Direct-write fabrication of phase-shifting mask to characterize optical lithography illumination

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EE290B Class Project
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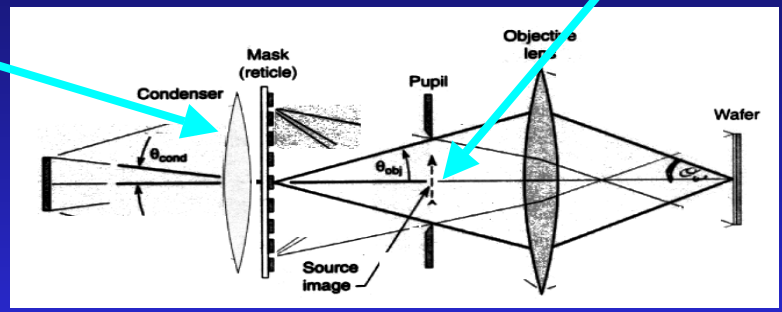
Outline

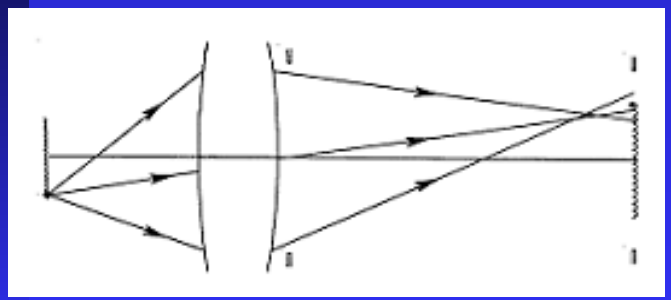
- Linear phase grating – concept & motivation
- Mask Fabrication Requirements
- Experiment and Results
- Discussion
- Conclusion

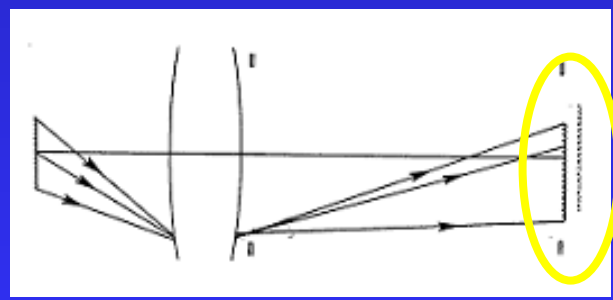
Variations in illumination angular distribution (pupil fill)

