# Electron Beam Lithography

*Marco Salerno*

# Outline

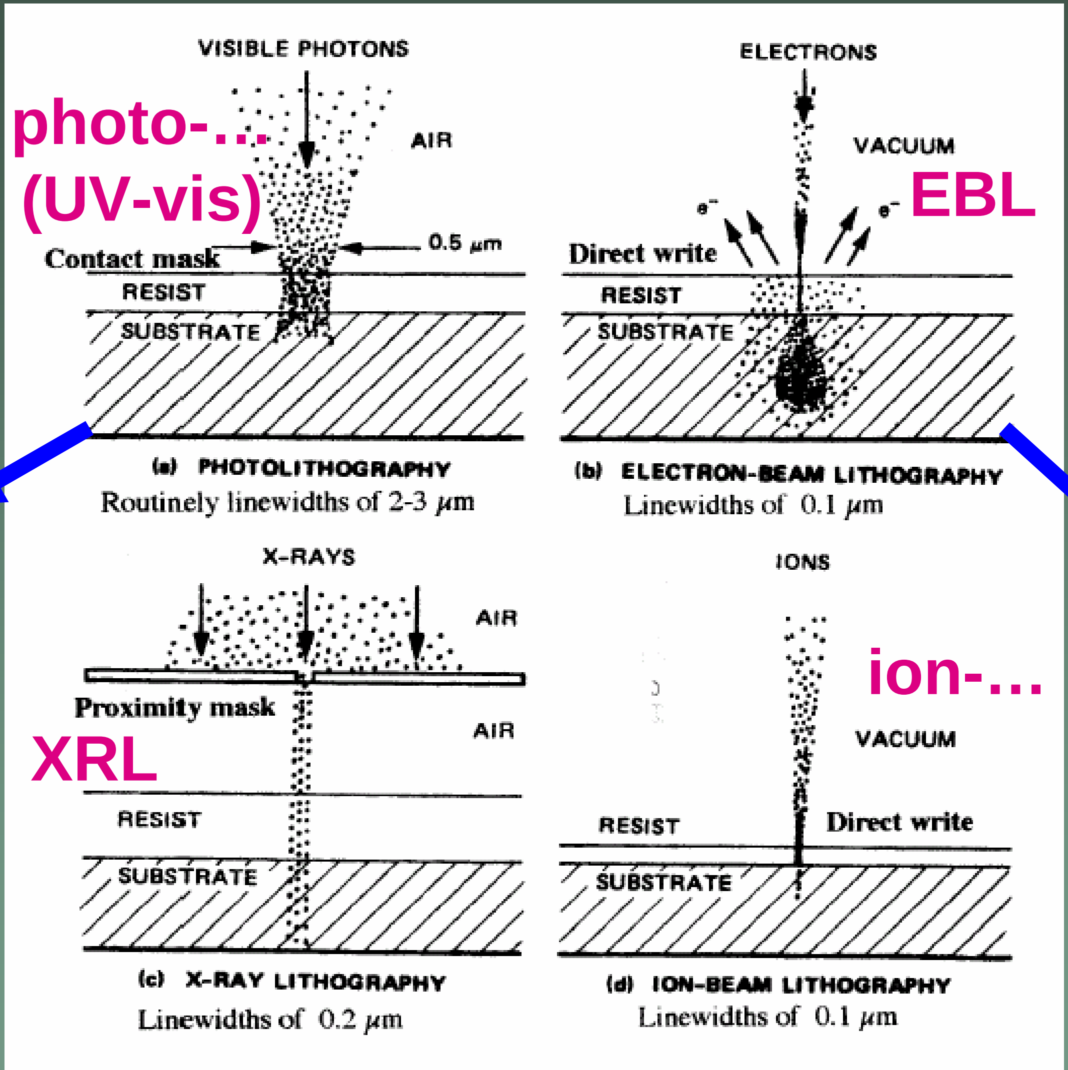
- general lithographic concepts
- EBL extensions to SEM
- SEM imaging issues
- EBL stage motion & calibration
- EBL exposure & specific issues

# Types of conventional lithography

$\lambda = h / p$

| | λ(E), [nm,eV] |
|---|---|
| γ | 1240 / E |
| e | 1.23 / √E |

$\lambda$ = 0.2-0.4 μm




(30 nm res)

**EUV**
$\lambda$ = 40-5 nm
(Intel)

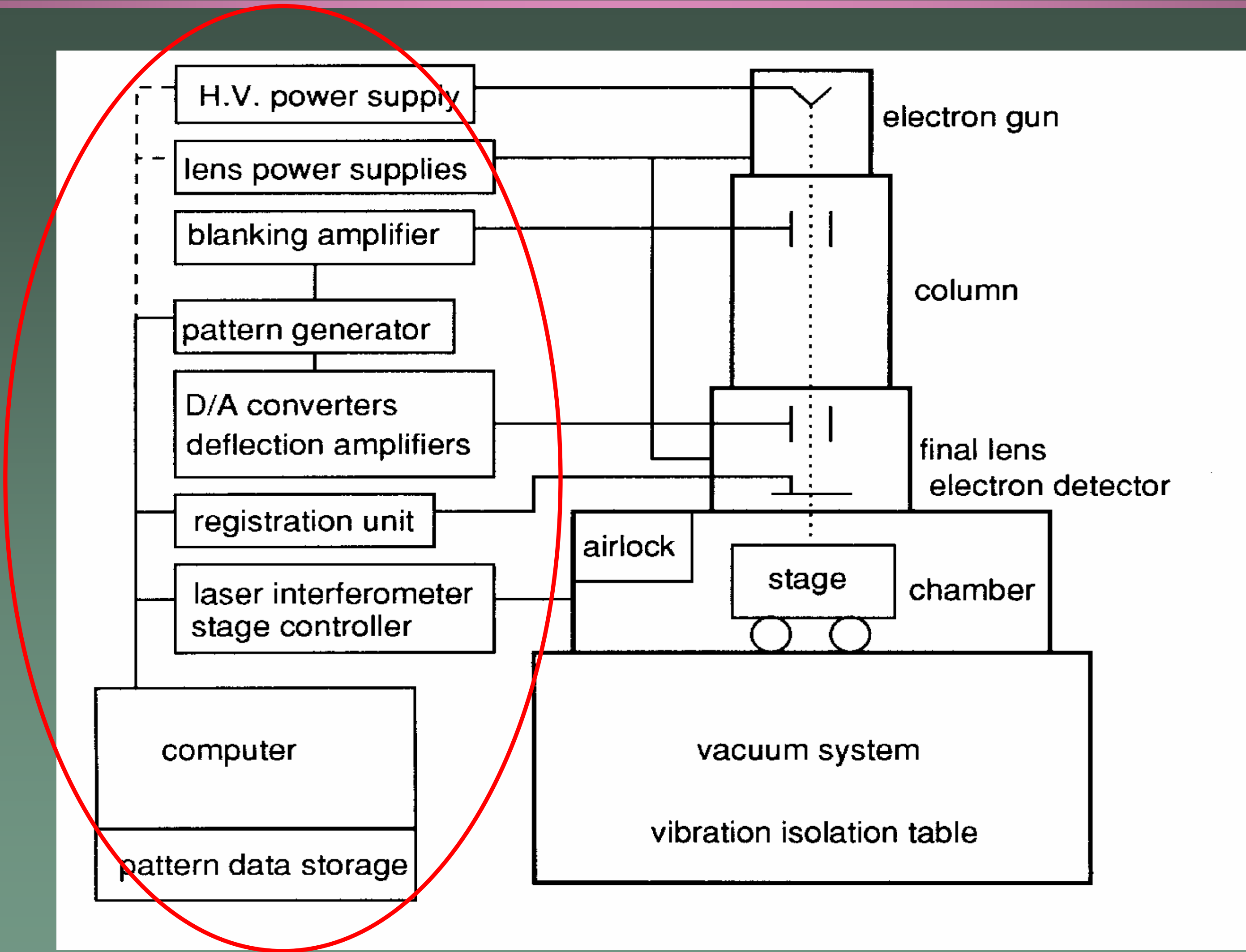
(10 nm res, Ta mask)

**SCALPEL**
(Lucent Tech)

- 2 membrane mask (hi and low e diffusion)
- scaled down

(20 nm res)

# Technical setup of EBL tools

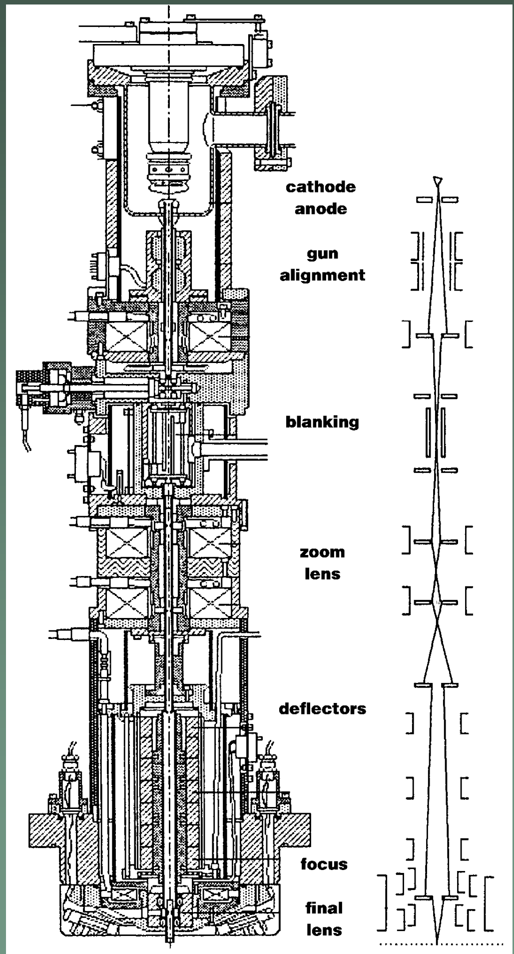



***+ rack with external control***
***+ PC (CAD)***

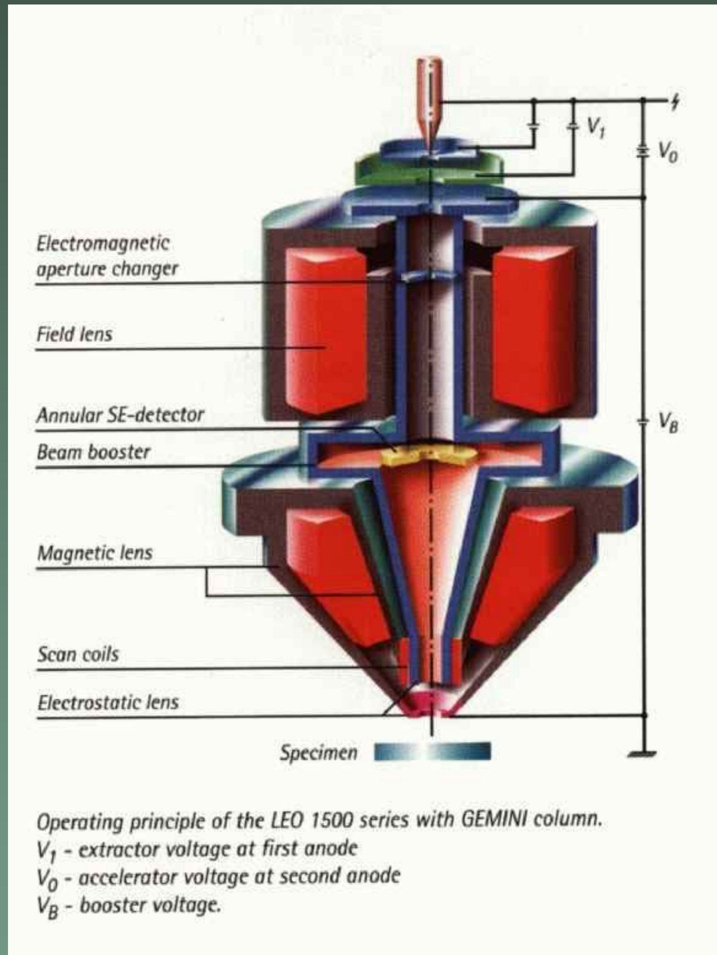
Source: SPIE Handbook of Microlithography
www.cnf.cornell.edu/SPIEBook/SPIE1.HTM

