Solid Immersion and Evanescent Wave Lithography at Numerical Apertures > 1.60

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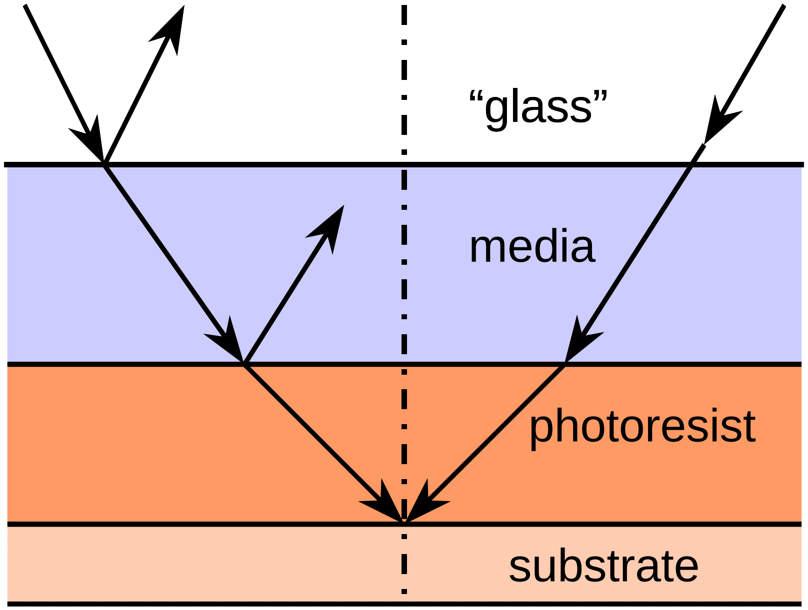
Outline

- The imaging limits of materials
- Pushing the limits of immersion lithography
- The solid immersion lens
- Solid immersion lithography (SIL)
- Evanescent wave lithography (EWL)
- Imaging 26nm at 1.85NA

Material and Optical Limitations

$$NA = n_i \sin \theta$$

1. Sin θ increases slowly at large angles (*sin 68°=0.93*)
2. Hyper-NA will be forced upon material refractive index
3. Resolution will become a function of the lowest index (fluid, optics, photoresist).

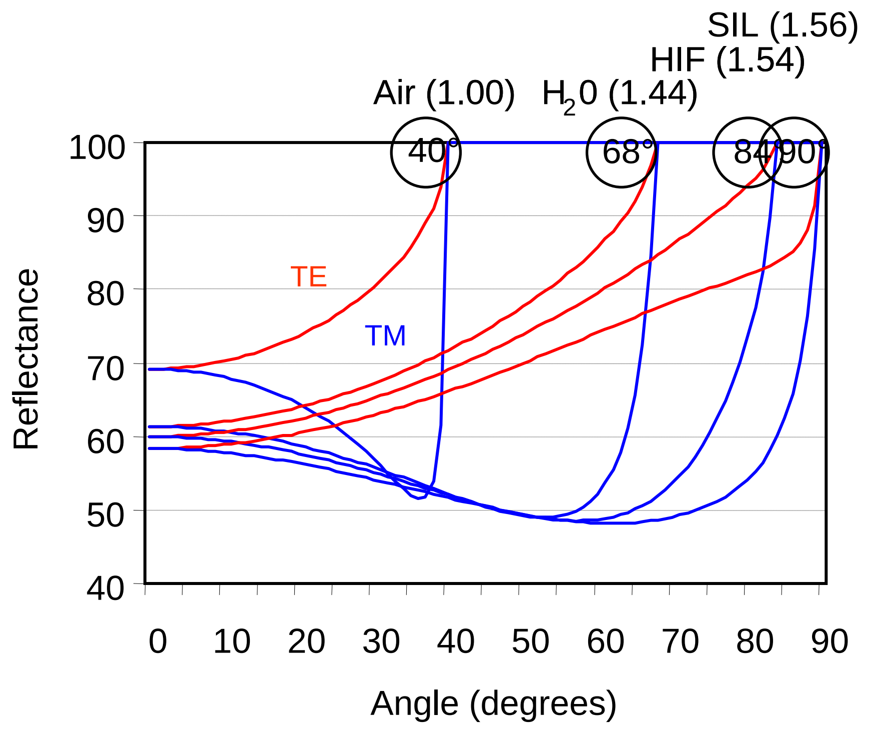


$$\boxed{hp_{min} = \frac{k_1 \lambda}{n_i \sin\theta}} = \frac{(0.25 \text{ to } 0.30)(193nm)}{n_i(0.93)} = \boxed{\frac{52}{n_i} \text{ to } \frac{62}{n_i}}\ nm$$

