Lecture 16 –
Introduction to Optical Lithography

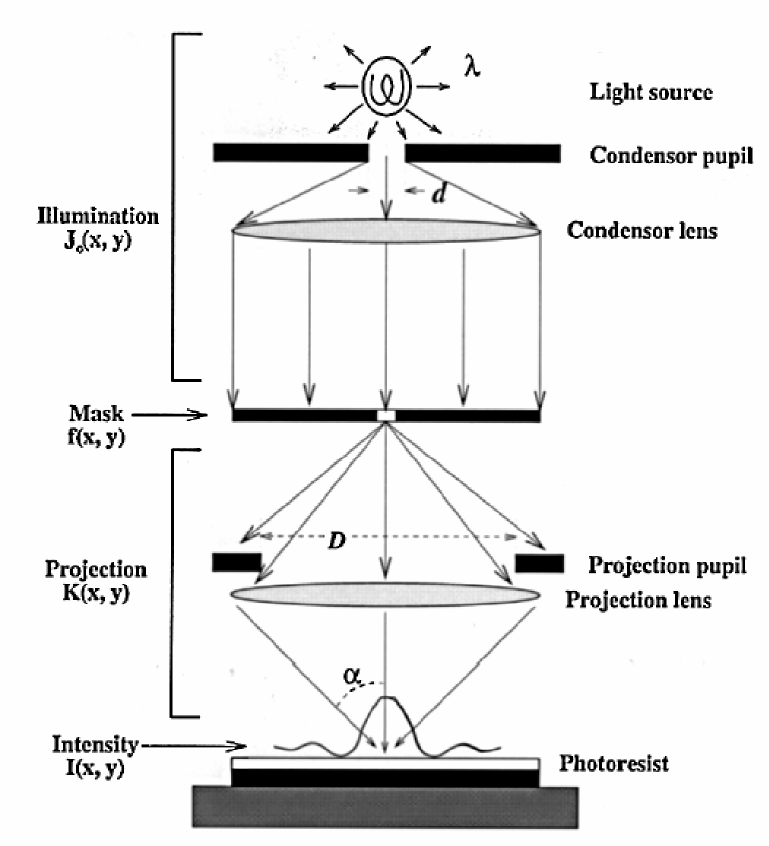
EECS 598-002 Winter 2006

Nanophotonics and Nano-scale Fabrication

P.C.Ku

Optical Lithography

- An optical system that transfers the image from the mask to the resist layer + the process of forming an etching mask (i.e. the resist development and etc.)

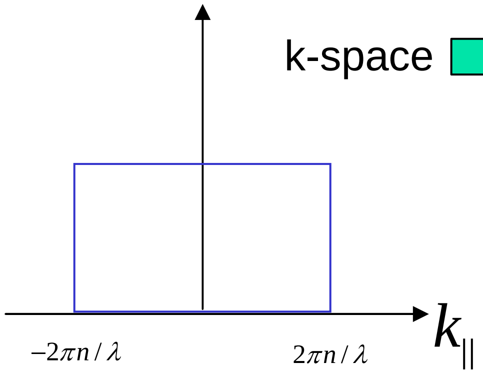


Resolution limits for imaging

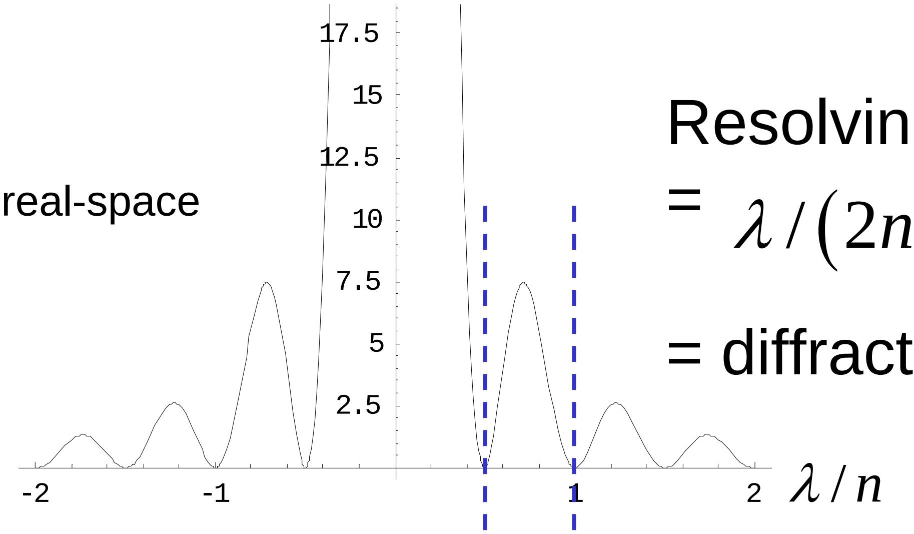
- Small features correspond to large (kx, ky) components.
- In traditional optical microscopes, the detector sees the light in the far field region.

$$k^2 = \omega^2 \mu_0 \varepsilon = k_x^2 + k_y^2 + k_z^2$$

$$\Rightarrow \sqrt{k_x^2 + k_y^2} < \omega n / c \Rightarrow \left| k_{\|,\max} \right| = 2\pi n / \lambda$$



k-space ➡ real-space



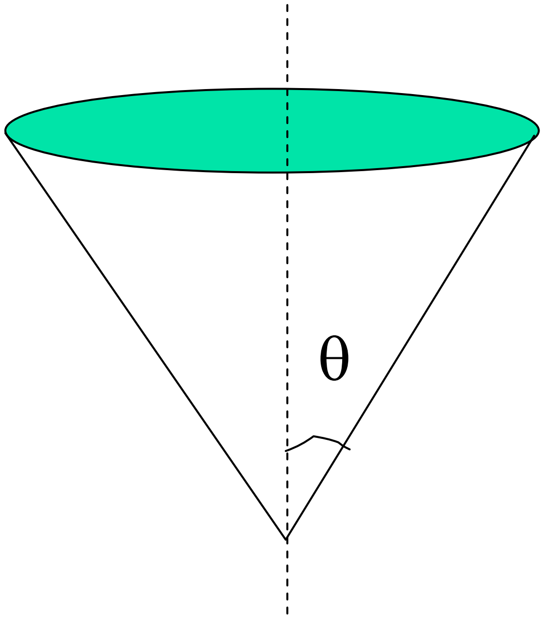
Resolving power

= $\lambda/(2n) \equiv \lambda_{eff}/2$

= diffraction limit

Finite-size lens

- In a real system, the cutoff spatial frequency is often limited by the size of the lens which is quantitatively described by a numerical aperture (NA).