# Types of Electron Beam Columns

## Typical Electron Beam Column



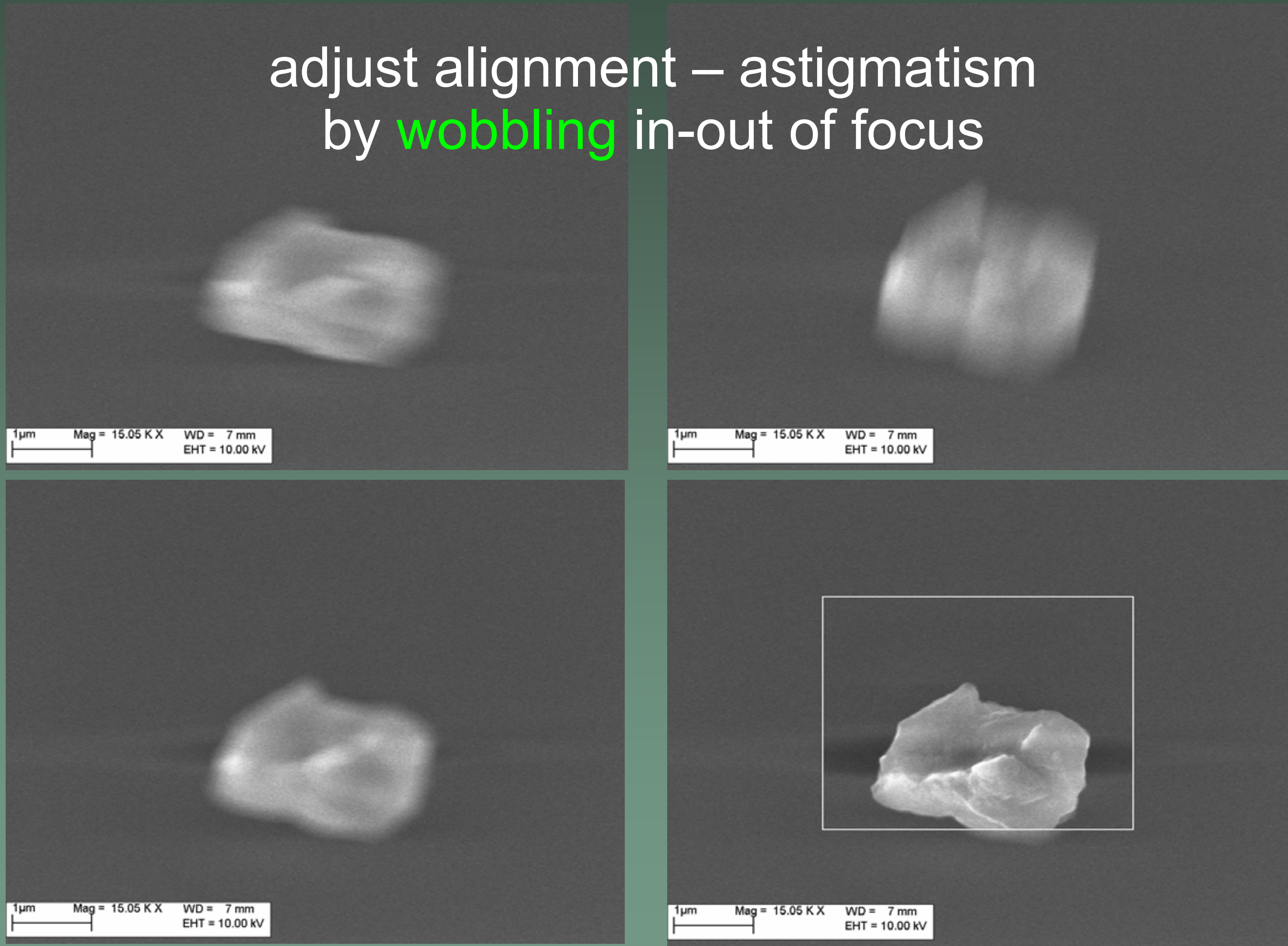

## Zeiss Gemini™ column




- no e- cross over → no Boersch-effect (additional energy spread)
- beam booster voltage of 8 kV for E<20 kV (+ final retardation) → no stray field effects
- sample is not part of the column e-optics → feels low em field (ok for e.g. magnetic samples)

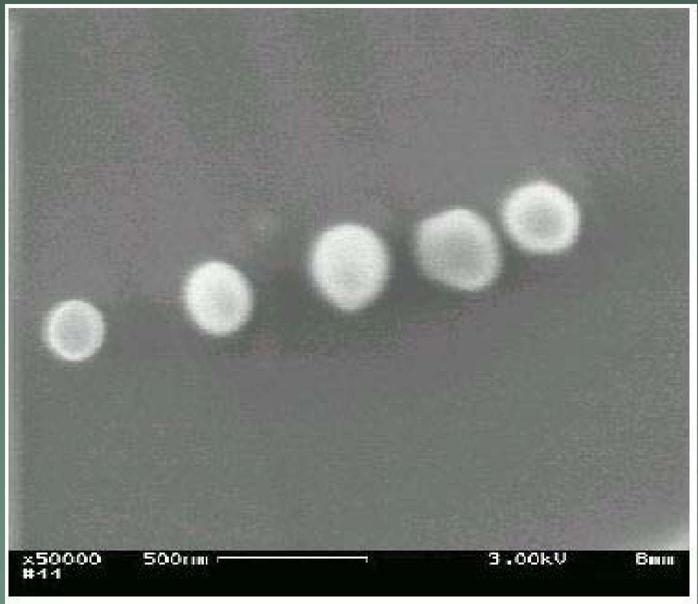
# good in EBL means good in SEM!

adjust alignment – astigmatism
by wobbling in-out of focus

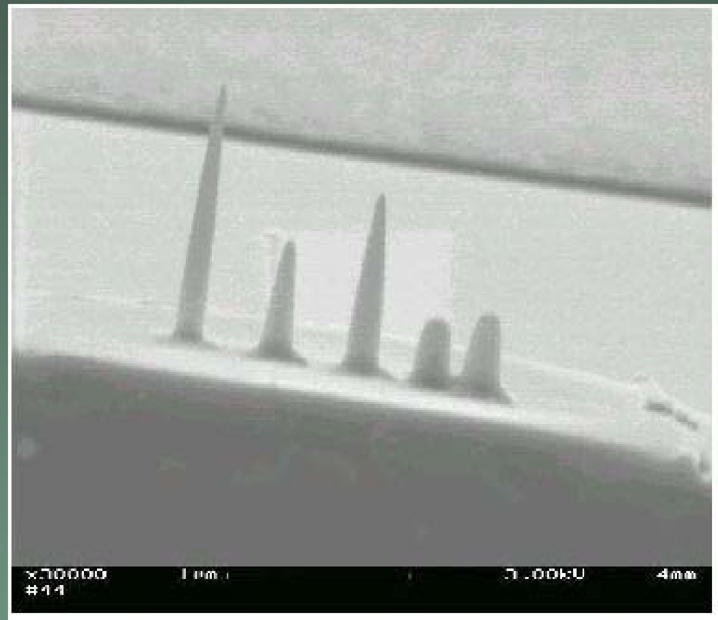


# Focussing - contamination dots

**top view**

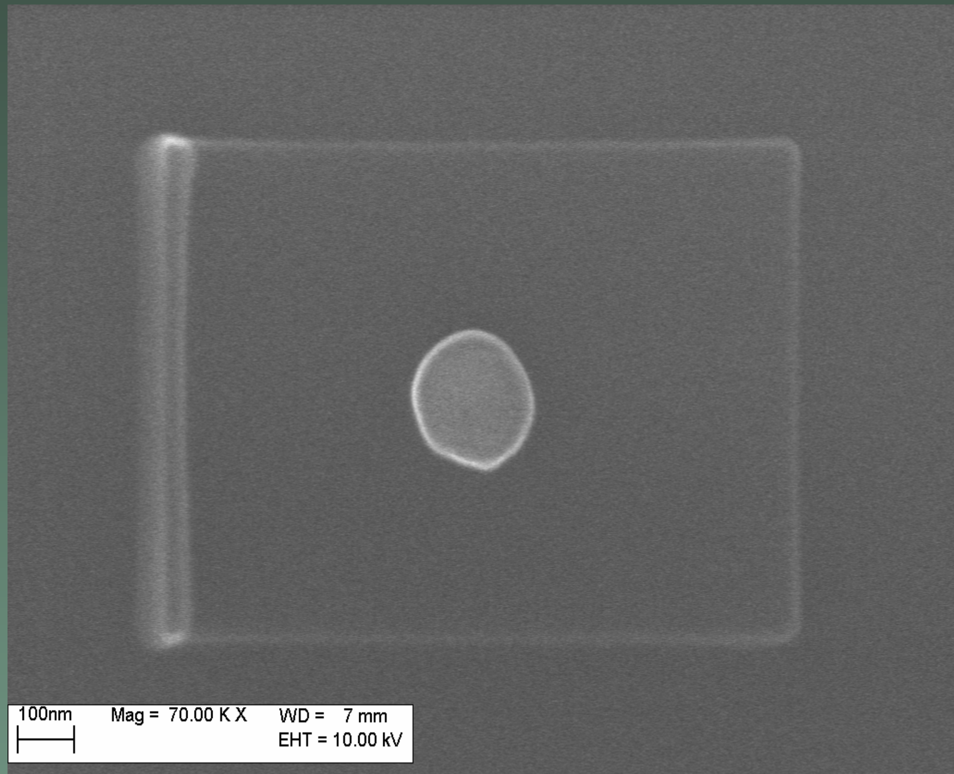



**side view**




( far – but not too much far – from the region of exposure: 0.5-1 mm)

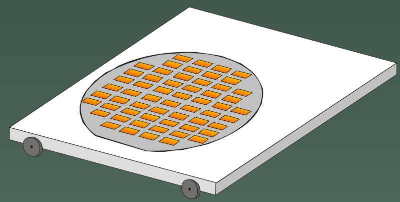
# Fundamental rule for SEM imaging




**Take always the LOW MAG images FIRST!!!**

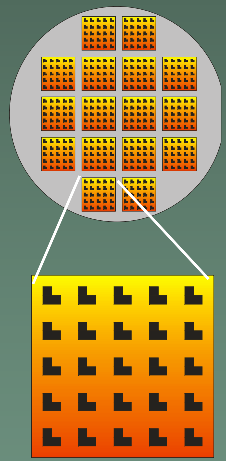
# Types of coordinate systems

**1. Stage**



**(X,Y)**

**2. Sample**



**(U,V) - global**

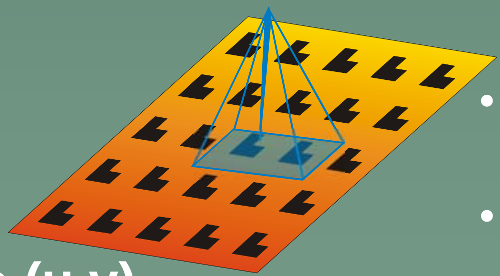
**3. Drawing**

**(u,v) - local**

**(repeated in positionlist: SPL)**

**Beam:**

**has to move according to (u,v)**



- **zoom, shift, rotation in both axis**
- **no specific labeling**

# Coordinate Transformations 1

**Sample (U,V) ← Transformation → Drawing (u,v)**

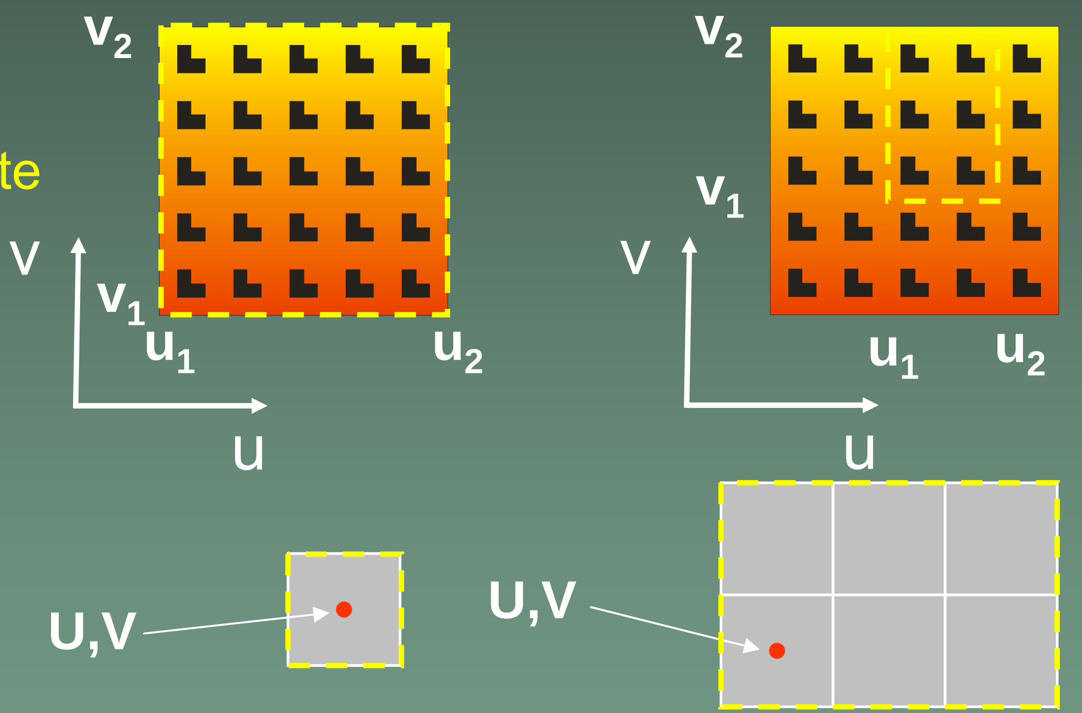
Working area = area in layout used during overall exposure, WA ≤ (CAD) Layout