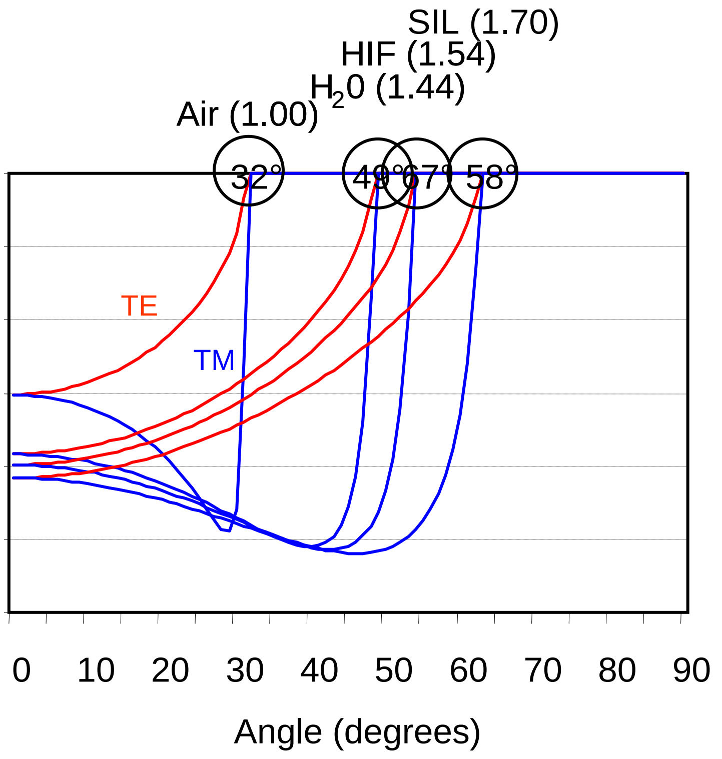
Technology Limits in Media

TIR from Snells' Law:

$$\theta_c = \sin^{-1}(n_L/n_H)$$



Fused silica (n=1.56)



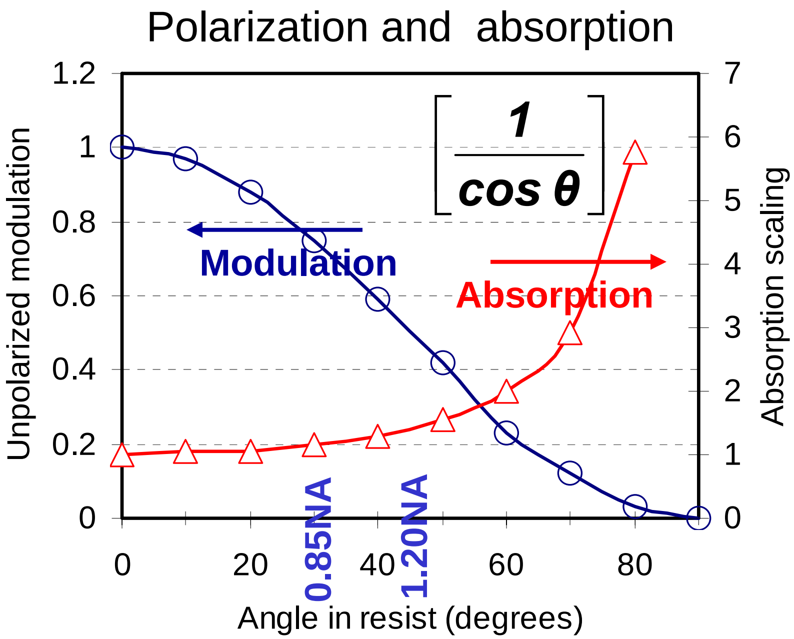
Sapphire (n=1.92)