$$\mathrm{NA} \equiv n \sin\theta$$

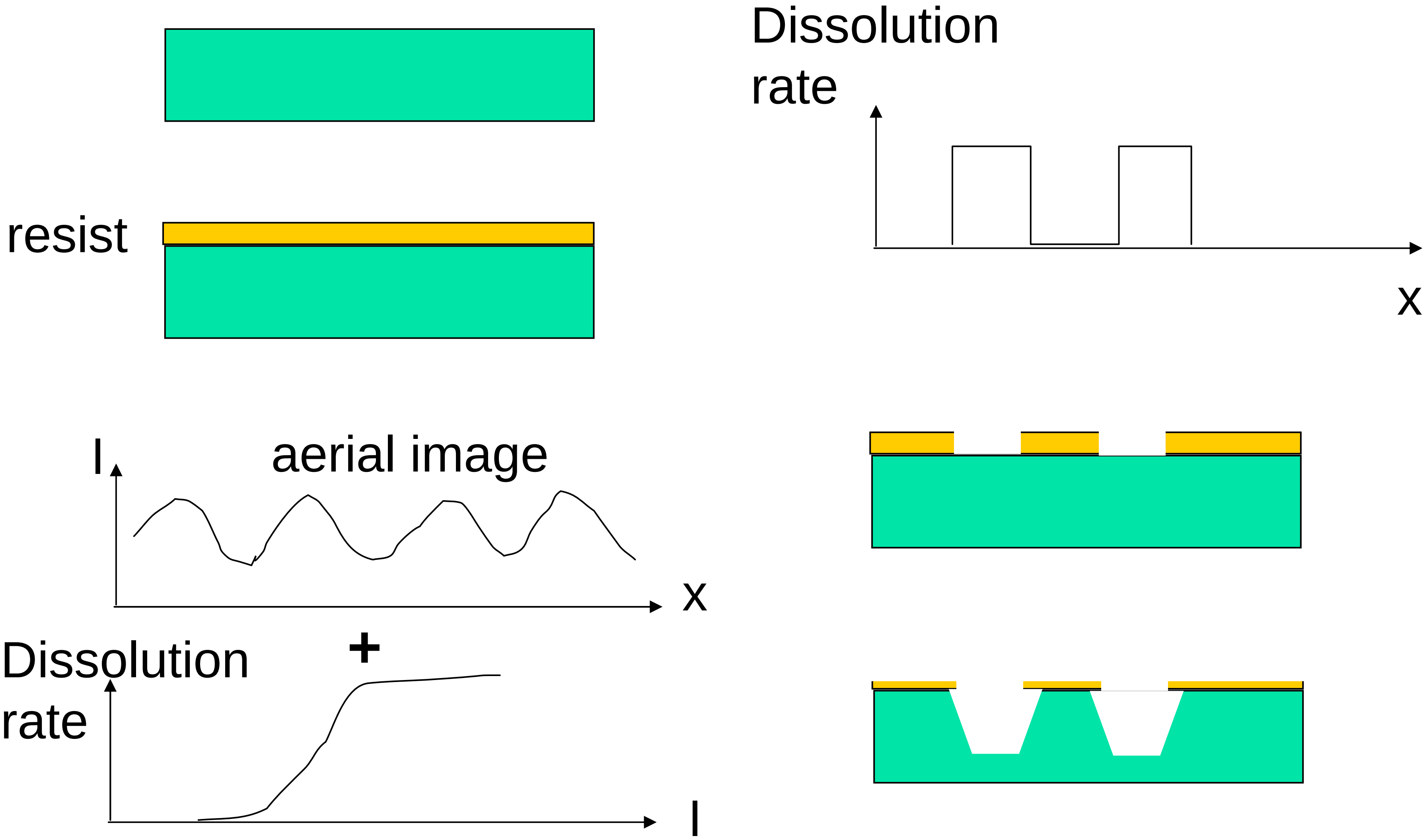
$$\Rightarrow \frac{k_{\|,\max}}{k} = \sin\theta \Rightarrow k_{\|,\max} = \frac{2\pi}{\lambda}\mathrm{NA}$$

Resolving power →

$$\lambda / (2\mathrm{NA}) \equiv \lambda_{eff} / 2$$

where $\lambda_{eff} = \lambda / \mathrm{NA}$

Patterning process



Some clarifications

- The minimum feature size:
  - The fundamental limit of optical lithography is not determined by the optical system alone but rather is an overall contributions from the optics, resist, develop and etching processes.
- Process window:
  - Capability of printing small features does not always guarantee a good quality and a repeatable and controllable patterning.
- Alignment:
  - Alignment to the underlying layer is equally as important as the optics.

How was our prediction in the past?

