Materials Design for Attenuating Phase Shift Photomasks

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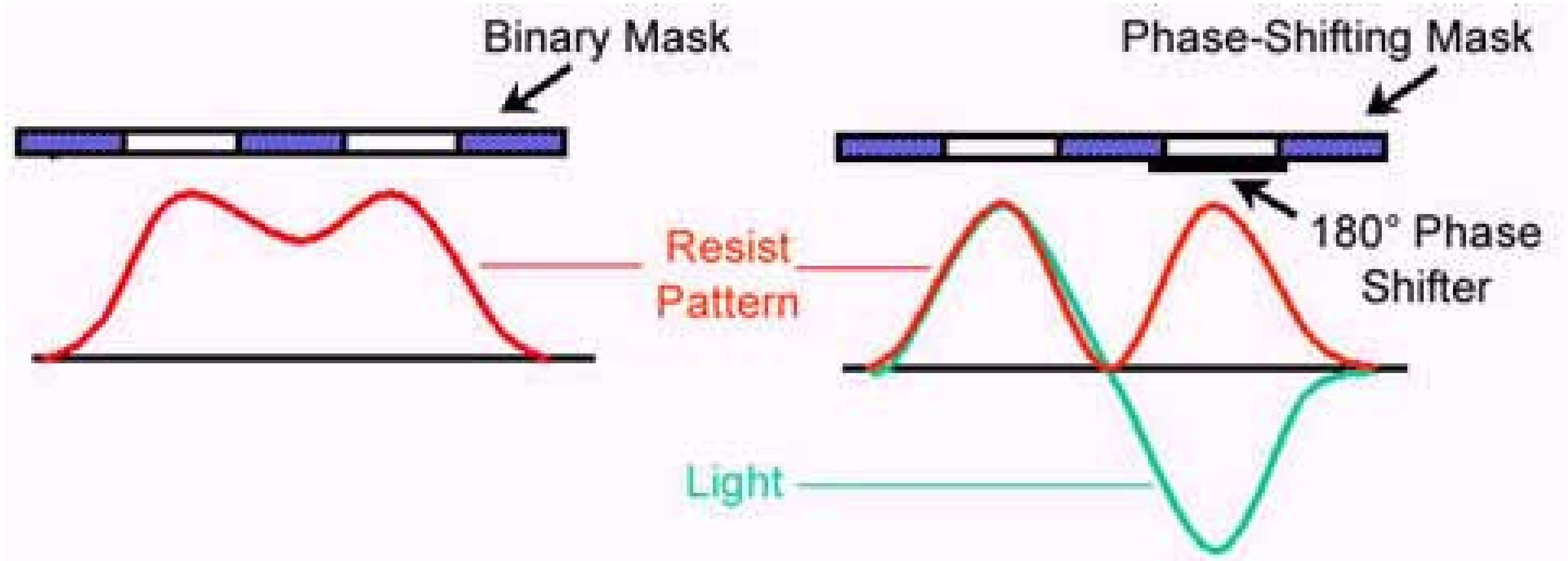
G. A. M. Reynolds, R. H. French, et al., **SPIE Proceedings**, BACUS Sept. 1998.

National Technology Roadmap for Semiconductors:
Available at http://notes.sematech.org/ntrs/Rdmpmem.nsf

Introduction

- Optical Lithography
  - Under goes Continuos Improvements
  - Method of Choice till 2008-11
- Multiple Improvements
  - Shorter Wavelengths
  - Improved Resist Processes
  - Off-Axis Illumination
  - Phase Shift Masks
- Phase Shift Lithography
  - Photomask Not Just Opaque Chrome
  - Important Optical Device
    - Optical Properties
    - Imaging Performance
- Need New Photomask Materials
  - Multiple Requirements
  - Optimized Properties

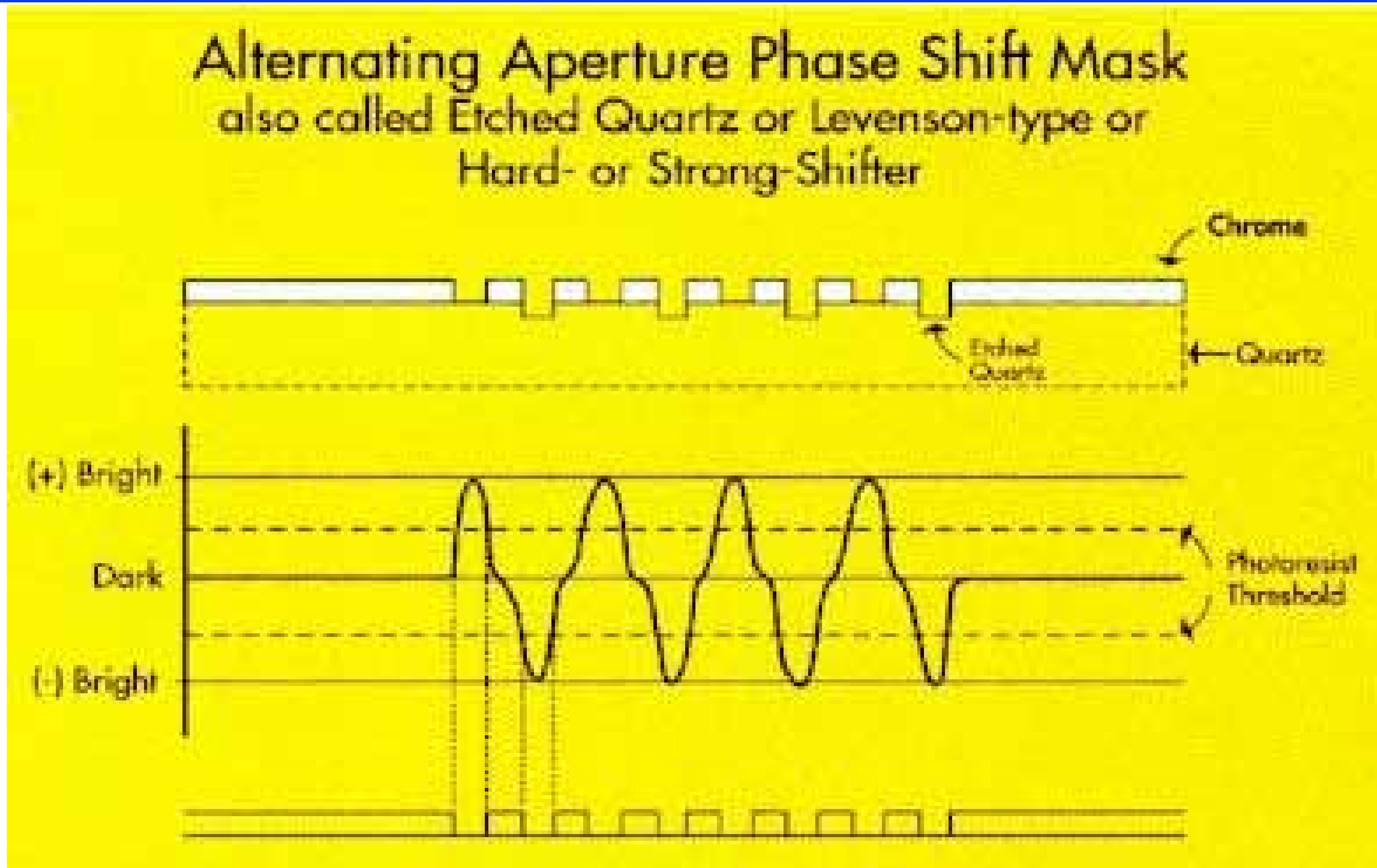
Strong Phase Shift Photomasks



- Phase Contrast Enhancement For Strong Shifters
  - Phase Shifted Light
    - Has Equal Intensity to the Main Line Light
  - Larger Effect Than Weak Phase Shifters Like Att. Phase Shifers
  - But Much More Complex Mask Layout and Manufacturing

