# EE143 – Fall 2016
# Microfabrication Technologies

# Lecture 3: Lithography
# Reading: Jaeger, Chap. 2

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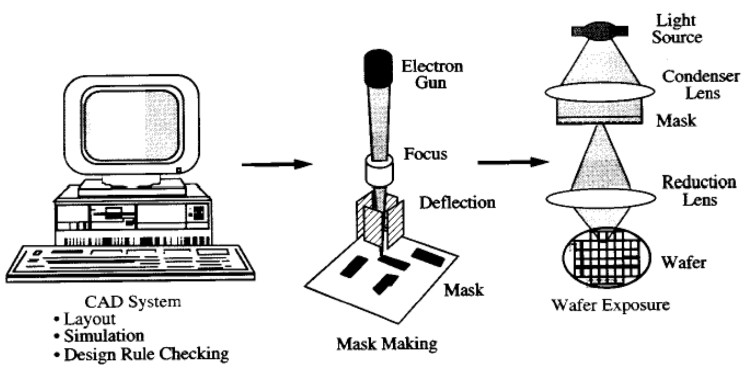
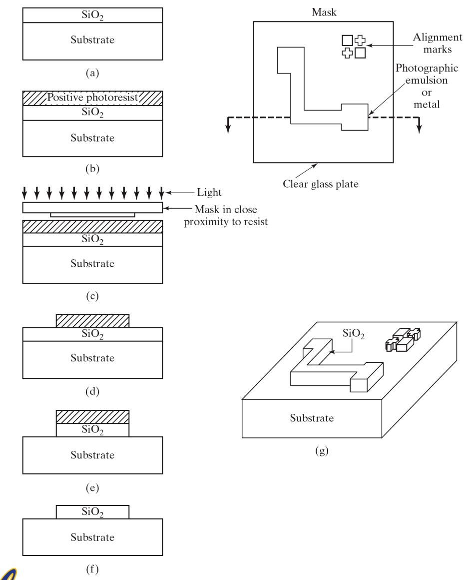
## The lithographic process

Design => Mask => Wafer



# Photolithographic Process




(a) Substrate covered with silicon dioxide barrier layer

(b) Positive photoresist applied to wafer surface

(c) Mask in close proximity to surface

(d) Substrate following resist exposure and development

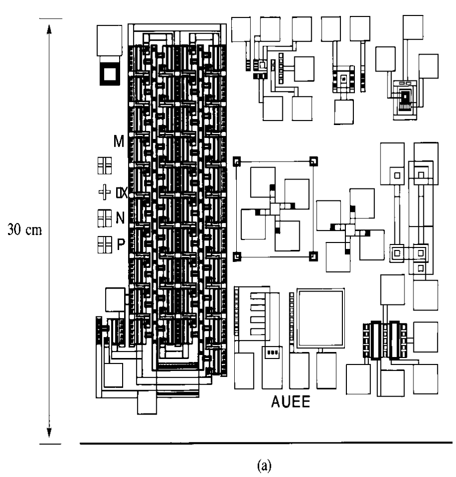
(e) Substrate after etching of oxide layer

(f) Oxide barrier on surface after resist removal

(g) View of substrate with silicon dioxide pattern on the surface

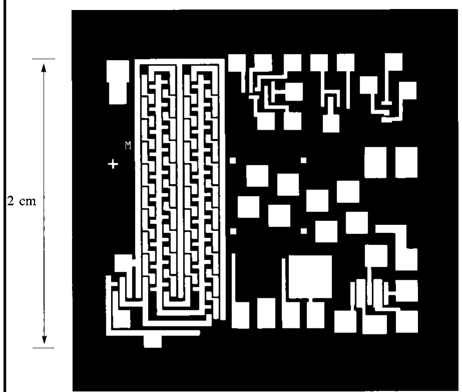


# Photomasks - CAD Layout




- Composite drawing of the masks for a simple integrated circuit using a four-mask process
- Drawn with computer layout system
- Complex state-of-the-art CMOS processes may use 25 masks or more

# Photo Masks

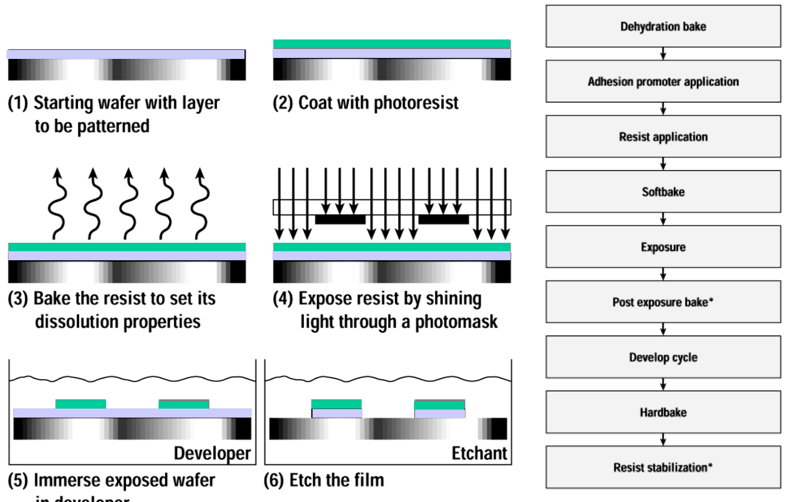



(b)

- Example of 10X reticle for the metal mask - this particular mask is ten times final size (10 μm minimum feature size - huge!)
- Used in step-and-repeat operation
- One mask for each lithography level in process

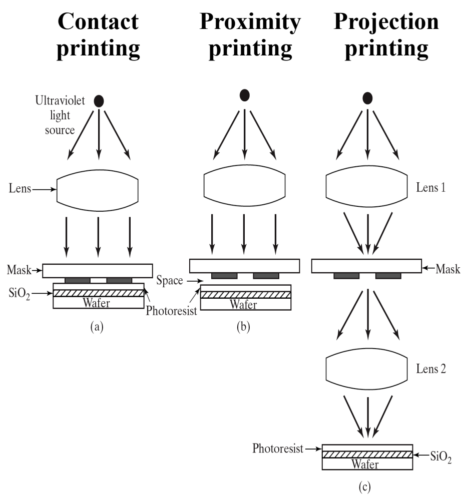


# Lithographic Process




*Optional steps

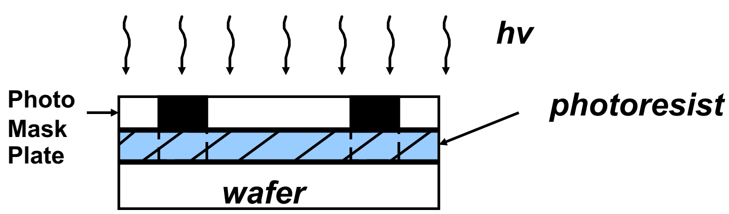
# Printing Techniques




- **Contact printing damages the mask and the wafer and limits the number of times the mask can be used**
- **Proximity printing eliminates damage**
- **Projection printing can operate in reduction mode with direct step-on-wafer**