~~1.0 μm~~

~~0.7 μm~~

~~0.5 μm~~

~~0.35 μm~~

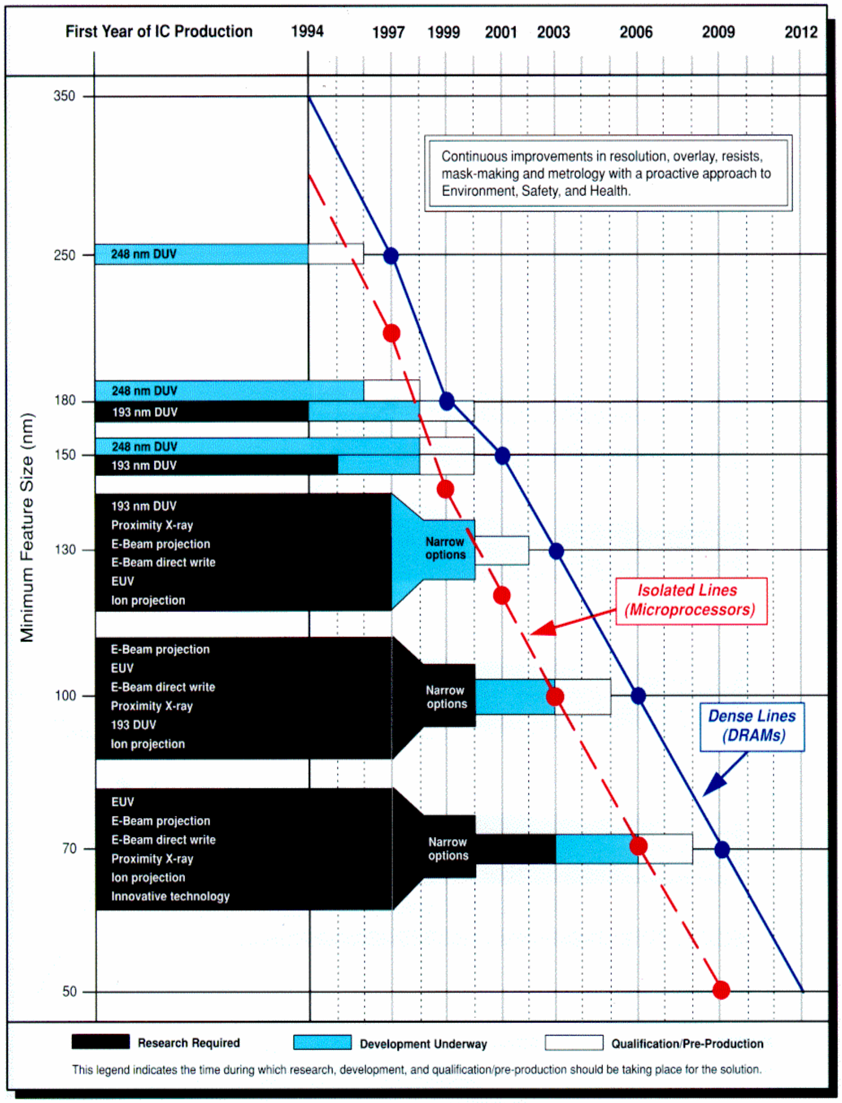
~~0.25 μm~~

~~0.18 μm~~

~~0.13 μm~~

0.10 μm ?

ITRS prediction in 1998



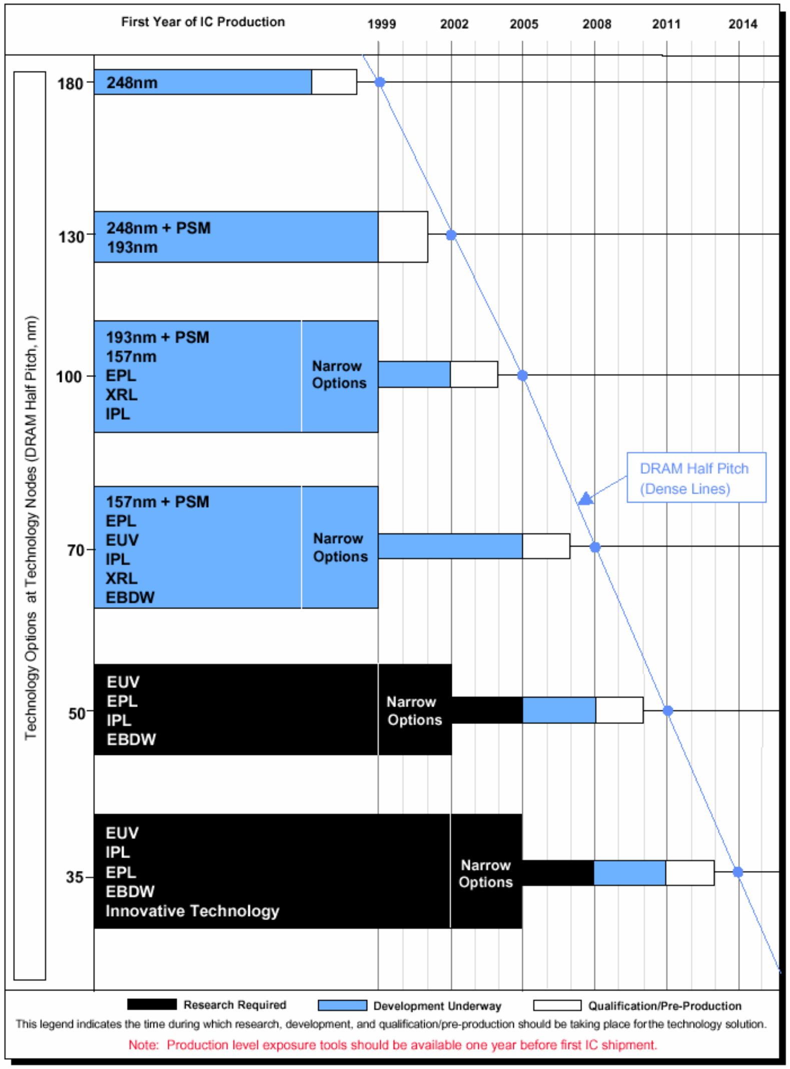
Continuous improvements in resolution, overlay, resists, mask-making and metrology with a proactive approach to Environment, Safety, and Health.

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

ITRS 1998:

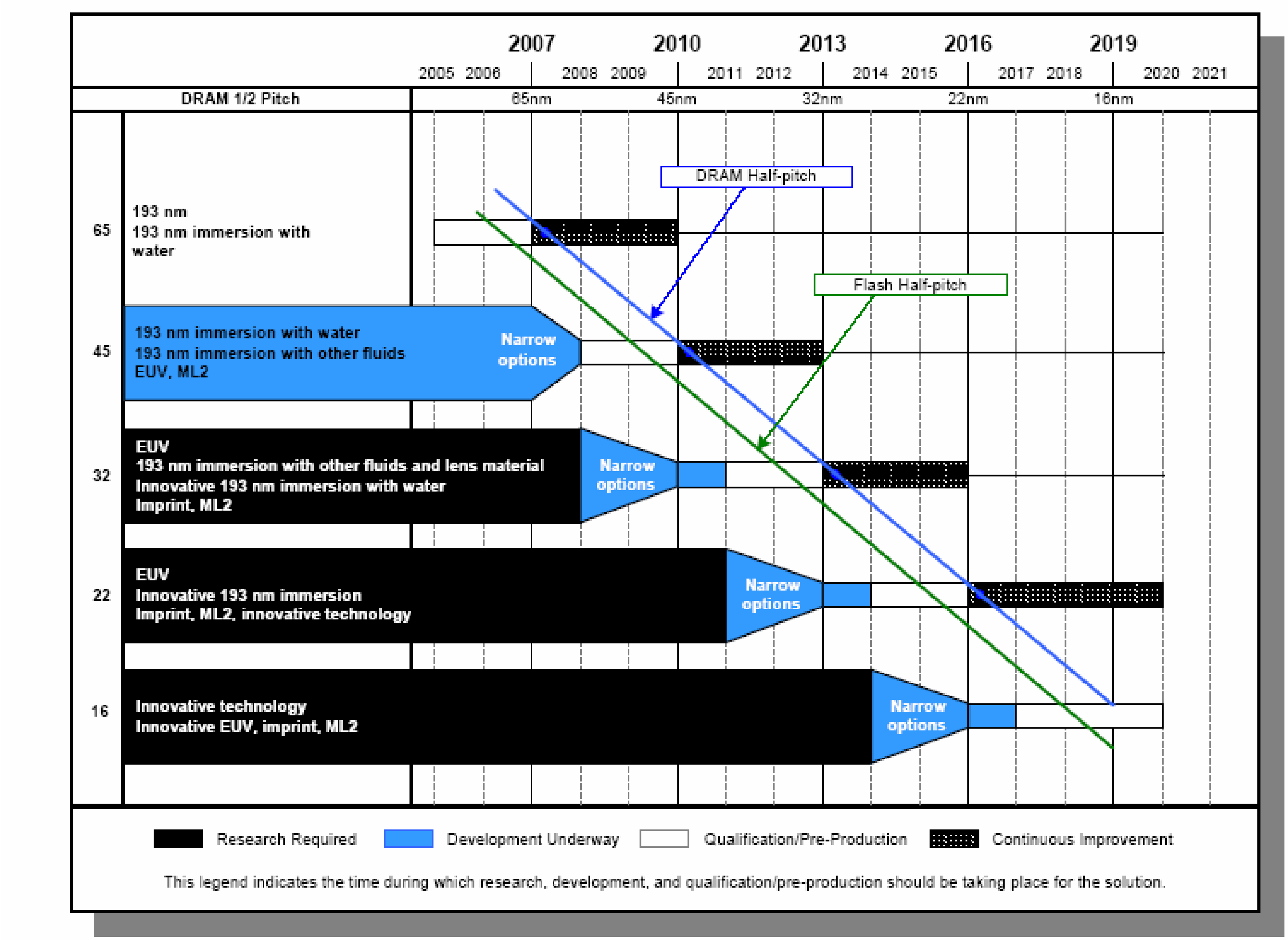
193 DUV litho cannot produce 65 nm process.