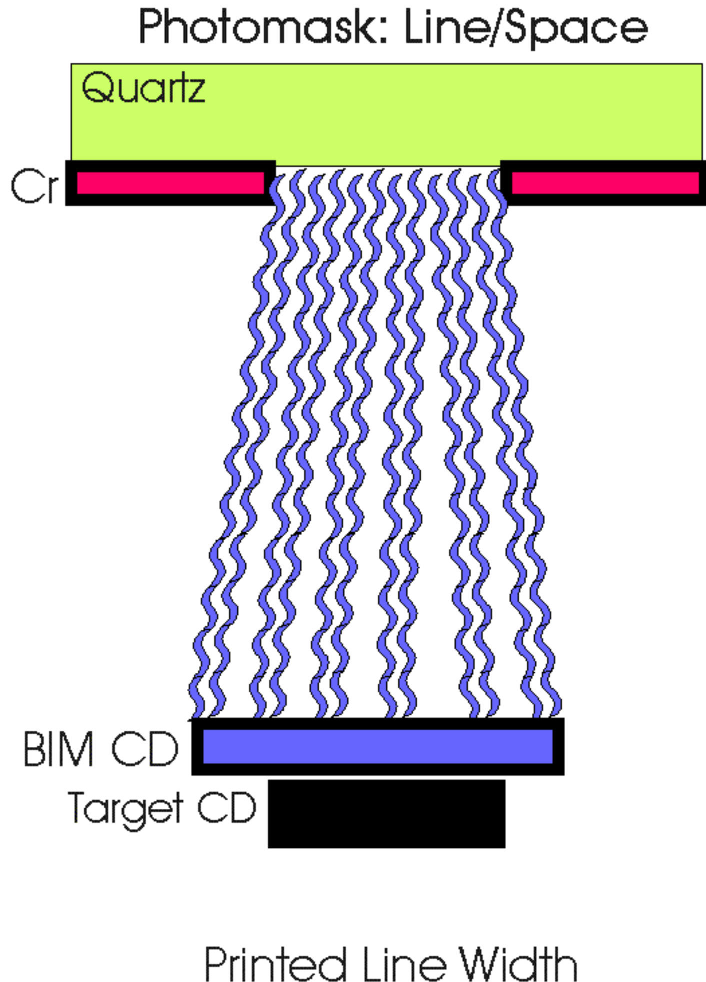
http://www.numeritech.com/

Alternating Phase Shifter Photomasks

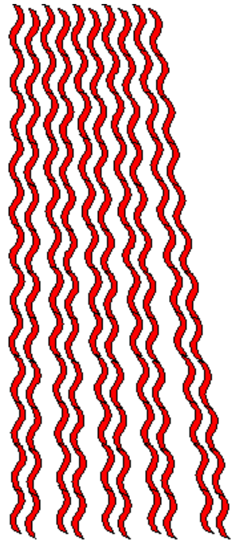
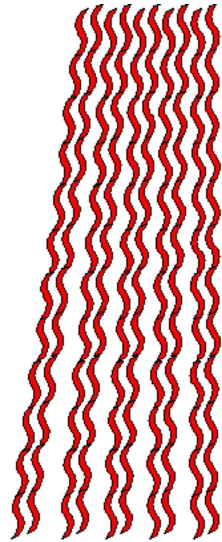


- Alternating Phase Shift Masks
  - A Strong Phase Shift Approach

Attenuating Phase Shift Photomasks

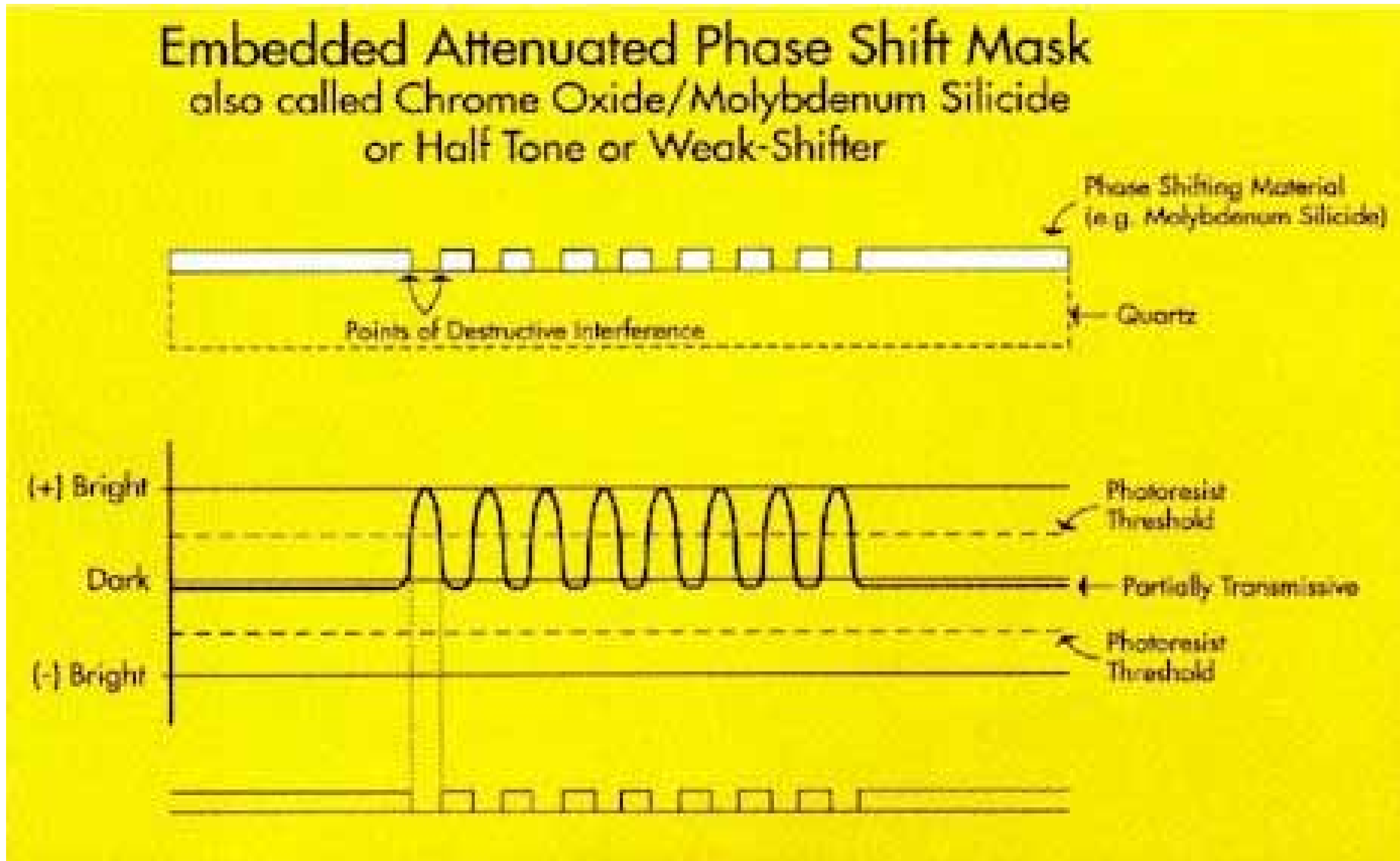


- Phase Contrast Enhancement
  - Compensates for Diffraction
- Attenuating Phase Shifters
  - APS Photomasks
  - Critical Tuning of Optics Required
- Sub Resolution Printing
  - Features < Wavelength of Light
- Improved Depth of Focus
  - Increases Process Latitude
  - Chip Yield