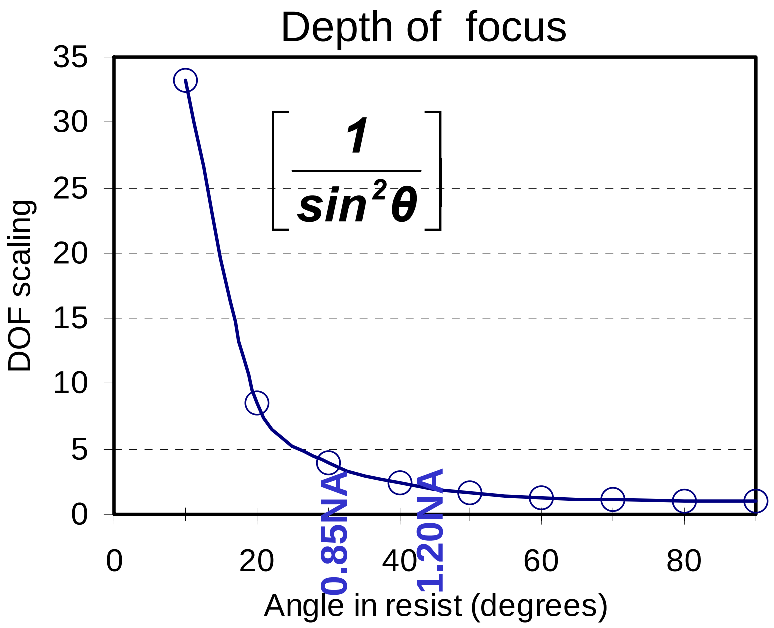
Technology Limits in Media

		Numerical Aperture							
		1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
Half-Pitch (nm)	*k1=0.25*	37	34	32	30	28	27	25	24
	k1=0.30	45	44	39	36	34	32	30	29
Angle in media	*Water (1.44)*	65°	76°	🟥	🟥	🟥	🟥	🟥	🟥
	HIF (1.55)	57°	65°	75°	🟥	🟥	🟥	TIR	🟥
	HIF2 (1.65)	52°	58°	65°	76°	🟥	🟥	🟥	🟥
	Photoresist (1.70)	50°	55°	62°	70°	🟥	🟥	🟥	🟥
	HI PR (1.85)	45°	49°	54°	60°	67°	77°	🟥	🟥
	Fused silica (1.54)	58°	65°	77°	🟥	🟥	🟥	🟥	🟥
	Sapphire (1.92)	43°	47°	52°	56°	62°	70°	🟥	🟥

Impact of Angle in Photoresist

Simple Approximations

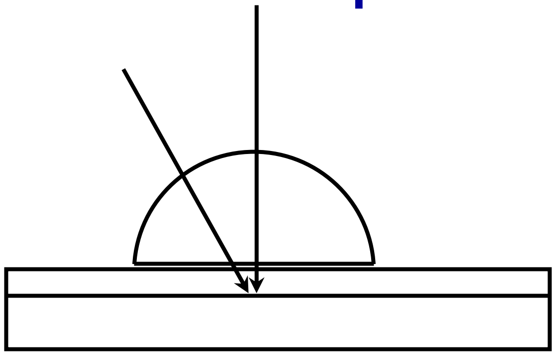




- ➢ Oblique absorption requires low k photoresist
- ➢ Paraxial DOF scales with $1/\sin^2(\theta)$
- ➢ Angles above 30° (0.85 NA) require attention
- ➢ Oblique reflection becomes an issue > 30°

A Solid Immersion Lens

- A high index solid immersion lens is placed in close proximity to an image plane
- “Dry imaging for NA values > 1.0
- Used in optical storage applications



- Energy coupled into the thin film decays exponentially:

$$A(z) = e^{-\left(\frac{2\pi n_{upper}}{\lambda}\left[\sin^2\theta - \left(\frac{n_{lower}}{n_{upper}}\right)^2\right]^{1/2} + \alpha\right)z}$$

n_{upper} = lens

n_{lower} = air

z = gap

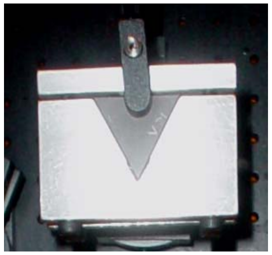
Solid Immersion Lithography

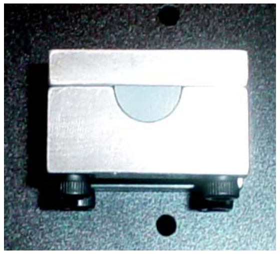
Sapphire SIL Breadboard

Sapphire Properties:

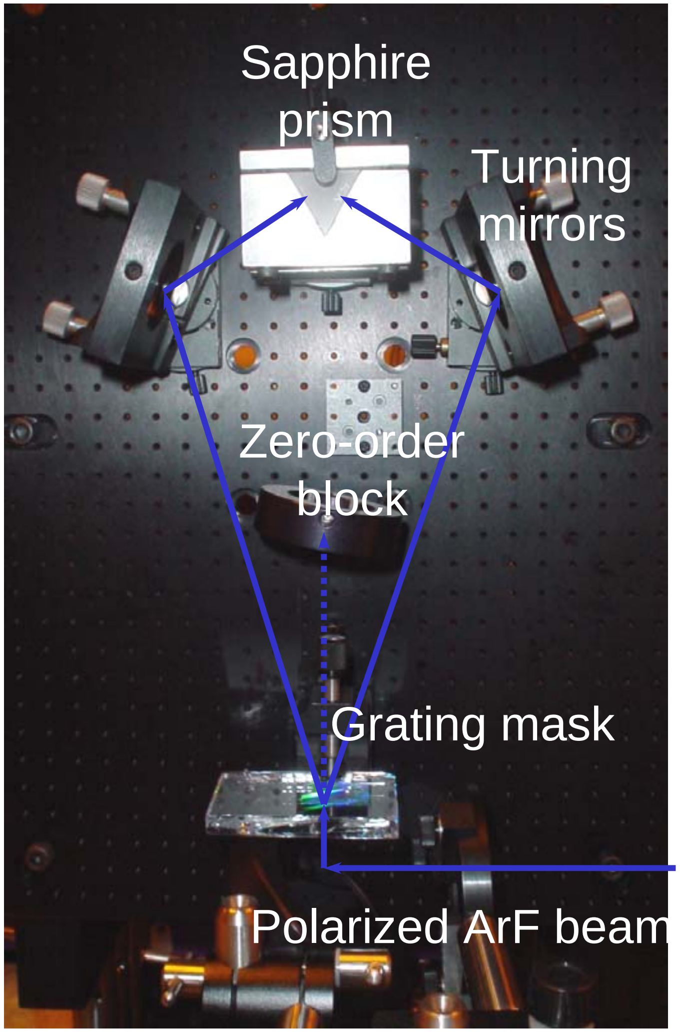
- Hexagonal, single-crystalline Al_2O_3
- n = 1.92, birefringence ~$8x10^{-3}$
- Equilateral prism at 60° is 1.67NA
- Designed for NA 1.05~1.92
- MgF_2 is ideal AR layer

