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E-Beam Lithography 2024

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Electron Beam Lithography

Université de Technologie de Troyes - avril 2024



- **Overview of E-Beam Lithography (EBL):**
 - ☞ Knowledge, concepts, tools, tips, tricks
 - ☞ **2h ... I made choices !**
- **Focus on 1 kind of equipment:**
 - ☞ # UTT one 😊

- **Introduction**
- **EBL: basic principals**
 - Exposure
 - Developing
 - System composition
 - Calibration
 - Design recommendations
- **EBL: concrete practice**
 - Driving parameters
 - Limitations
 - Recommendations
 - Sum-up
- **EBL nowadays**
 - Competition at industry level
 - Tendencies and job evolution

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- Lithography:
 - ☞ Greek: lithos # stone & graphia # writing
 - ☞ Shaping/modifying locally a material called a "resist"
 - ☞ Registering a targeted design as a ghost image inside a material called generally "resist" which will be next developed
 - ☞ ...
- Must be thought with all the other steps: technology of micro/nano fabrication
 - ☞ Materials deposition: conductors, insulators, semi-conductors, topological insulators, bio-materials, ...
 - ☞ Materials etching : dry and wet etching, removal, ...
 - ☞ Characterization: physical, electrical, chemical, biological, ..., aging, ...
 - ☞ **Take always into account:**
 - ☞ **The limits of each step**
 - ☞ **Start by the last one ... up to integration / packaging !**

- Decrease diffraction # decrease wavelength
- $\lambda_{\text{electrons}}$ at 100keV = 0.0037nm
- Simple to produce, simple to shape
- Maskless (generally)

But ...

- Under vacuum
- Max. resolution few nanometers at 200kV (on bulk substrate)

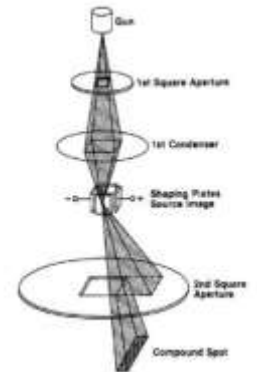
Why a so big difference between λ and ultimate resolution ?

- Electrostatic repulsion
- Lenses defects and aberrations
- Electrosensitive materials and their chemistry

- **Beam type:** Gaussian / Variable or fixed shape
 - **Focused beam** (point per point exposure): like a SEM - Gaussian beam
 - **Non focused beam** (area exposure):
 - Projection of a variable shape
 - Projection of a fixed shape (cell projection): needs a mask with holes

- **Scan type:** Vector / Raster
 - **Vector scan:** only necessary parts are scanned
 - **Raster scan:** all the exposure area is scanned
 - Beam is blanked when necessary

- **Exposure type:**
 - **Fixed stage** during exposure ... field by field with stitching
 - **Moving stage** during exposure: continuous exposure (e.g.: RAI TH FBMS mode - avoid stitching in optical guides)



Different EBL techniques

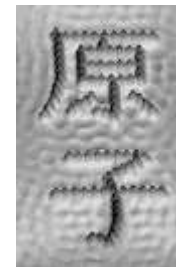
- Shaped beam - Vector scan - fixed / moving stage
- Cell projection (need a mask)
- Multi-beams, micro-columns
 - For mask production
 - High resolution (~30nm), high speed ... high cost



- Gaussian beam – vector scan - fixed / moving stage
 - Very high resolution ... ~8nm
 - Intermediate speed & cost



- STM
 - Atomic resolution
 - Very slow
 - Low temperature (mK)



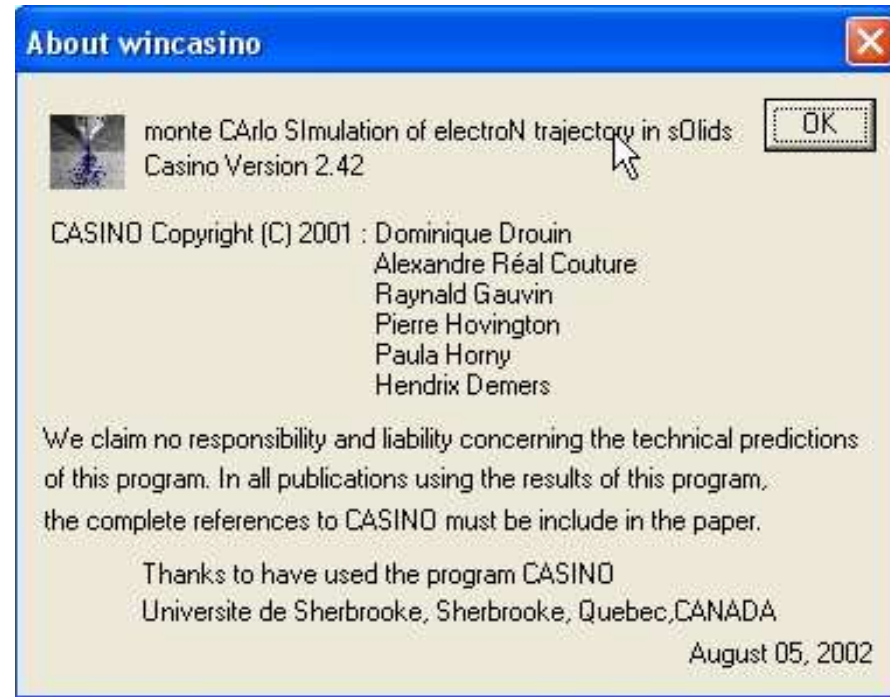
Direct writing of atomic ideograms realized and observed by AFM. These 2 ideograms (Yuán Zǐ) mean “atom” in Chinese and are made of iron atoms on a copper surface (D.M. Eigler and Co. in IBM research center of Almaden).

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- **Electrosensitive material:**
 - Also sensitive to X-Rays, UV, ions, neutrons, ...
 - A lot of resists used in UV-lithography are sensitive to electrons
- **Chemical bonds creation or break:**
 - Organic resist: 6 – 10eV → secondary electrons
 - Inorganic resist: > 50eV → high energy electrons → beam itself → high resolution → dose increase
- **Positive resist:**
 - Chemical bonds break → ↘ molecular weight (e.g.: **PMMA**, *PMMA/CoMAA*, *PMGI*, *ZEP520*, *CSAR*, ...)
- **Negative resist:**
 - Chemical bonds creation → ↗ molecular weight (e.g.: *ma-N 2400*, *PMMA*, *calixarene*, ...)
- **Chemically amplified negative resist:**
 - Chemical bonds break → acid radical creation
 - Thermally activated cross-linking (PEB – Post Exposure Bake) → ↗ molecular weight (e.g.: *SU8*, *SAL601*, ...)
- **Inorganic materials:**
 - Phase or crystallinity change, chemical bond break or make a hole: *HSQ*, *WO₃*, *SiO₂*, *AlF₃*...

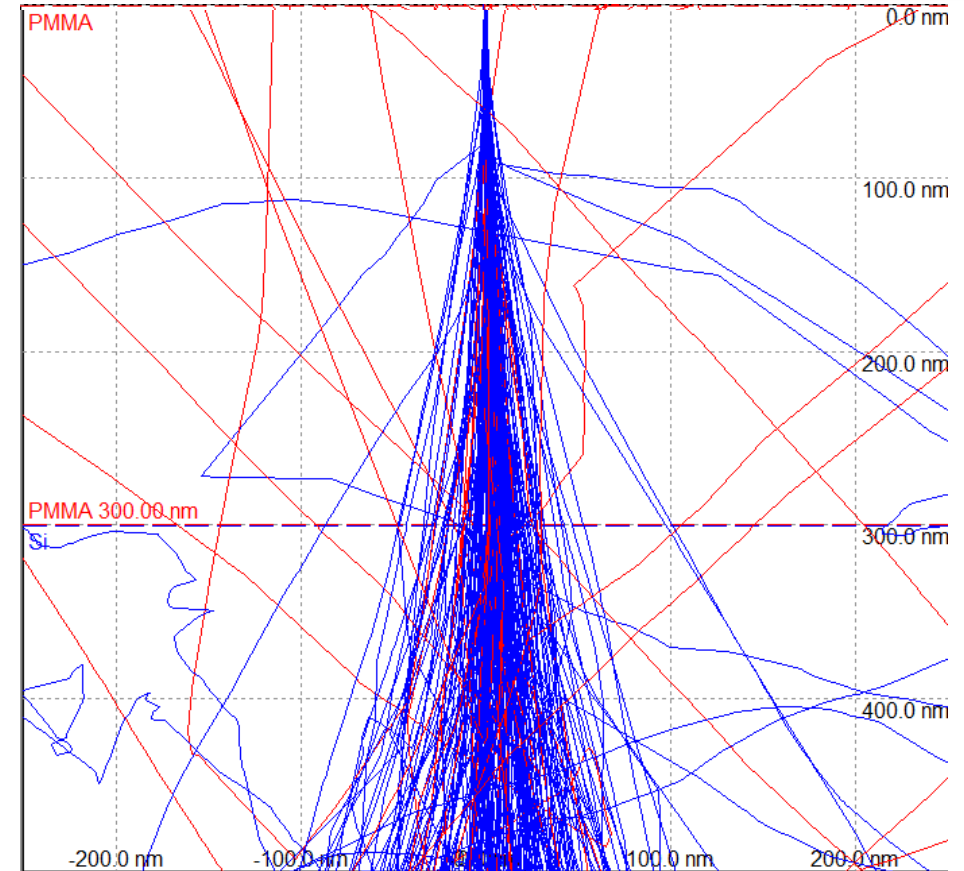
Exposure: where does it take place ?

👉 Close to electrons' trajectories

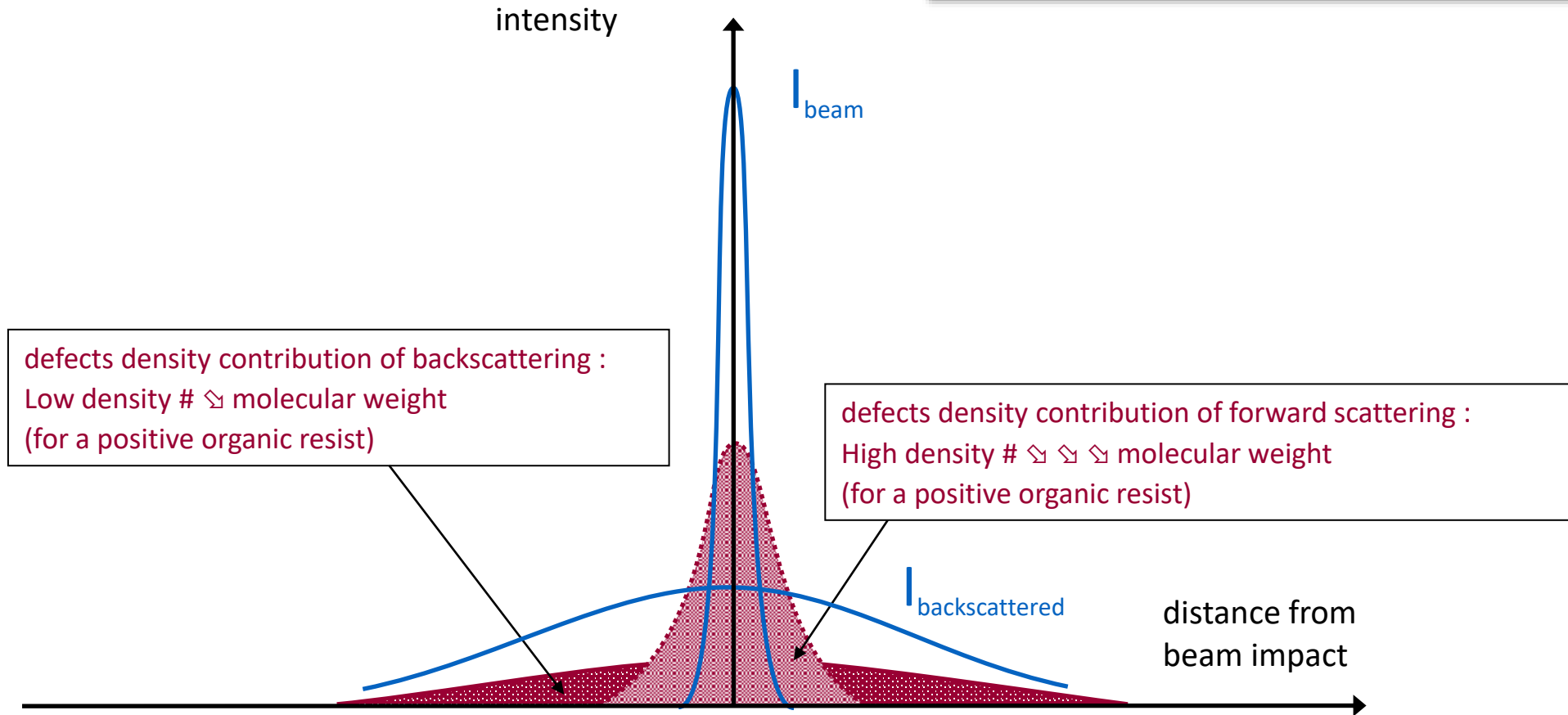


<http://www.gel.usherbrooke.ca/casino/>

1. Modification of the molecular weight
2. Scattering leads to creation of a molecular weight gradient
3. Additive effects (organic resist)
 - ☞ proximity effect