AES CD

Phase Contrast Enhancement



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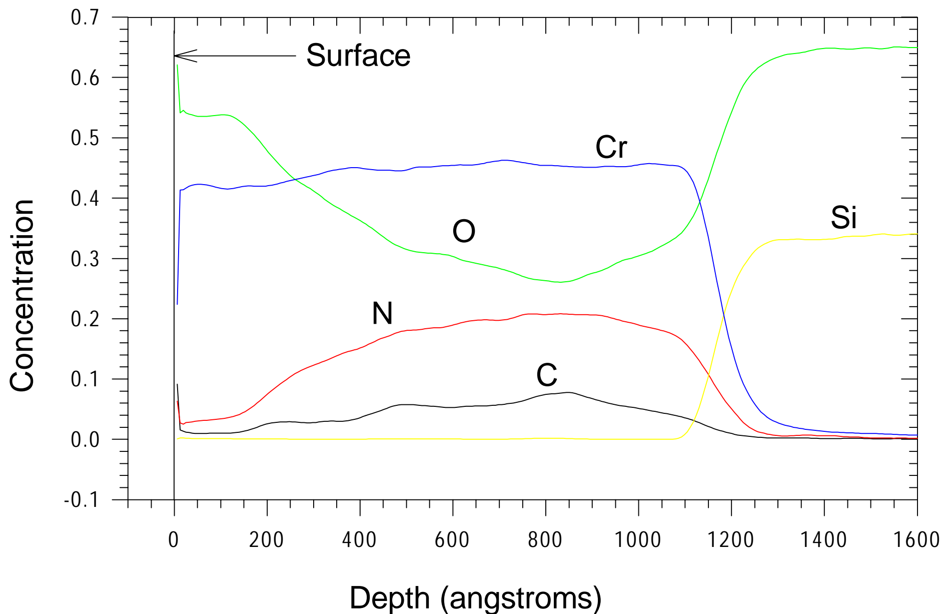
For I-line Graded Layer CrOCN: Optically Inhomogeneous



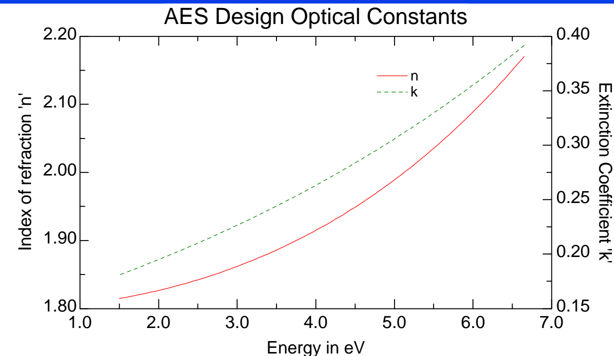
- **For I-line (365nm) Lithography**
- Anion Chemistry of Cr
  - Oxy-Carbo-Nitride
  - Continously Graded Film
- AR from One Side
- Shiny Metal on Other Side
- Micron Scale - Grading of Layer
  - Achieves Arbitrary Optical Properties of Material
  - Directional Reflectivity
    - » Optically Inhomogeneous
  - Also Chemical, Mechanical and Physical Property Control
- Optical Wavefront Engineering

Att. Phase Shift Property Requirements

- **Optical Properties**
  - 180° Phase Shift
  - 9% Transmission
- **193nm Radiation Durability**
  - Mask Lifetime
- **1% Uniformity**
  - 9” x 9” Photoblanks
- **Low Stress, Defect Free**
- **Must Be Manufacturable!**
- **Mask Fabrication**
  - Dry Etch Selectivity
  - Wet Etch Durable
  - Stable for Resist Strip
- **Inspect / Repair**
  - Optical Pattern Inspection
  - Additive & Subtractive Repair
- **Alignment Frames**
- **Die Adjacency Opaquing**
- **High Precision Printing**
  - CD and DOF

Optics of 193 nm Att. Phase Shift Photomasks

- AES Material
  Optical Constants =>

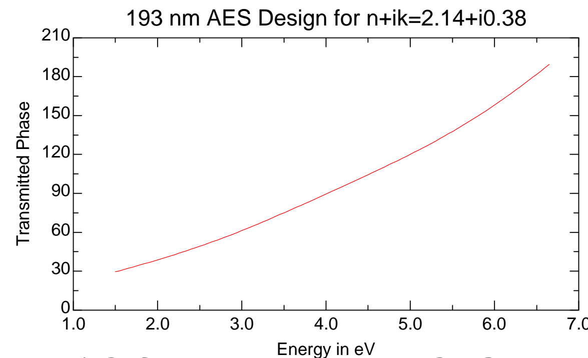


- **Attenuated Embedded Shifter Designs**

193 nm

1	aes-demo	850 Å
0	shinqtz	2.286 mm

- **Attenuated Embedded Shifter Phase Shifts**

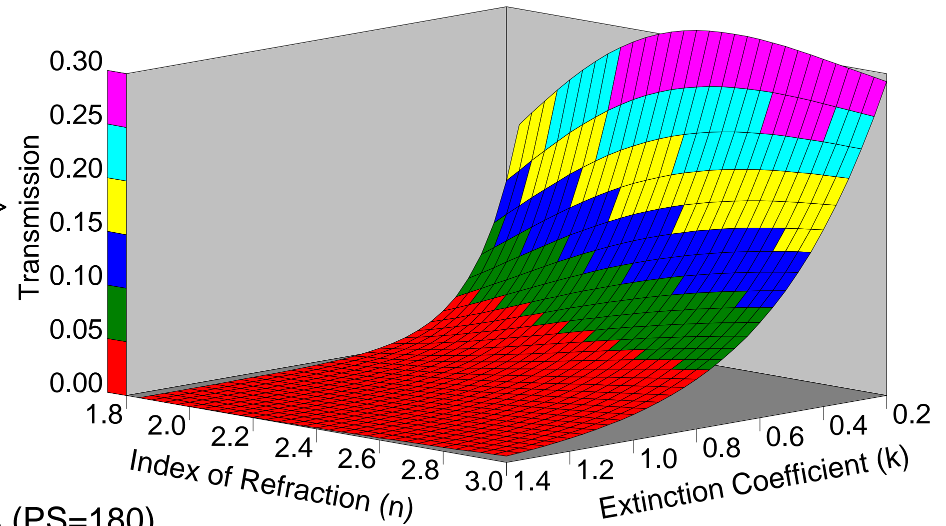


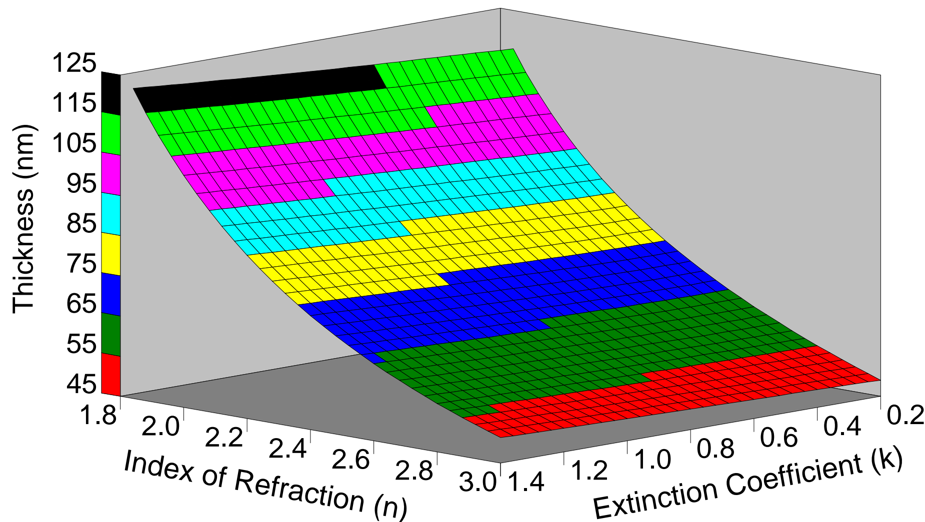
193 Trans. = 9.8%

- **NEED TUNABLE OPTICAL MATERIAL FAMILY**

193nm Att. Embedded Shifter Design Maps

- For 180° Phase Shift
  - AES Transmission =>
  - AES Thickness





MATERIALS DESIGN & PROPERTY OPT.