case 1:
WA = Complete Layout

case 2:
WA = Part of Layout

case a:
WF = WA

case b:
WF < WA




Write Field = area in WA used in different exposure steps, WF ≤ WA

**(U,V) coordinates (in SPL) = center of the first WF**

# Coordinate Transformations 2

**Sample (U,V)** ← **Transformation** → **Beam (zoom, shift, rot.)**

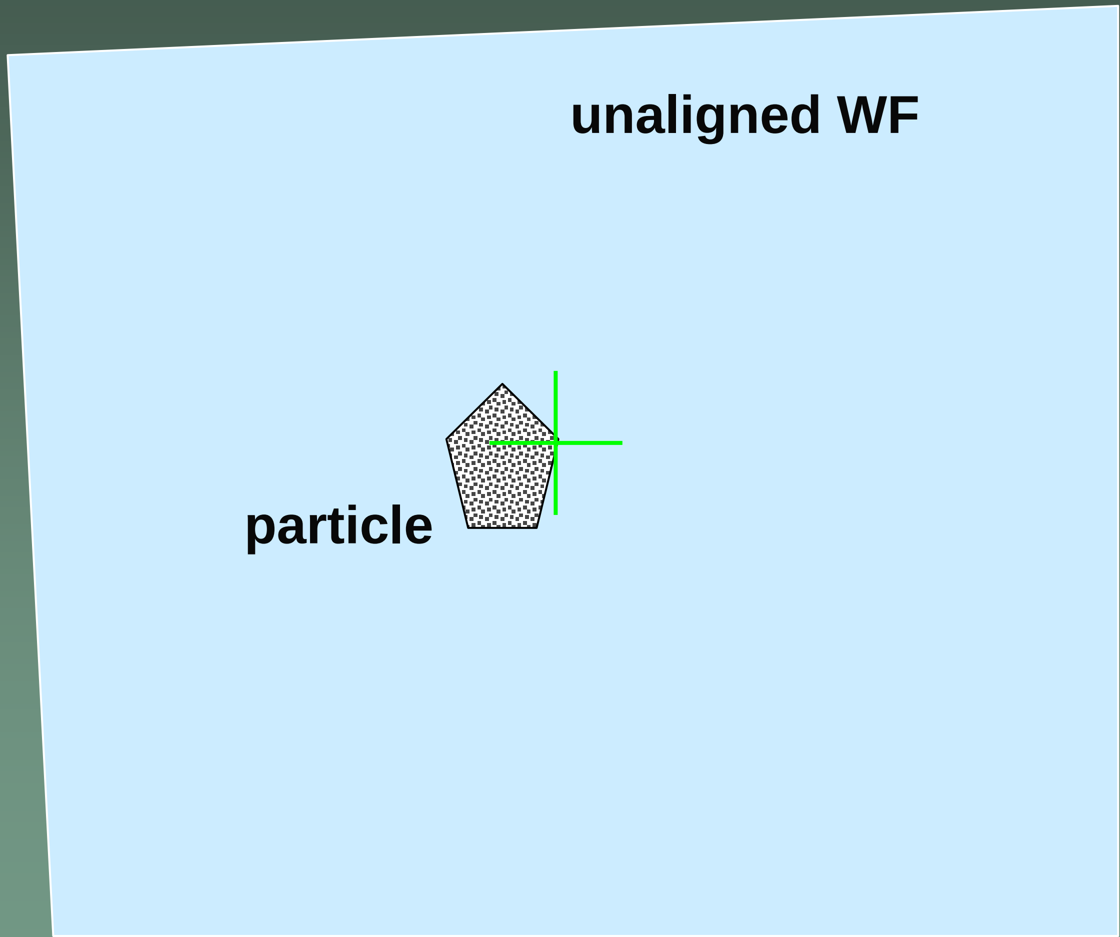
necessary to avoid Stitching problems, e.g.:


…why?

→ wrong beam movement, new calibration required

# Coordinate Transformations 2

**2. Sample (U,V)** ← **Transformation** → **4. Beam (zoom, shift, rot.)**

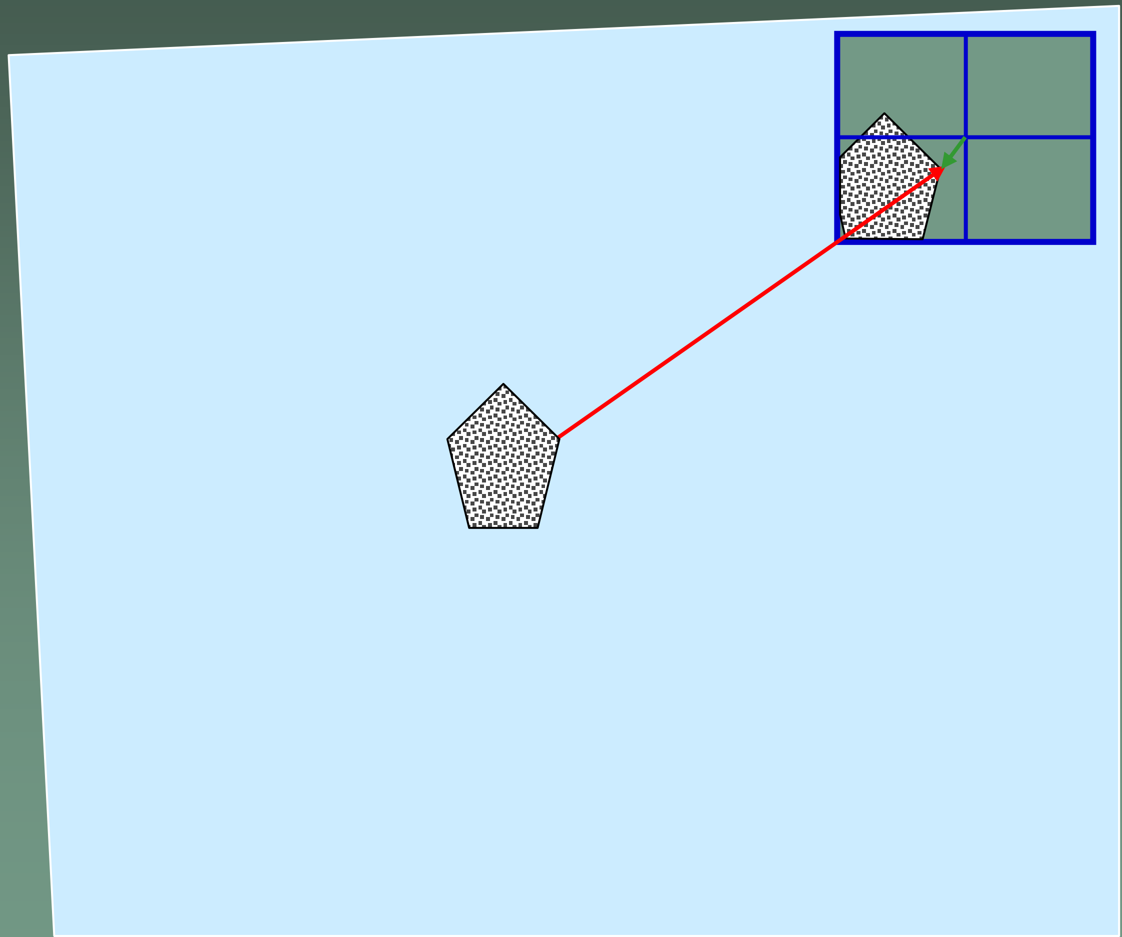



Self calibration technique using a particle and the stage:
its motion assumed perfect, on nm scale

**Procedure:**
- choose WF
- find dust particle
- choose a point on it & move it to middle of image

# Coordinate Transformations 2

**2. Sample (U,V)** ← **Transformation** → **4. Beam (zoom, shift, rot.)**



**Procedure:**

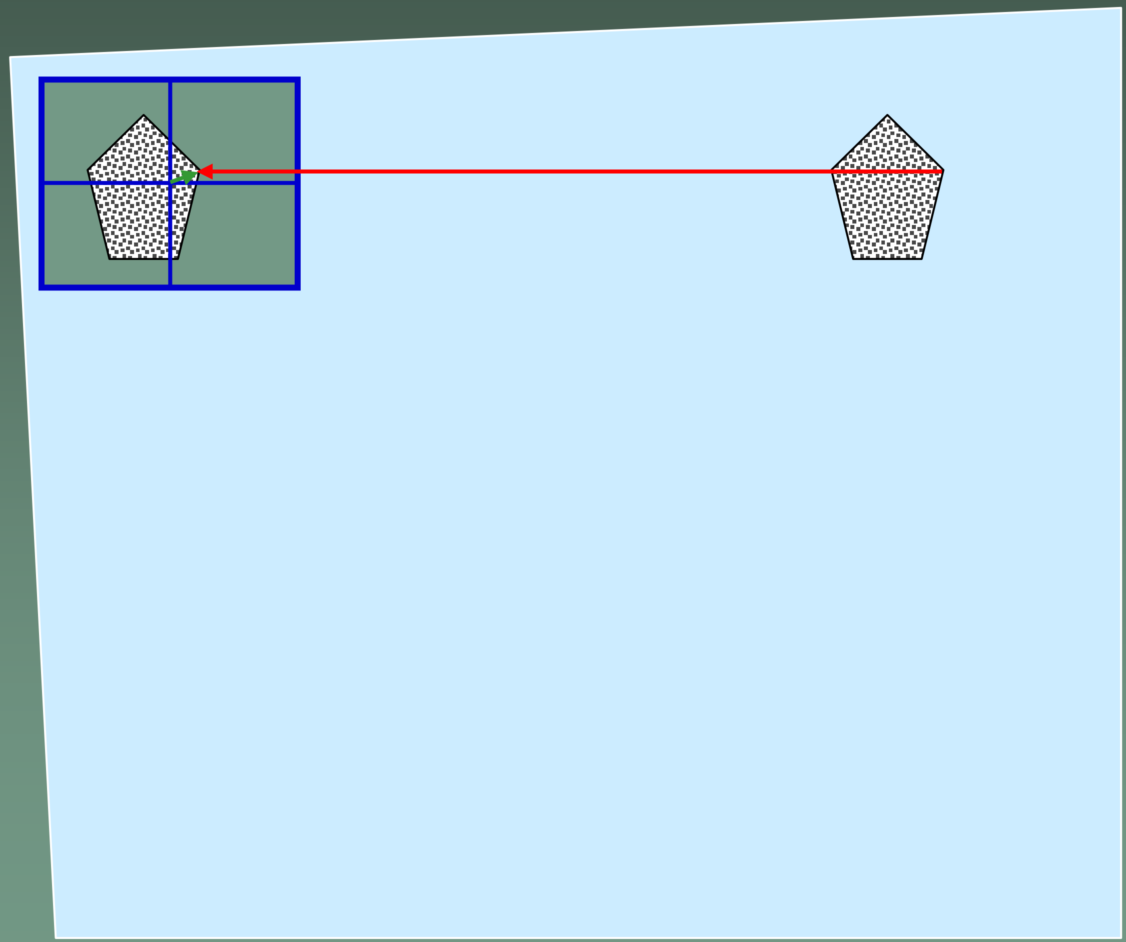
- move stage so that particle appears in next corner of write field