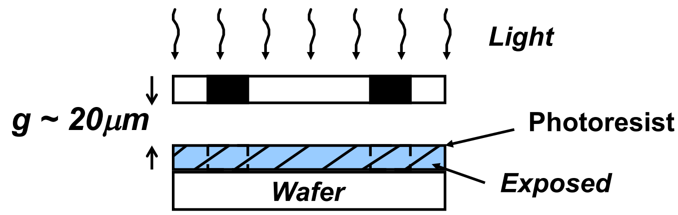
# Contact Printing




→ **Resolution R < 0.5µm**

→ **mask plate is easily damaged or accumulates defects**

# Proximity Printing




Resolution $R \propto \sqrt{\lambda g}$

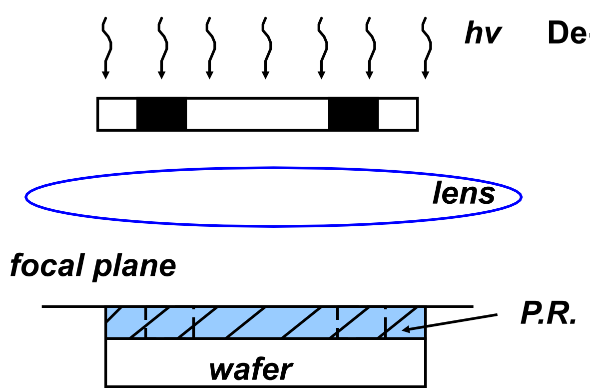
$\lambda$: wavelength of the light source

$g$: g

~ 1μm for visible photons,
much smaller for X-ray lithography



# Projection Printing



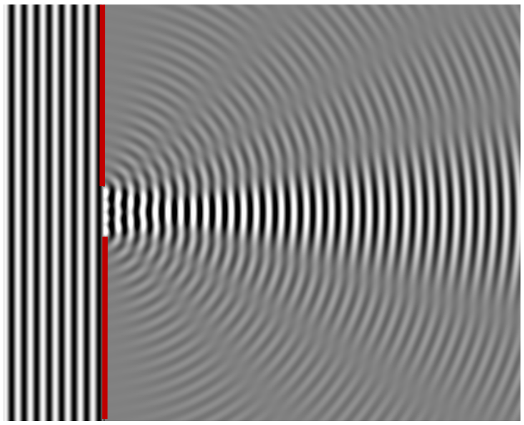

De-Magnification: nX

10X stepper
4X stepper
1X stepper

Resolution: 250 nm to < 100 nm

(The Deep-UV stepper at Berkeley's Marvell Nanolab, ASML 5500/300, has 250 nm resolution)

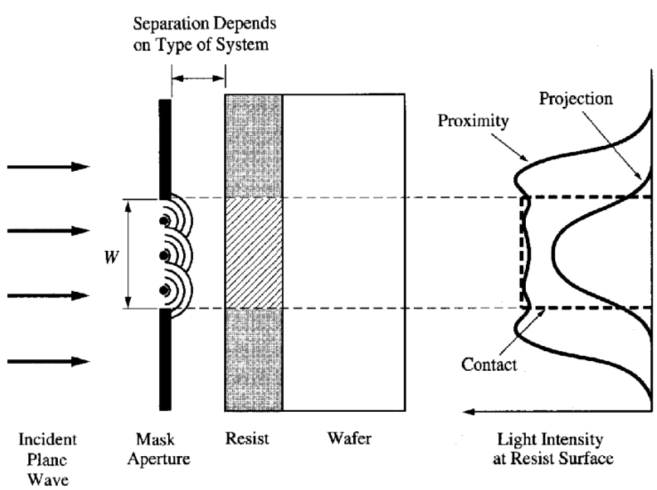
# Diffraction





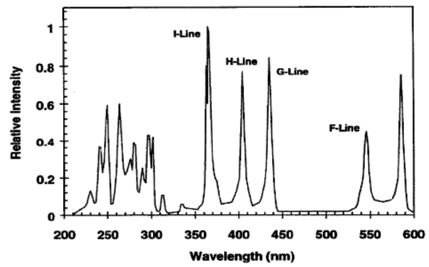
# Aerial Images

## formed by Contact Printing, Proximity Printing and Projection Printing



## Light Sources

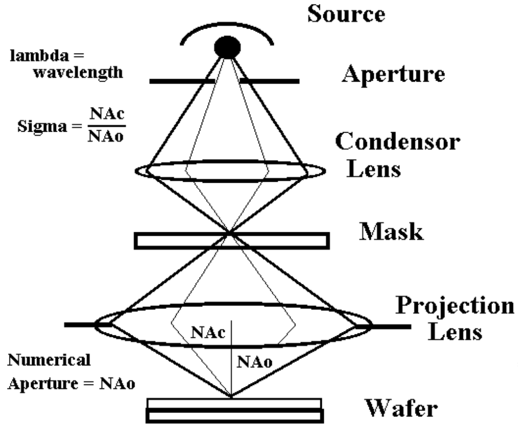
- Hg Arc lamps 436(G-line), 405(H-line), 365(I-line) nm




- Excimer lasers: KrF (248nm) and ArF (193nm)
- Laser pulsed plasma (13nm, EUV)
- Source Monitoring
  - Filters can be used to limit exposure wavelengths
  - Intensity uniformity has to be better than several % over the collection area
  - Needs spectral exposure meter for routine calibration due to aging



## Optical Projection Printing Modules




Optical System: illumination and lens

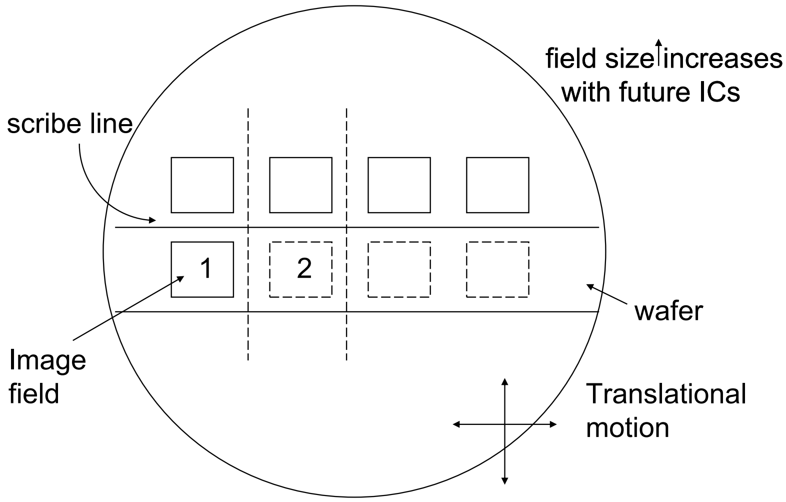
Resist: exposure, post-exposure bake and dissolution