- **Choose Component Materials**
  - Si_3N_4 & TiN, Al_2O_3 & CrO, Cr-OxyFluorides
- **Choose APS Microstructure**
  - Alloy, Cermet, Multilayer, Graded, Polymer
- **Material + Microstructure = APS Family**
  - Si_3N_4 / TiN ML Film
  - AlN / CrN Alloy
  - $CrO_xC_yN_z$ Graded Film
- **Synthesized/Characterized**
  - 165 New Materials
  - 40 Families: Nitrides, Oxides, Polymers

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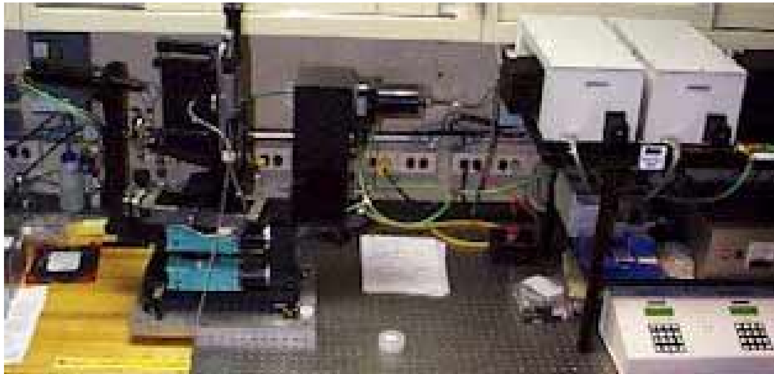
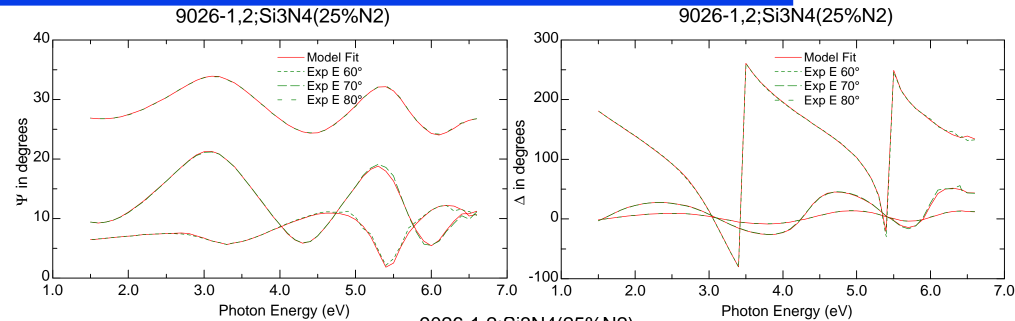
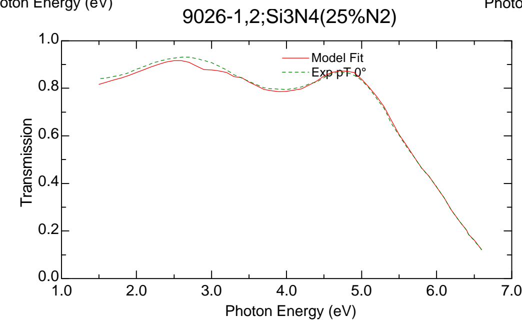
Optical Characterization: Si_3N_4:O

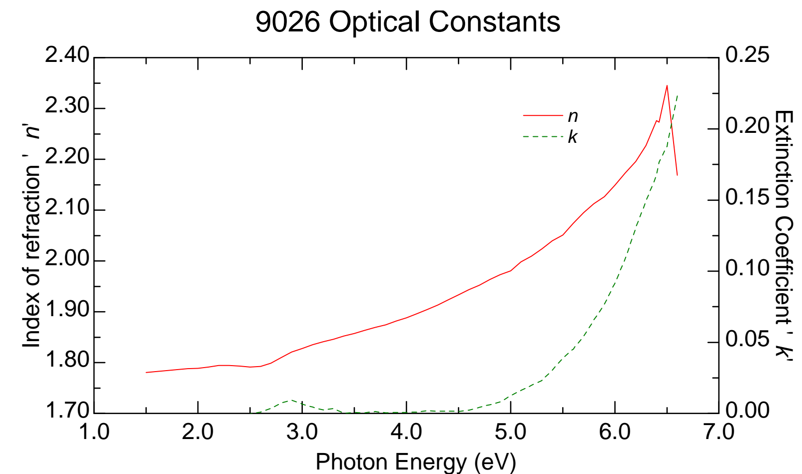






- **Spectroscopic Ellipsometer**
  - 186 nm to 1500 nm
  - MgF_2 Polarizers & Optics
  - Auto Retarder
  - Hg-Xe & Deuterium Lamps
  - 6" x 6" Scanning Stage
    - » Transmission Mapping

4	ema (9026)/50% void	39.62 Å
3	(9026) Coupled to #1	1260.7 Å
2	ema (9026)/50% void	0.11715 Å
1	9026	0 Å
0	shinqtz	2.3 mm



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Materials Screening: Optical Database

Material Family	Structure	Material Family	Structure	Material Family	Structure
Nitride Based		**Oxide Based**		**Polymer Based**	
Cr Nitrides	A	Hf Oxynitride	A	CrC-Poly	Cm
Hf Nitrides	A	Hf Oxides	A	TAF	Pol
Ti Nitrides	A	Cr Oxides	A	TAF/FES,FBS	Pol
Mo Nitrides	A	Zr-Oxides	A	TAF / Cr Flacac	Pol
Nb Nitrides	A	Al_2O_3	A	TAF/FAPS	Pol
W Nitrides	A	Al_2O_3/CrOx	ML	TAF / PolyFAPS	Pol
AlN/Al	Cm	Al_2O_3-Ru	Cm	PhMeSilicate	Pol
AlN/CrN	A	Al_2O_3/RuO_2	ML	Phenan Silicate	Pol
AlN/CrN	ML	HfO_2/RuO_2	ML	PhenanPhenyl Silicate	Pol
AlN/HfN	ML	Ru:SiO_2	Cm	**Carbide Based**	
AlN/TiN	ML	RuO_2/ZrO_2	ML	Cr Carbide	A
AlN/MoN	ML	Ru Oxides	A		
AlN/NbN	ML				
AlN/W_2N	ML				