Condenser lens designed to create image of source in objective lens pupil



Impact of condenser lens aberrations is to shift or skew pupil-fill

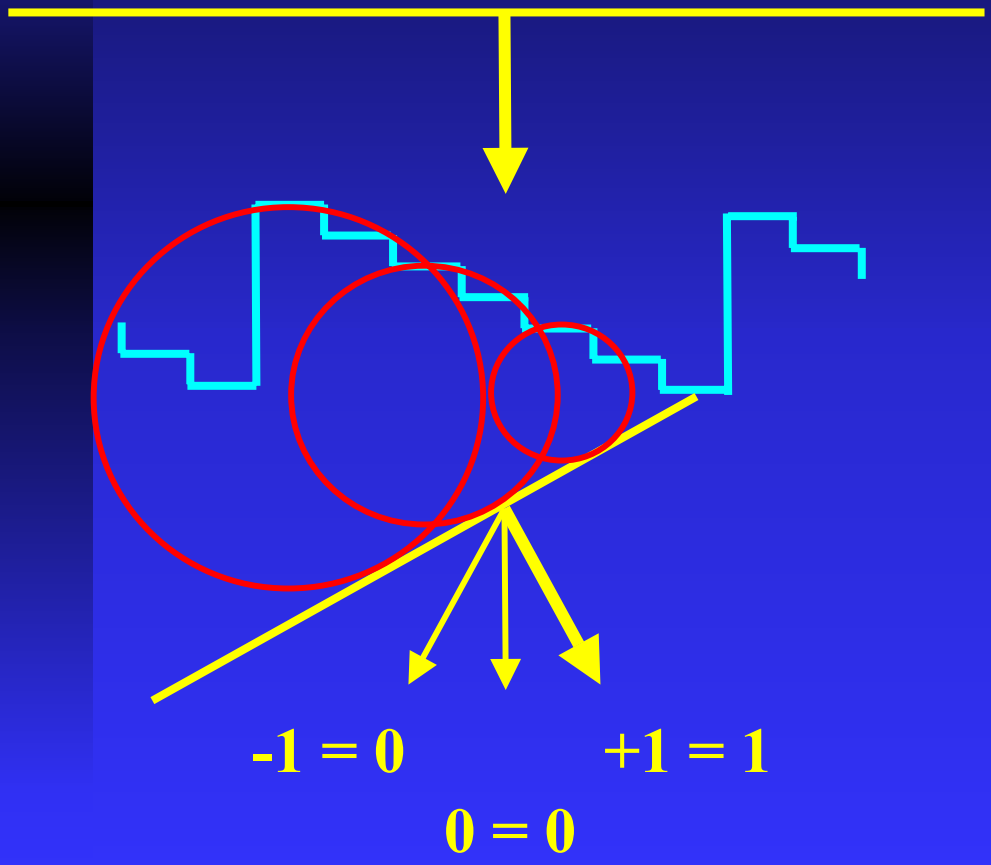


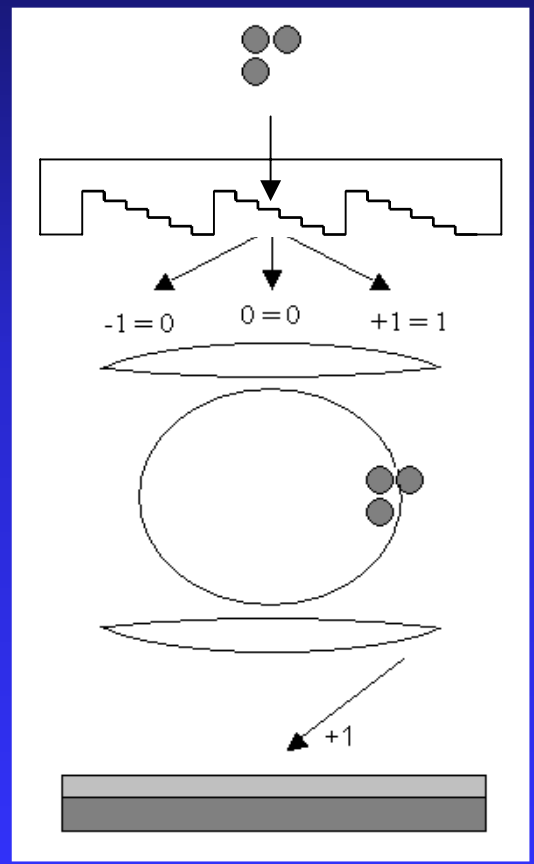


Measurement of actual pupil-fill is needed

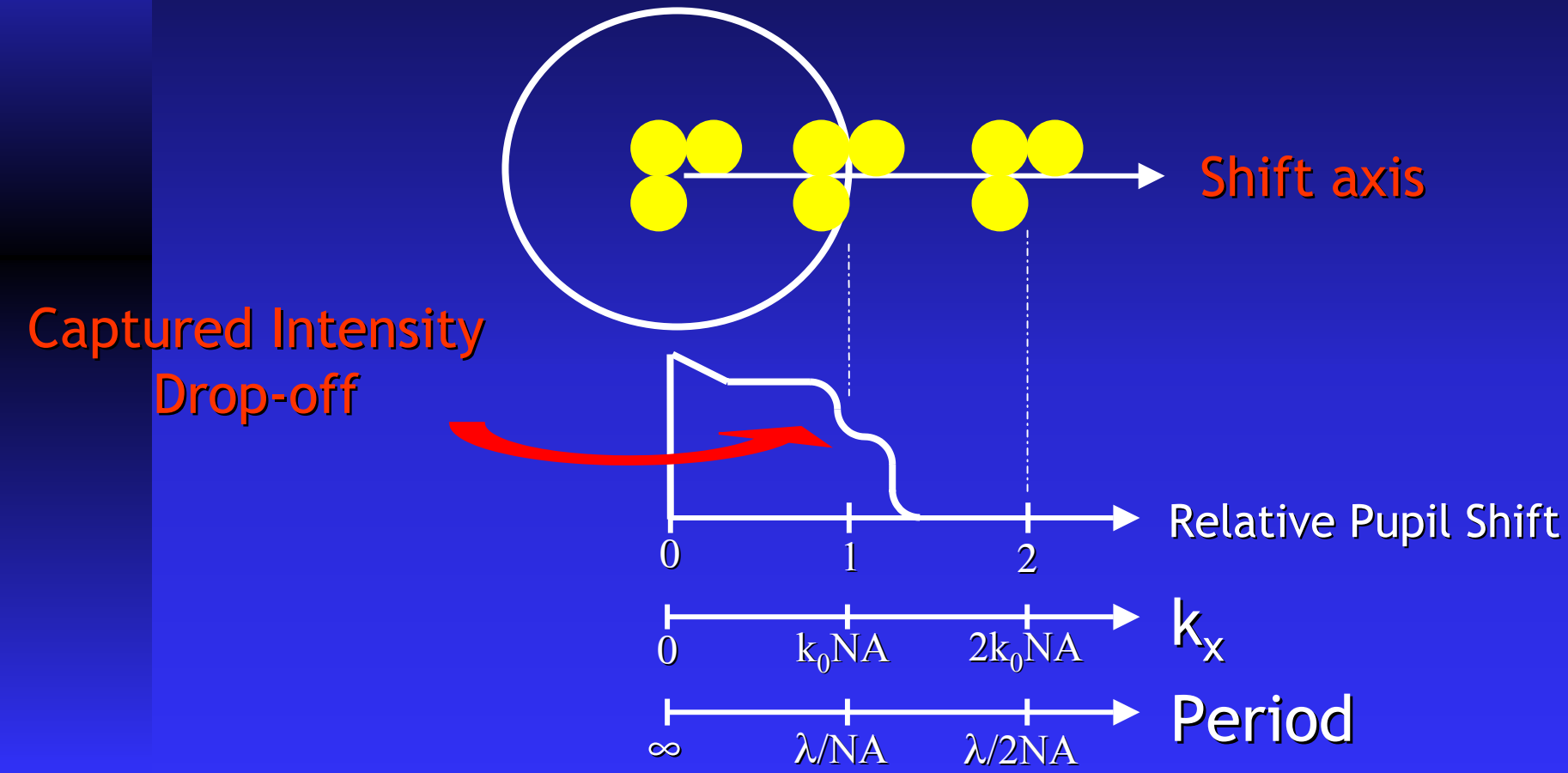
Concept: Linear Phase Grating