ITRS 1999



157 nm appears on the map.

ITRS 2005 report



This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

otes: RET and lithography friendly design rules will be used with all optical lithography solutions, including with immersion; therefore, ey are not explicitly noted.

Note: 157 nm off the chart now.

Major challenges (at this moment…)

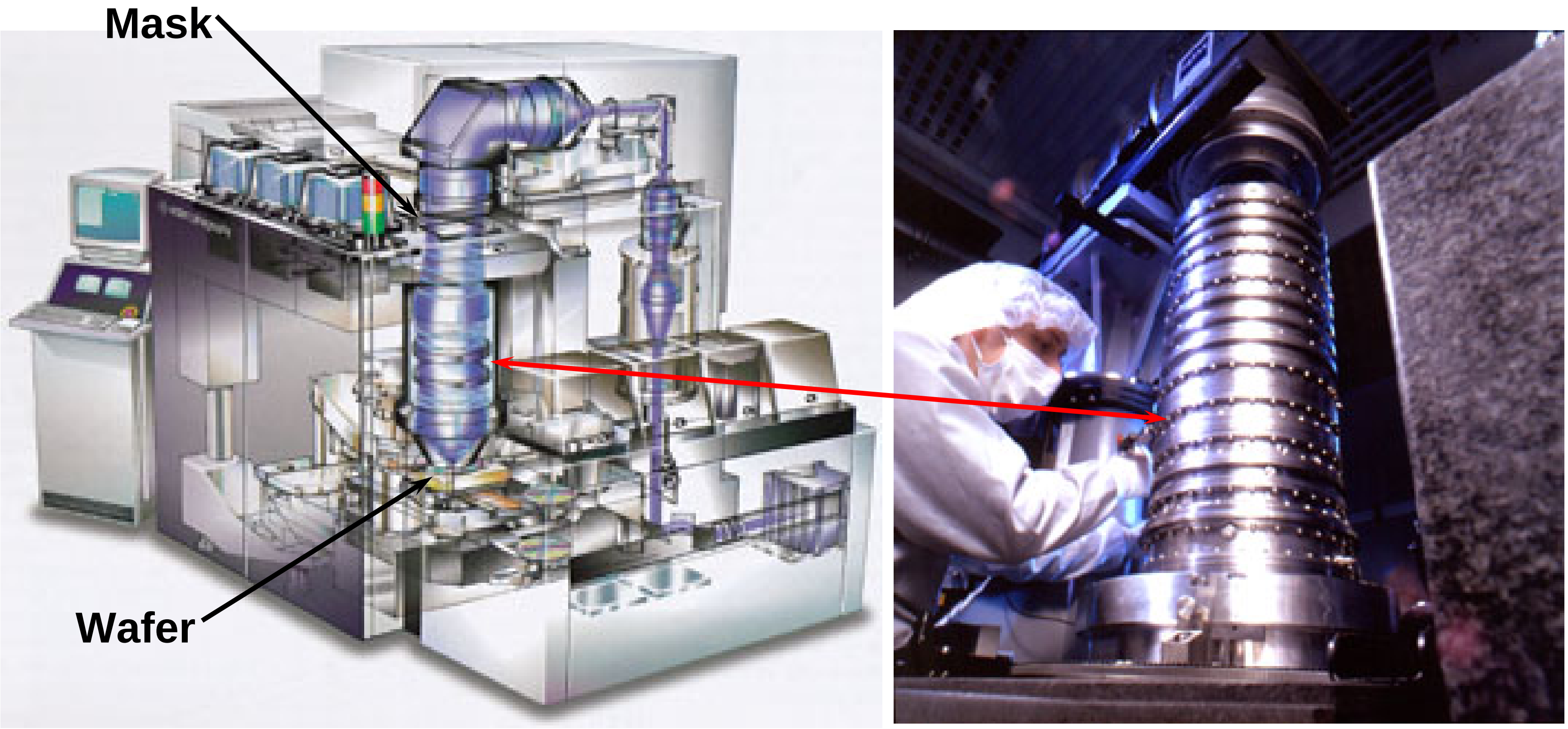
½ -pitch	65 nm	45 nm	32 nm	22 nm	16 nm
	2007	2009	2012	2015	2018
Options	193nm-i NA>1.0	193-I NA=1.35	193-I high index fluids		
			EUV NA=0.25 ML2	EUV ML2	EUV?? ML2
			Disruptive low-cost approaches (Imprint, etc.)	Disruptive approaches (Imprint, etc.)	Disruptive approaches (Imprint, etc.)
Challenges	Irregular designs	Defectivity Resist technology Mask blank specs (birefringence) RET High-NA polarization effects Optics durability Overlay	**193-i** High-n fluid Polarization effects **EUV** Source power, lifetime etc Defect free masks Reticle protection Optics lifetime and contamination Optics quality **ML2** **Imprint** templates **Resist** (resolution, LER, sensitivity)	**EUV** RET **ML2:** Throughput **Imprint** 1:1 masks Overlay correction **Resist** limits	**EUV** High NA RET **ML2:** Throughput **Imprint** 1:1 masks Overlay correction **Resist** limits

Data from ENIAC.