- Materials Screening Program
  - Three Patent Applications

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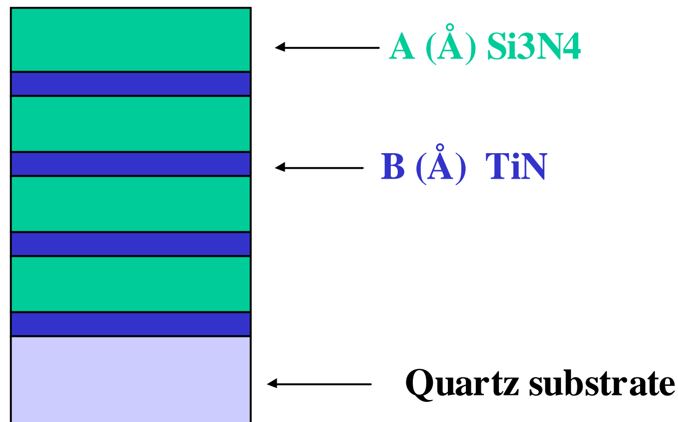
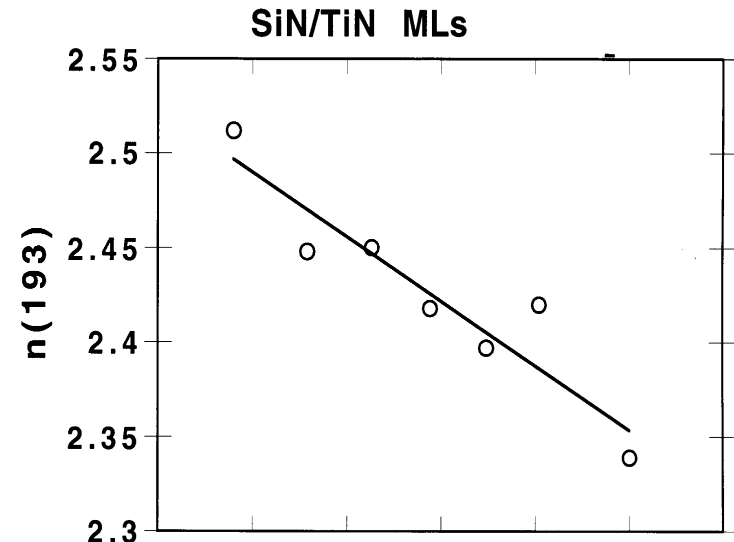
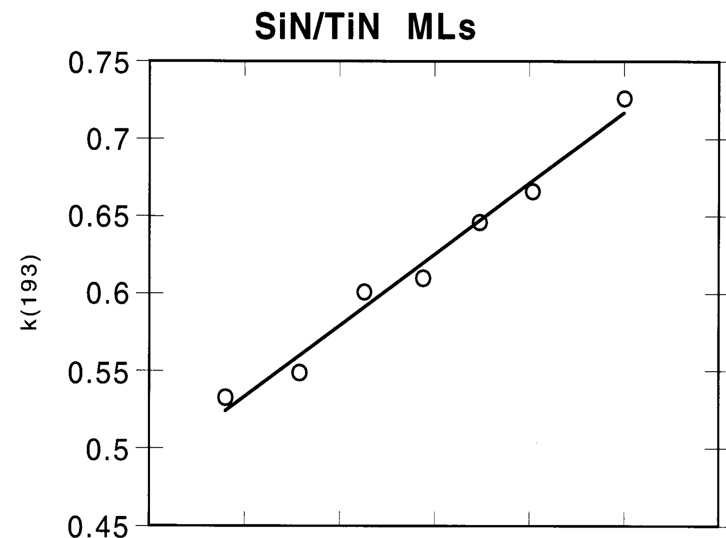
Multi-Layers: Optically Homogeneous

Si_3N_4/TiN Optical Superlattices



- Nano Scale - Multilayering
  - Tunable Optical Properties
  - Arbitrary Optical Constants
  - Optically Homogeneous
    - Like a Uniform Material
- Also Chemical, Mechanical and Physical Property Control





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Advantages of Optical Superlattices

- Tailoring of optical properties (i.e. chemistry)
  - is by control of layer thickness.
- Sputtering conditions with broad process latitude.
- Simplicity of elemental metal sputtering targets
- Thin layers---> uniform etching;
  - better radiation stability at 193 nm.
- Chemically stable layers can be selected
  - with attractive etch properties.
- Metallic layer reduces resistivity
  - and decreases transmission for inspection.

Optically Tunable Materials: Applicable to 248 nm APS

- SiTiN Family Can Make 193 nm and 248 nm APS
  - High and Low Transmissions
  - Inspectable at Various Wavelengths
- Flexible Materials Family

Table 1. Inspection transmission at various inspection wavelengths for 6 % and 9% transmission 193 nm APS photoblanks and a 9% transmission 248 nm APS photoblank.

	Lithographic Wavelength		**Inspection Wavelength**		
	193 nm	**248 nm**	**248 nm**	**365 nm**	**488 nm**
High T 193 nm	10%		35%	62%	70%
Lower T 193 nm	6%		22%	44%	60%
High T 248 nm		14.4%	14.4%	36%	61%

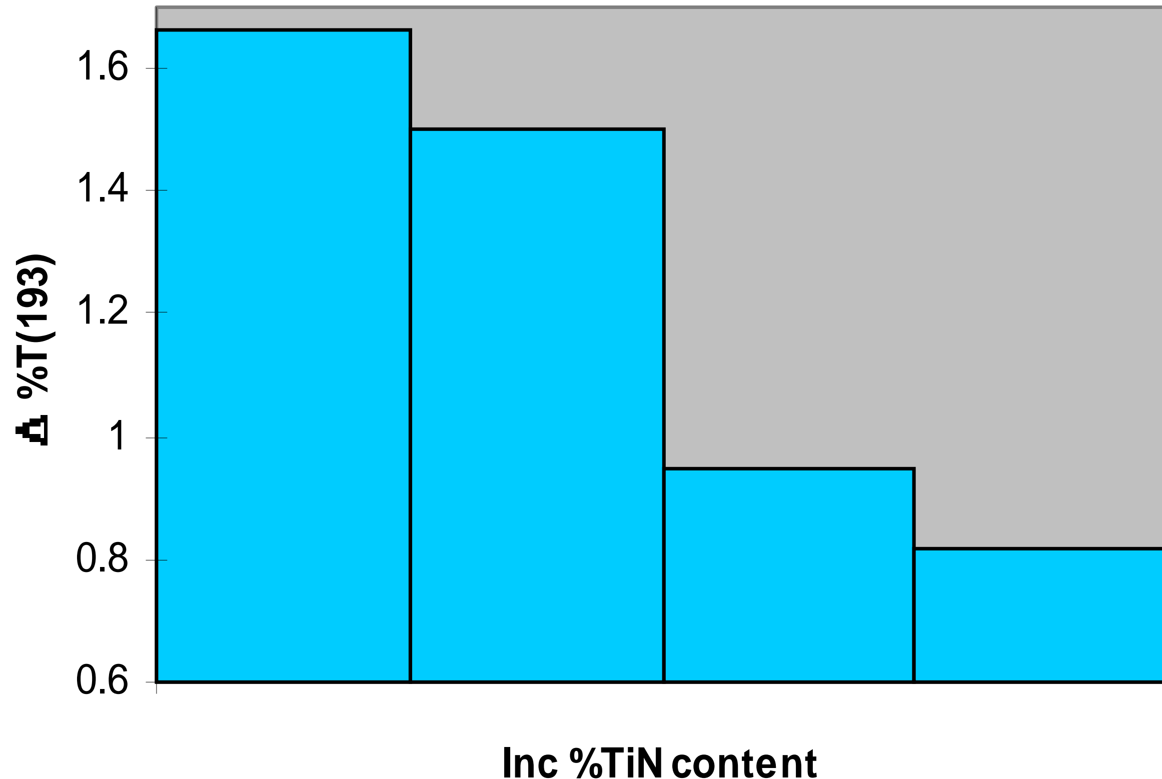
Optics Summary

- SiN/TiN Multilayers
  - Flexible Materials Family
  - Very Reproducible
  - High Uniformity
- Produce High Transmission 193 nm & 248 nm APS
- Inspectable 193 nm APS
- Lithographic Printing Performance Evaluations

Accelerated and Marathon Radiation Durability

- Masks Have a Long Lifetime
  - 3 to 6 Months of 24 hours a day Exposure
  - 5 kJ Dose at 193 nm
- Radiation Durability Essential
- Increase Radiation Durability
  - TiN content
  - Bi-layer dependence
  - Stacking order