Selective diffraction at angle determined by period:





Monitor Pupil Fill with Multiple Linear Phase Grating Periods

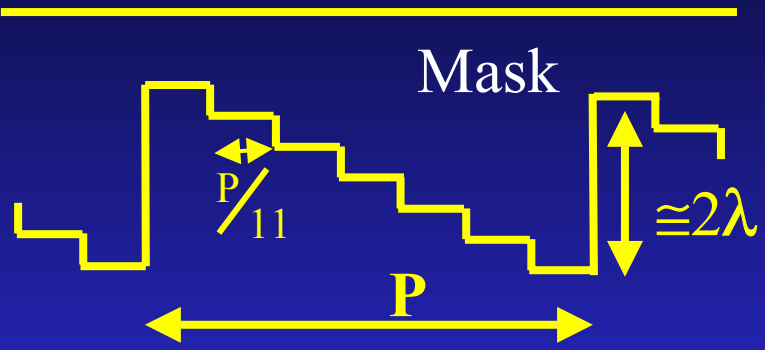


Mask Requirements

$$P = \frac{M\ \lambda}{\Delta r\ NA}$$

Δr = Relative Pupil Shift

P = Grating Period



Pupil shift	0.7	1	1.3	1.6
Period (nm)	3540	2480	1910	1550
P/11 (nm)	322	226	174	141

Mask Fabrication Options:

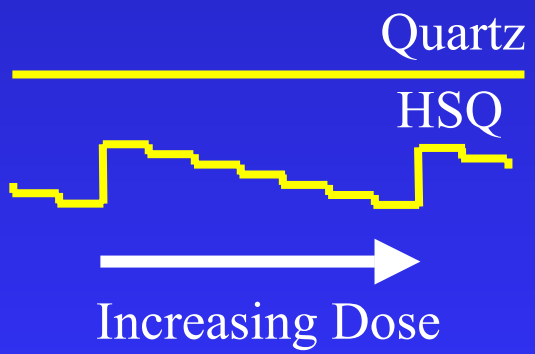
- Conventional Litho and Etch ($S = 2^N$)
  (S = # phase steps, N = # Litho steps)
- Direct write in photoresist

Mask Fabrication: Direct-write in HSQ

Why HSQ?

- Previous work (EUV gratings)
- Flowable oxide
- 1-step direct write process
- Negative photoresist behavior
- Low surface roughness
- Stability after development
- optical properties (?)

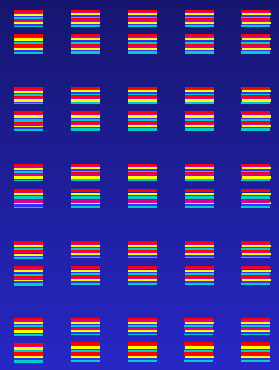
How?

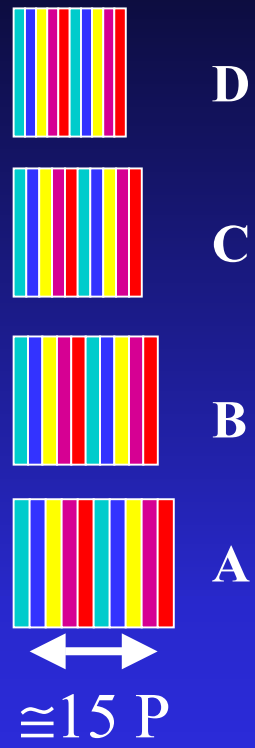


- 1 min prebake
- Spin on HSQ (pure FOX 15)
- 5 min bake @ 170°C
- 10 sec Chill
- Expose
- Develop in Ldd26

Experimental Procedure

- Layout – 4 gratings per set
- 5x5 array of grating sets
- Increase base dose between sets
- Dose range w/in grating period
- 3 exposure trials
- HSQ thickness ≅ 500nm
- Measure profile with AFM



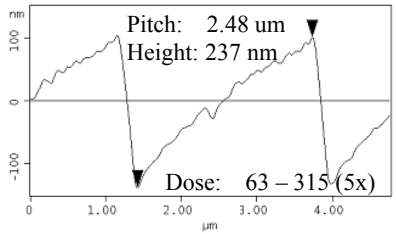


	Trial 1	Trial 2	Trial 3
Base Dose (D_B) (uC/cm^2)	200	25	25
Base Dose increment (ΔD_B)	6%	8%	6%
Dose Range (R) (uC/cm^2)	1 to 5 x	1 to 5 x	1 to 10 x
HSQ thickness (t) (nm)	557	455	470

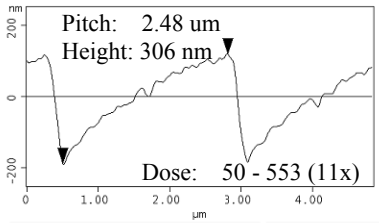
Grating ID	A	B	C	D
Pupil shift	0.7	1	1.3	1.6
Period (nm)	3540	2480	1910	1550
P/11 (nm)	322	226	174	141