Exposure: Beam Point Spread Function

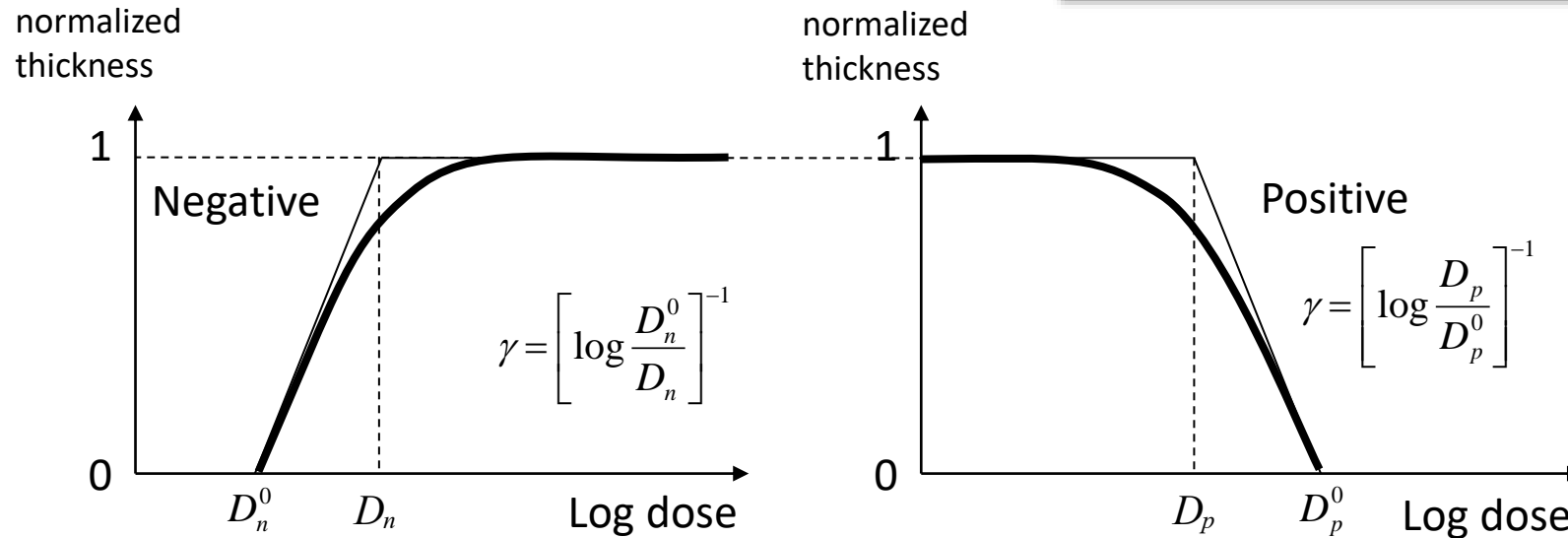


👉 2 gaussian curves model

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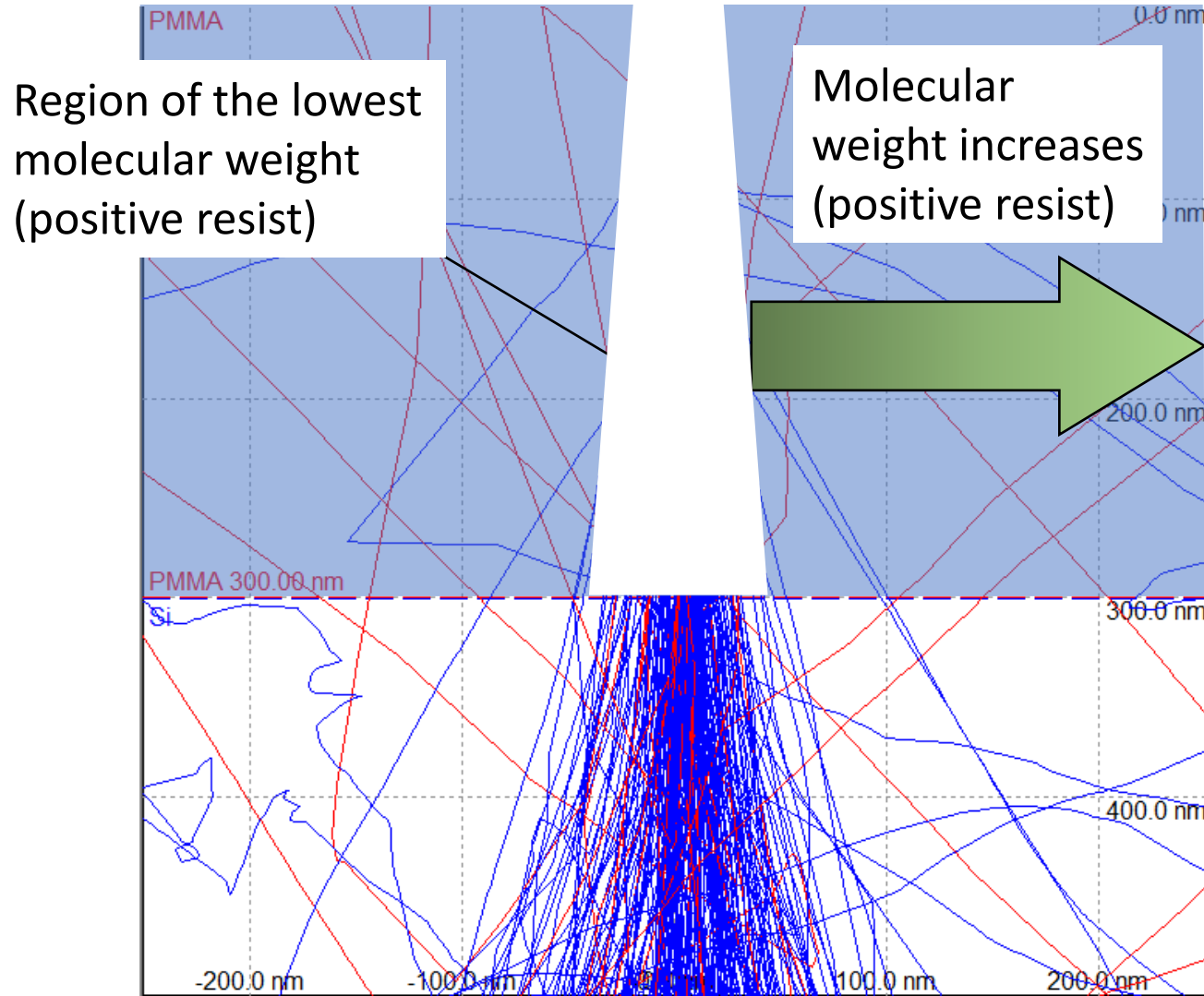
- **EBL results from lithography + developing**
- **Organic resist:**
 - No dissolution
 - Put in solution:
 - Solvent cage around the polymer fragments
 - Transport phenomenon in the solution:
 - Speed is inversely proportional to Molecular Weight
 - Can be difficult in small openings
i.e. high resolution: <10nm holes in thick positive tone resist
- **Inorganic resist:**
 - Chemical reaction with acid or base (HSQ, WO_3 , SiO_2)
 - Self-developing (AlF_3)

Developing: resist contrast



- Development speed = f(molecular weight, concentration, duration, temperature)
- Contrast γ # curve slope
- High contrast # high selectivity on molecular weight
 - Vertical walls
 - Higher process latitude
 - Higher resolution
 - Less sensitive to proximity effects
- Low contrast:
 - 2.5D lithography / grey scale lithography - e.g. optical microlens fabrication