- take small image with SEM

- measure offset

# Coordinate Transformations 2

**2. Sample (U,V)** ← **Transformation** → **4. Beam (zoom, shift, rot.)**



**Procedure:**

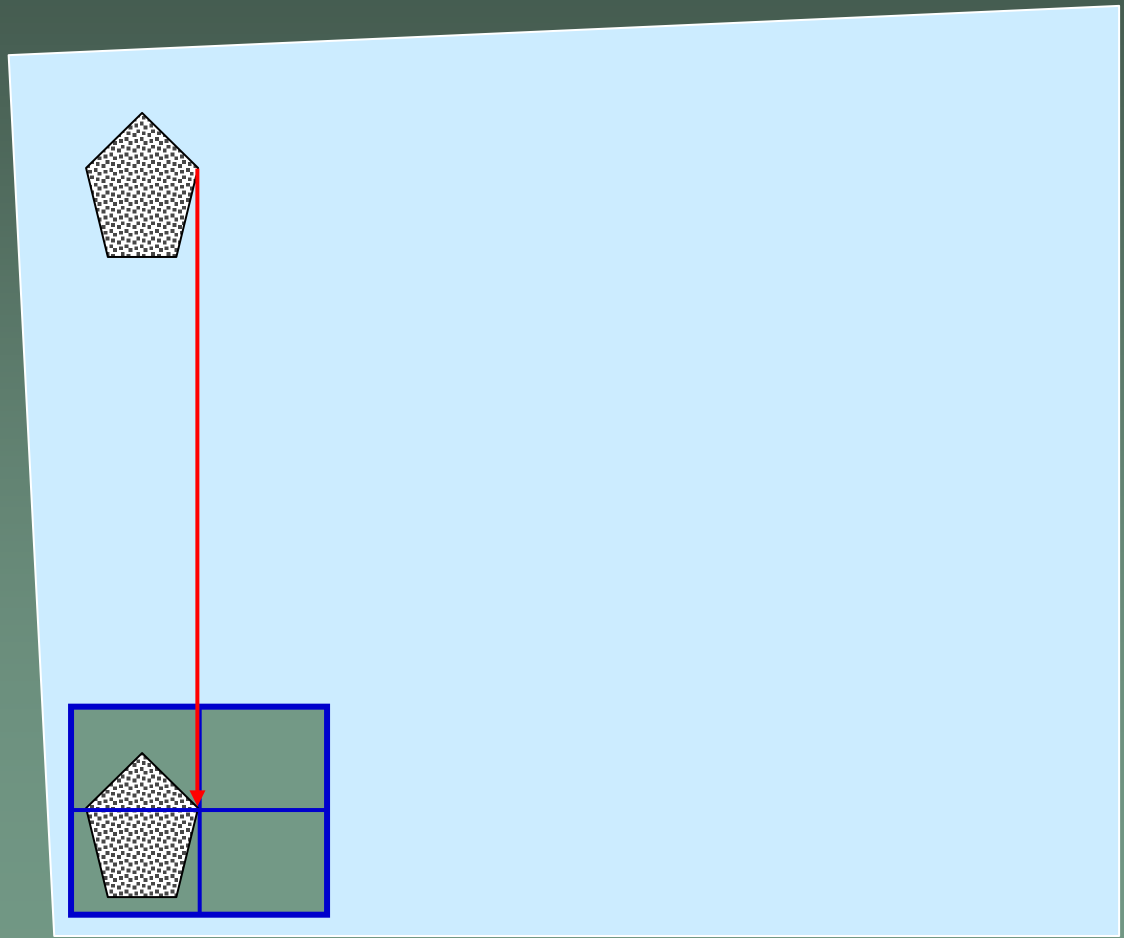
- move stage so that particle appears in next corner of write field

- take small image with SEM

- measure offset

# Transformations

**2. Sample (U,V) ← Transformation → 4. Beam (zoom, shift, rot.)**

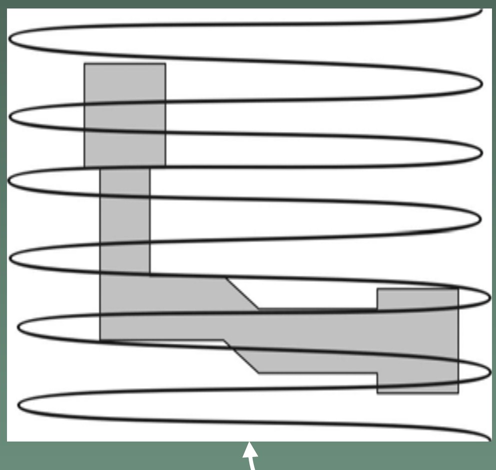


**Procedure:**

- move stage so that particle appears in next corner of write field
- take small image with SEM
- measure offset → calculate rotation, zoom

# Stage Movement methods

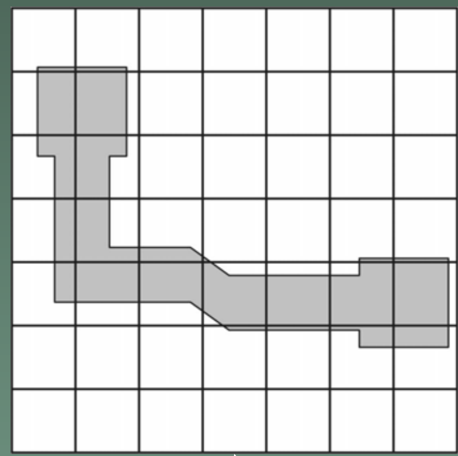
**moving stage**



**stripes**

**versus**

**stationary stage**

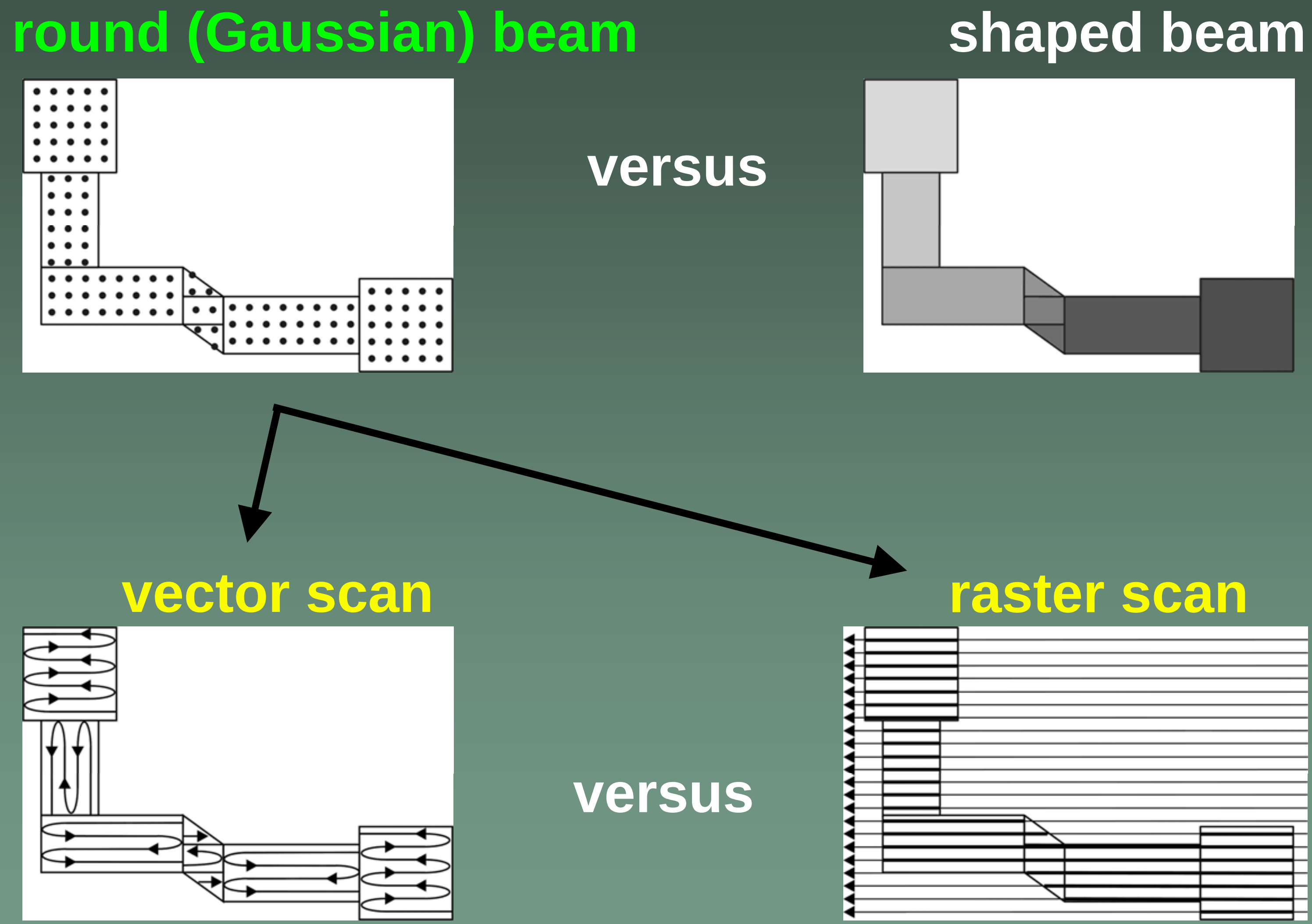


**fields**

**write "on-the-fly"**

**step & write**

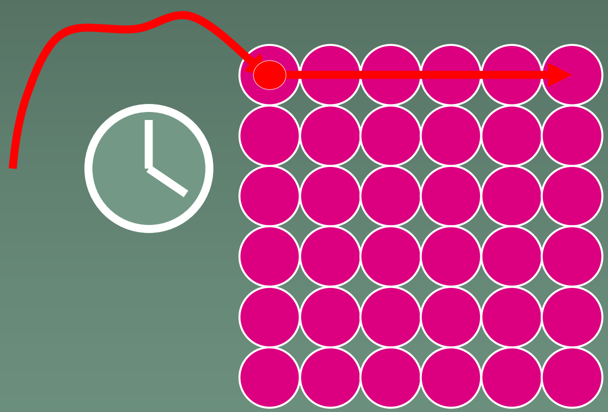
# Writing methods

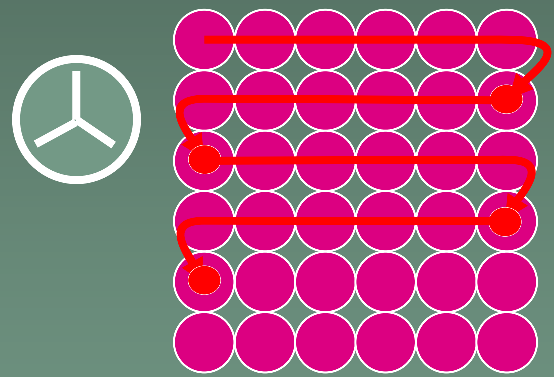


# Settling and flyback time

**Settling time** = waiting period at beginning of each element

**Flyback time** = waiting period between lines.





Flyback time = settling time × flyback factor

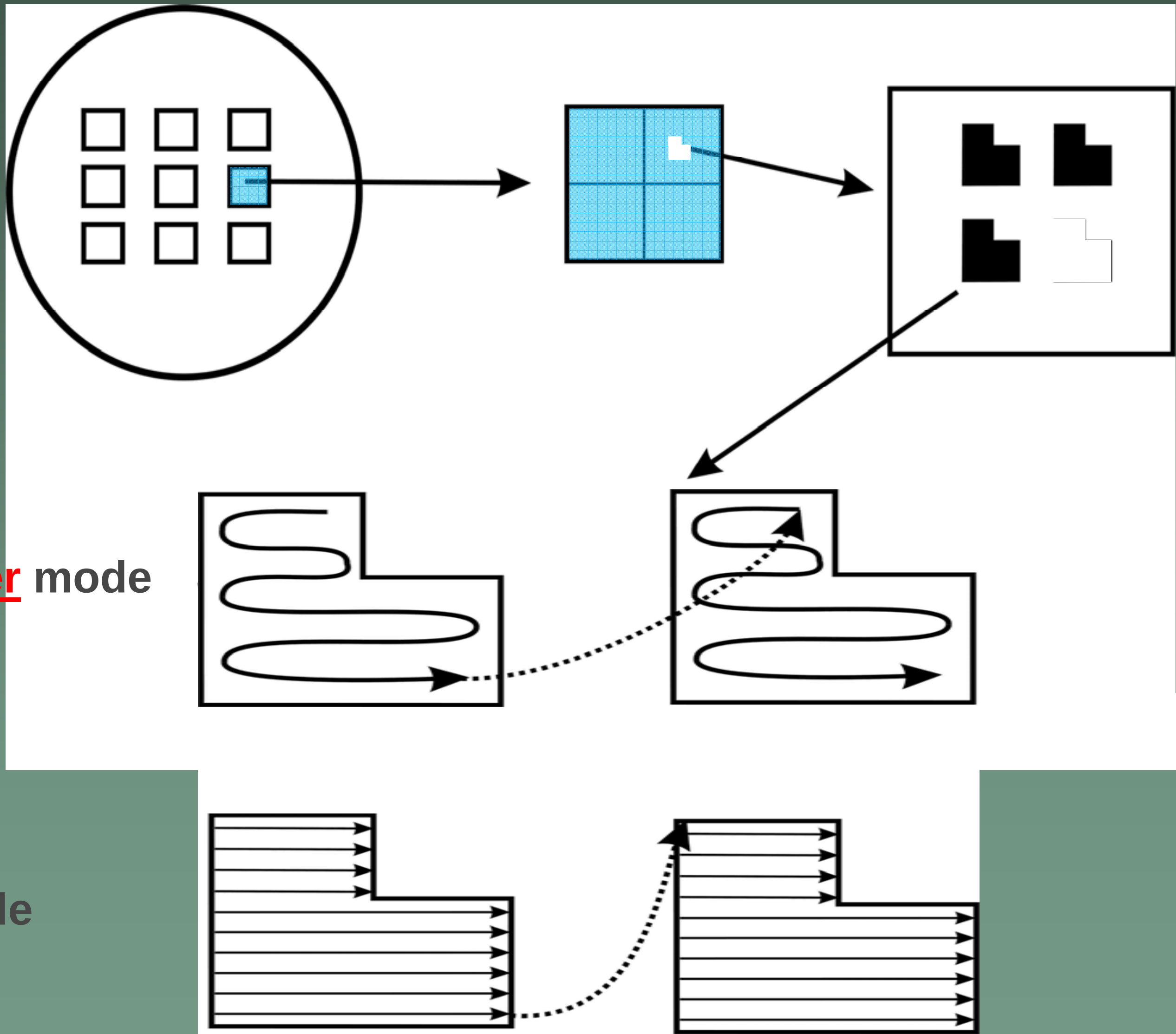
# Different Strategies

| company | beam | scan mode | stage |
| --- | --- | --- | --- |
| Raith | gaussian | vector | fixed |
| Etec | gaussian | raster | moving |
| Leica | shaped | --- | fixed |