Evolution of optical lithography

Contact and proximity printing	Defects, gap control
1:1 projection printing	Overlay, focus, mask cost
Step-and-repeat projection printing	Reduction possible
Step-and-scan projection printing	Easier focus; better usage of lens area

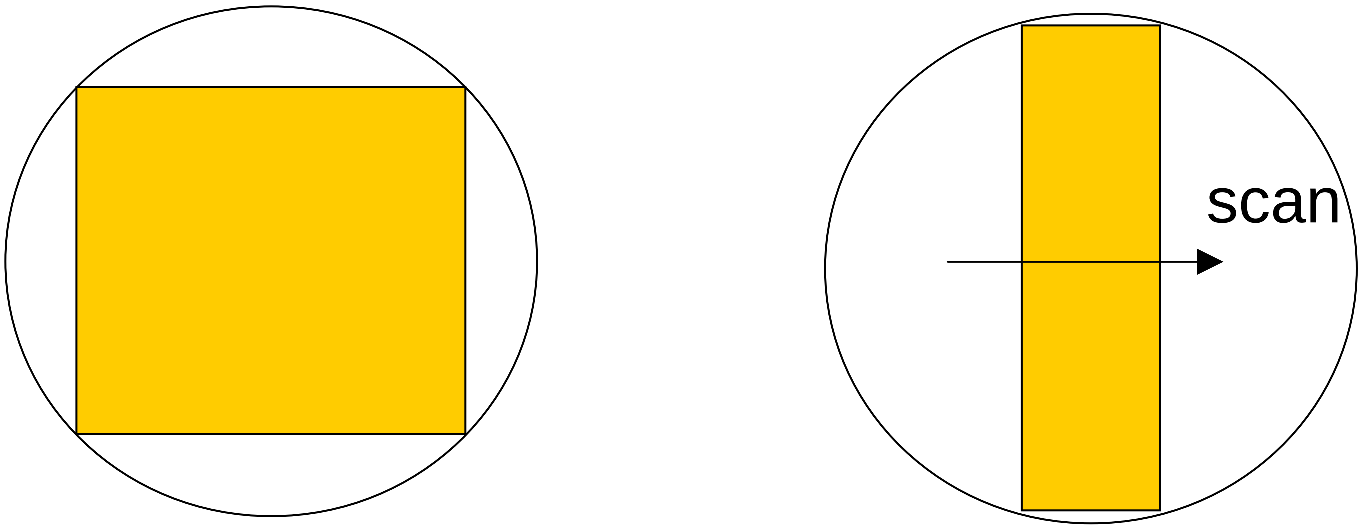
A step-and-scan system (stepper or scanner)