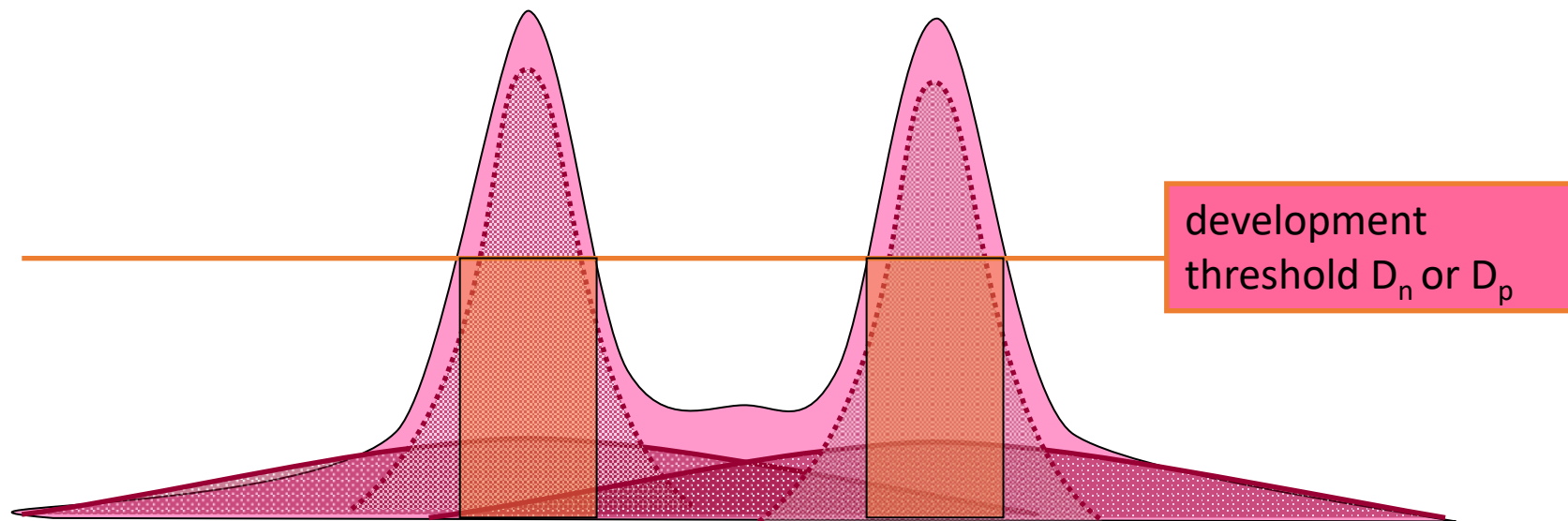
Developing: resist profile



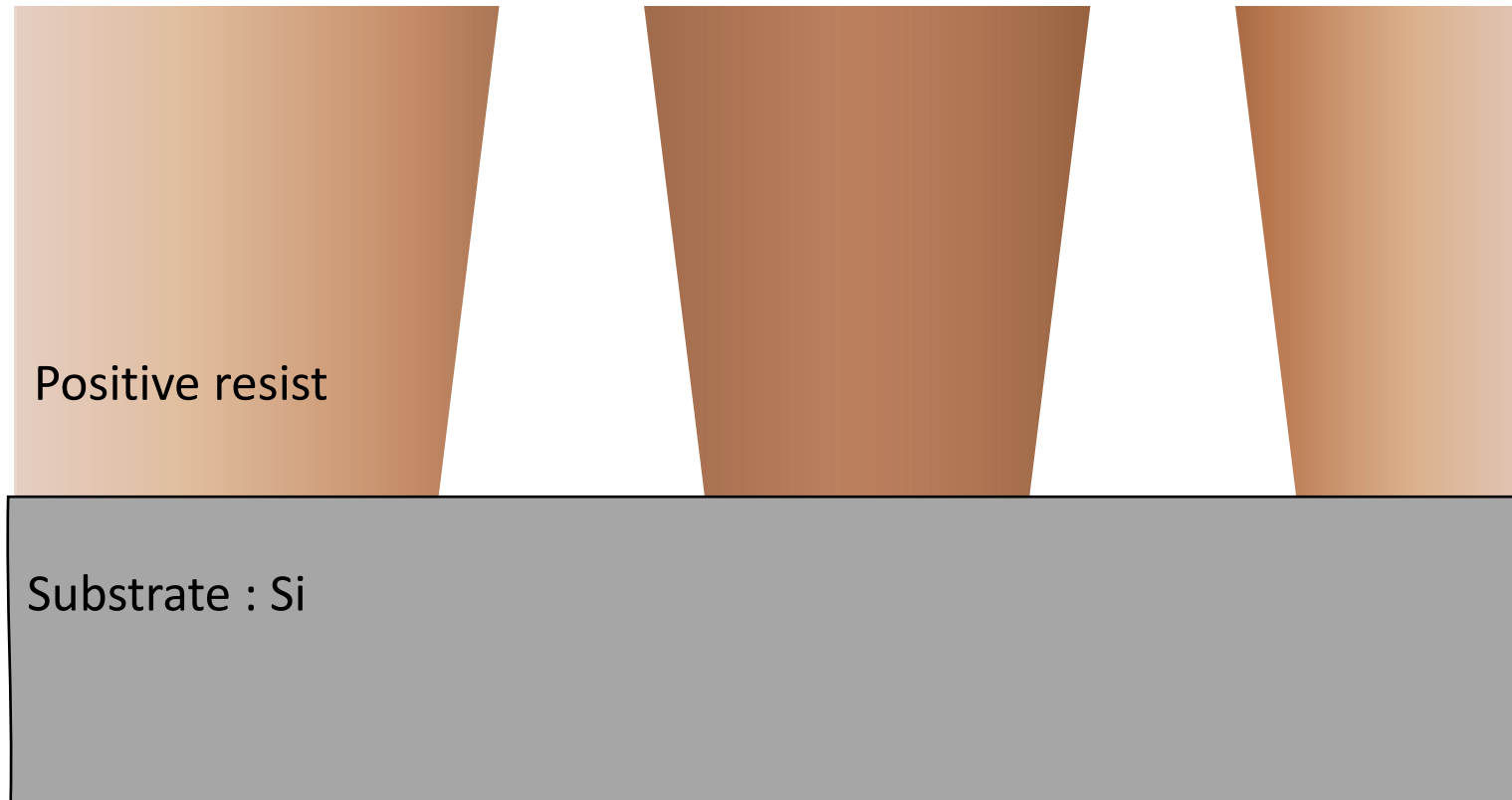
Region of the lowest
molecular weight
(positive resist)

Molecular
weight increases
(positive resist)

- Molecular weight modification is additive on organic resists

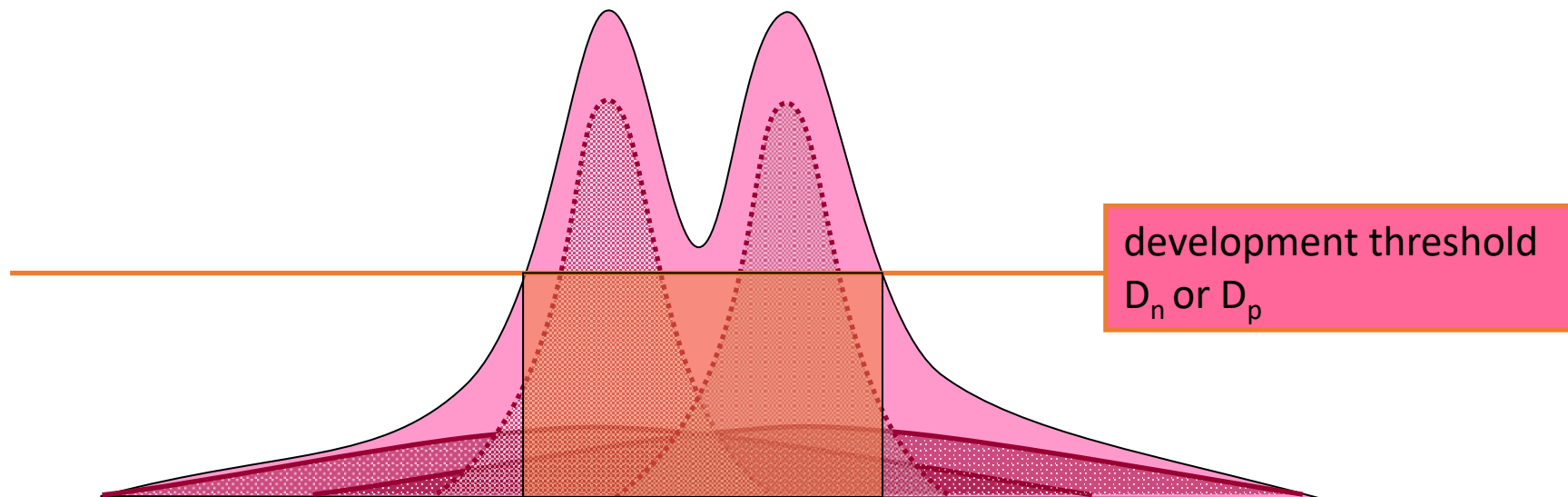


Developing: proximity effects

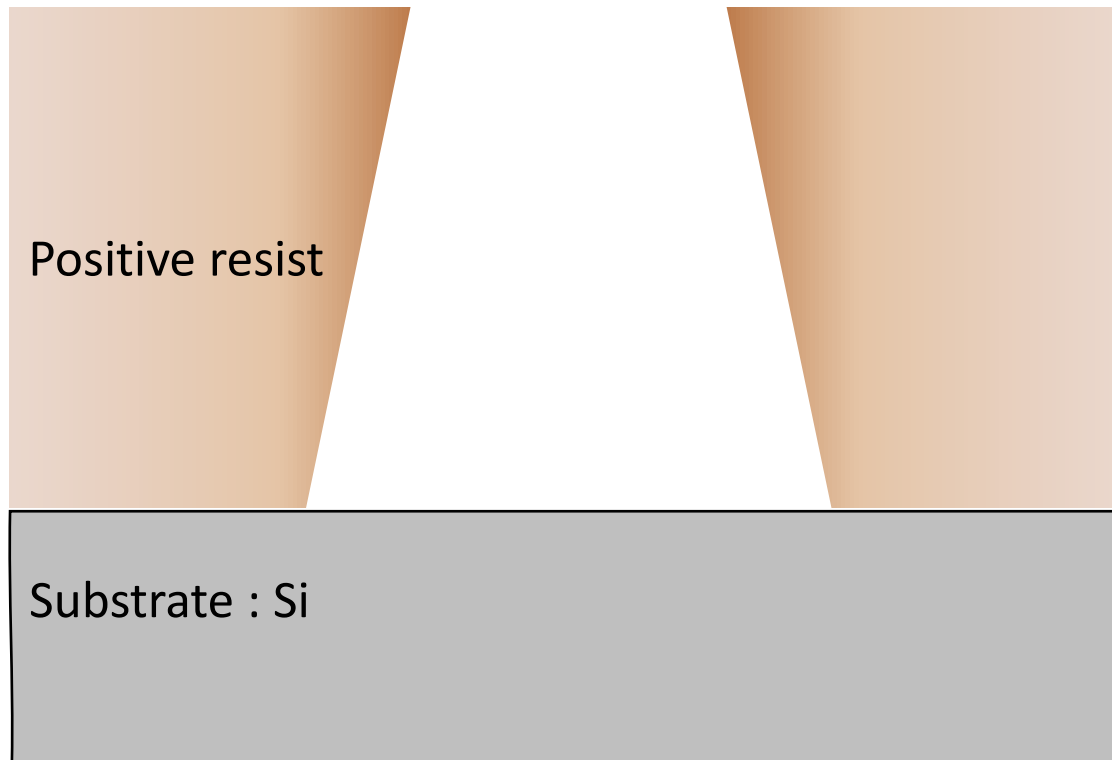


Developing: proximity effects

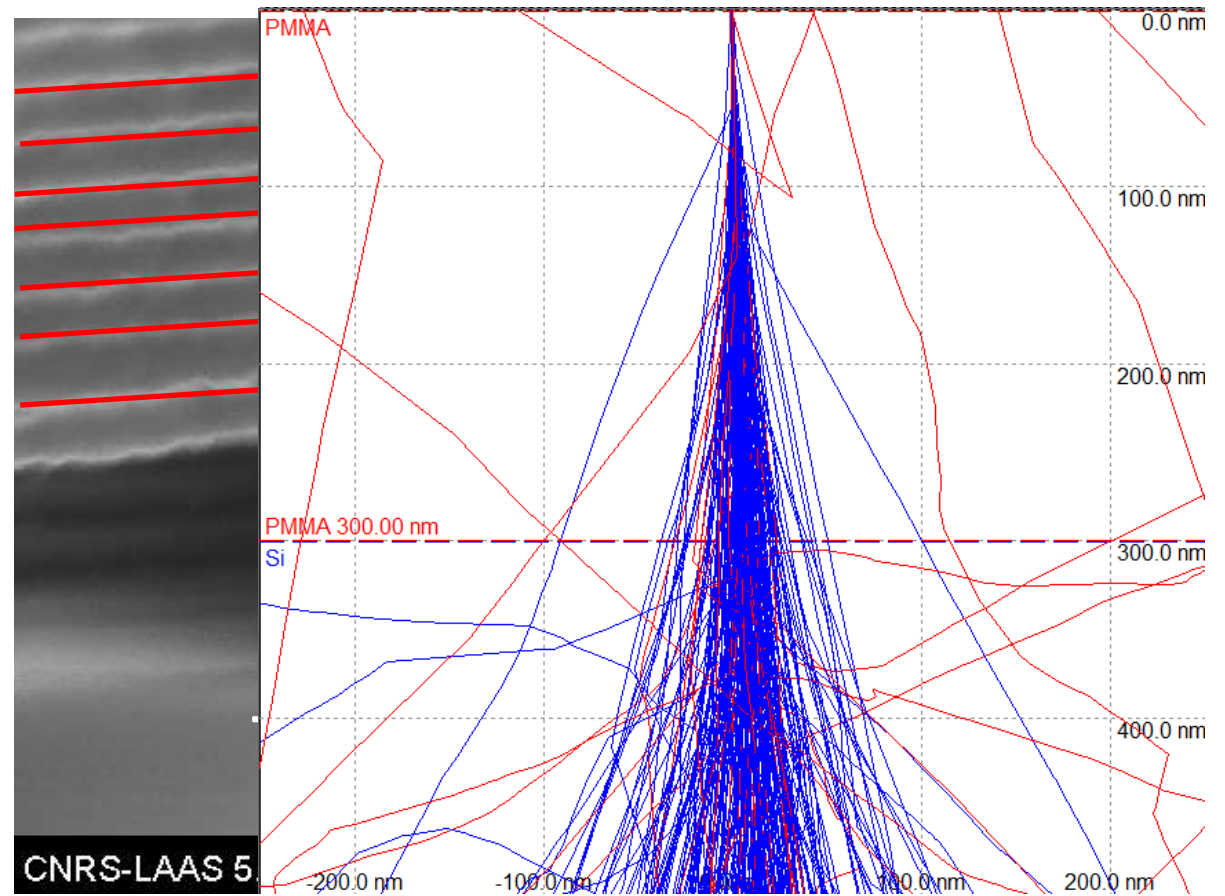
Molecular weight modification is additive on organic polymers
... and can lead to proximity effect: ↘ resolution