Mask: transmission and diffraction

Wafer Topography: scattering

Alignment:

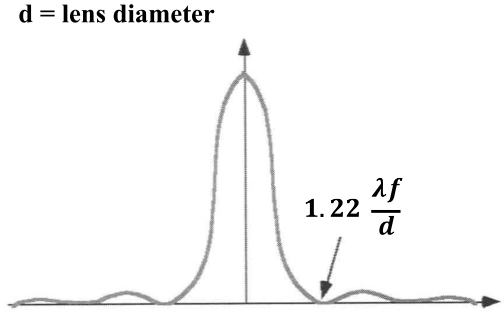
# Optical Stepper

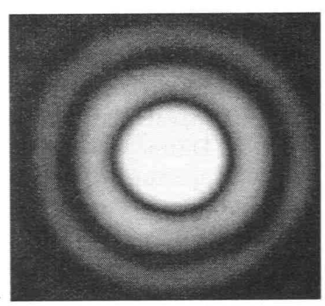




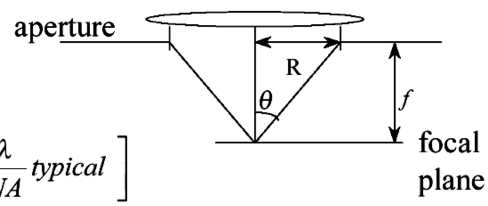

# Resolution in Projection Printing

**f = focal distance**
**d = lens diameter**



## Resolution Limits in Projection Printing




$$l_m = k_1 \frac{\lambda}{NA} \qquad \left[0.6\frac{\lambda}{NA}\ typical\right]$$

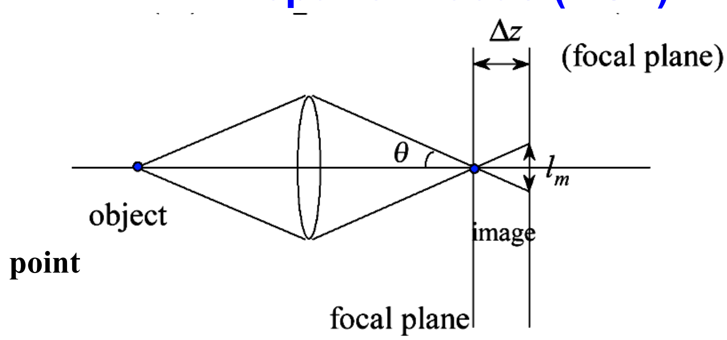
$NA \equiv$ *numerical aperture of lens*.

$= n.\sin\Theta$, **where n is the index of refraction**

$k_1$ = a constant between 0.25 and 1, depending on optics, resist, and process latitude



## Depth of Focus (DOF)



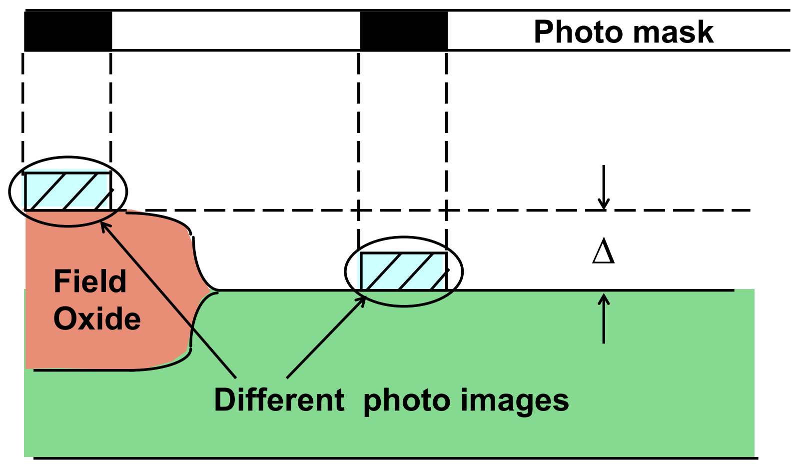

$$\Delta z = k_2 \frac{\lambda}{(NA)^2}$$

$$0.5 < k_2 < 1$$

$$\approx \frac{\pm\, l_m/2}{\tan\theta} \approx \frac{\pm\, l_m/2}{\sin\theta} = \pm\frac{\lambda}{2(NA)^2}$$

*for small* $\theta$

## Example of DOF problem





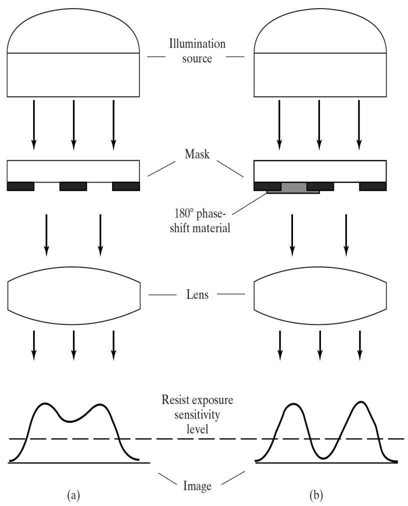

## Trade-offs in Projection Lithography

$$(1)\; l_m \cong 0.6\frac{\lambda}{NA} \quad \textit{want small}\; l_m$$

$$(2)\; DOF = \pm\frac{\lambda}{2(NA)^2} \quad \textit{want large}\; DOF$$

**(1) and (2) require a compromise between λ and NA !**

# Sub-Resolution Exposure: Phase Shift Masks




Pattern transfer of two closely spaced lines

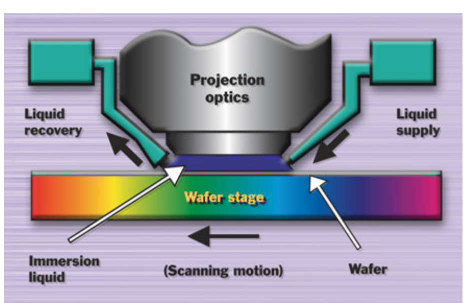
(a) Conventional mask technology - lines not resolved