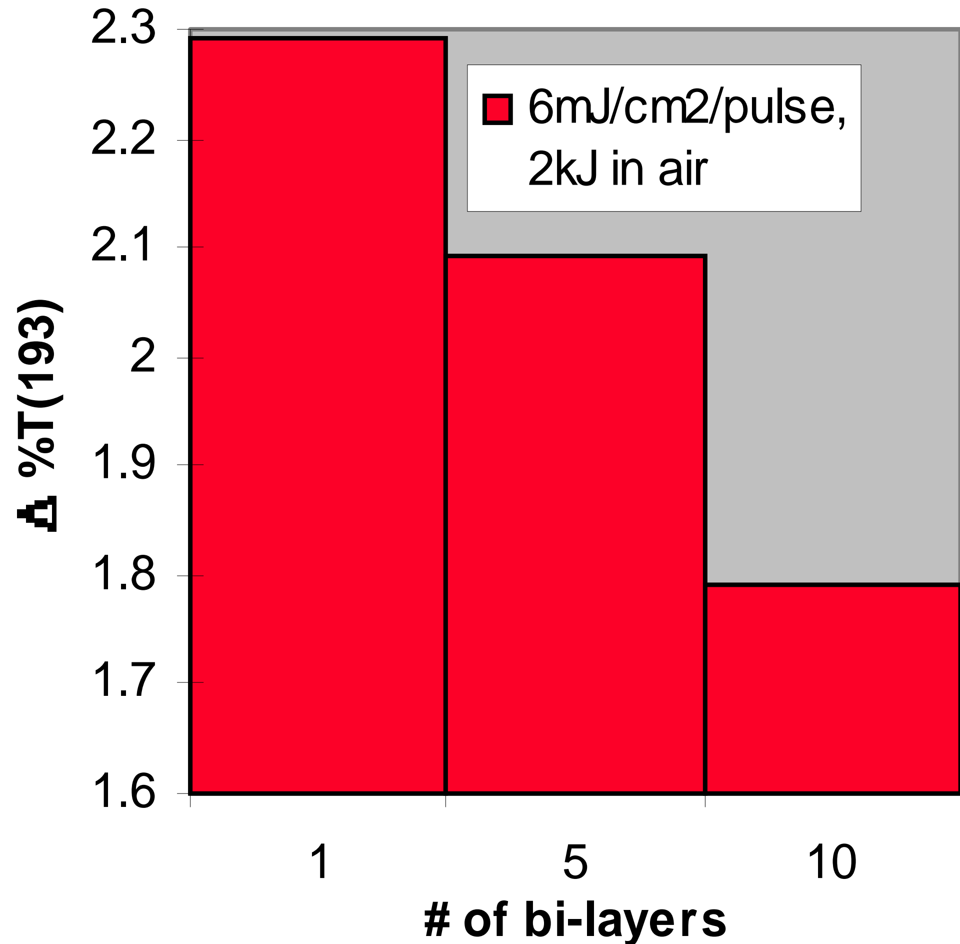
Increasing Radiation Durability: TiN Content



- Vary %TiN
  - in Si_3N_4/TiN
- Increase amount of TiN
  - increases radiation durability

Increasing Radiation Durability : Bi-Layer Dependence

- Change number of bi-layers
  - in TiN/Si_3N_4 MLs, fix %TiN
- Increase number of bi-layers
  - increase radiation durability



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Radiation Durability of Si_3N_4/TiN ML APS Blanks

- Criteria for success
  - Transmission remains at 9% +/- 0.5%
  - Phase shift remains at 180° +/- 2°

- Single component Si_3N_4 is not Radiation Durable

- Multilayer APS Films
  - Designed For Enhanced Radiation Durability
    - » ML stacking order important
    - » Chemical Composition of ML Components Important

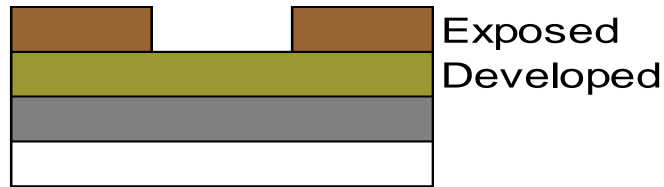
193nm APS Blank For Fugitive Chrome Mask Process

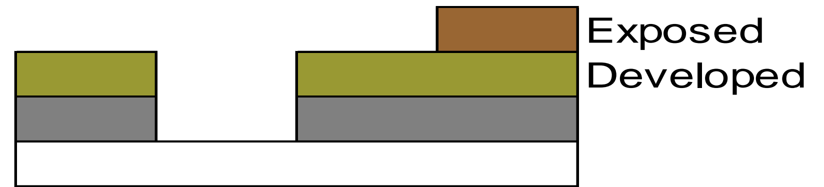
- 193 nm APS for Fugitive Chrome Mask Process
  - 193 nm APS Film With Top AR Chrome Film
- e-beam Writeable
  - without Charging
- Easy Inspection of Chrome Level
- Hard Cr - Dry Etch Mask
  - Avoids Resist Etch Selectivity
- Stable in Wet Chrome Etchants
- Allows Opaque Alignment Frame
  - Die Adjacency Opaquing
- Also Compatible with Tri-Tone APS Mask Designs
  - » Use Chrome Features, APS Features and Clear Features

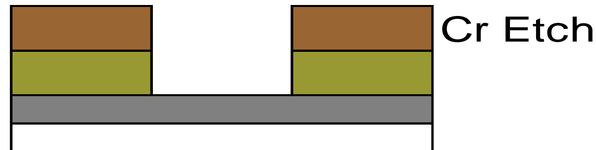
Fugitive Chrome Mask Fabrication Process

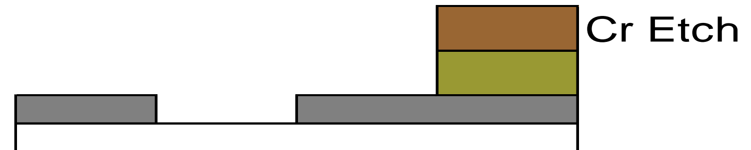
1 st Level

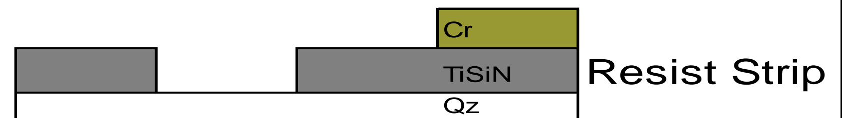
Second Level











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Chemical Durability of APS Films

- **CR-7 : Cr Etchant**
  - Room temperature
- **H_2SO_4**
  - 80°C
- **Nano-Strip**
  - 80°C
- **NH_4OH**

- SiN/TiN ML APS Films Durable
  - 120 minutes in Nano-Strip
  - 120 minutes in concentrated H_2SO_4
  - 20 minutes in CR-7
  - NH_4OH rinsing

- Compatible with a Fugitive-Cr Mask Process

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Dry Etch Mask Process for Si_3N_4/TiN ML APS Blanks

- PlasmaTherm ICP Etcher
  - 250 or 500 Watts ICP, Variable Watts of RIE
    - » Low RIE Power Enhances Chemical Etch