Developing: proximity effects



- 2 exposures: 20keV – 2keV
- Negative resist
- Design: 2 superimposed perpendicular gratings
- 1 development
- Suspended structures



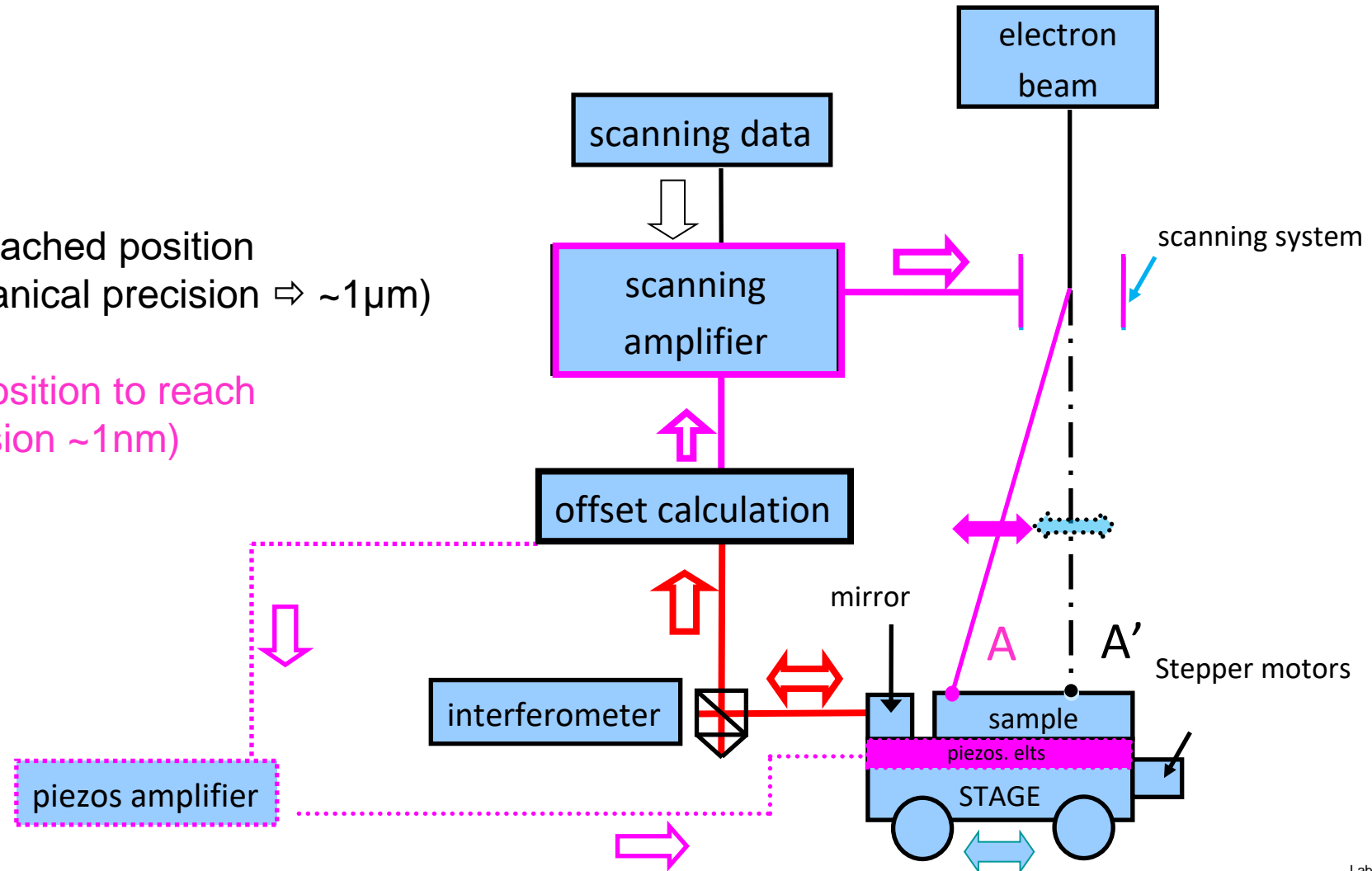
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- **Computer Assisted Design (CAD) software**
- **Electron optics and detectors:**
 - SEM-like
 - SEM imaging capabilities (SE & BSE)
- **Beam blanker**
- **Pattern generator:** for beam scanning control (electronics)
- **Software:** link between user / CAD / beam scanning / beam blanking, ...
- ☞ **Minimum configuration**
- ☞ **Able to work on one field only**

- **Pattern bigger than one field:**
 - ☞ Pattern is cut into fields
 - ☞ Fields stitching ($\leq 50\text{nm}$ precision on Raith e-line machine)
- **Need of a LASER interferometer:**
 - Position precision measurement: 2nm or less (0.15nm)
 - Reference for moving
 - ☞ Allow field calibration: size, rotation & shift

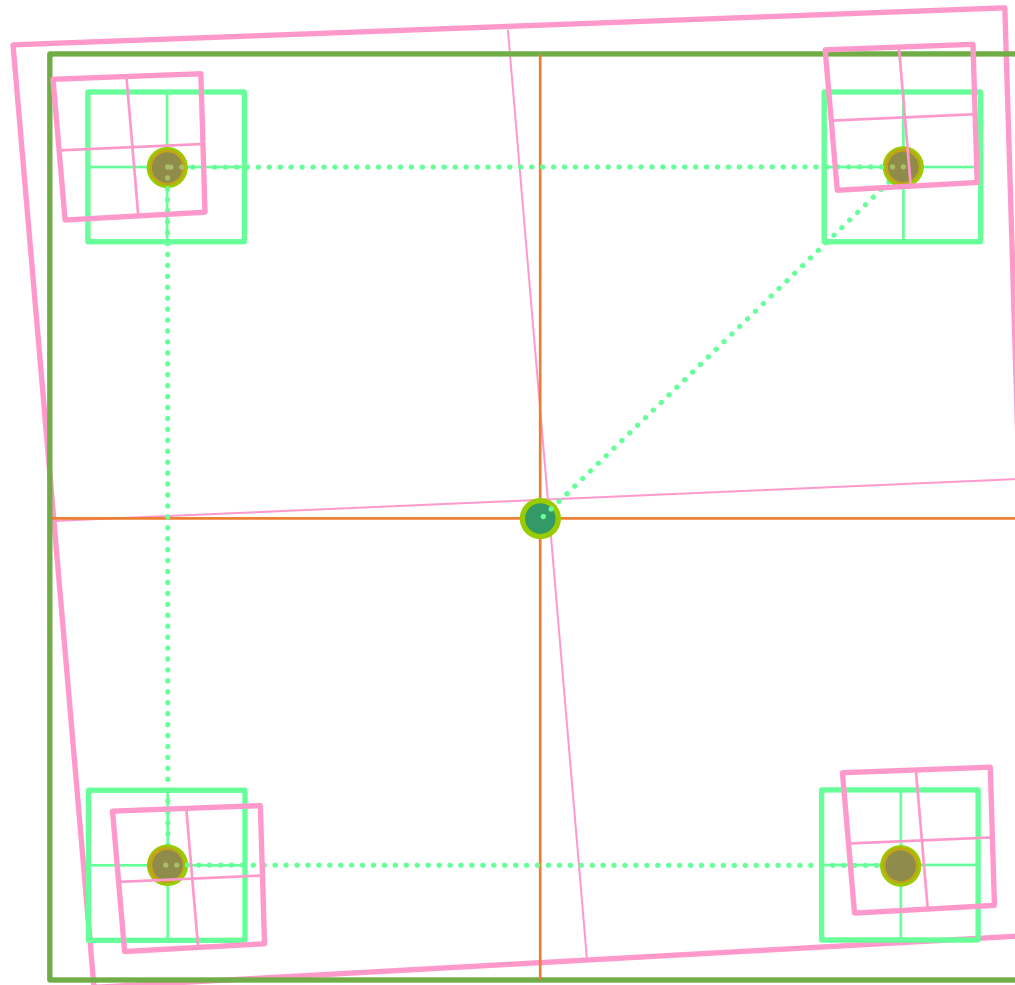
System composition: synoptic

- A': reached position (mechanical precision $\Rightarrow \sim 1\mu\text{m}$)
- A: position to reach (precision $\sim 1\text{nm}$)



- **Specimen not always in the axis of mechanical displacement: authorized misalignment 2°**
 - Alignment registration on sample edge/flat/notch
 - Software correction (mechanical precision)
 - **SEM fields are limited in size and position:**
 - Big field # big distortions
 - Not always in the axis of mechanical displacement (electromagnet lenses)
 - Be careful: electronic rotation induces distortions (non-linear electronics)
 - **Field size is not calibrated**
 - Need a mark to calibrate the machine: first level exposure
 - Need reference marks made by a calibrated machine: next levels exposure
- ☞ Electron optics with low distortions
- ☞ Stepper motors (precision: 1 or few μm)

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Field calibration: stitching

Before field calibration



After field calibration

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- **Drawings' file type:**

- ☞ World-famous GDSII (binary files) ... DXF, ASCII, ..., conversion possible
- ☞ DATATYPE parameter used for dose coding (be careful DATATYPE=1000 means DoseFactor=1)

- **Softwares used:**

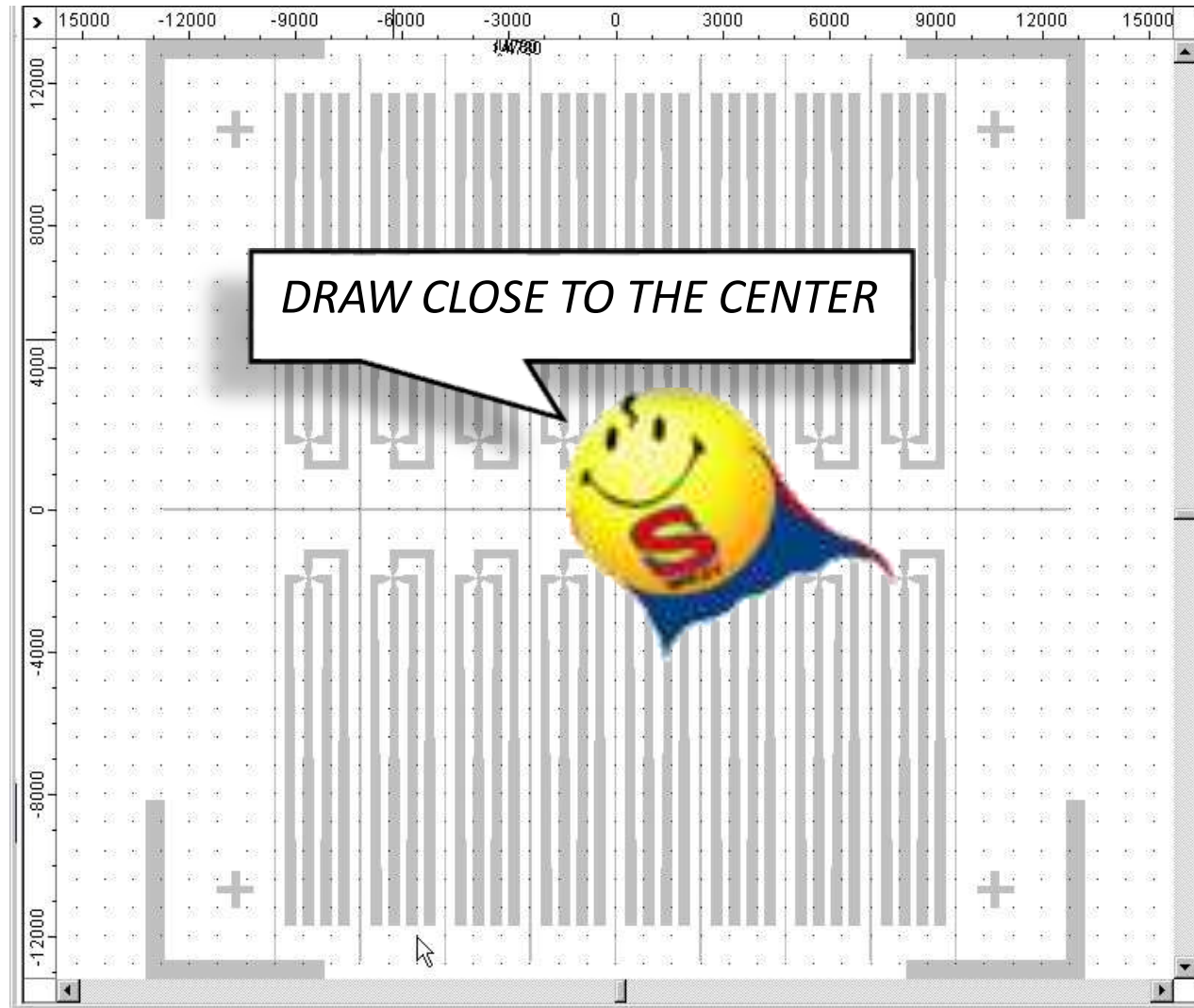
- ☞ Best one: E-Beam writer's software
- ☞ If not: must be compatible with the machine
 - ☞ **Klayout (include a PYTHON library ... useful for scripting GDS2 files)**
 - ☞ CADENCE, LayoutEditor, CleWin (GDS hierarchy not fully compatible with RAITH)
 - ☞ **GenISys Beamer:**
 - ☞ Process simulation
 - ☞ Data preparation/correction
 - ☞ Powerful but expensive (100k€)