(b) Lines can be resolved with phase-shift technology



# Immersion Lithography

- A liquid with index of refraction *n > 1* is introduced between the imaging optics and the wafer.




$$l_m = 0.6\frac{\lambda_{water}}{NA}$$

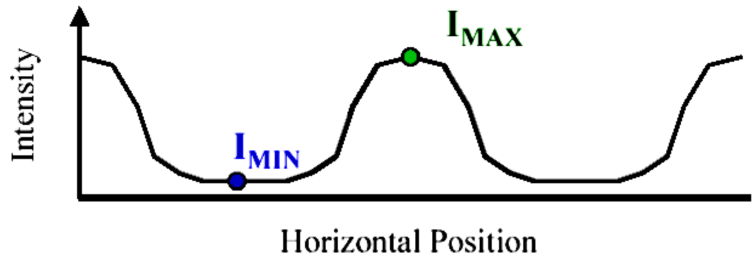
$$\lambda_{water} = \frac{\lambda}{1.3}$$

Advantages

1) Resolution is improved proportionally to *n*. For water, the index of refraction at l = 193 nm is 1.44, improving the resolution significantly, from 90 to 64 nm.

2) Increased depth of focus at larger features, even those that are printable with dry lithography.

## Image Quality Metric: Contrast




Contrast:

$$C = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$

The contrast is always between 0 (no variation) and 1 (perfect minimum).

**Contrast is also sometimes referred as the Modulation Transfer Function (MTF)**

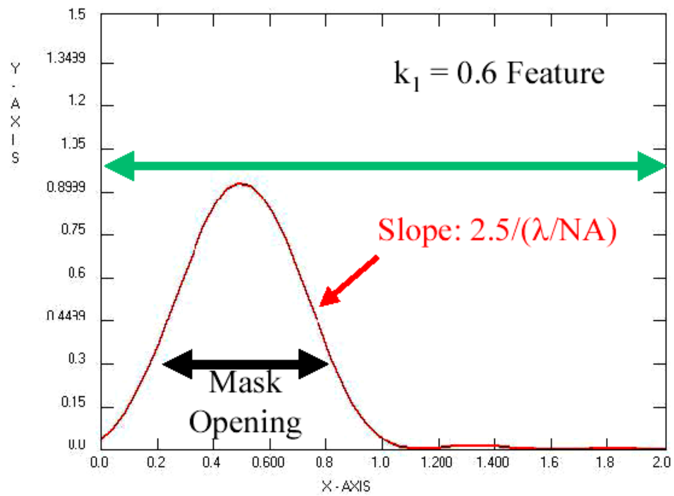


## Questions:

**How does contrast change as a function of feature size?**

**How does contrast change for coherent vs. partially coherent light?**

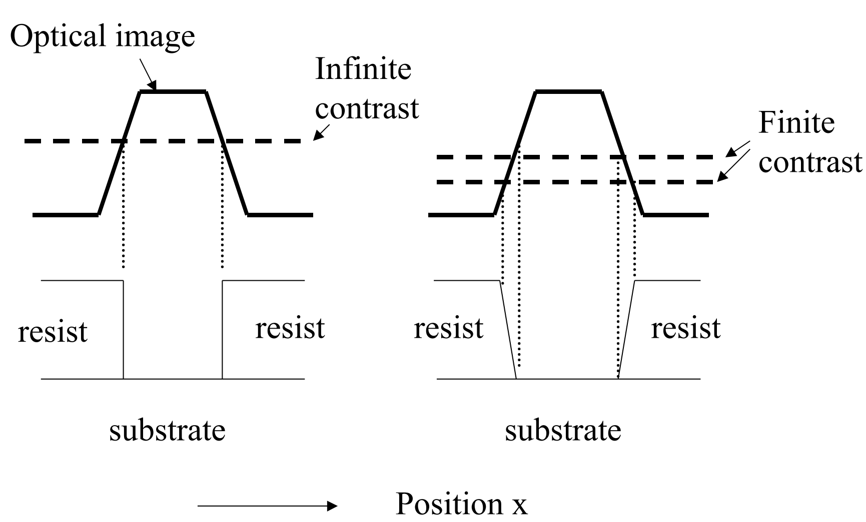
## Image Quality metric: Slope of image



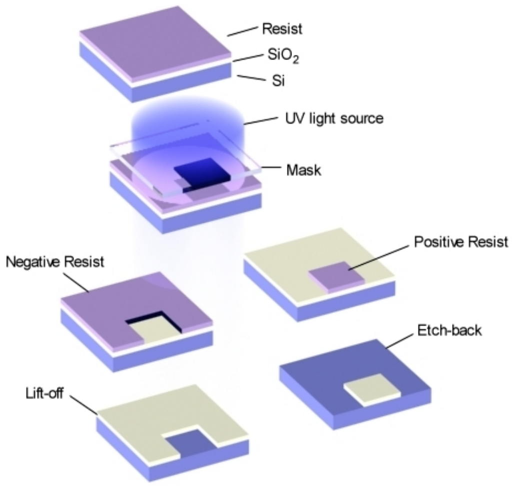

*** simulated aerial image of an isolated line**



## The Need for High Contrast



## Resists for Lithography



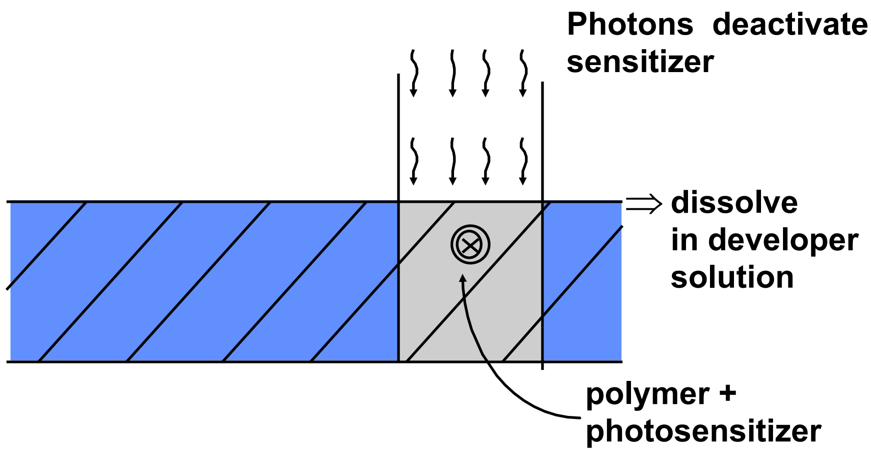

- Resists
  - Positive
  - Negative
- Exposure Sources
  - Light
  - Electron beams
  - X-ray sensitive