Step-and-repeat vs step-and-scan

Step-and-repeat

Step-and-scan



Evolution of optics

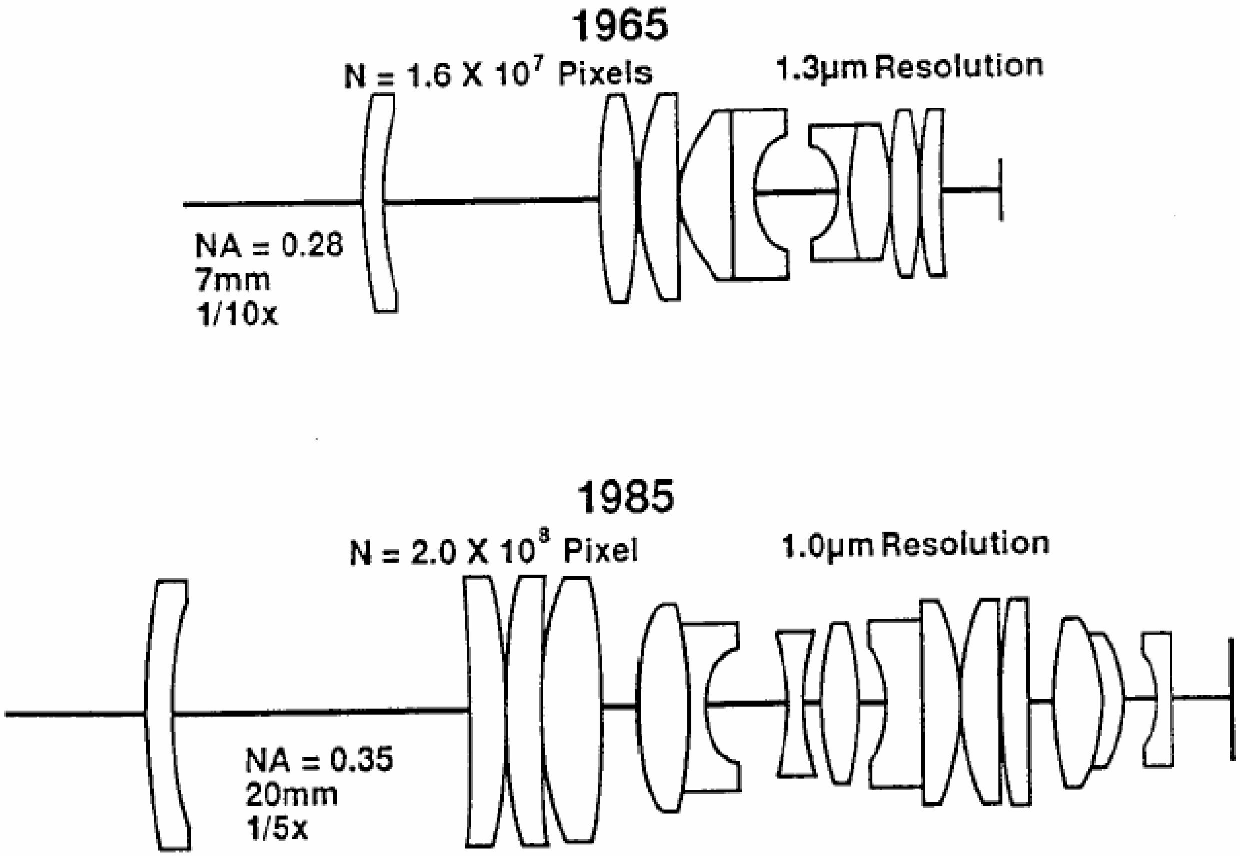
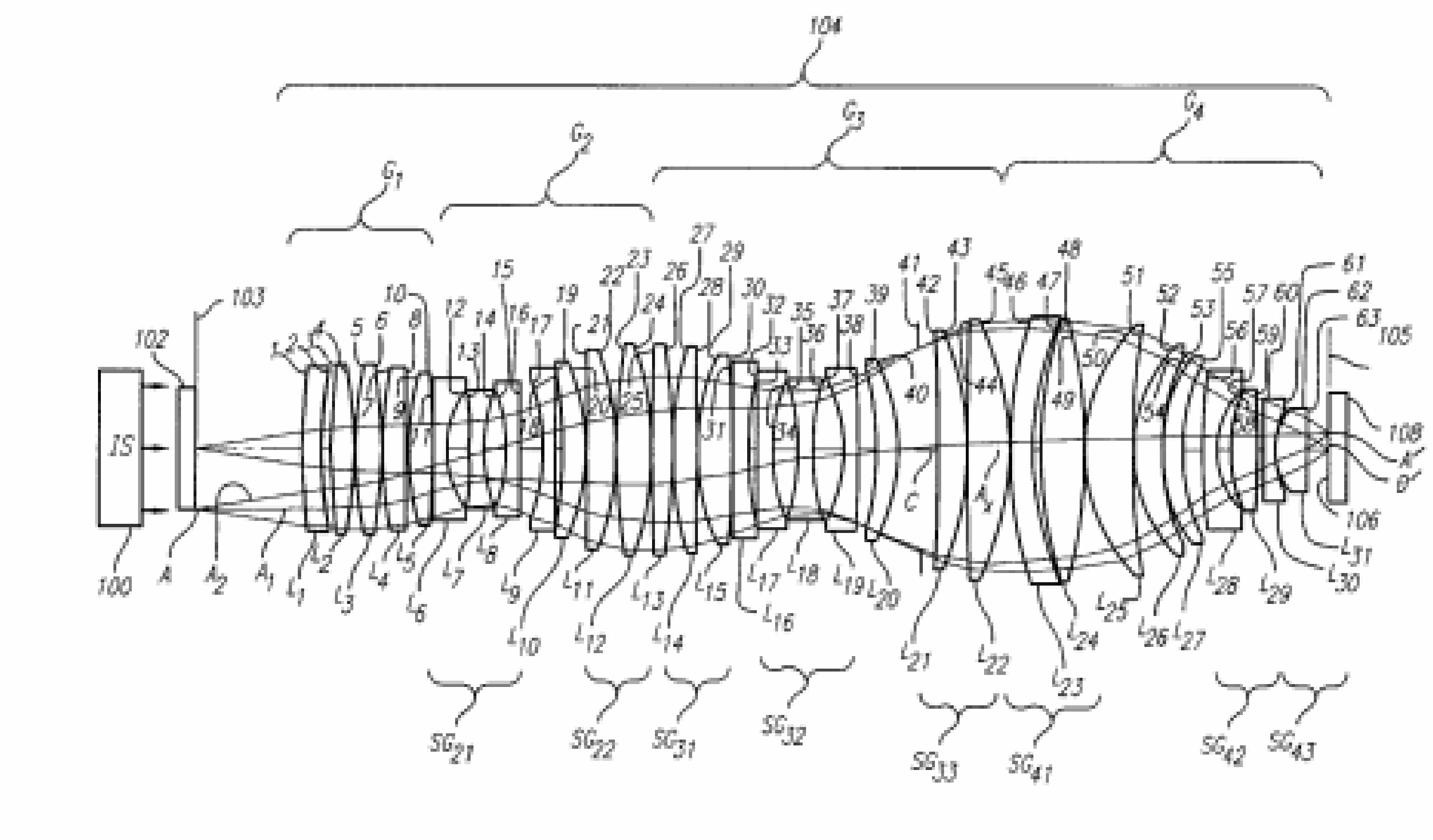


Figure 9. Comparison of ground-controlled approach (GCA) projection lenses, showing evolution in complexity from 1965 to 1985.

From *Introduction to Microlithography*

An example of the optics (NA=0.6, 4X reduction)



US Patent 5969803

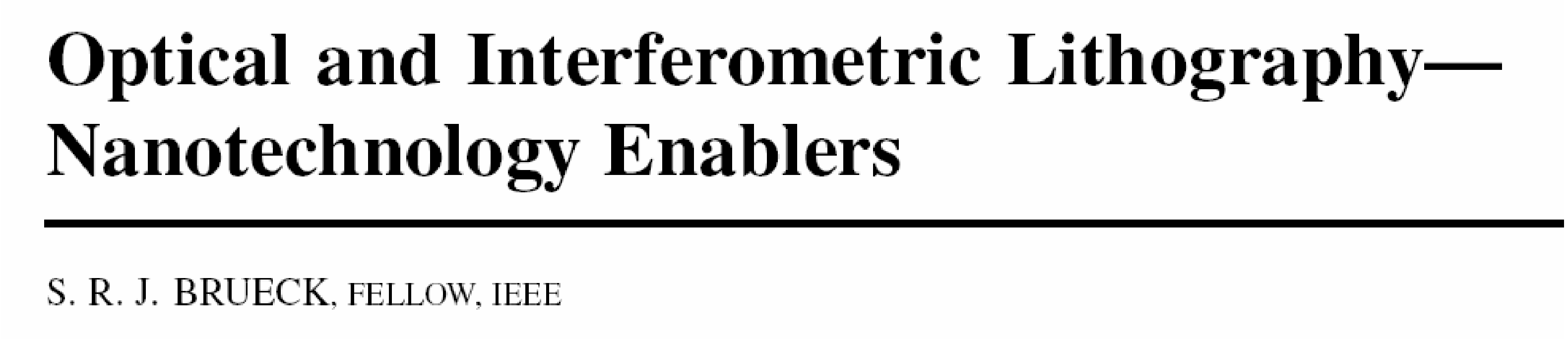
Challenges in lens design

- Larger lens (required by better resolution) → aberration
  - Suitably rotating the lens in the step-and-scan system can minimize the aberration
- Finite linewidth of laser source → dispersion
- Aspheric lens → more expensive
- Tighter spec on surface quality of lens
- Shortening the wavelength → more expensive raw materials

Resolution vs minimum linewidth

- Resolution often refers to the smallest pitch of a dense line/space pattern. It is limited by the diffraction limit.
    - Important for DRAM/flash.