Experimental Results

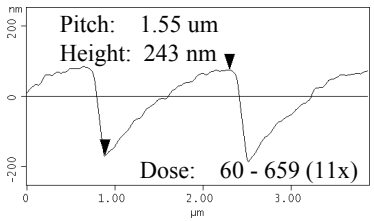
a) Grating 13b Trial 2



b) Grating 13b Trial 3



c) Grating 16d Trial 2



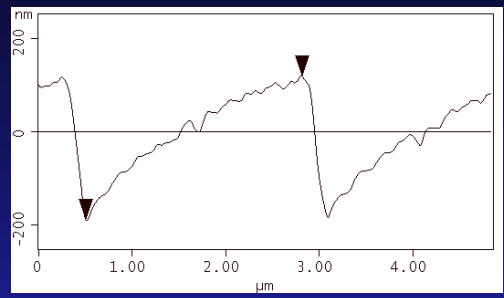
Grating ID	Pitch (nm)	Start dose (uC/cm^2)	End dose (uC/cm^2)	Height (nm)	Slope (deg)	Sidewall slope (deg)
Trial 2:						
1a	3540	25	125	bottom did not clear		
1d	1550	25	125	bottom did not clear		
8a	3540	43	214	230	4.0	42.6
8d	1550	43	214	200	8.1	53.1
13b	2480	63	315	240	6.1	43.8
16a	3540	80	397	250	4.4	42.8
16d	1550	80	397	225	9.3	52.9
25a	3540	160	792	top 1/3rd overdosed		
25d	1550	260	792	top 1/3rd overdosed		
Trial 3:						
8a	3540	38	413	340	6.1	42.7
8d	1550	38	413	290	12.2	54.1
13b	2480	50	553	300	7.8	46.7
16a	3540	60	659	310	5.5	44.1
16d	1550	60	659	top 1/3rd overdosed		

Target = 451nm

Target = 16°

Target = 90°

Discussion



- Resist height not linear with dose
- Period influences max height
- Dose gradient Change ≠ Physical Gradient Change
  (Example: grating 8a: 119% dose grad inc = 45% slope inc
  grating 8d) 119% dose grad inc = 48% slope inc
- Roughness – not bad, but may add flare
- HSQ designed for semiconductor interlevel dielectric, not steep profiles (flowable)

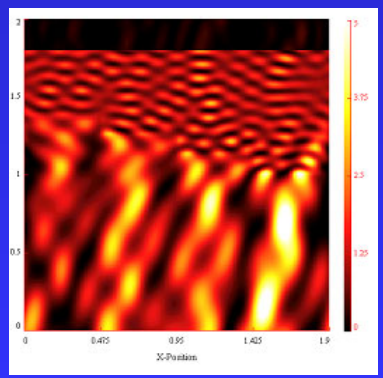
Future Considerations

Not ruled out yet…

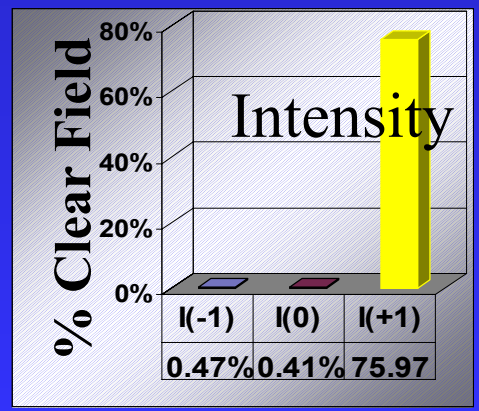
- Potential improvements by: process temperature, other HSQ solutions, current, voltage, other resists

But.. If it works:

- optical properties (n & k) – electromagnetic performance?
- quartz substrate charging effects
- compatibility with stepper (out gassing, mechanical stability)

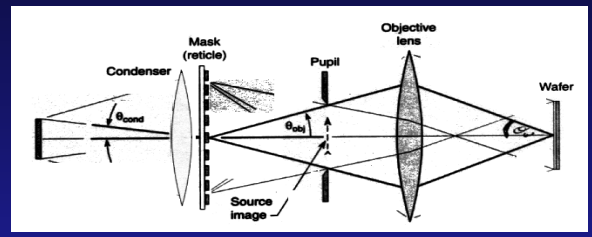


Near Field Simulation

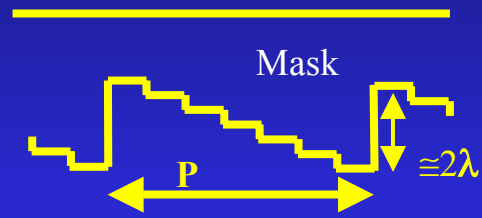


Conclusion

- Motivation: Measure ‘pupil-fill’



- Experiment



- Results: Direct-write in HSQ ?
  - many hurdles yet to overcome
  - feasibility remains unclear