# 1st Strategy (Raith)

**gaussian beam, vector scan, fixed stage**

wafer



**meander mode**

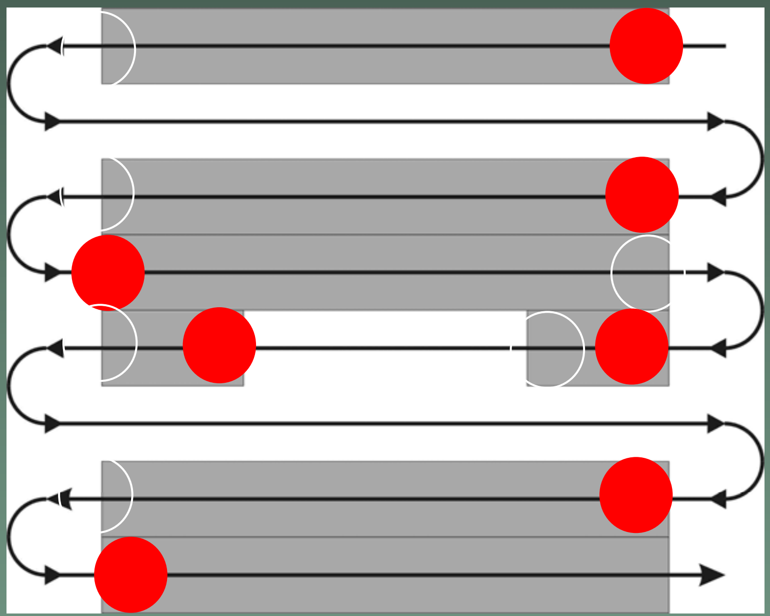
**line mode**

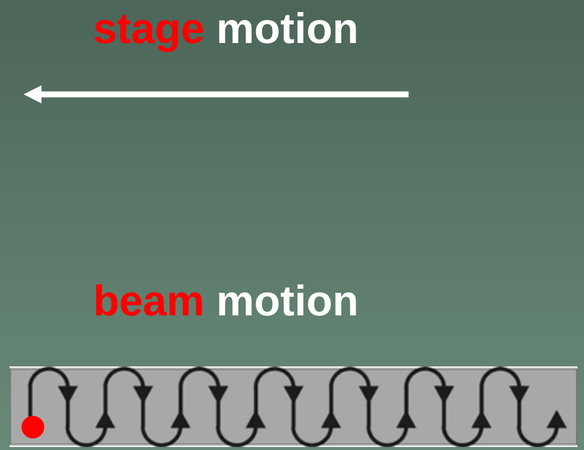
+ fast writing of sparse patterns (unwritten areas are skipped)
+ easy dose variation from shape to shape
– settling time & hysteresis → calibration
– overhead time caused by stage settling

Apps: nano litho, R&D, …

# 2nd Strategy (Etec)

**gaussian beam, raster scan, moving stage**





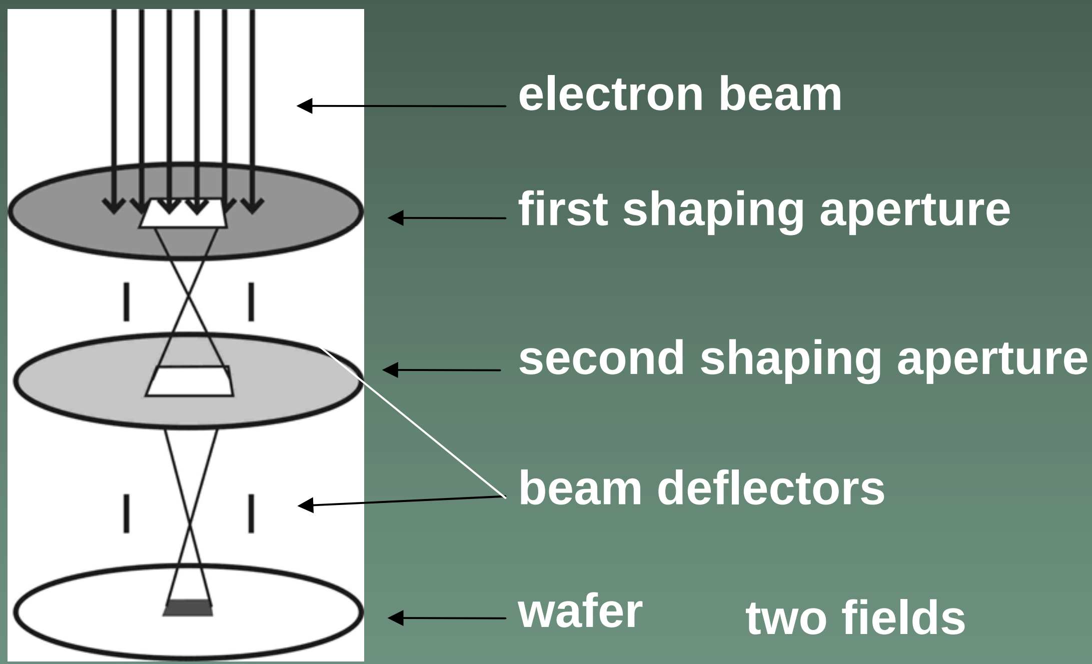

+ very simple
+ very repeatable
  calibration possible
– sparse patterns take as long as dense patterns
– difficult to adjust dose during writing

Apps: mask making

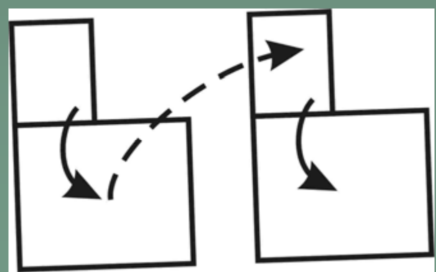
**(e.g. used by MEBES (Etec Systems Inc.))**

# 3rd Strategy (Leica)

## shaped beam, moving stage




two fields

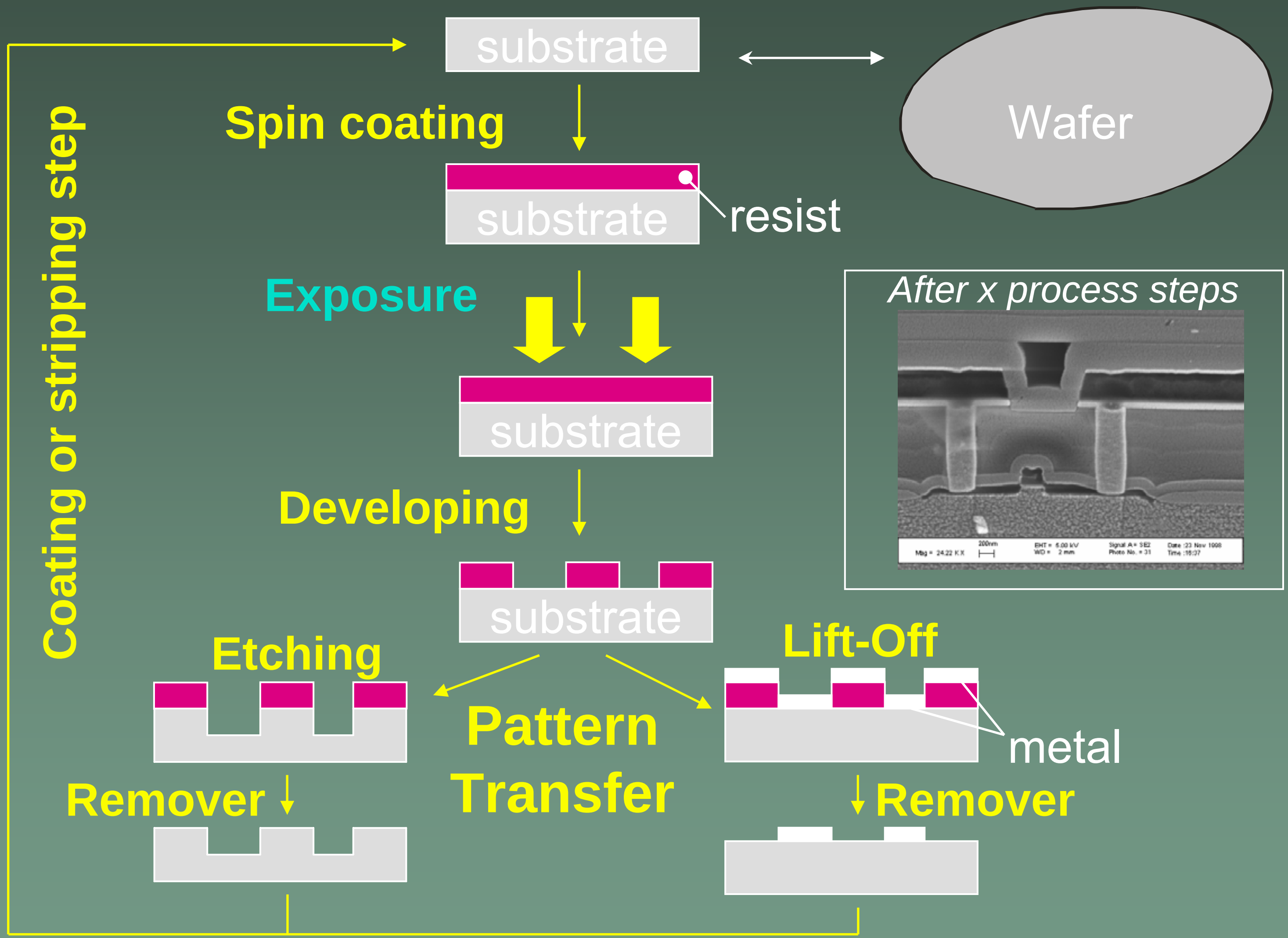


~ Gaussian vector scan, but :
an entire rectangle (up to 2x2 $\mu m^2$)
in a single "flash"

+ ≈ 10 x faster than equivalent gaussian beam machines
– extremely complex electron optical column
– complicated calibration routines
– resolution and focus varies with shape size