- Minimum linewidth is the minimum line or space that we can resolve. It has no fundamental limit.
    - Important for logic chips (e.g. the gate length of a transistor)



Optical and Interferometric Lithography—Nanotechnology Enablers

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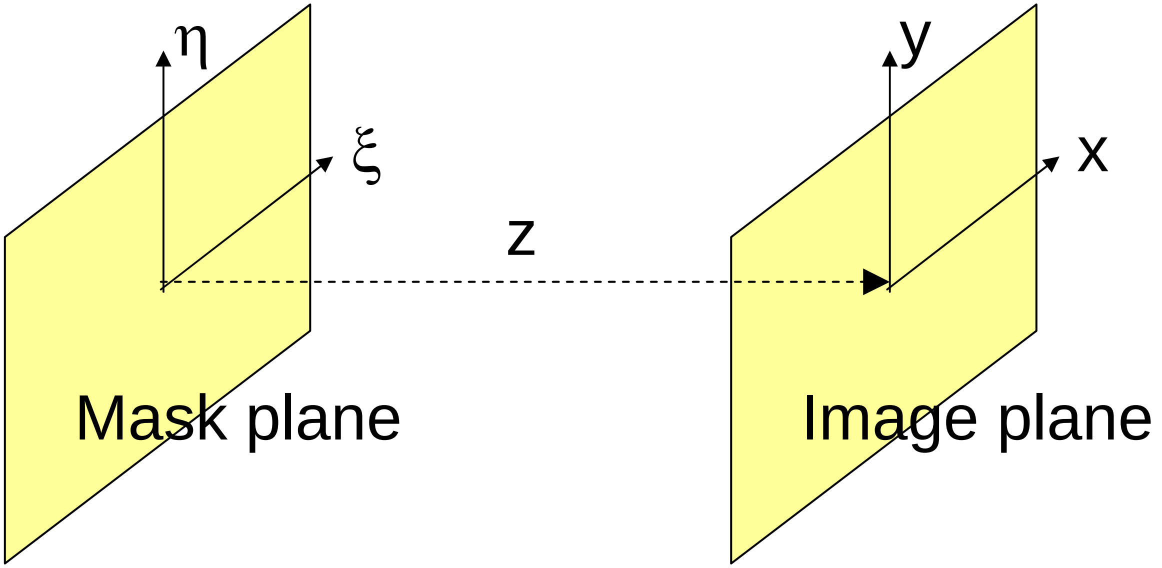
There’s no fundamental limit to optical lithography!

Fundamentals of lithographic optics

- Diffraction
- Partial coherence
- Depth of focus
- Reflection and interference
- Polarization dependence

Fraunhofer diffraction (scalar; far-field)

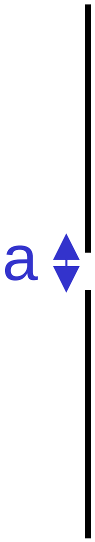


$$U(x,y)=\frac{e^{ikz}e^{i\frac{k}{2z}(x^2+y^2)}}{i\lambda z}F\left[U(\xi,\eta)\right]_{\substack{f_x=x/\lambda z\\ f_y=x/\lambda z}}$$

↑

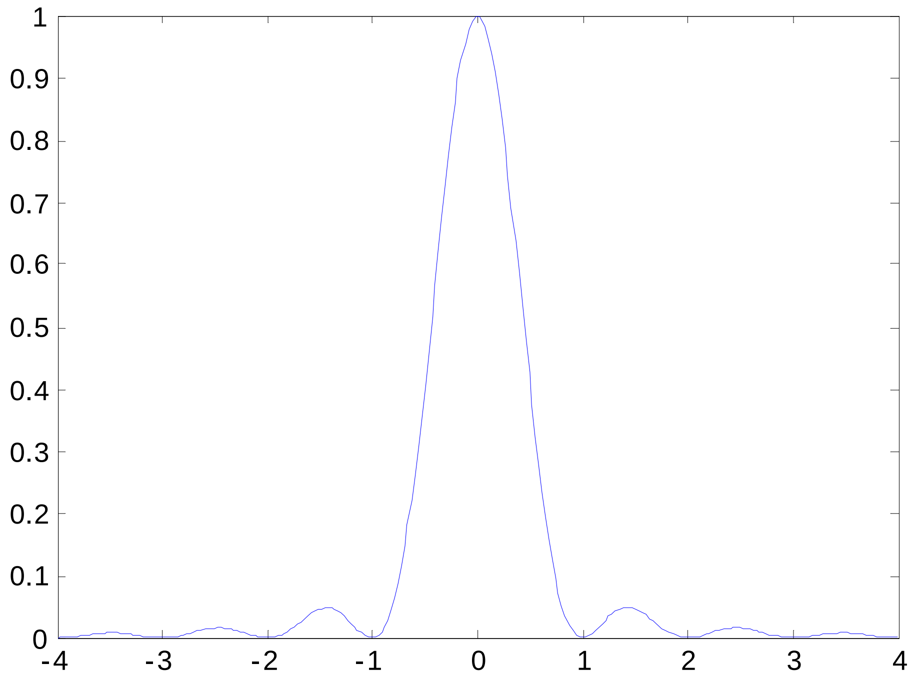
EM field

Diffraction from an aperture



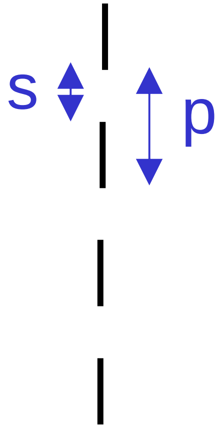
$$F\left[U(\xi)\right]_{f_x=x/\lambda z} = a\,\mathrm{sinc}\left(\frac{ax}{\lambda z}\right)$$