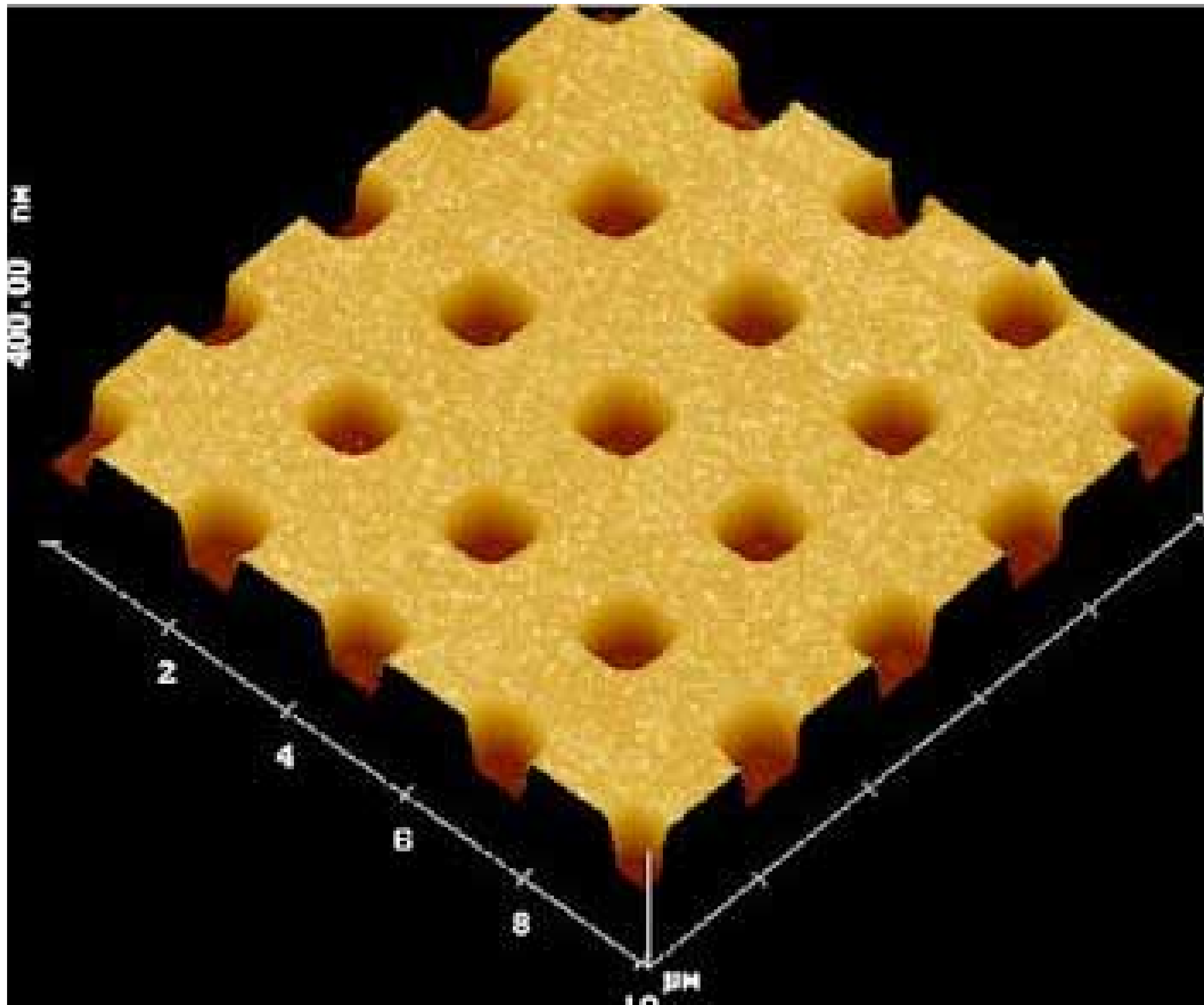
- Etch Processes: SF_6+He, CF_4+He
  - Variables: RIE Power and Etch/Diluent Gas Ratio

- Dry Etch Process
  - CF_4 ICP 250 Watt Etch
    - » 100% 50 Watt RIE
    - » 20% 15 Watt RIE

Dry Etch Process Summary

- Low RIE Provides Best Selectivity to Qz
- High RIE Provides Best CD Undercut
- CF_4 Provides Best Selectivity and Roughness
- Fabricate Masks with a 2 Step Process
  - 80% High RIE - Produce Low Undercut
  - 40% Low RIE - Produce Good Qtz Selectivity

AFM Mask Images



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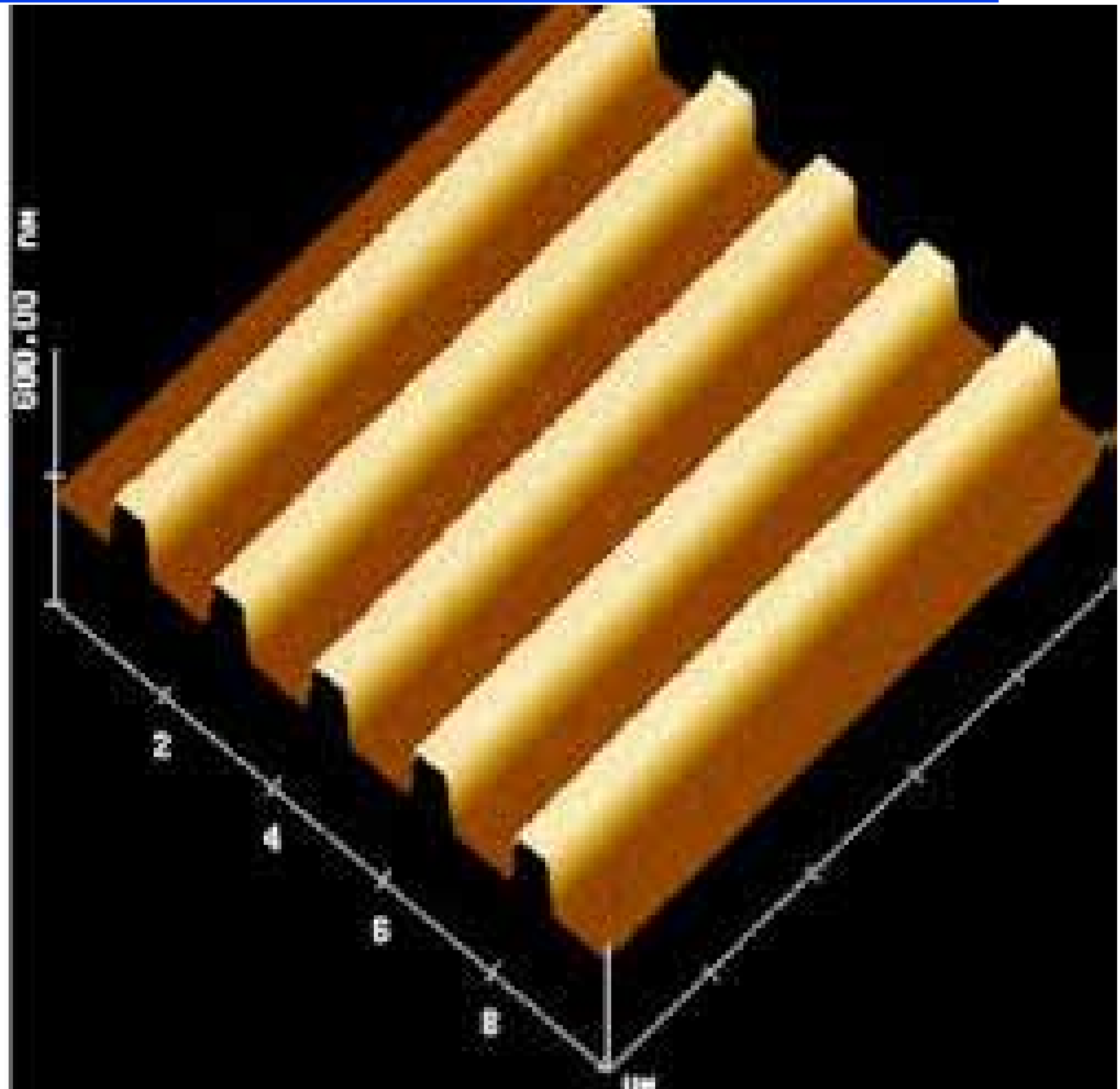
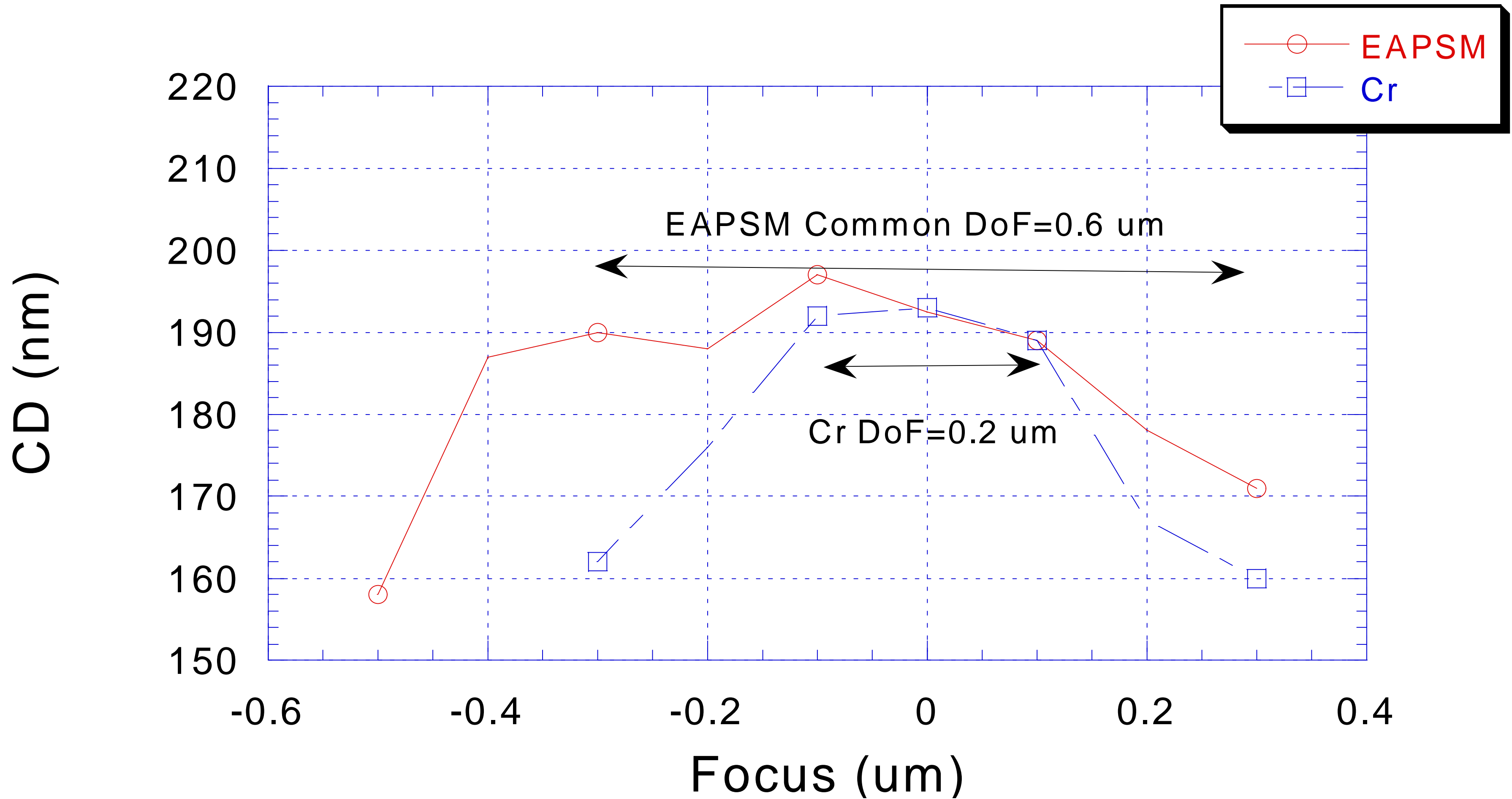
AFM Mask Images