Apps: mask making, advanced chip development

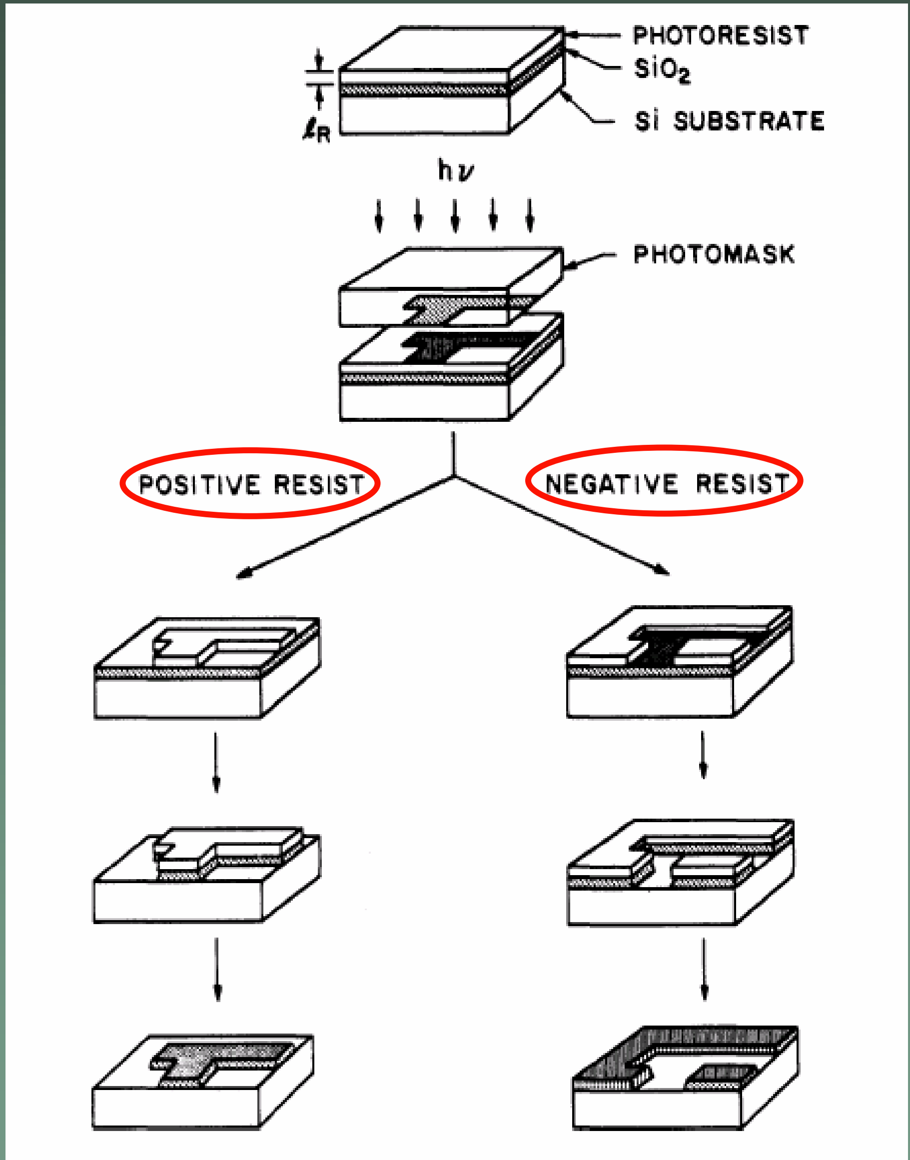
# Process steps



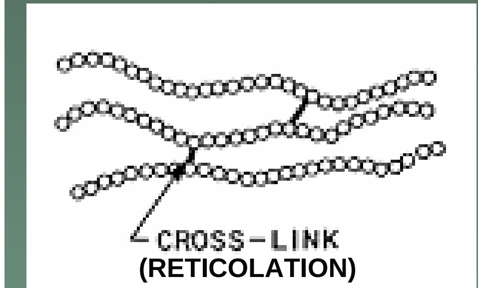
# Resist polarity



→
*lower MW*
*i.e.*
*more soluble*







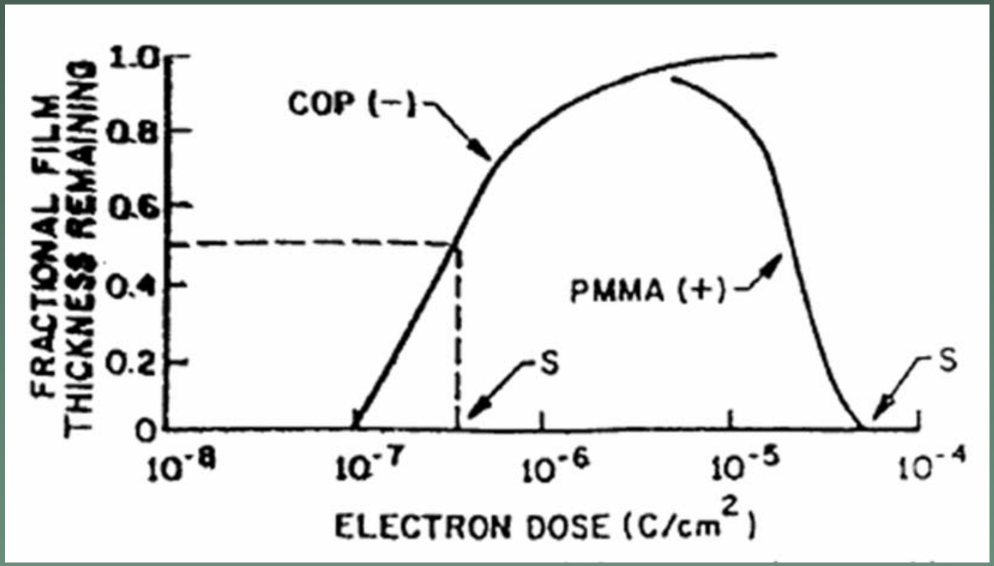

→
*higher MW*
*i.e.*
*less soluble*

# EBL resist contrast

Hurter-Driffield contrast curve (1890)

Contrast $\gamma = [\log_{10}(D_1)-\log_{10}(D_T)]^{-1}$

***COP copolimero glicedil metacrilato-etil acrilato (neg.)***




***PMMA PoliMetil-MetAcrilato (pos.)***

**High contrast:** **+ Steeper side walls**

**+ Greater process latitude**

**+ Better resolution (not always)**

**+ Less sensitivity to proximity effects**

**Low contrast:** **+ 3d lithography**

# Which resist for which application?

- positive or negative: depends on which will give a minimum area to be exposed
- literature and resist suppliers for resist performance with respect to e.g.

  *resolution, sensitivity, etching stability*
- check suitability for your lab, e.g. required baking steps and chemicals

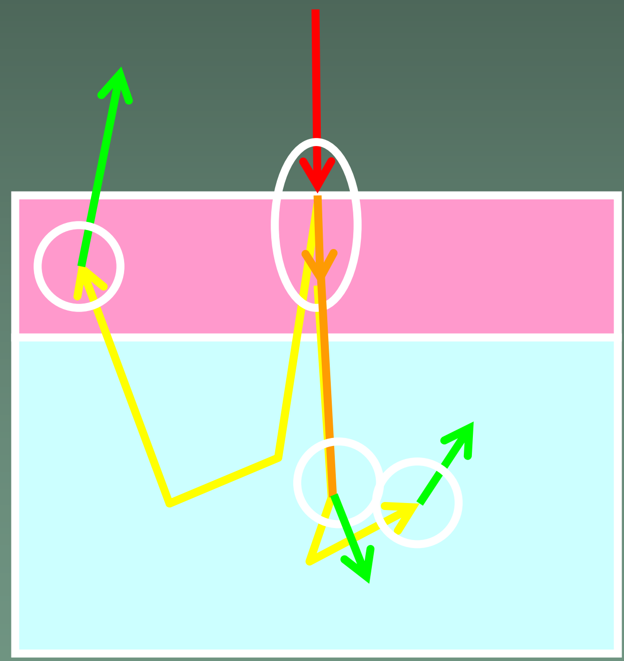
- avoid Chemically Amplified Resists because of the critical Post Exposure Bake
- make tests with positive resist, as the same substrate can be used more times

$\Rightarrow$ use for example PMMA 950K

# Forward scattering events

**Properties**

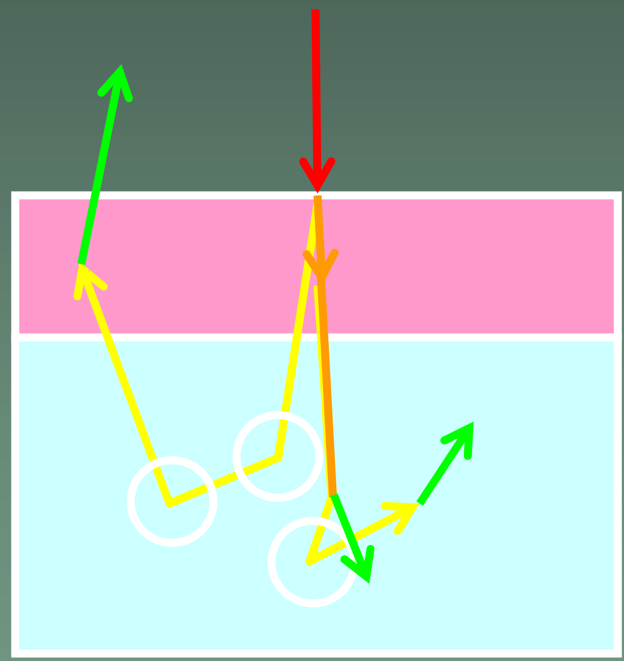
- **very often**
- **small angles**
- **hence very inelastic**
- **generation of SE with a few eV**



# Backscattering events

**Properties**

- **occasionally**
- **large angles**
- **hence mainly elastic**
- **high kinetic energy, range of the PE**

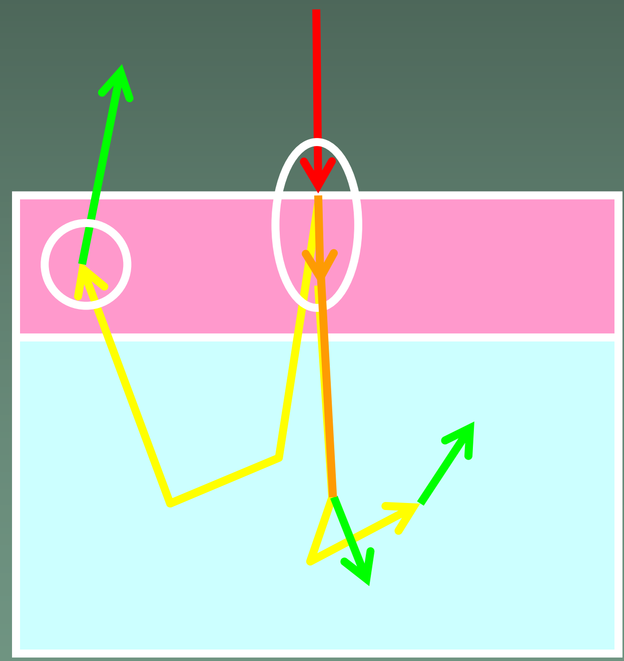


# What leads to an exposure?

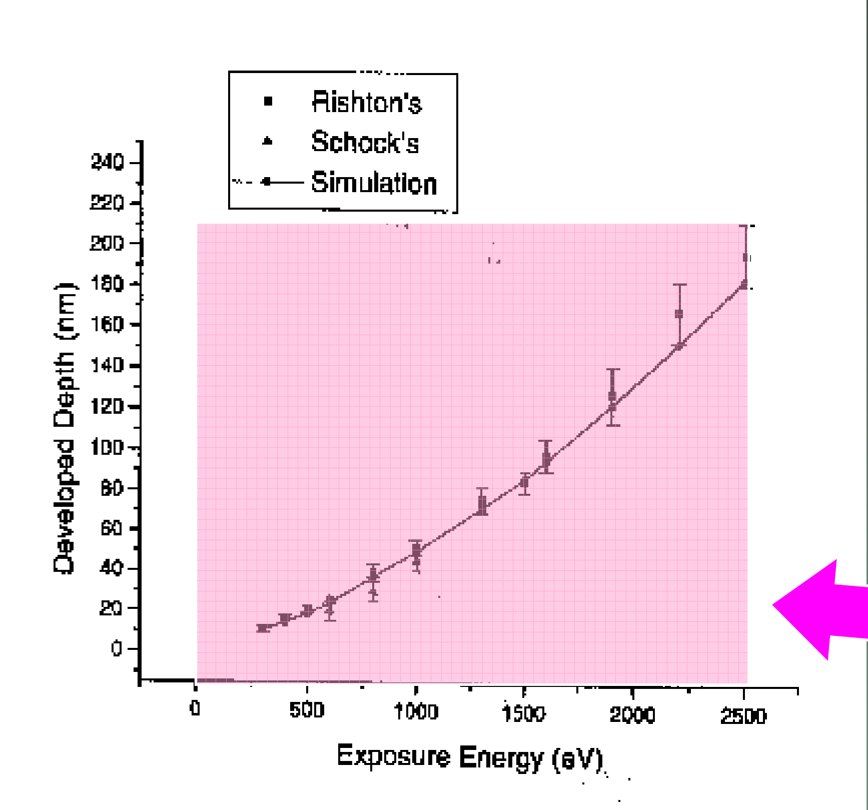
**SE with few eV kinetic energy are responsible for most of the resist exposure**