prism





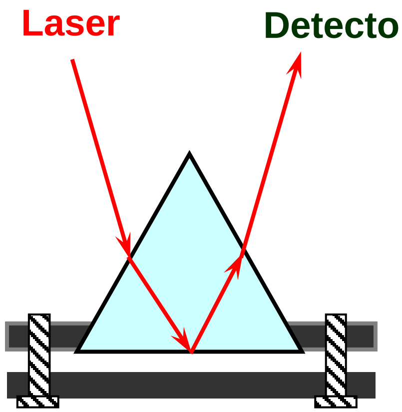
cylinder



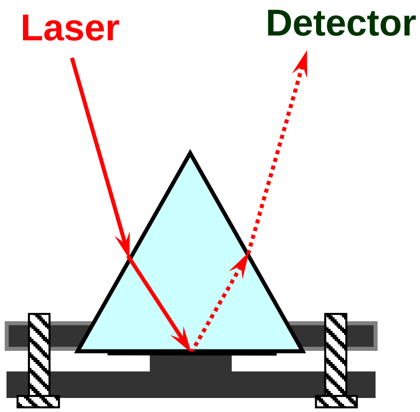
Challenges:

- Gap and gap control
- Birefringence
- CAR resist diffusion length limit
- Resist/BARC process optimization

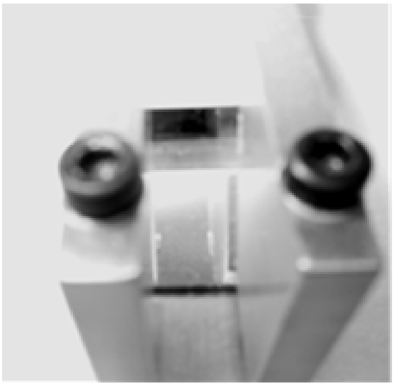
Optical Coupling in the Prism



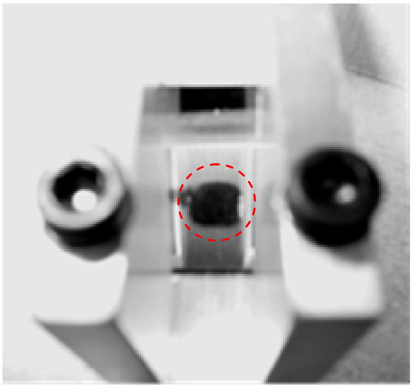
(a) Baseline (no wafer).



(b) Reflection (with wafer).



(a) Before pressure is applied.