193 nm ISI Printing Performance



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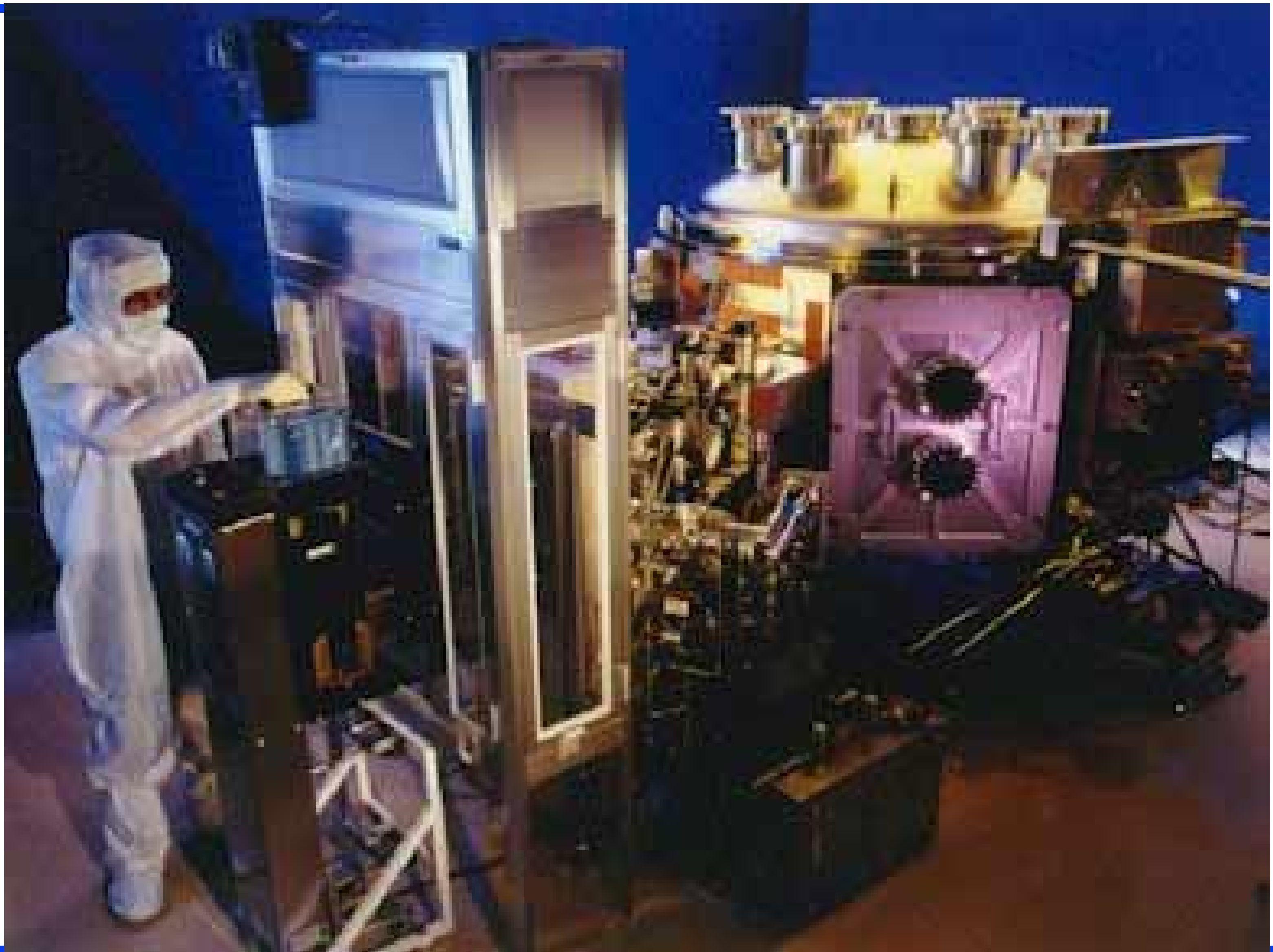
Veeco LLNL Ion Beam Deposition Tool



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Conclusion

- **Phase Shift Lithography**
  - Phase Interference Contrast
  - Achieve Sub Resolution Printing
  - Extensible to 157 nm
- **Materials Design**
  - Multiple Property Optimization
    - » Optical
    - » Mechanical
    - » Wet and Dry Chemical Etch
    - » Radiation Durability
- **Based on**
  - Tunable Optical Materials
  - Multilayer Microstructure