## Two Resist Types

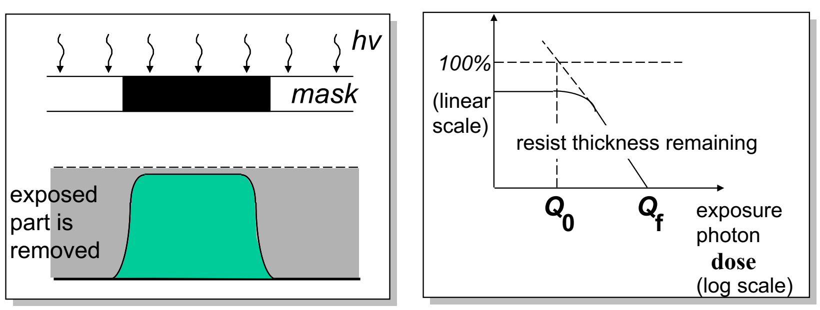
- Negative Resist
  - Composition:
    - Polymer (Molecular Weight (MW) ~65000)
    - Light Sensitive Additive: Promotes Crosslinking
    - Volatile Solvents
  - Light breaks N-N in light sensitive additive => Crosslink Chains
  - Sensitive, hard, Swelling during Develop
- Positive Resist
  - Composition
    - Polymer (MW~5000)
    - Photoactive Dissolution Inhibitor (20%)
    - Volatile Solvents
  - Inhibitor Looses N2 => Alkali Soluble Acid
  - Develops by “etching” - No Swelling.

## Positive P.R. Mechanism



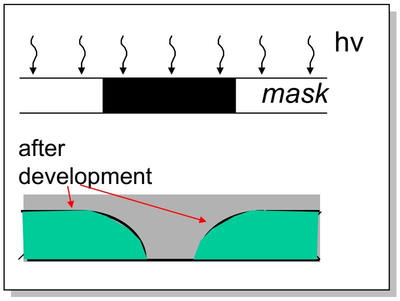


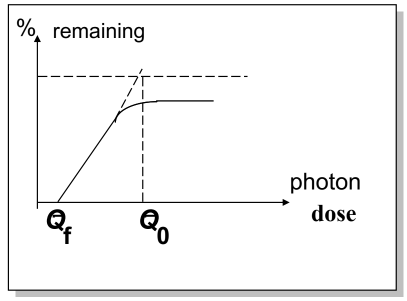

## Positive Resist




$$\text{Resist Contrast} = \frac{1}{\log_{10}\left(\frac{Q_f}{Q_0}\right)}$$

## Negative P.R. Mechanism



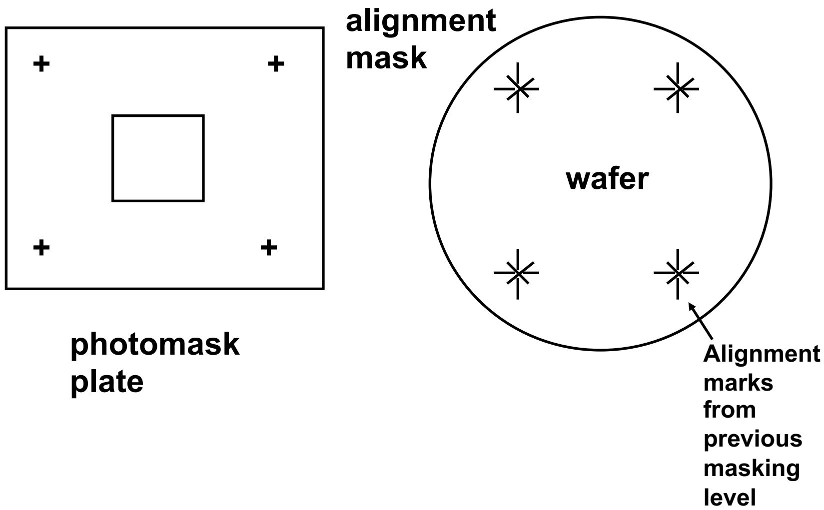

**hv => cross-linking => insoluble in developer solution.**



## Positive vs. Negative Photoresists

- **Positive P.R.:**
  - ✓ **higher resolution**
  - ✓ **aqueous-based solvents**
  - × **less sensitive**
- **Negative P.R.:**
  - ✓ **more sensitive => higher exposure throughput**
  - ✓ **relatively tolerant of developing conditions**
  - ✓ **better chemical resistance => better mask material**
  - ✓ **less expensive**
  - × **lower resolution**
  - × **organic-based solvents**

## Overlay Errors

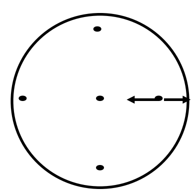





## (1) Thermal Run-in/Run-out errors

$$R = r \cdot \left( \Delta T_m \cdot \alpha_m - \Delta T_{si} \cdot \alpha_{si} \right)$$

run-out error — wafer radius

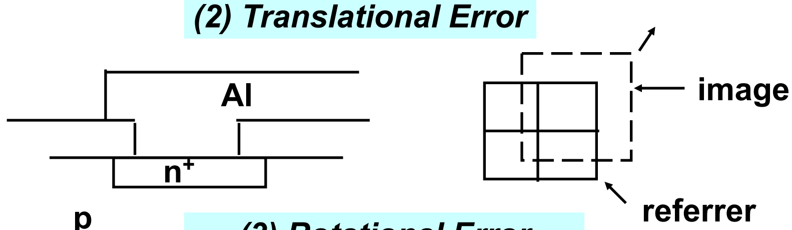


$\Delta T_m, \Delta Tsi$ = change of mask and wafer temp.