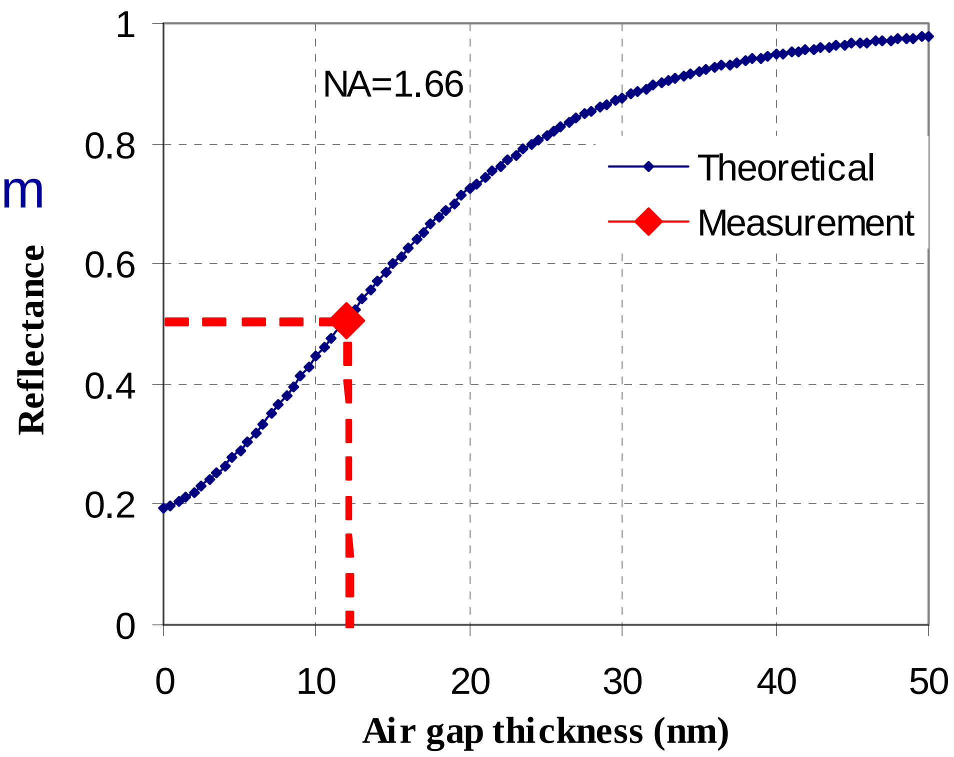
(b) After pressure is applied.

Estimation of Gap Thickness

- Reflectance measurement used to estimate gap thickness.
- Gap controllable from 0-50nm
- 12nm air gap utilized.

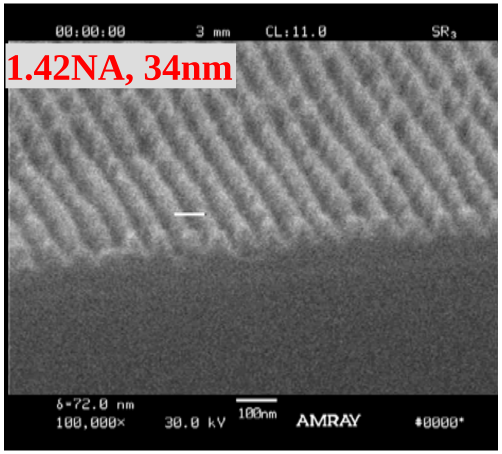
Immersion solid (sapphire), N_0=1.92
Air gap, N_1=1.00, d_1=0~50 nm
Resist, N_2=1.71-0.399i, d_2=78 nm
BARC, N2=1.70-0.1i, 92 nm
Substrate N_{sub}=0.87-2.76i