Intensity $\propto a^2\,\mathrm{sinc}^2\left(\frac{ax}{\lambda z}\right)$

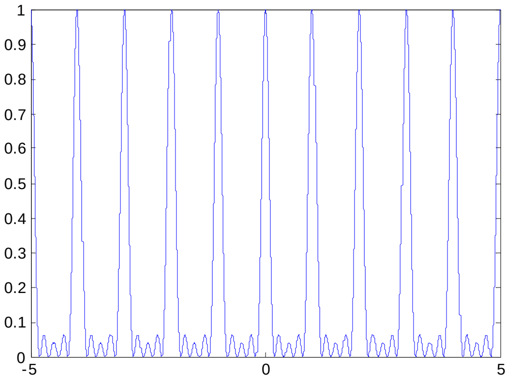


Before the lens

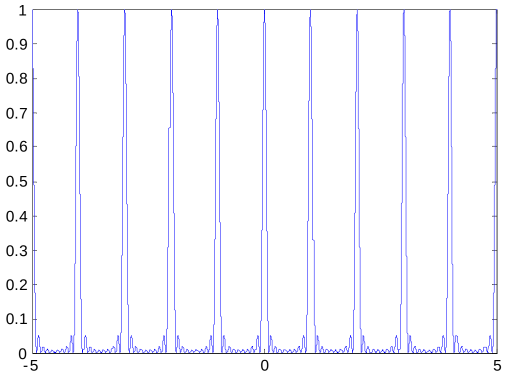
Diffraction of a line/space (N spaces) pattern



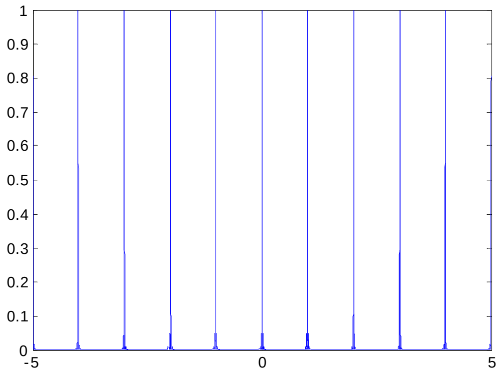
$$I(x) \propto \boxed{\left(\frac{\sin \frac{N\pi p x}{\lambda}}{\sin \frac{\pi p x}{\lambda}} \right)^2} \left(\frac{\sin \frac{\pi s x}{\lambda}}{\frac{\pi s x}{\lambda}} \right)^2$$



N=5

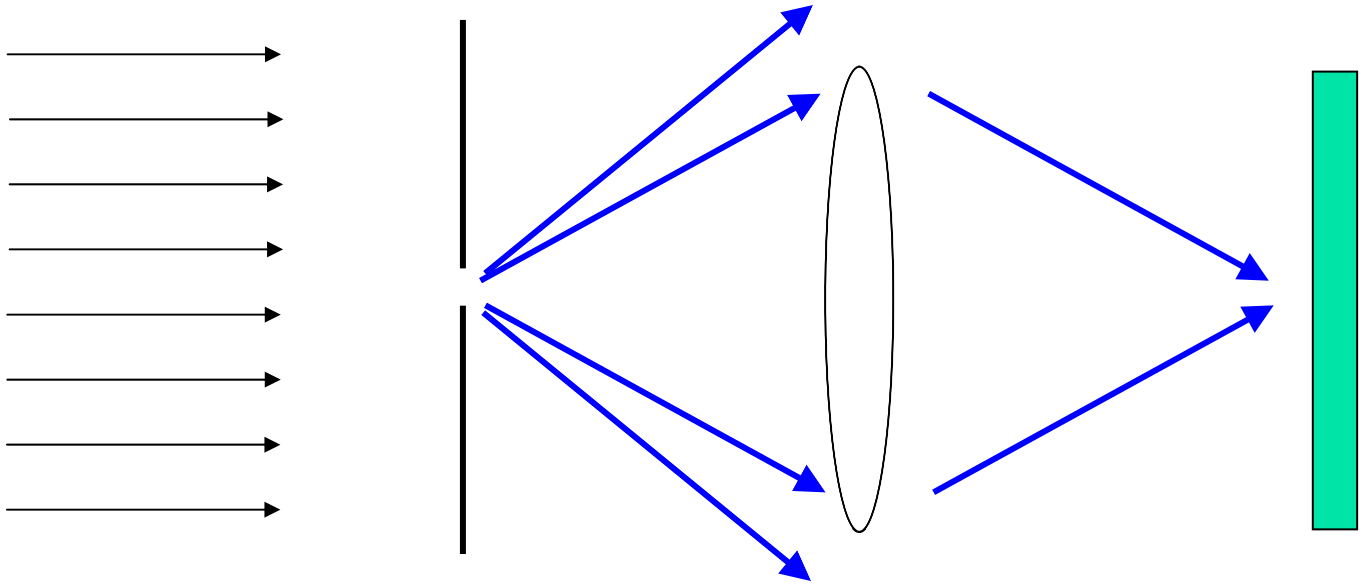


N=10



N=100

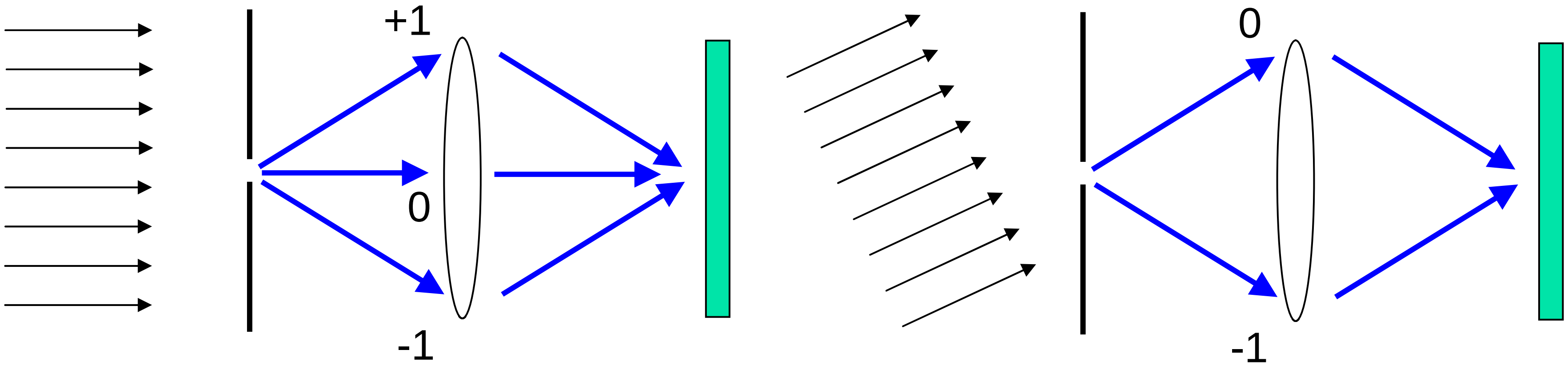
Basic lithographic optics configuration



illumination mask projection lens photoresist (image plane)

Image formation

- Need to have at least the 0-th and the 1st diffraction orders being collected to recover the pitch information.



Oblique incidence can improve the minimum pitch but result in a less image contrast.