- **Drawing's grid must match the step-size of exposure**
 - ☞ To prevent coordinates from being rounded by the machine without control
- **Design is exposed with an orthogonal matrix XY of points:**
 - ☞ All structures non-parallel to X or Y axis are divided in small parts in order to fit the drawing : time and memory consuming
 - ☞ Try to follow the axes
- **Avoid nanostructures with stitching**
 - ☞ Better in the center of one field

Design recommendations: drawing without knowledge

WHAT IS THE DIFFERENCE BETWEEN THE 2 IMAGES

CLUE :
they have the same scale (μm)

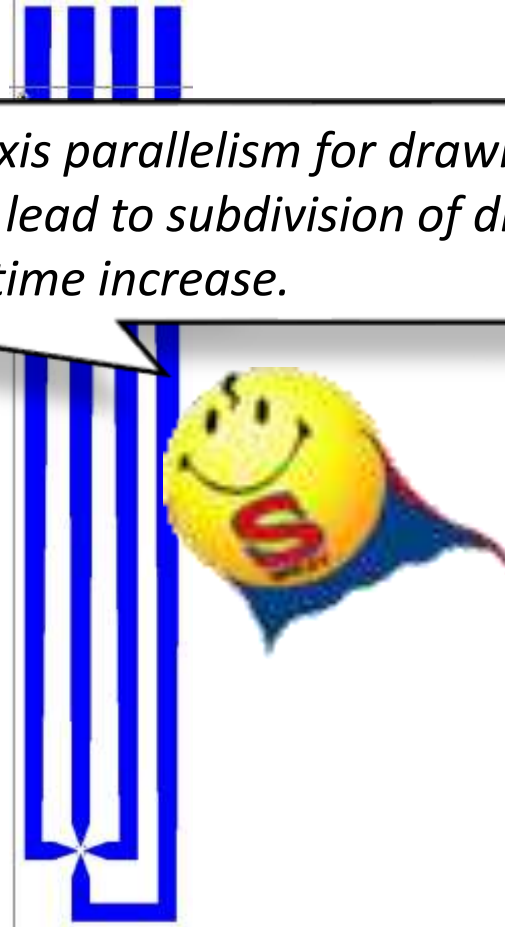


Design recommendations: drawing without knowledge

WHAT IS CURIOUS ON THIS DRAWING ?

CLUE :
This is not an effect from the
display

*Promote X-Y axis parallelism for drawing
If not, this will lead to subdivision of drawing
and exposure time increase.*



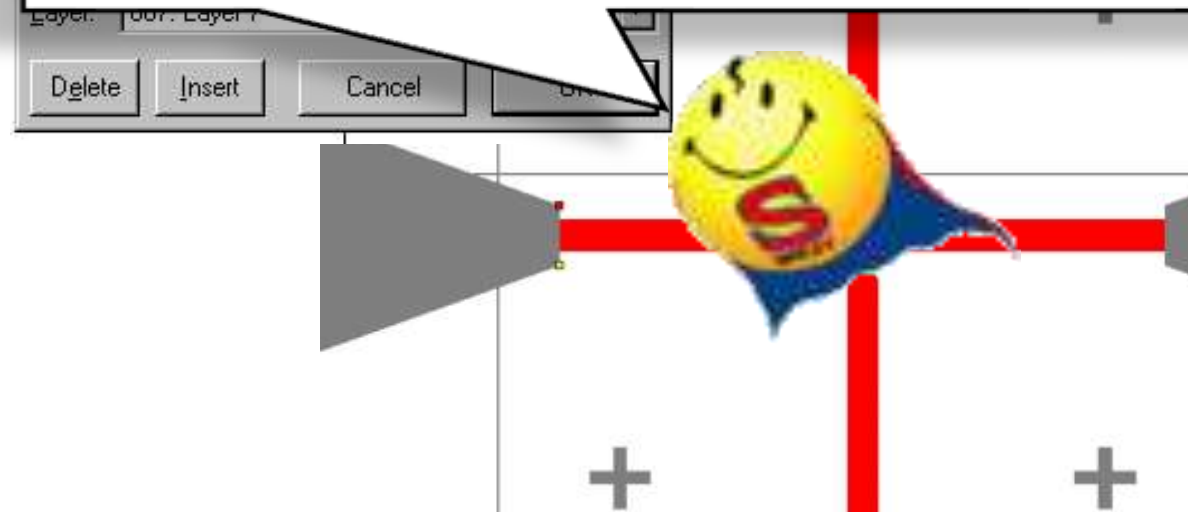
Design recommendations: drawing without knowledge

#	U/ μm	V/ μm
001	-8965.000	1850.000

*If not necessary: fit all values to microns or multiple
USE ADAPTED DESIGN GRID(S)*

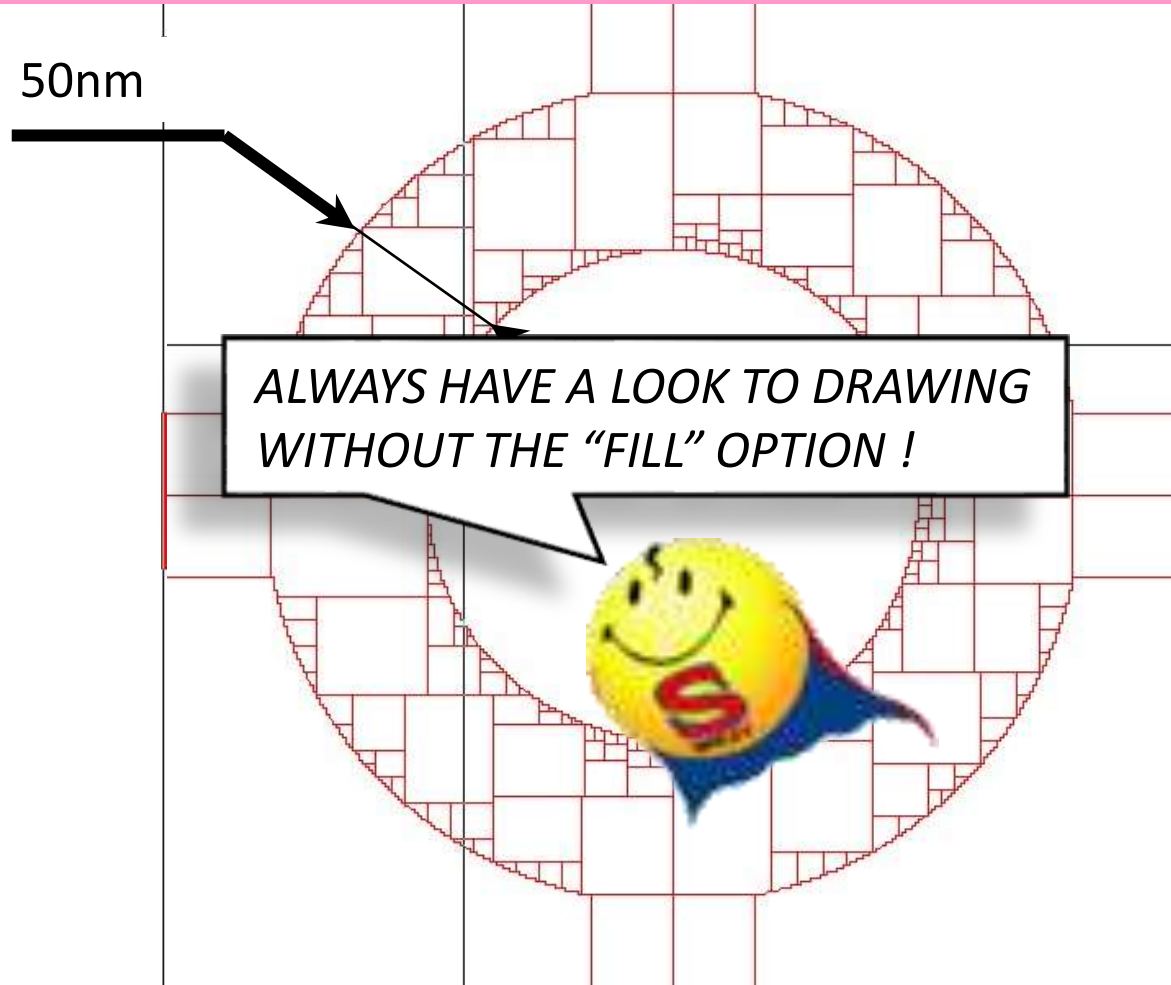
The smallest design grid step should be the exposure step-size:

- *ASK FOR THE VALUE !*
- *SNAP TO GRID !*
- *SNAP TO ELEMENTS !*

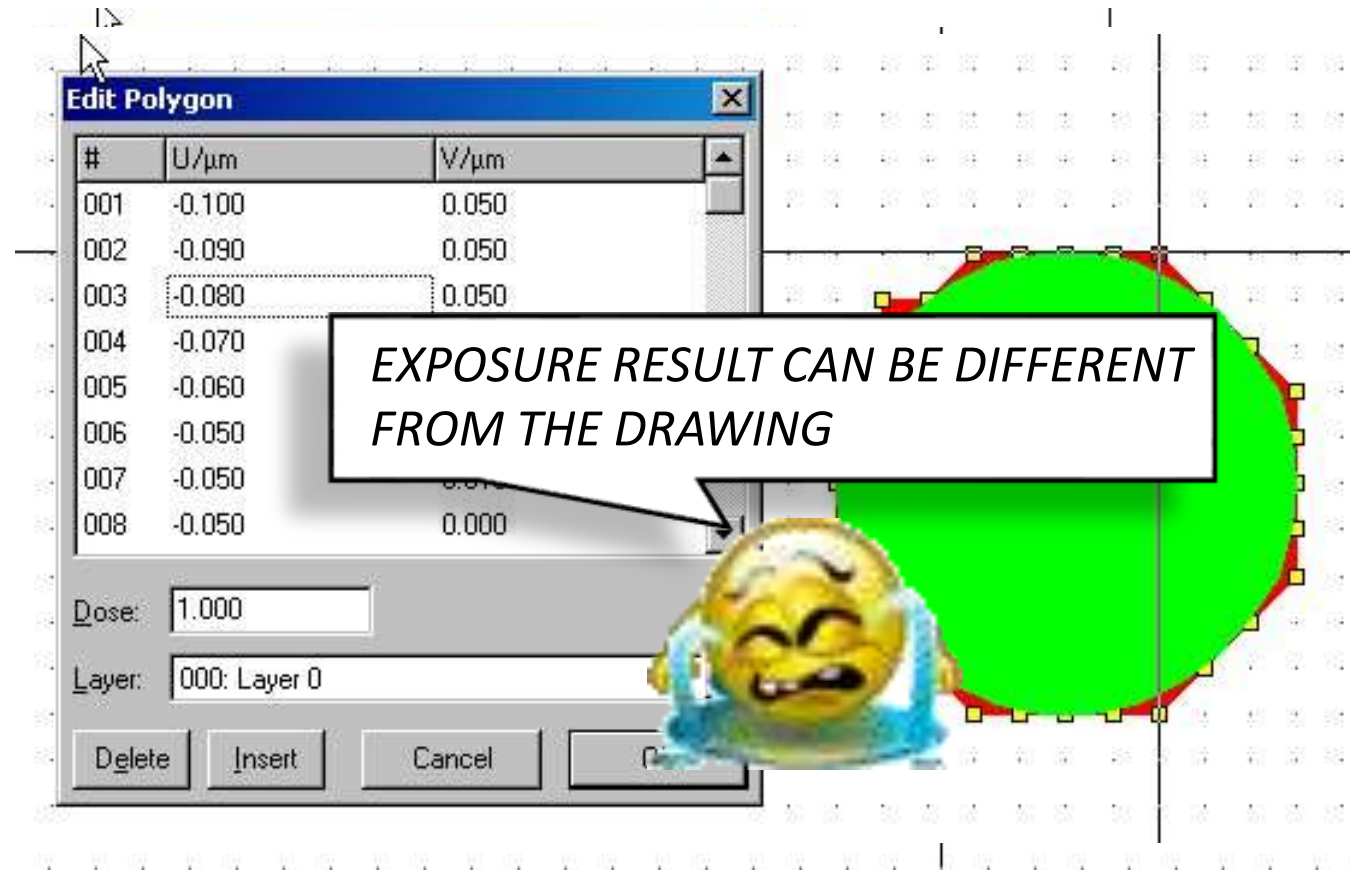


Design recommendations: drawing without knowledge

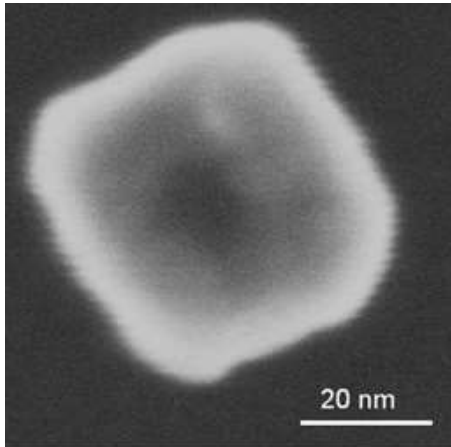
WHAT IS THERE BEHIND THE DRAWING ?



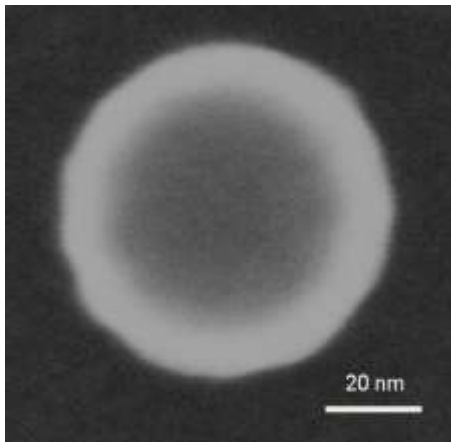
Design recommendations: rounding effect



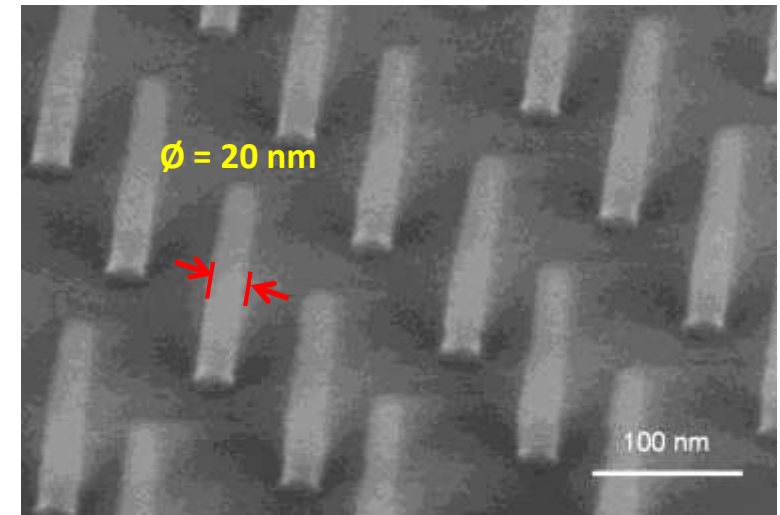
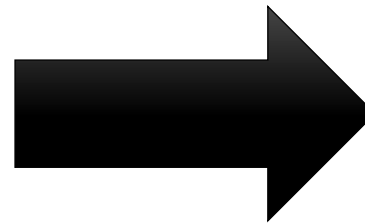
Design recommendations: rounding effect



Circle: \varnothing 50nm
Exposure step-size: 10nm

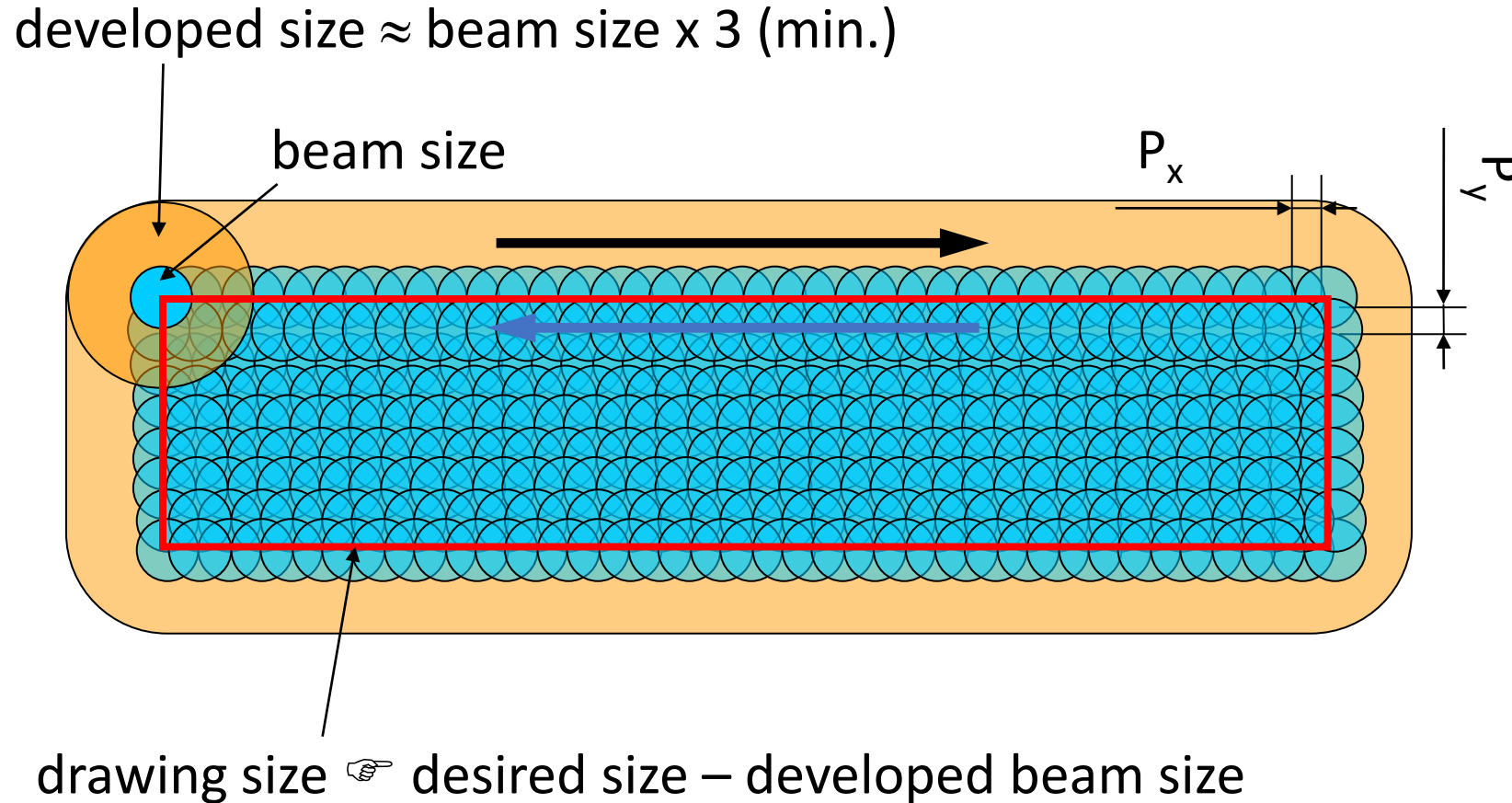


Circle: \varnothing 50nm
Exposure step-size: 2nm



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Driving parameters: design exposure



Driving parameters: exposure dose

total number of points

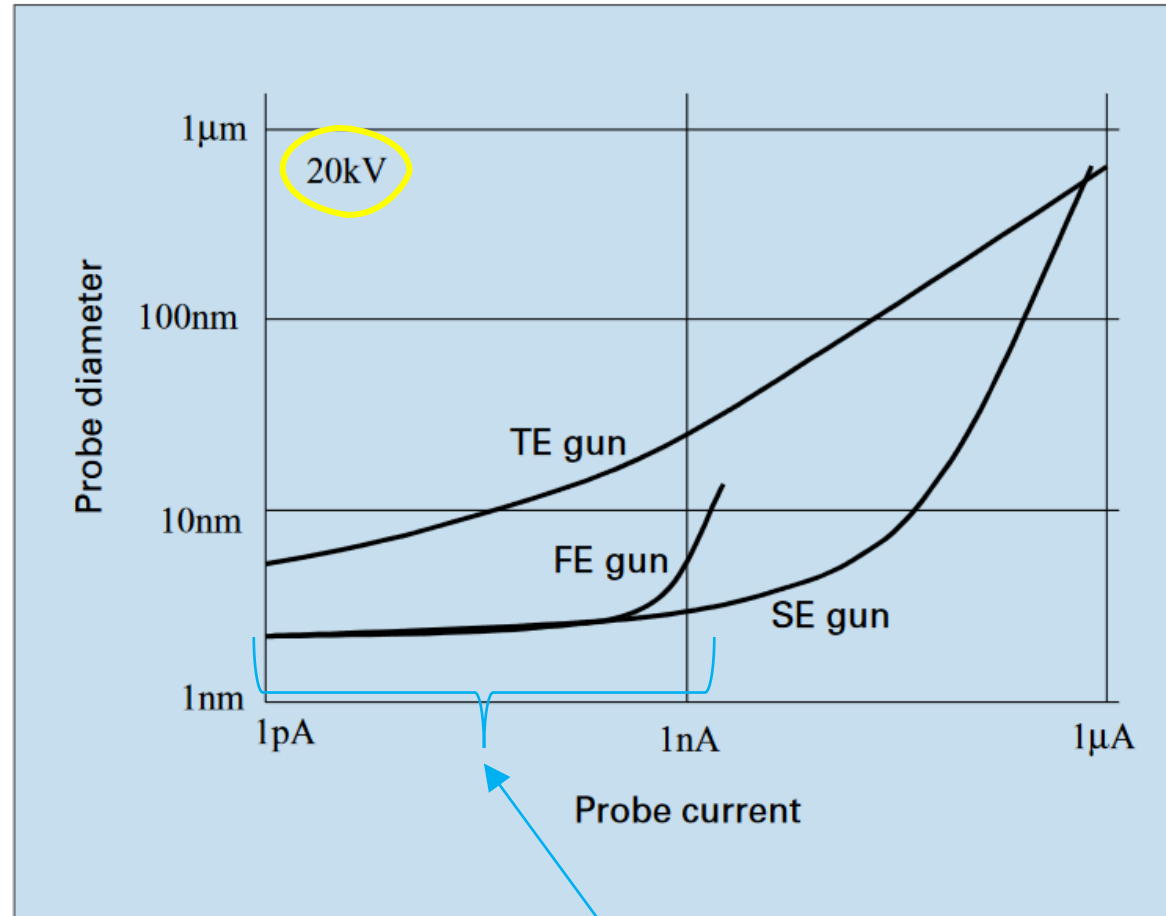
- Area dose: σ ($\mu\text{C}/\text{cm}^2$) = $\frac{I \cdot t \cdot n \cdot \text{point}}{p_x^2 \cdot p_y^2 \cdot p_{xy} \cdot p_y}$
- Line dose: σ (nC/cm) = $\frac{I \cdot t \cdot \text{point}}{L}$
- Point dose: σ (pC) = $I \cdot t_{\text{point}}$