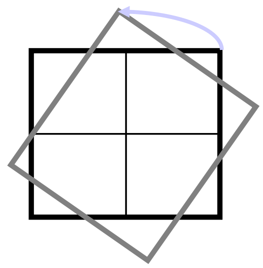
$\alpha_m, \alpha_{si}$ = coefficient of thermal expansion of mask & Si

## Rotational / Translational Errors

*(2) Translational Error*

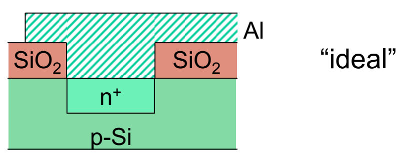


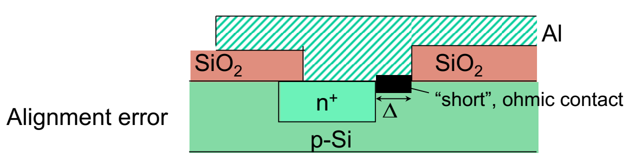

*(3) Rotational Error*



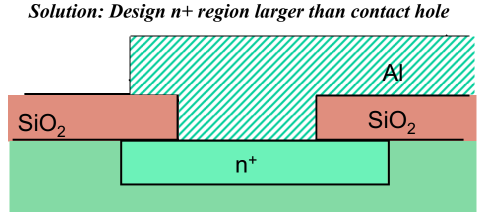


## Overlay implications: Contacts

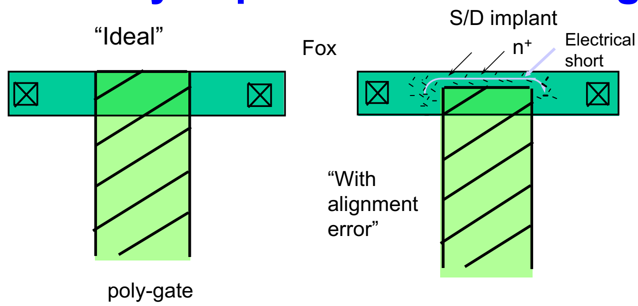


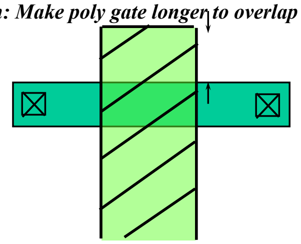

***Solution: Design n+ region larger than contact hole***



## Overlay implications: Gate edge




***Solution: Make poly gate longer to overlap the FOX***





## Total Overlay Tolerance

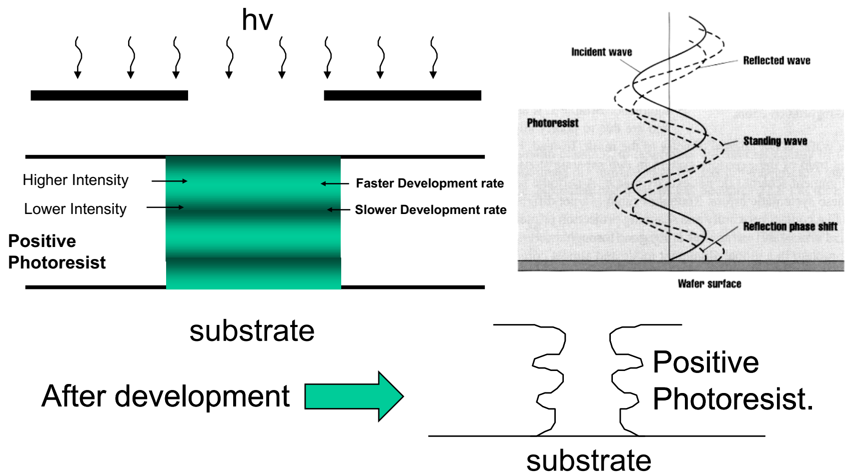
$$\sigma^2{}_{total} = \sum_i \sigma_i{}^2$$

**$\sigma_i$ = std. deviation of overlay error for $i^{th}$ masking step**

**$\sigma_{total}$ = std. deviation for total overlay error**

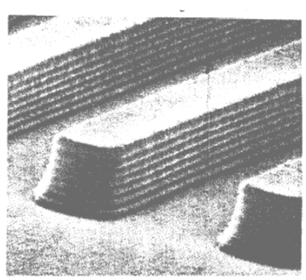
**Layout design-rule specification should be > $\sigma_{total}$**

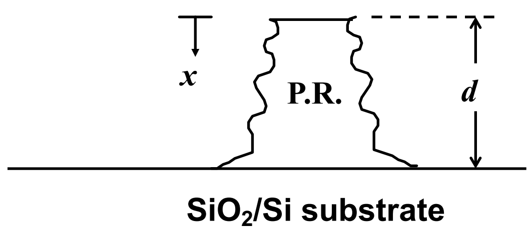
## Standing Waves




1-39

## Standing waves in photoresists





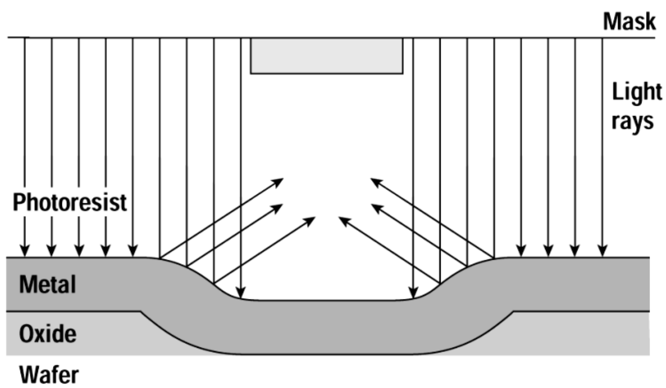

**Intensity = minimum when** $x = d - m\frac{\lambda}{2n}$ **m = 0, 1, 2,...**

**Intensity = maximum when** $x = d - m\frac{\lambda}{4n}$ **m = 1, 3, 5,...**

**n = refractive index of *resist***

1-40

## Proximity Scattering

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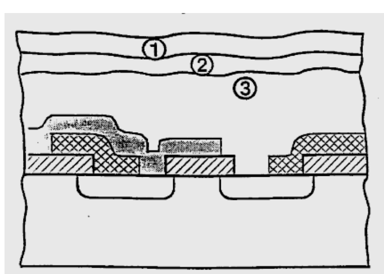
## Approaches for Reducing Substrate Effects

- Use absorption dyes in photoresist
- Use anti-reflection coating (ARC)
- Use multi-layer resist process
  - 1: thin planar layer for high-resolution imaging
  - 2: thin develop-stop layer, used for pattern transfer to 3
  - 3: thick layer of hardened resist

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## Electron-Beam Lithography