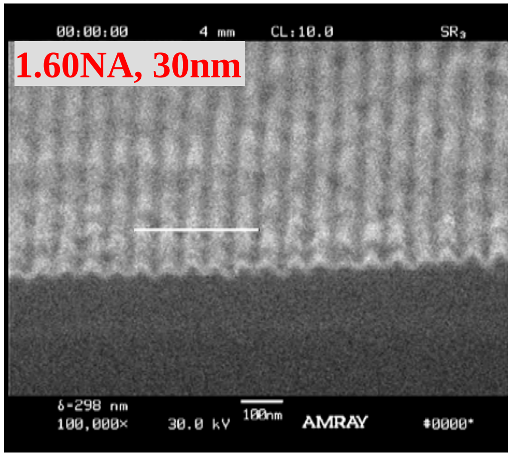
Resist assembly

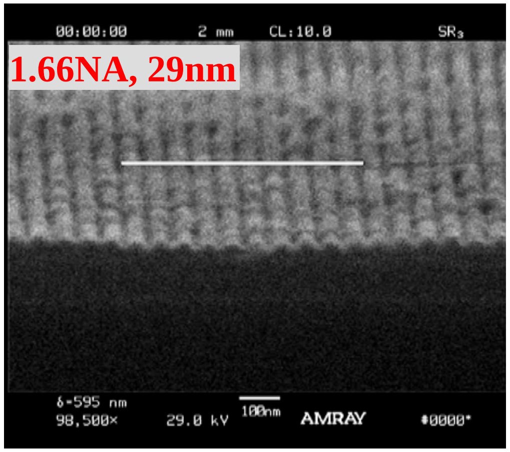


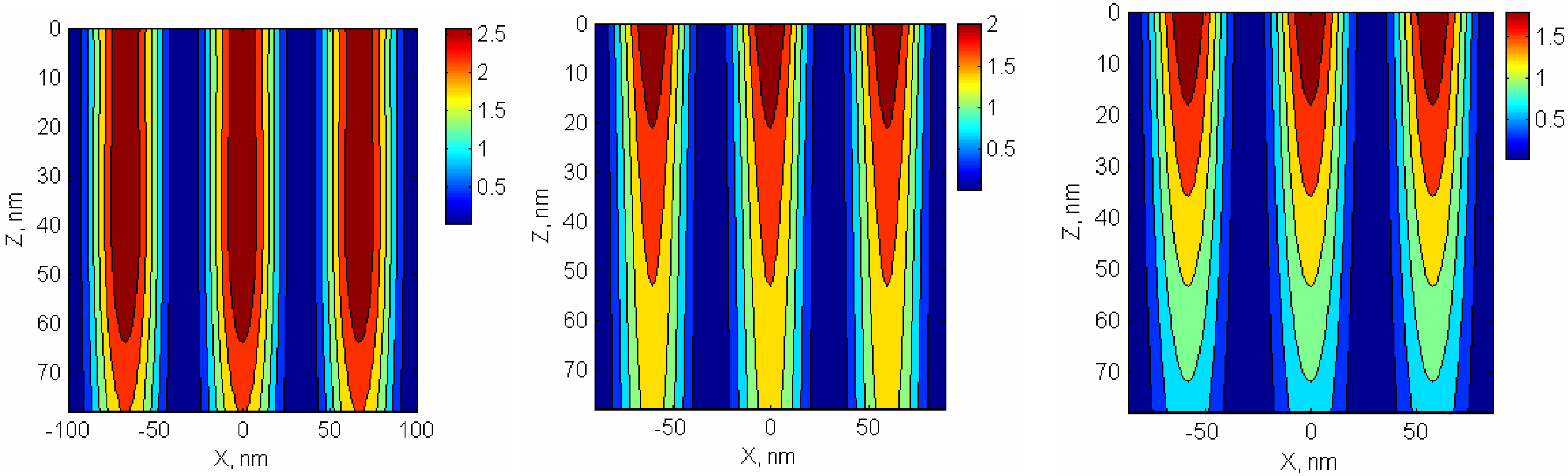
Solid Immersion Lithography

at the Resist Limit





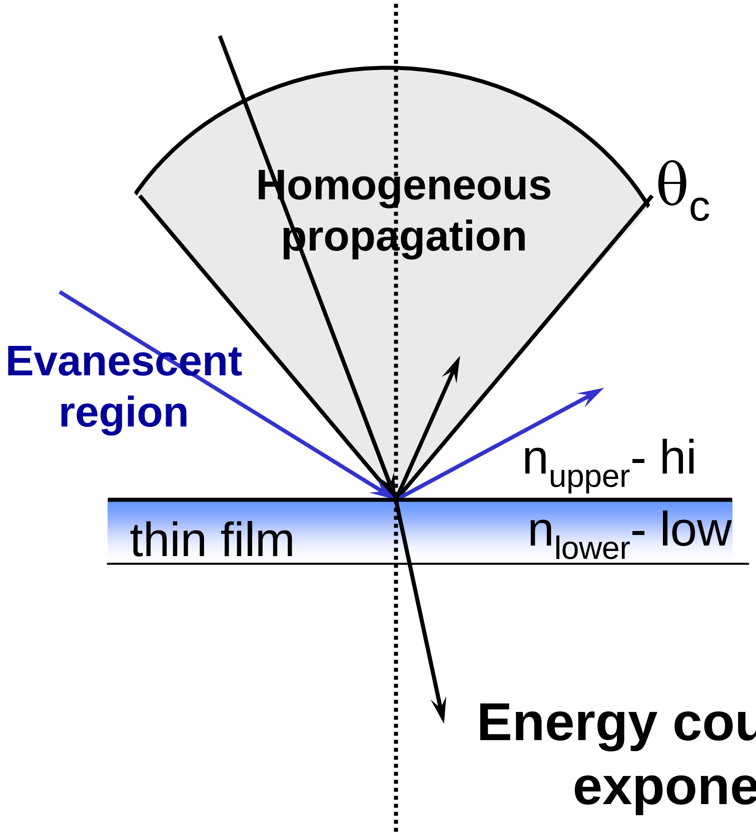


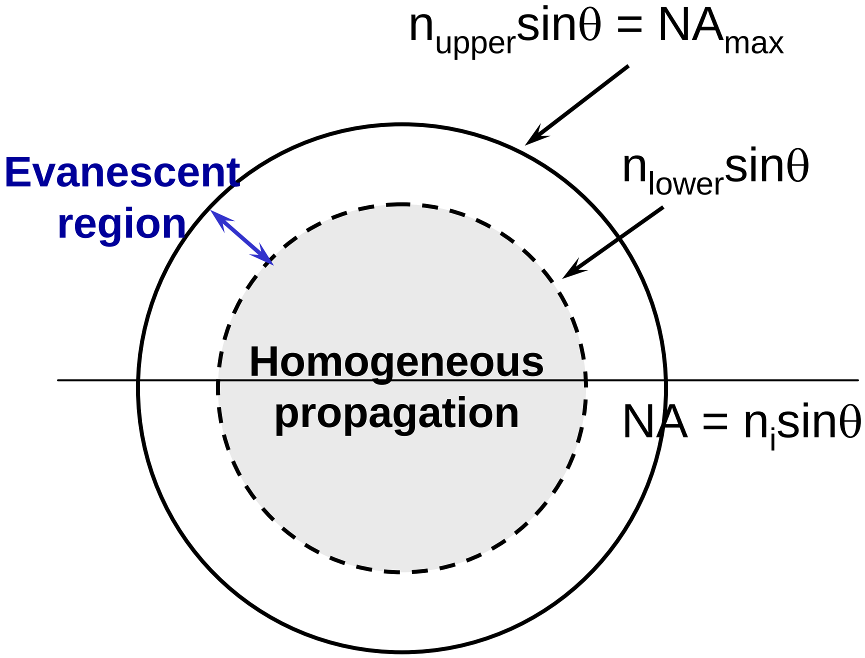


***ILSim* simulations**

Beyond the Resist Limit

Evanescent Wave Coupling





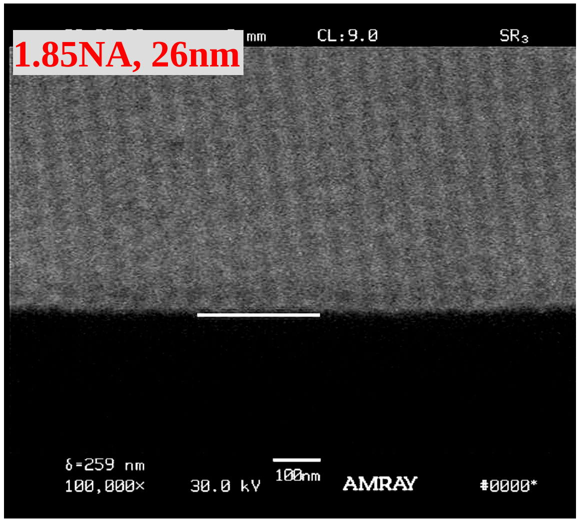
Energy coupled into the thin film decays exponentially:

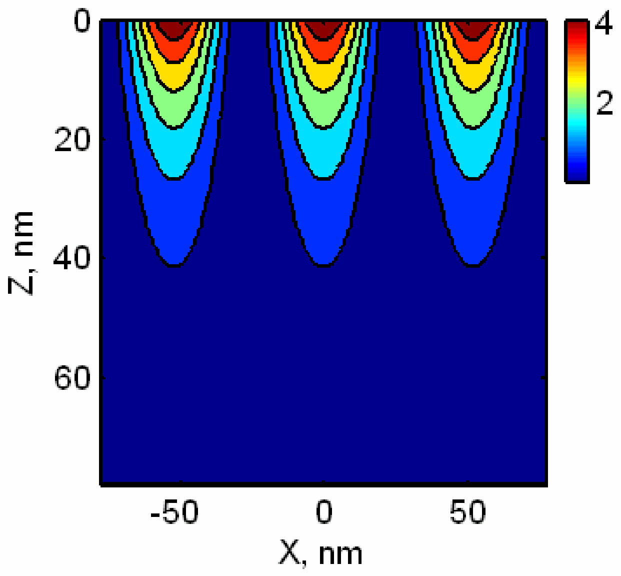
$$A(z) = e^{-\left(\frac{2\pi n_{upper}}{\lambda}\left[\sin^2\theta - \left(\frac{n_{lower}}{n_{upper}}\right)^2\right]^{1/2} + \alpha\right)z}$$

Evanescent Wave Lithography

Beyond the Resist Limit - 26nm hp at 1.85NA

- ➢ NA (1.85) has been pushed higher than the index of the resist (1.70).
- ➢ Image pattern depth of <10 nm.
- ➢ Sets the stage for new material development toward 25nm.
- ➢ Potential with TSI and hard-mask imaging layers.