- Depends on:
 - Substrate
 - Energy
 - Resist: nature, thickness
 - Developer: nature/concentration, duration, mechanical agitation, temperature
 - Design: size/pitch/distance between structures (proximity effects), way of exposure, ...
- Also depends on user's experience

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Limitations: beam diameter = f(current)

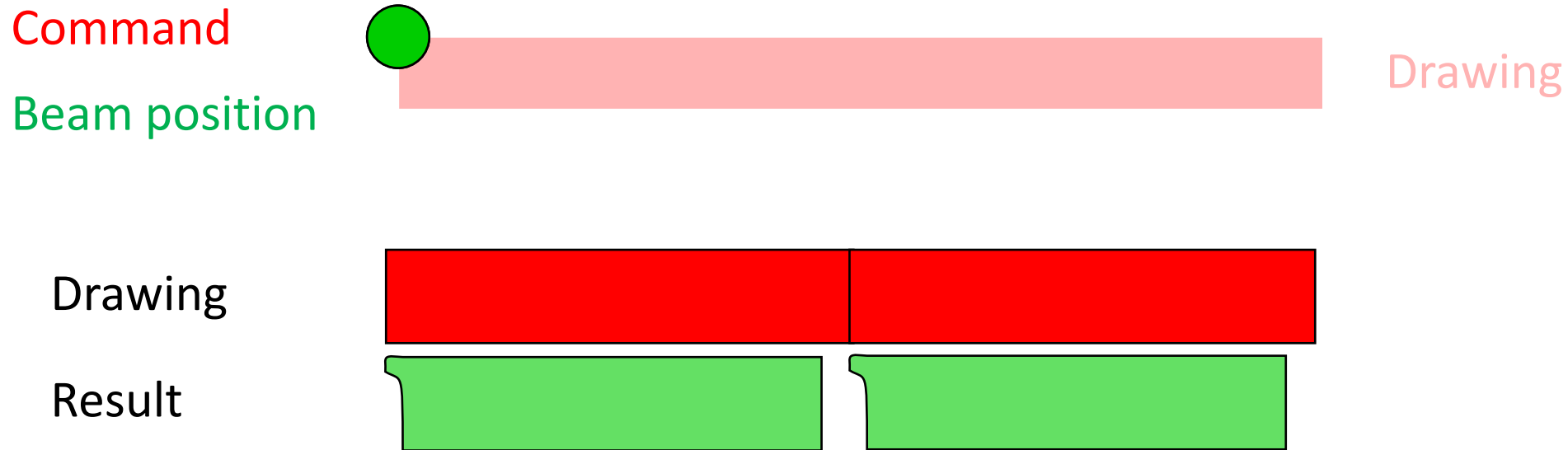


Beam diameter almost constant at "low current" 👍

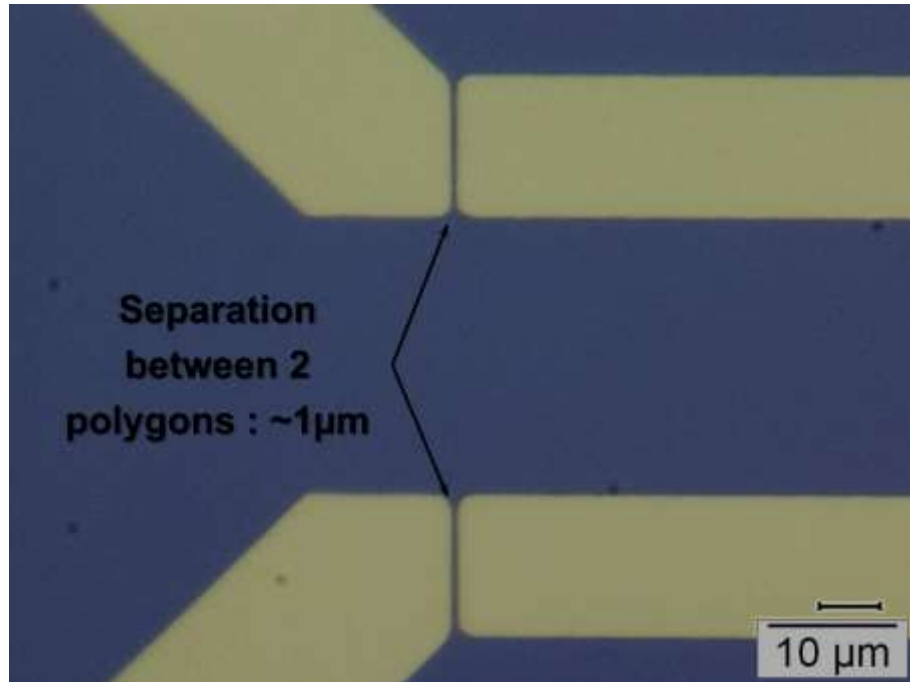
- **Beam size does not depend so much on current using a S-FEG gun**
- " t_{point} " limited by scanning generator maximum frequency
- " p_x " define the Line Edge Roughness (LER)
- For equipment based on standard scan coils:
 - **Beam speed: p_x/t_{point} limited by scan coils frequency bandwidth**
- Line Width Roughness (LWR) and LER depend on noises:
 - Mechanical & acoustic vibrations
 - Electric/magnetic fields
 - Electronics noises,
 - Temperature variation ...

Limitations: beam speed effect

- Origin : scan-coils (inductance)
- Induce phase-shift between command and beam position

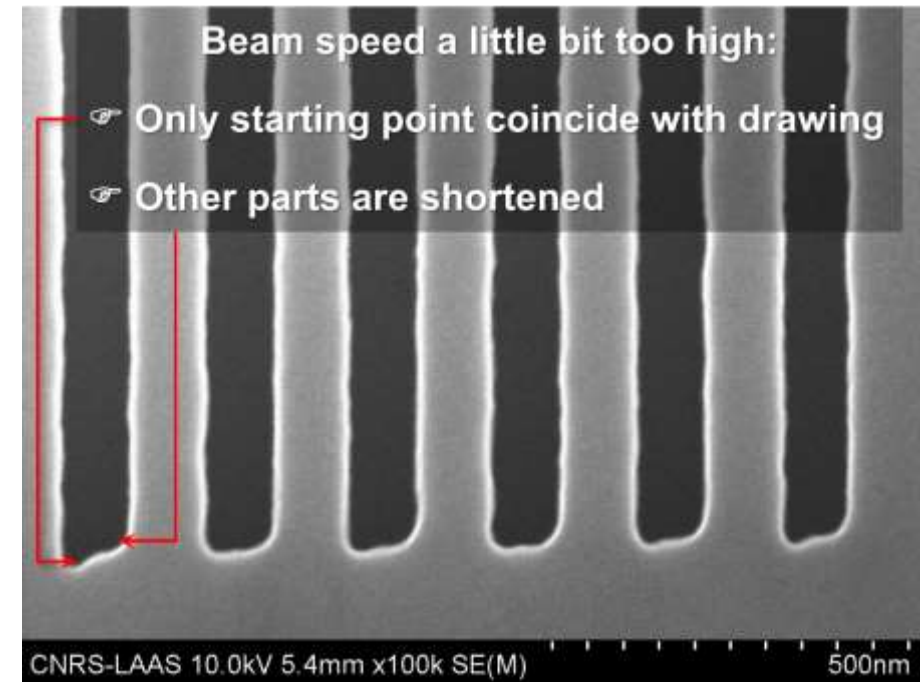


Limitations: beam speed effect



1µm stitching error between 2 polygons induced by a too high beam speed when using SEM scan coils for patterning

☞ Cut the polygons and overlap parts if needed



Distortion at beginning of each line induced by a too high beam speed when using SEM scan coils for patterning

For equipment based on standard scanning coils

$$\sigma = \frac{I \cdot t_{\text{expo}}}{S} = \frac{I \cdot t_{\text{point}}}{p_x \cdot p_y} = \frac{I}{F \cdot p_x \cdot p_y}$$

- **Surface too large: exposure time $\approx \infty$**

- ☞ Minimize the surface – moderation of request
- ☞ « Mix & Match » - huge surfaces made by photolithography

- **Pitch between points: define the Line Edge Roughness (LER)**

- ☞ Pitch $\approx 1/3$ minimum point diameter after developing
- Linked to beam diameter (and developing): if $\Phi_{\text{beam}} \nearrow p$ can \nearrow
- Does not change the exposure time: if $p \searrow t_{\text{point}} \searrow$ (i.e.: $F \nearrow$)
- *Define the maximum current according to the maximum frequency*

- **Highest current: to decrease exposure time**

- ☞ $I \nearrow$ ☞ reach max. beam speed ($\sim 5\text{mm/s}$) ☞ \nearrow pitch ☞ max LER ☞ I_{max}

- **Higher sensitive polymer: to decrease exposure time**

- ☞ Reach F_{max} ☞ $\nearrow p$ if possible or $\searrow I$ ☞ \nearrow time exposure (interesting ?)

- **Decrease the HV (dose=f(HV)): to decrease exposure time**

- ☞ HV \searrow (beam size \nearrow , penetration depth \searrow) ☞ dose \searrow ☞ $F \nearrow$ and/or $p \nearrow$ (interesting ?)

- Current / beam energy / pitch between points / field size / resist / technology / reasonable time ... need experience
- Stage movement between fields, beam stabilization time, data transfer, ...
 - ☞ Can double exposure time
- Always too long ...
 - e.g.: 1cm² of 150nm square fully random with a precision of 10nm on each structure
 - 10Go data, 100h exposure ... on a machine equivalent to UTT one (20keV, 10MHz, 135pA)
Because of the combination of resolution and precision, current must be low ☞ exposure time is high.
 - 1h on a more powerful machine (100keV, 5nA, 125MHz)
If scanning generator maximum frequency is higher, current can be increased while maintaining a good resolution
 - Collaboration with RENATECH (CNRS public facilities/clean-rooms network) could be a solution for exceptional needs.

- Beam drift:
 - Room air-conditioning stability: $\sim 0.1 - 0.5^\circ\text{C}/\text{h}$
 - E-beam writer temperature stability (chiller temperature control: $\pm 0.1^\circ\text{C}$)
 - Mechanical drift: holder/machine temperature
(mechanical expansion: $\approx 1\mu\text{m}/0.1^\circ\text{C}$ of variation)
- Magnetic fields: powering cables, motors,...
- Earth magnetic field: perturbation by moving heavy metal parts (vehicles, lift)
- Mechanical vibrations: building, lift, vehicles, pumps, compressor, ..., sound
- Flat / structured substrate: depth of focus, variable resist thickness, ...

- Electronics quality:
 - Speed
 - Noise
 - Stability
 - Reliability
- DAC:
 - Number of bits
 - Maximum frequency
- Scanning:
 - Beam scanning: frequency bandwidth
 - Field or field + subfields
 - Matrix correction: 4 points or more
 - Dead times:
 - Stabilization: stage, beam
 - Data transfer and treatment
- Computer:
 - PC under Windows
 - Workstation under LINUX
- Beam blanking speed
- ...

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Recommendations: EBL from A to Z

- Project / design to realize

Bibliography, description,
bottlenecks, issues ...

watch out for proximity effects,
total surface, ...

- Adjustments.

Like a SEM column !

- Exposure / development

Do you know how to use
the E-beam machine ?

Easy to do !

- Characterization / measurements

Do I know how to use
dedicated machines !?!

- Is it simple ? . . .

yes ... with experience

Elements to take into account:

■ Sample :

- ☞ Conductor / insulator ?
- ☞ Sensitive to electrons ?
- ☞ Size / shape / fragility / surface roughness / flatness / available quantity for tests / price / ...