**Hence forward scattering within the resist is responsible for exposure**

**And backscattering is responsible for exposure far from incidence**

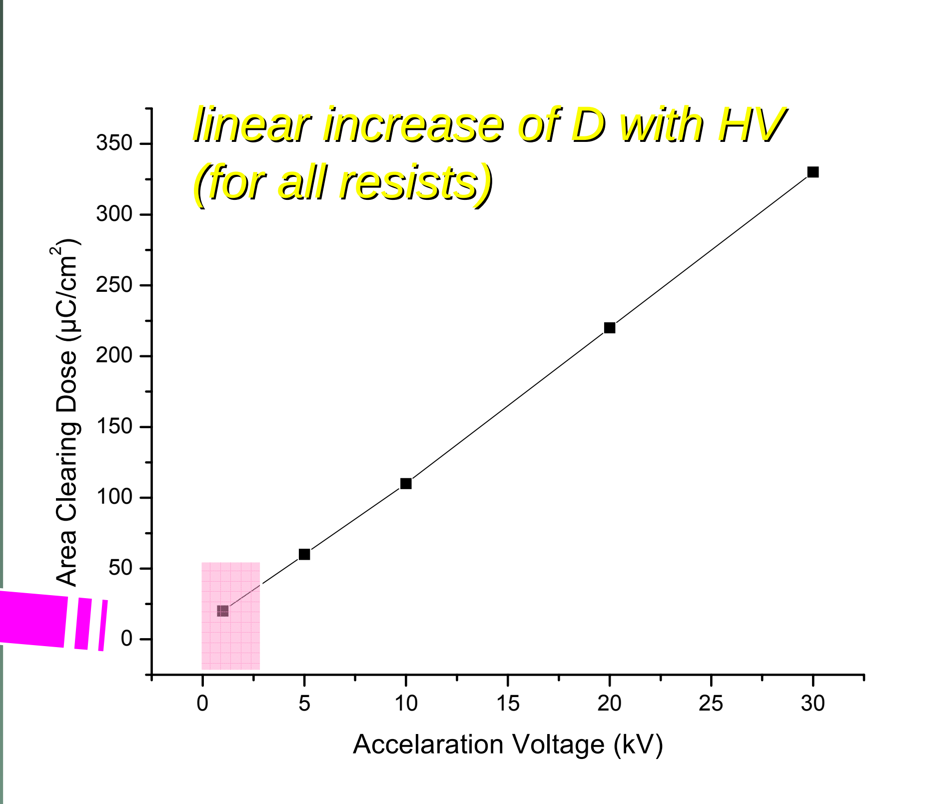


# Effect of Voltage on Dose




Y. Lee, W. Lee, and K. Chun 1998/9, "A new 3 D simulator for low energy (~1keV) Electron-Beam Systems"

At small kVs one should keep an eye on the penetration depth

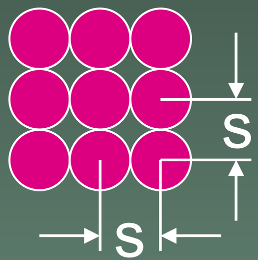



→ *resist sensitivity increases when one goes down in kV*

→ *can do faster exposures ( but may loose resolution ! )*

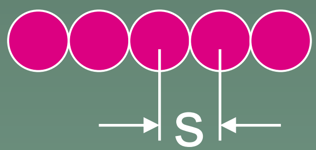
# Dose definition for different CAD elements

number of electrons $\propto T_{dwell} \times I_{beam}$



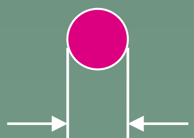

$$\text{Area Dose} = \frac{I_{beam} \cdot T_{dwell}}{s^2}$$

Unit is µAs/cm²




$$\text{Line Dose} = \frac{I_{beam} \cdot T_{dwell}}{s}$$

Unit is pAs/cm



$$\text{Dot Dose} = I_{beam} \cdot T_{dwell}$$

Unit is pAs

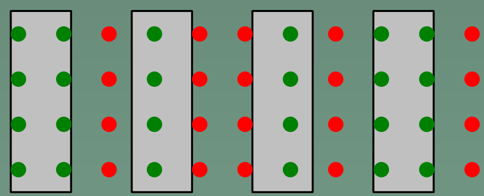
# Structure size and step size

## Important note:

**The used exposure step size has to be fit to the structure definition in the layout!**

## Example:

**Exposure of gratings:**
**step size (s) does not match grating period (g)**



*e.g. s = 8 nm, g = 10 nm*

# Dose table for PMMA (950k)

| | 10 kV | 20 kV | 30 kV |
|---|---|---|---|
| Areas | 100 µC/cm² | 200 µC/cm² | 300 µC/cm² |
| Lines | 300 pC/cm | 600 pC/cm | 900 pC/cm |
| Dots | 0.1 pC | 0.2 pC | 0.3 pC |

(developer: MIBK + IPA, 1:3)

**Above values are good starting points.**

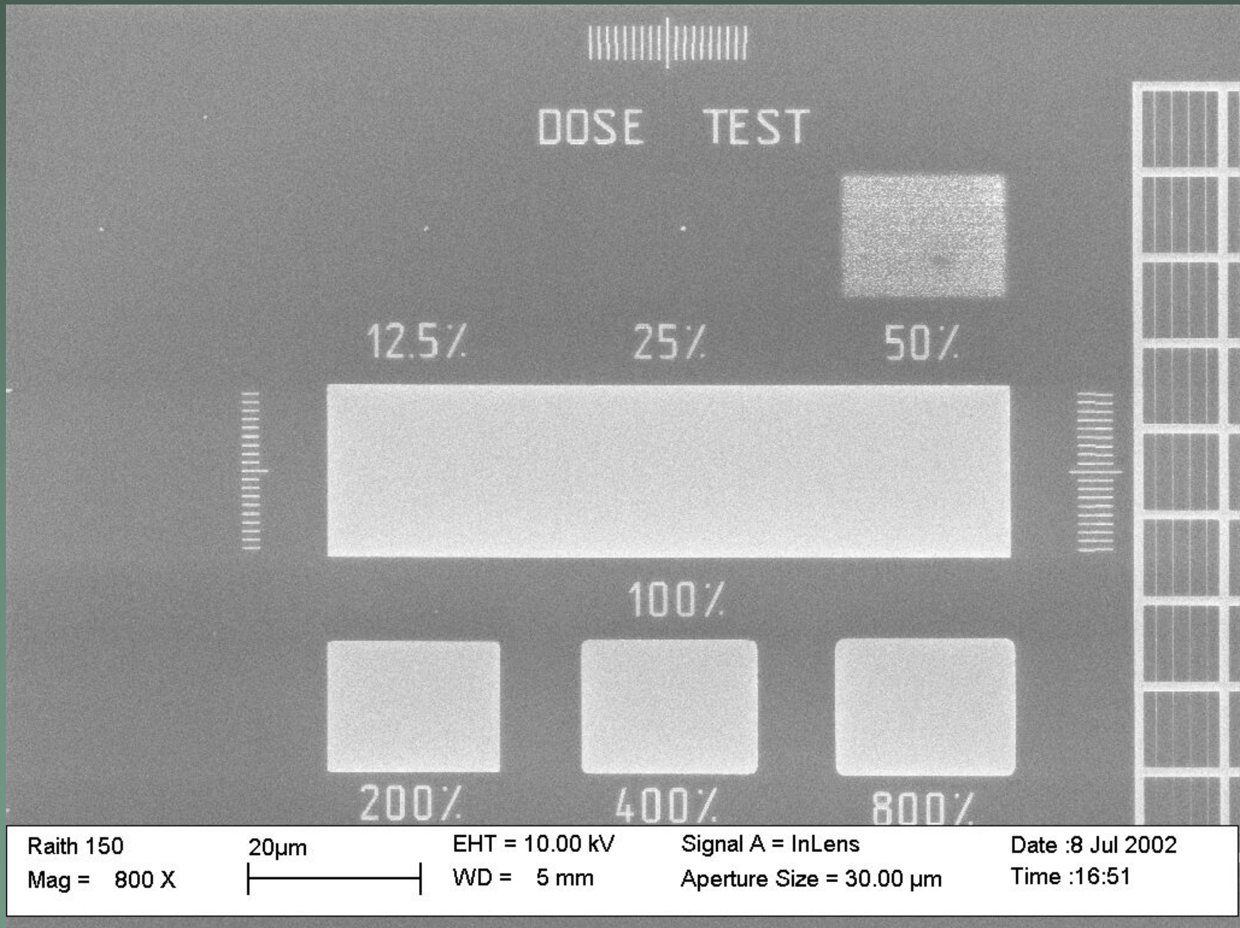
**Best way to get optimum results:**

**→ Dose Scaling:**

**SPL Dose Factor 0.5 – 5, (for Dots: 0.1 – 10)**

# Dose scaling

test structures
with different Dose Factors




(or e.g. taxi-checkers)

# Influence of operating parameters

| | Low | High |
|---|---|---|
| **Acceleration voltage** (penetration depth) | + Clear surface structures<br>+ Less damage<br>+ Less charge up<br>+ Less edge effect<br>– Lower resolution | + Higher resolution<br>– Unclear surface structures<br>– More edge effects<br>– More sample damage (heating) |
| **Aperture** ($I_{beam}$) | + Higher resolution<br>+ Less damage (heating)<br>+ Larger depth of focus<br>– Grainy image | + Smooth image<br>+ Good Signal to noise<br>– More damage (heating)<br>– Lower resolution<br>– Smaller depth of focus |
| **WD** | + Higher resolution<br>– Smaller depth of focus | + Larger depth of focus<br>– Lower resolution |

(A guide to Scanning Microscope Observation, Jeol web page 1999)

# Resolution limits

beam:

- Thick resists (forward scattering)
- Thin resists (~0.5 nm by diffraction, de Broglie wavelength)
- SE range (5-10 nm)

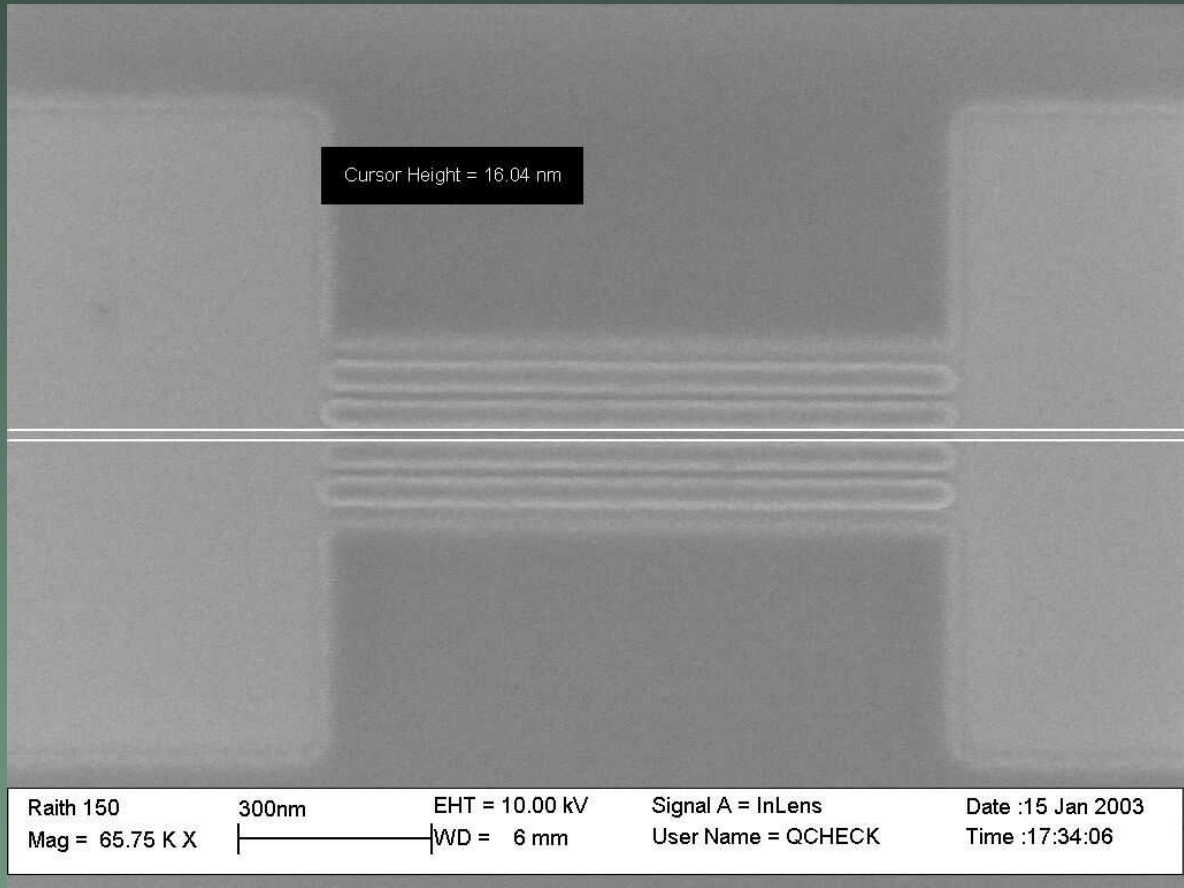
resist:

- Polymer size (5-10 nm)
- Chemically Amplified Resists (acid diffusion ~50 nm)

**In practice, best achievable resolution:**
**in polymer resists ~ 20 nm**
**(in inorganic resists, currently impractical, ~ 5 nm)**

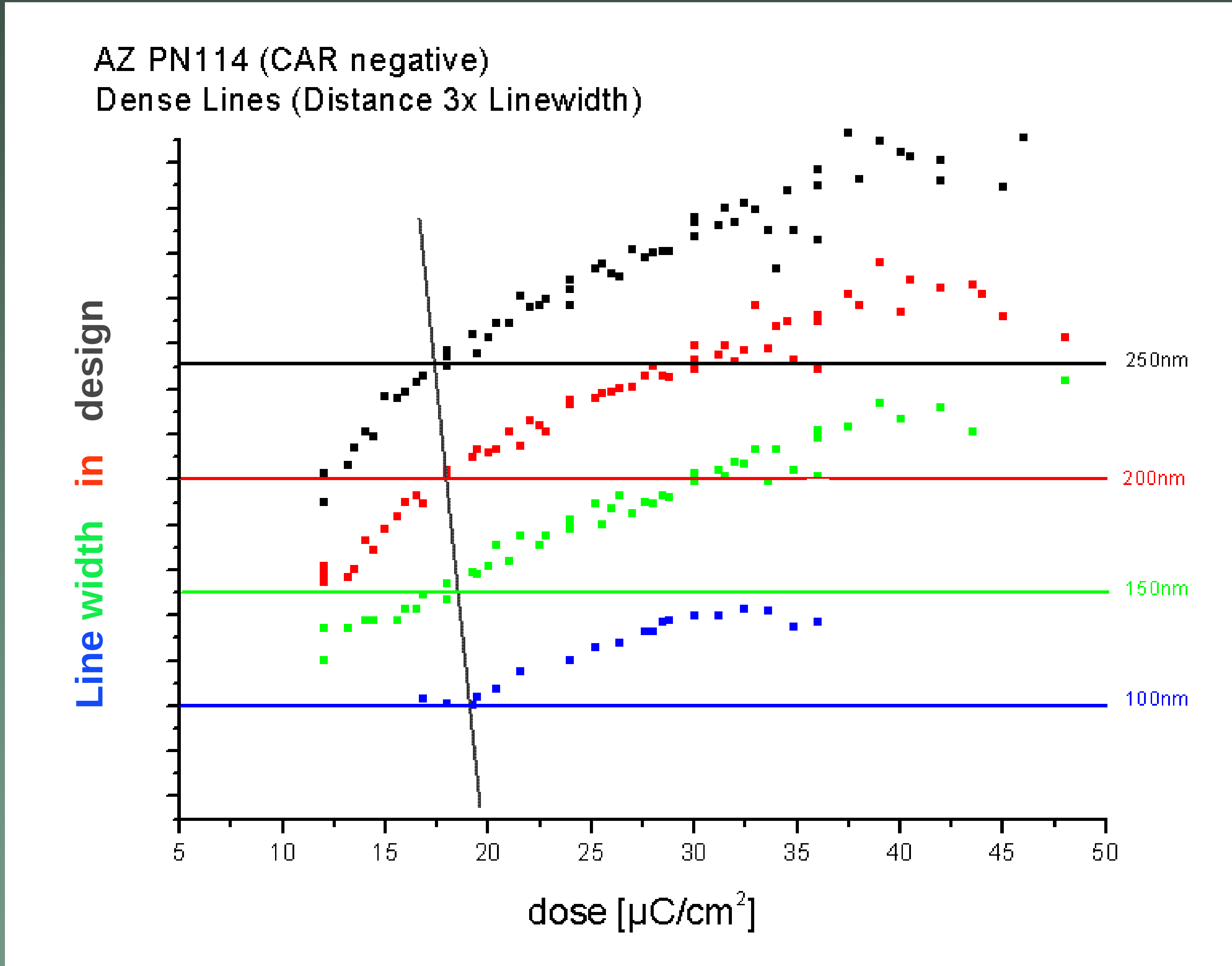
**(Mark A. McCord, Introduction to Electron-Beam Lithography, Short Course Notes Microlithography 1999, SPIE's International Symposium on Microlithography 14-19 March, 1999; p.63)**

# What is possible ?



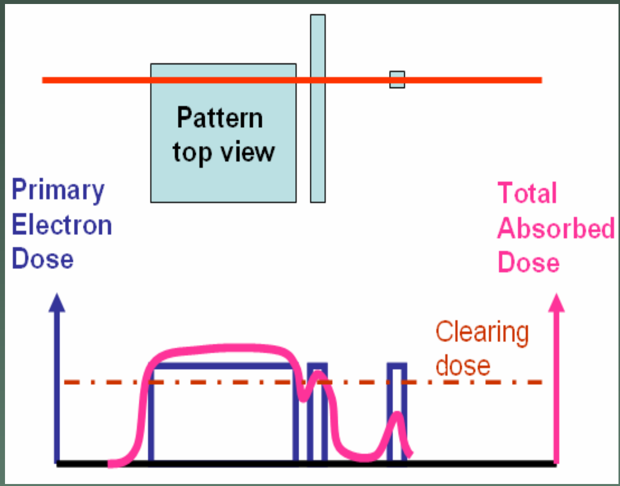

*Ultra high resolution in PMMA (45 nm thickness):*
*16 nm line width <u>(in resist)</u>*

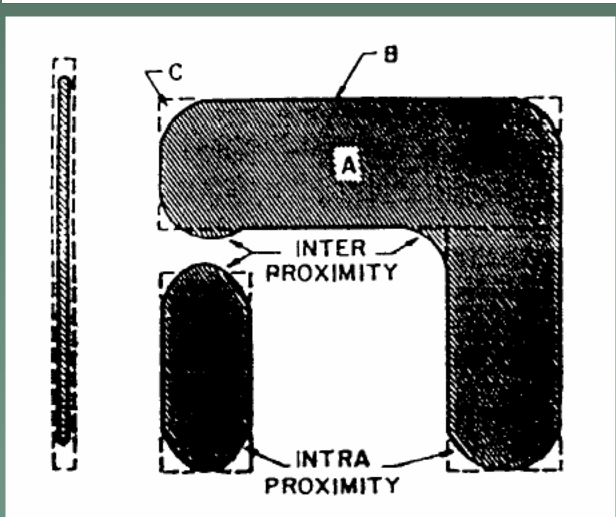
# Design must be adapted to dose




Johannes Kretz, Infineon, Munich

# Proximity effect

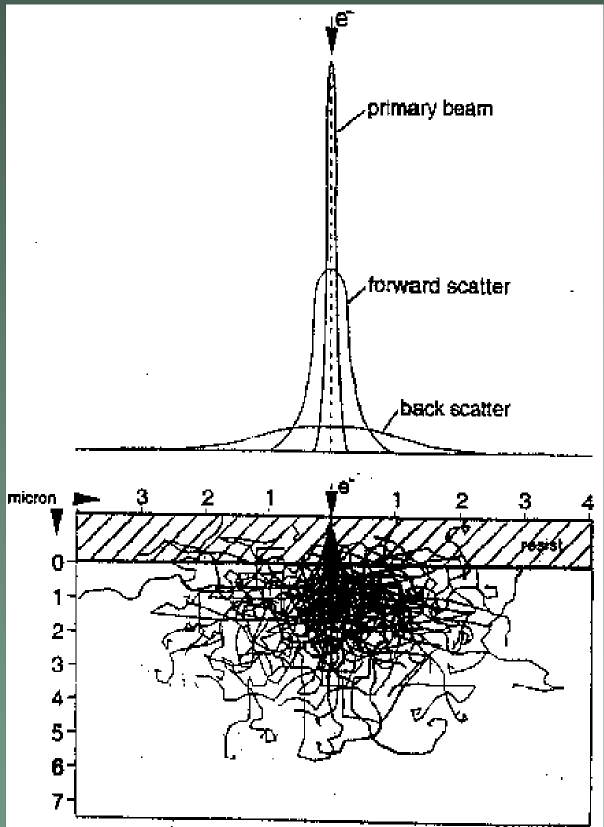



INTER AND INTRA PROXIMITY EFFECTS IN E-BEAM EXPOSURE CAUSED BY ELECTRON SCATTERING

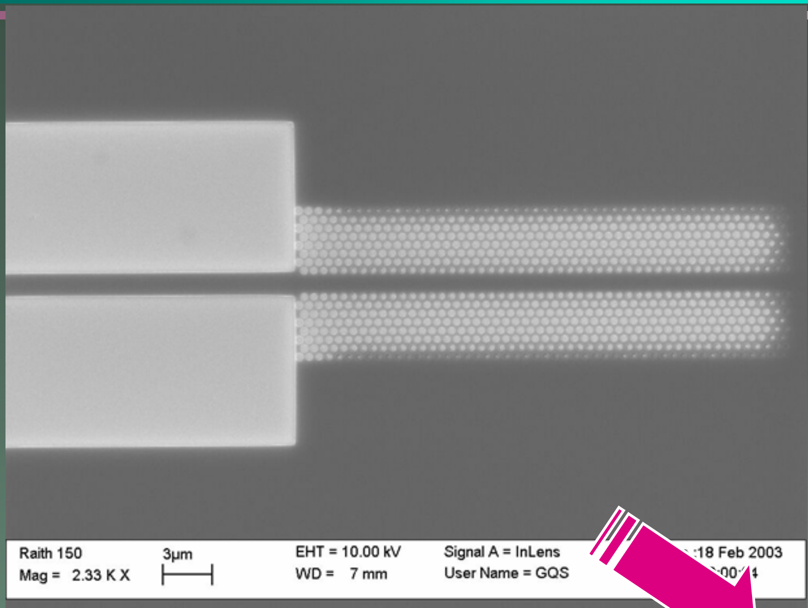
*e trajectories for:*

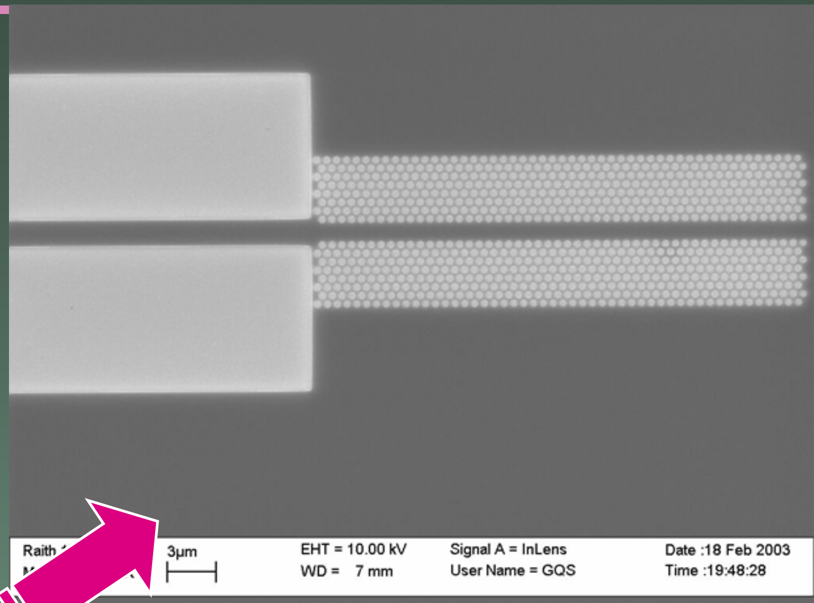
- *1.5 μm thick resist   on Si wafer*
- *50 trajectories,  25 keV beam energy*




(Kyser, Viswanathan, "Monte Carlo simulation of spatially distributed beams in EBL", J. Vac. Sci. Technol. 12(6), 1305 ('75))

# Proximity Effect Correction software




# Conclusions

- still a **Top-down** approach

- **planar** technique: possibly repeated, but no real 3-D outcome

- carries all **limitations of SEM**: slow, invasive, need vacuum, problems with insulators, …

- ok for research, prototyping, R&D, **not for mass production**