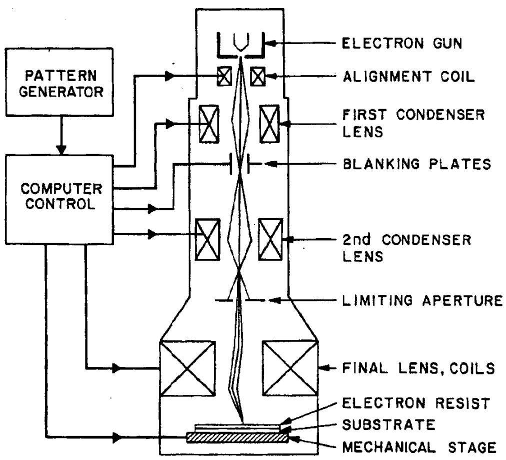



**Fig. 13** Schematic of an electron beam machine.[12]

$$\lambda = \frac{12.3}{\sqrt{V}}$$ **Angstroms for $V$ in Volts**

***Example: 30 kV e-beam => $\lambda$ = 0.07 Angstroms***

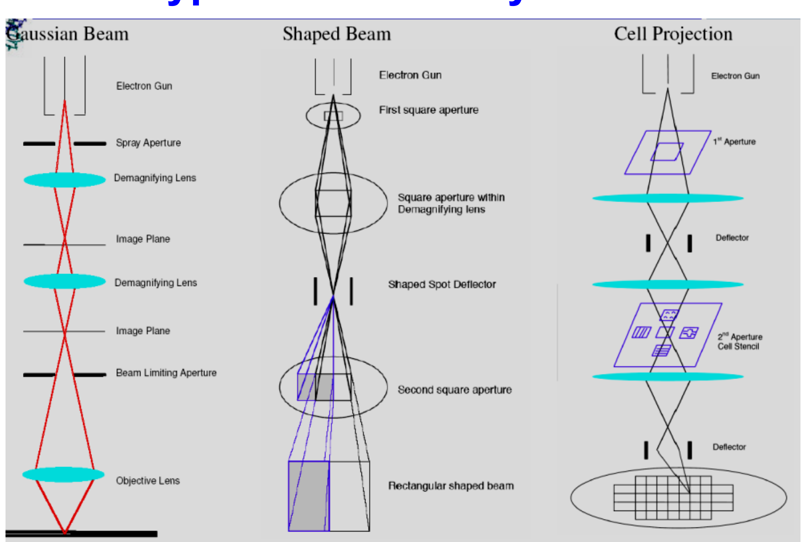
**NA = 0.002 – 0.005**

**Resolution < 1 nm**

**But beam current needs to be 10's of mA for a throughput of more than 10 wafers an hour.**



## Types of Ebeam Systems



## Resolution limits in e-beam lithography

resolution factors

- beam quality ( ~1 nm)
- secondary electrons ( lateral range: few nm)

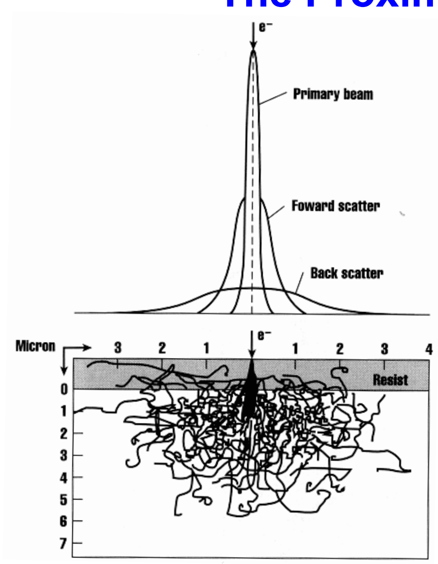
performance records

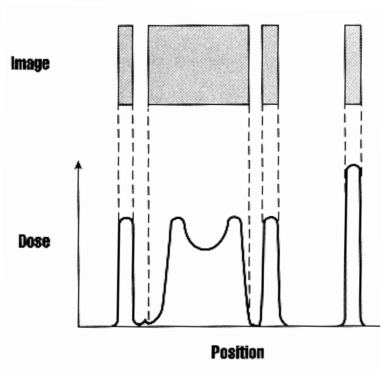
organic resist PMMA ~ 7 nm

inorganic resist, b.v. $AlF_3$ ~ 1-2 nm

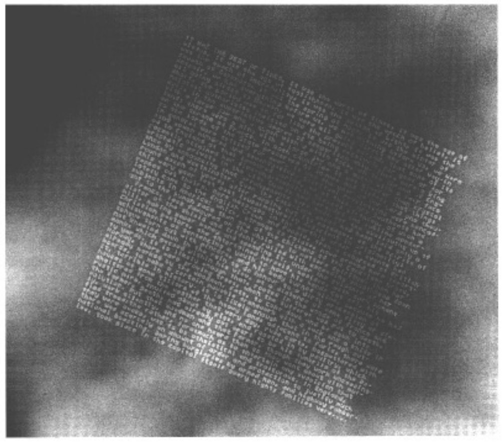


## The Proximity Effect



## 2nd Feynman Prize

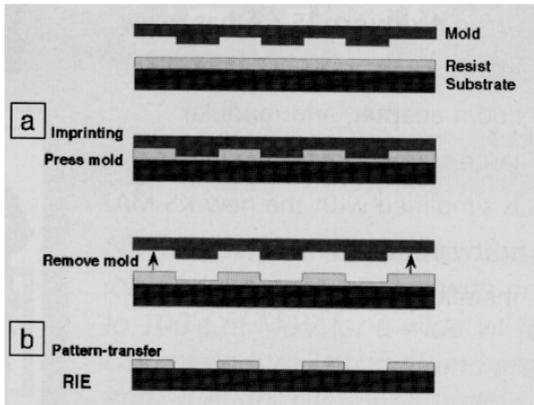


1985: Tom Newman, Fabian Pease (Stanford University) used e-beam lithography to write part of *A Tale of Two Cities* at the length scale requested by Feynman.




**Richard Feynman**

## Nanoimprint lithography (NIL)




The mold is typically patterned $SiO_2$ on Si. It is made with e-beam lithography.

The mold is pressed on the substrate. The resist is heated above its glass transition temperature.

The mold is removed.

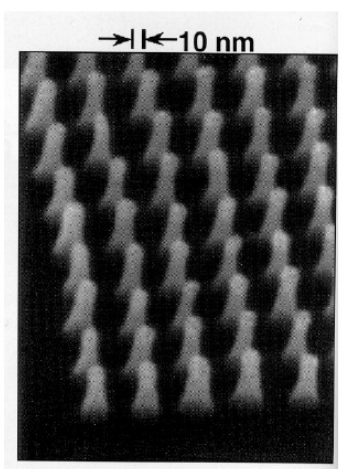
An anisotropic reactive ion etch is used to remove the resist until the substrate is exposed.

The substrate is patterned by etching or lift-off techniques.

Stephen Chou et al. *Science* **272** (1996) 85.
*Mat. Res. Soc. Bull.* July 2001, p. 512.



