow

1. **Design Preparation:** Import DXF/STEP geometry, generate process drawings, identify tolerance-critical regions.
2. **Fabrication Trials:** Conduct small-area coupons via laser cutting (femtosecond fiber source), micro-EDM, and wet etch.
3. **Metrology and Analysis:**
   - Optical profilometry for edge fidelity.
   - SEM imaging for burr analysis.
   - Coordinate-measuring machine (CMM) for dimensional validation.
4. **Optimization:** Statistical comparison of process parameters (power, feed rate, dwell) using Python for DoE analysis.
5. **Integration:** Prepare mask for alignment testing on satellite mock-up jig.

Deliverables

- Fabricated CAM samples (0.5 mm and 0.1 mm Ta).
- Dimensional and surface metrology report.
- Manufacturing process flow documentation and parameter tables.

2 Part 2: X-ray Lithography (XRL) Feasibility Study

This section combines all three tracks—**A (Tech/Market Review)**, **B (Modeling/Simulation)**, and **C (Prototyping/Beamtime Planning)**—for a comprehensive exploration.

Track A — Technical and Market Review

Objectives

- Review physical principles of XRL: exposure geometry, photon–resist interaction, and mask architecture.
- Analyze historical development and reasons for stagnation (e.g., mask complexity, synchrotron dependence).
- Evaluate recent resurgence driven by compact accelerator sources and modern resists.
- Compare economic and technical metrics vs EUV and DUV lithography.

Deliverables

- 10–12 page literature review and trend analysis.
- "Go/No-Go" matrix for potential commercialization paths.
- One-slide industry summary: *"XRL in 2025 — Claims vs Constraints"*.

Track B — Modeling and Simulation

Objectives

Develop quantitative understanding of image formation, resist exposure, and mask thermal performance using primarily Python, supported by COMSOL and RedHawk for cross-validation.

Simulation Modules

(a) **Aerial Image Modeling:**

- Compute intensity profiles via Beer–Lambert absorption through absorber/membrane stack.
- Vary photon energy (0.5–5 keV), mask–resist gap, and absorber thickness.
- Output contrast and resolution metrics.

(b) **Resist Response Simulation:**

- Stochastic exposure model for photon shot noise and resist blur.
- Derive CD and line-edge roughness (LER) as functions of dose.

(c) **Thermo-Mechanical Modeling:**

- Use COMSOL for membrane bow/deflection and thermal load from X-ray flux.
- Apply RedHawk for steady-state temperature profile validation.

(d) **Monte-Carlo (Optional):** Use Geant4 or PyPENELOPE to model scattering and energy deposition in resist stack.

Outputs

- Python simulation repository with parameter sweeps and plots (contrast vs gap/energy, CD vs stack).
- Analytical report summarizing results, limitations, and interpretation.

Track C — Prototyping and Beamtime Planning

Objectives

- Translate simulation insights into preliminary mask and test pattern designs.
- Define resist candidates, process flow, and equipment list for eventual exposure.
- Outline a speculative beamtime roadmap for verification.

Implementation Steps

1. Design dense line/space and hole patterns (0.1–2 µm pitch) for exposure trials.
2. Create GDS layouts and identify suitable substrate and absorber combinations.
3. Build process table (spin, bake, develop) for candidate X-ray resists (PMMA, SU-8, ZEP).
4. Draft beamtime request template detailing dose, exposure time, and expected outcomes.

Deliverables

- GDS layout files and mask BoM.
- Preliminary beamtime proposal (2–3 pages).
- Integration roadmap for linking XRL mask learnings to CAM fabrication expertise.

3 Combined Workflow and Timeline (8 – 28 Nov 2025)

Week	Major Tasks and Milestones
Week 1 (8–14 Nov)	• Finalize design files and fabrication workflow for CAM. • Begin fabrication trials (laser, EDM, etch) and initiate metrology setup. • Compile XRL reading list; collect foundational literature and startup analyses. • Set up Python environment for aerial-image modeling.
Week 2 (15–21 Nov)	• Continue CAM fabrication and characterize sample coupons. • Implement intensity and resist modeling modules in Python. • Run initial COMSOL thermal simulations for mask stability. • Draft historical XRL review and early commercialization analysis.
Week 3 (22–28 Nov)	• Complete fabrication and compile CAM performance data. • Finish simulation sweeps and compile plots (contrast, CD, LER). • Design test coupons for XRL; prepare beamtime proposal. • Deliver final integrated report and presentation.

Expected Outcomes

- Fabricated and characterized X-ray mask with validated process tolerances.
- Comprehensive report on XRL feasibility—technical, economic, and simulation-based.
- Prototype design and roadmap for future XRL exposures.

Tools and Resources

- **Software:** Python (NumPy, SciPy, Matplotlib), COMSOL Multiphysics, RedHawk Analyzer.
- **Hardware/Facilities:** Laser micromachining setup, micro-EDM system, metallurgical lab, optical profilometer, SEM.
- **Collaboration:** Access to STAR Lab for CAM integration and external literature access for XRL commercialization review.

Risk Mitigation and Contingencies

- Parallelize CAM and XRL tracks to minimize schedule dependence.
- If fabrication trials delay, proceed with metrology of partial samples.
- If COMSOL licensing is limited, retain Python analytical equivalents for thermal modeling.
- Maintain version control and continuous documentation for reproducibility.

Beamtime Roadmap (Speculative)

- Identify regional synchrotron or compact X-ray facility (e.g., Indus-2, PSI).
- Draft exposure plan: test coupon with 0.1–1 µm features, 2–3 dose levels.
- Measure pattern transfer, resist contrast, and CD fidelity.
- Correlate with simulation results and define next-phase validation.