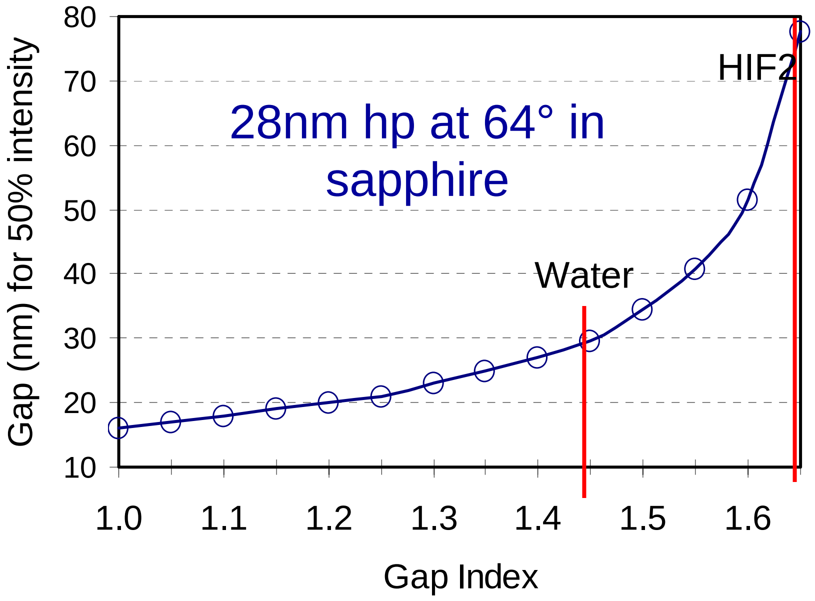


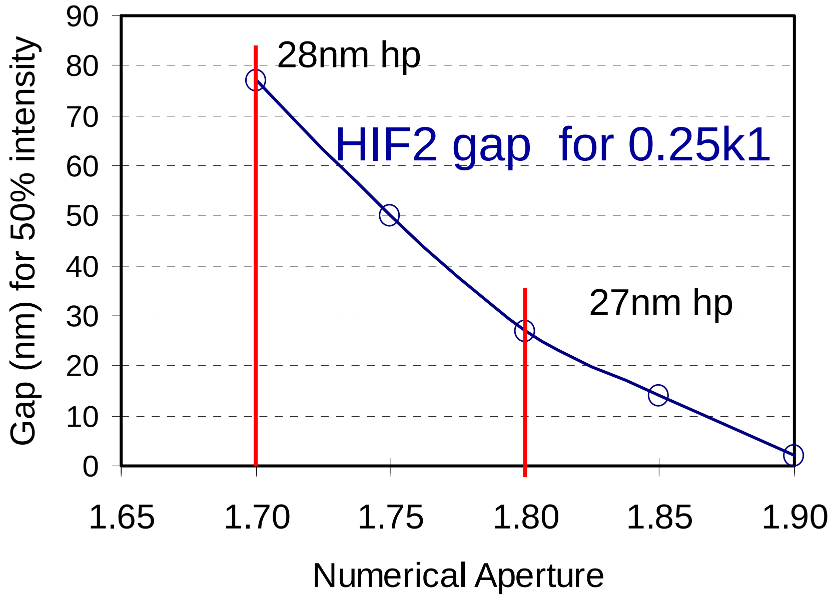


Gap Requirements / Tolerances

Assume 50% intensity loss across the image – *no loss in modulation*

1% gap Δ results in ~0.5-1% intensity Δ at 1.70NA – *dose control issue*





$$A(z) = e^{-\left(\frac{2\pi n_{upper}}{\lambda}\left[\sin^2\theta - \left(\frac{n_{lower}}{n_{upper}}\right)^2\right]^{1/2} + \alpha\right)z}$$

Implications of SIL and Evanescent Wave Lithography

1. **SIL / EWL is useful for determining the ultimate limits of optical lithography in the 25nm regime.**
2. **NA possible beyond the fluid index.**
3. **Higher index photoresists may not be necessary if top-surface imaging (TSI) can be employed.**
4. **SIL may be feasible if small fluid gaps can be maintained.**

Technology Limits in Media

		Numerical Aperture							
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	k1=0.30	45	44	39	36	34	32	30	29
Angle in media	***Water (1.44)***	🟩 65°	🟨 76°	🟨	🟨	🟥	🟥	🟥	🟥
	HIF (1.55)	🟩 57°	🟩 65°	🟨 75°	🟨	🟨	🟥	🟥	🟥
	HIF2 (1.65)	🟩 52°	🟩 58°	🟩 65°	🟨 76°	🟨	🟨	🟥	🟥
	Photoresist (1.70)	🟩 50°	🟩 55°	🟩 62°	🟨 70°	🟨	🟨	🟥	🟥
	HI PR (1.85)	🟩 45°	🟩 49°	🟩 54°	🟩 60°	🟩 67°	🟨 77°	🟨	🟨
	Fused silica (1.54)	🟩 58°	🟩 65°	🟨 77°	🟨	🟨	🟥	🟥	🟥
	Sapphire (1.92)	🟩 43°	🟩 47°	🟩 52°	🟩 56°	🟩 62°	🟨 70°	🟨	🟨

🟩 ***Can be achieved with immersion lithography***

🟨 ***May be possible with SIL / EWL***

🟥 ***Not likely***

Acknowledgements

SRC, DARPA/AFRL, Sematech, ASML, Photronics, TOK, JSR, Rohm and Haas, Brewer, NYSTAR, Corning Tropel