■ Particular properties for the resist and/or sample specificity:

- ☞ Previous and next technological steps?
- ☞ Sensitivity or resistance towards treatments: wet/dry etching, solubility, compatibility with metals, ... ?
- ☞ Positive or negative ?
- ☞ Final structure: bump or hole ? surface / density / size ?
- ☞ Etching or lift-off ?
- ☞ Resolution, thickness, dose, developer ?
- ☞ Easy to remove ?

■ Alignment marks : overlay, « mix & match »

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- SEM:
 - Alignment and astigmatism routines:
 - Round shape beam (no astigmatism)
 - Minimum size (highest resolution) for the parameters used
 - ☞ More and more simple:
 - ☞ Automatic alignment
 - ☞ Automatic adjustments
 - ☞ Needs experience to choose the right parameters:
 - ☞ Share informations
 - ☞ Try new parameters set: your ability in alignment and astigmatism routines allow you to explore quickly different parameters
 - ☞ Useful for EBL adjustments
- EBL
 - Need of experience # need to practice & share knowledges
 - Adjustments, calibrations, exposure, developing, characterization ... it takes time to be confident
 - When facing issues you will learn why and how to overcome them

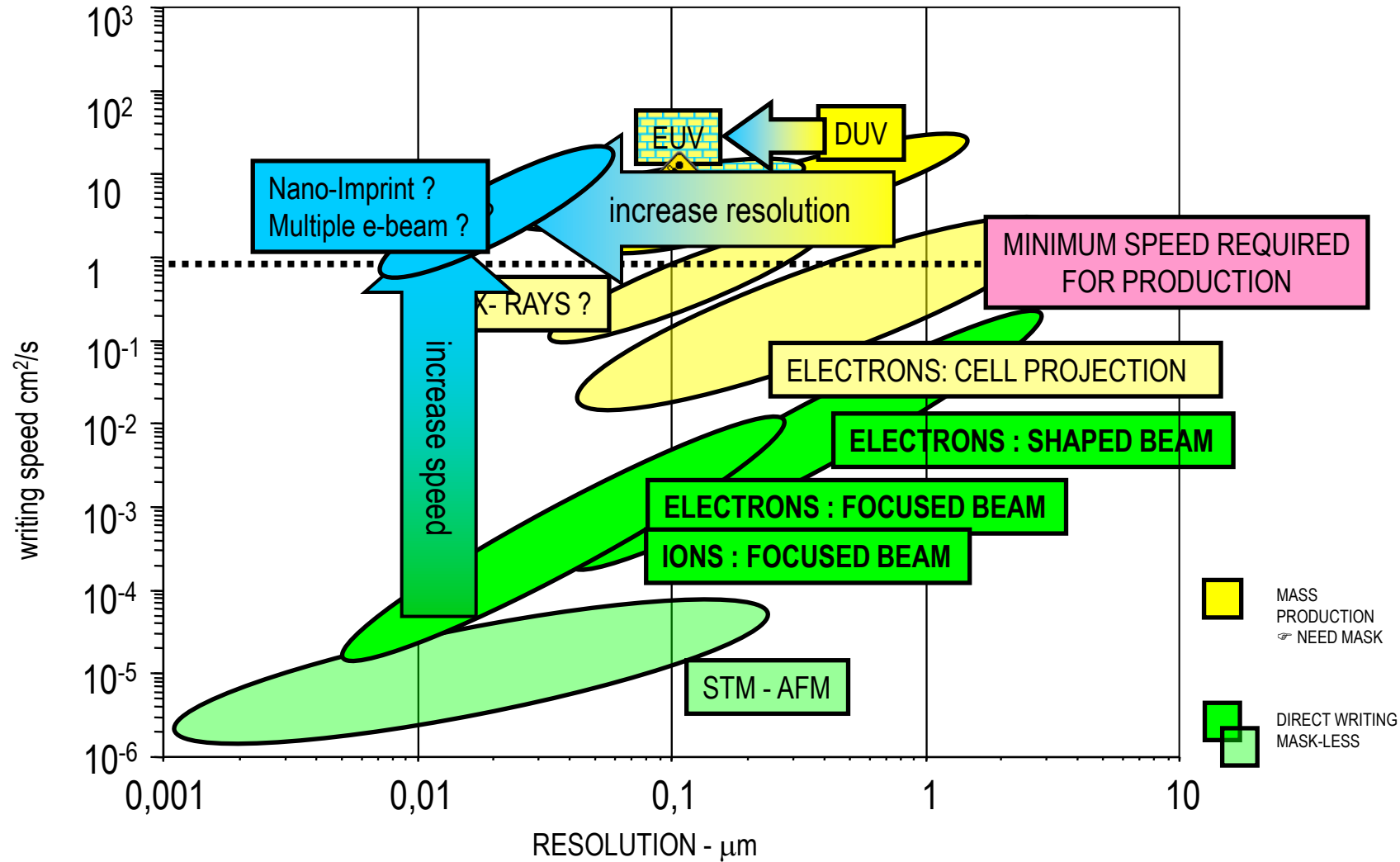
- [Raith](#)
- [Jeol](#)
- ELIONIX
- [Vistec](#)
- [Advantest](#)
- [Crestec](#)

- [Nanobeam](#)

- [Nabity: Nano Pattern Generation System](#)
- *Hitachi*

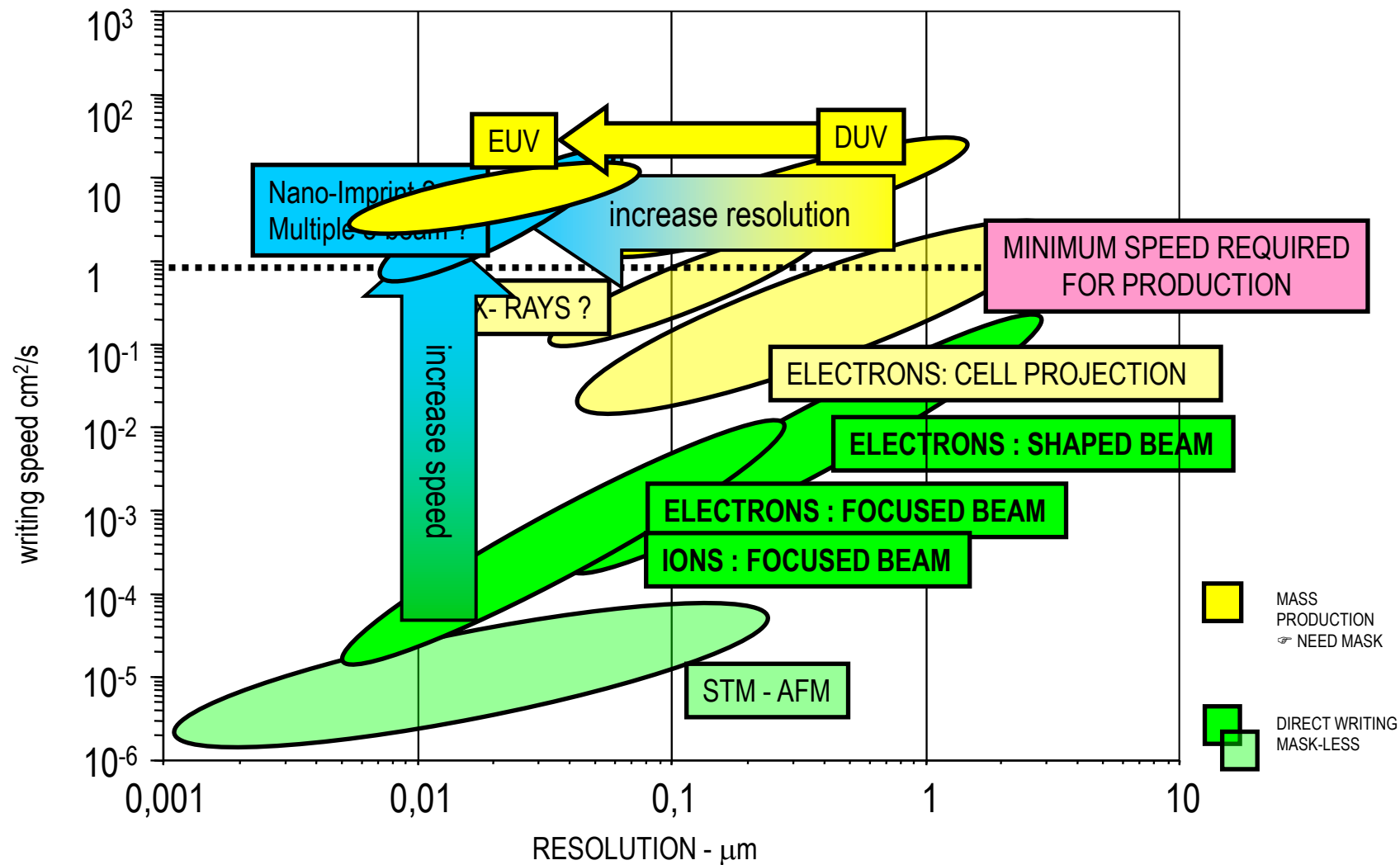
- Introduction
- EBL: basic principals
 - Exposure
 - Developing
 - System composition
 - Calibration
 - Design recommendations
- EBL: concrete practice
 - Driving parameters
 - Limitations
 - Recommendations
 - Sum-up
- EBL nowadays
 - Competition at industry level
 - Tendencies and job evolution

Competition at industry level: 20 years ago ...





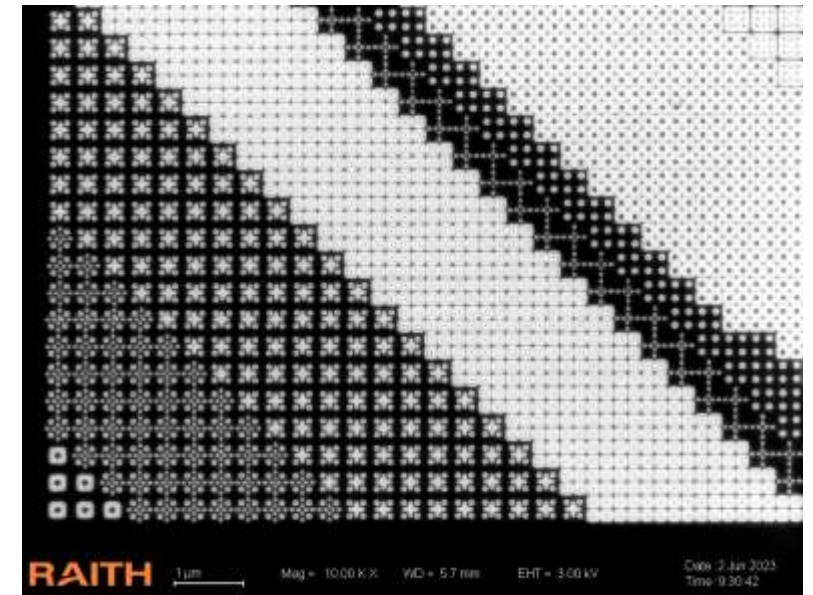
Competition at industry level: nowadays !



EBL nowadays

- Introduction
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- Still necessary for:
 - Optical mask fabrication: UV, DUV, EUV
 - Molds fabrication: Nano Imprint Lithography (molding)
- Large surfaces:
 - Optical metasurfaces: $\sim 1\text{cm}^2$ and more ... if possible
 - Structures are not regular
 - Large surface
 - High resolution
 - Critical Dimension (CD) control: $\sim 10\text{nm}$
 - 👉 Improve machines: current, speed, resolution
 - 👉 Improve resists: sensitivity, contrast, etching resistance, ...



■ Machines more and more automatic:

- Focus
- Astigmatism
- Calibrations

👉 **User: closer and closer to technology**

- 👉 Scientific project, materials compatibility, flow chart, characterization
- 👉 There is still plenty of knowledges to acquire

■ **Scripting (big tendency):**

- For complex and variable drawings
- To drive the machine
- 👉 Learn programming languages:
 - PYTHON, RUBY, MATLAB, ...
 - Probably deep learning to extract parameters from a collection of exposures