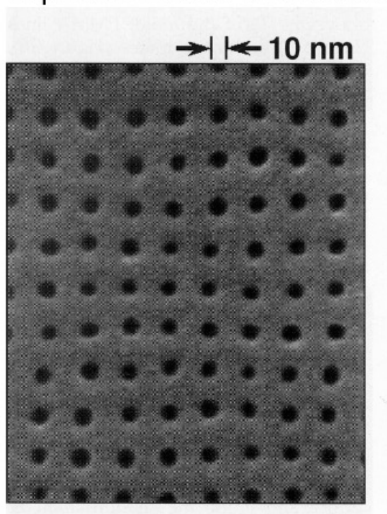
## SEM image of mold




This mold consists of $SiO_2$ pillars on an Si wafer.

It had already been used 10 times before the image was taken. The quality of the mold was not degraded by use.

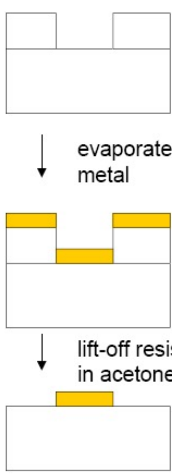
Holes imprinted into a PMMA resist layer

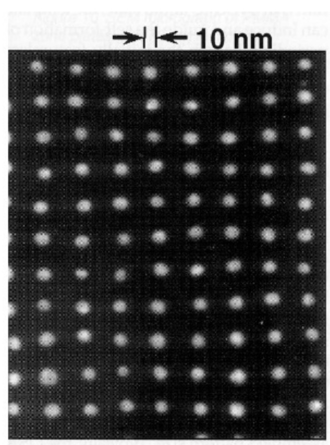



Stephen Chou, *Mat. Res. Soc. Bull*. July 2001, p. 512.

1-51

Metal dots after lift-off

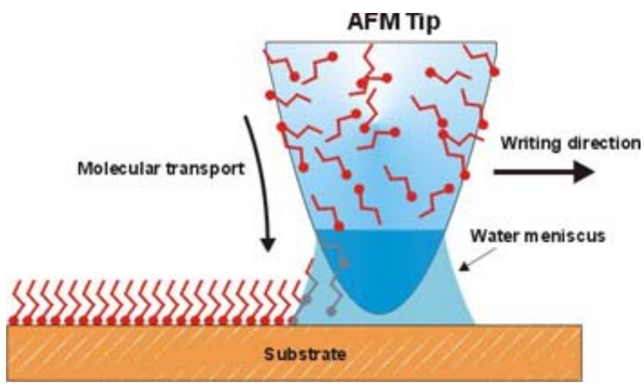



Stephen Chou, *Mat. Res. Soc. Bull*. July 2001, p. 512.

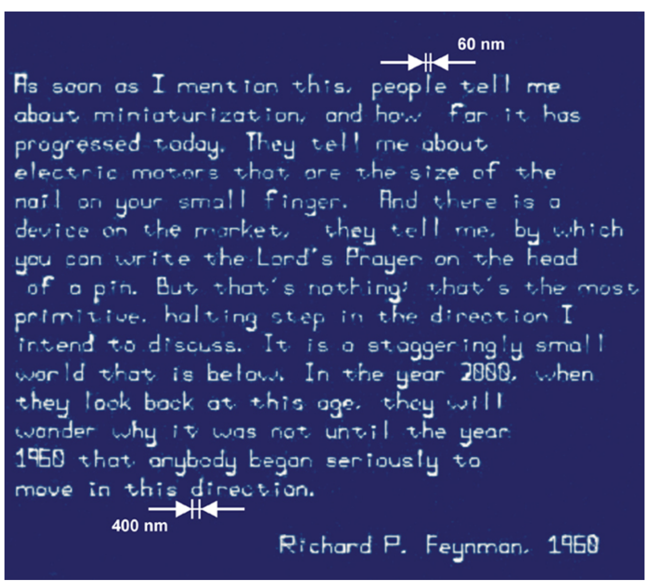
1-52

# Dip Pen Nanolithography



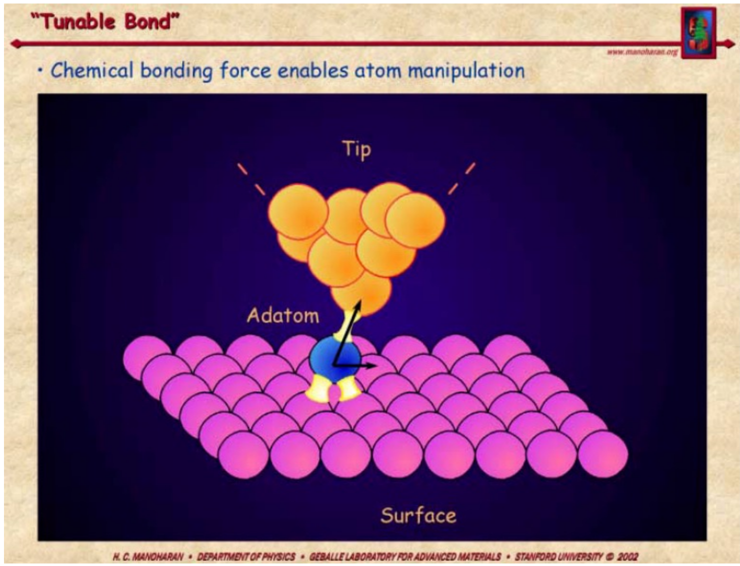

**Dip-Pen Nanolithography: Transport of molecules to the surface via water meniscus.**

1-53

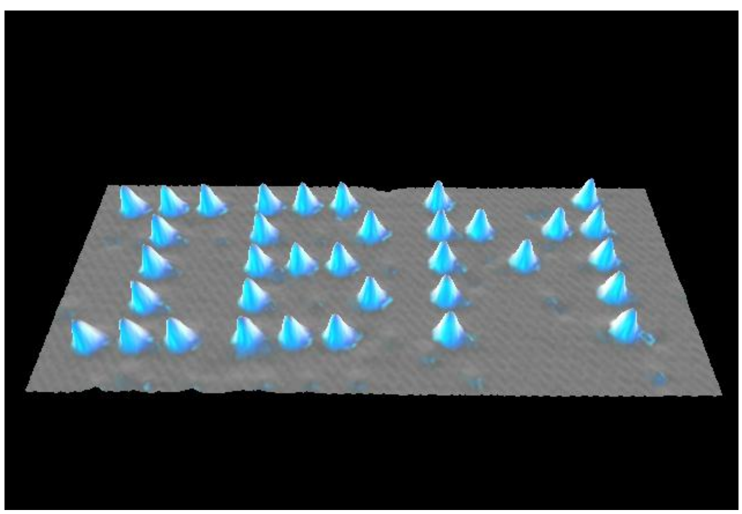



**Dip-pen Lithography, Chad Mirkin, NWU**

1-54




1-55



**Patterning of individual Xe atoms on Ni, by Eigler (IBM)**

1-56