<u>SUMMER SCHOOL ON</u>

<u>BASICS AND APPLICATIONS OF NANOLITHOGRAPHY</u>

ORGANIZERS

INSTITUTO DE CIENCIA DE MATERIALES DE ARAGÓN

INSTITUTO UNIVERSITARIO DE INVESTIGACIÓN EN NANOCIENCIA DE ARAGÓN

***SORAYA SANGIAO:** sangiao@unizar.es

***JOSÉ MARÍA DE TERESA:** deteresa@unizar.es

http://nanofab-deteresa.com (under construction)

***GROUP WEBPAGE:** http://nanofab.unizar.es

UNIVERSITY OF ZARAGOZA

SUMMER SCHOOLS IN JACA

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icma
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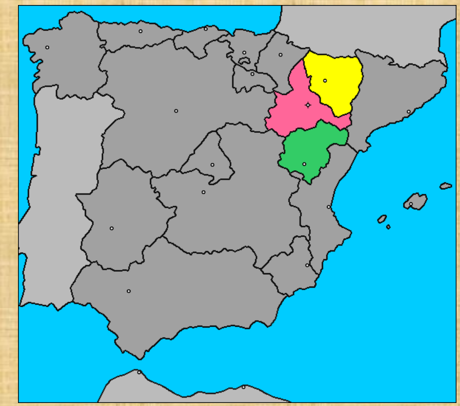
ARAGON: A TERRITORY LINKED TO ARTS AND SCIENCE



*__Miguel Servet__ (1509-1553): discoverer of the lung blood circulation. Dead in the bonfire in Geneva.

*__Santiago Ramón y Cajal__ (1852-1934): discoverer of the nerve cells connections. Nobel Prize in Medicine in 1906.

*__Miguel Catalán__ (1894-1957): discoverer of the multiplets, the splitting of the atomic energy levels.

FRANCISCO DE GOYA (aragonese painter, 1746-1828)

BALTASAR GRACIAN (aragonese writer, 1601-1658)

"Pon siempre un gramo de audacia en todo lo que hagas"

"Put a gram of audacity in all you do"

***Student reward: ONE FREE BEER on TUESDAY at 8pm for all students who asked at least TWO QUESTIONS per day**

SUMMER SCHOOL ON

BASICS AND APPLICATIONS OF NANOLITHOGRAPHY

QU'EST-QUE C'EST NANOLITO?

rednanolito

<u>NANOLITO</u>: Spanish network of excellence on Nanolithography, funded by the Ministry of Science (started in 2007)

Coordinating node:
Zaragoza (INA, ICMA)

Other nodes:
Madrid (ISOM, UCM, ICMM, IMDEA)
Barcelona (CNM, UB, ICN2)
San Sebastián (Nanogune)
Oviedo (U. Oviedo)
Eibar (Tekniker)

Webpage: www.unizar.es/nanolito
Twitter: @RedNanolito

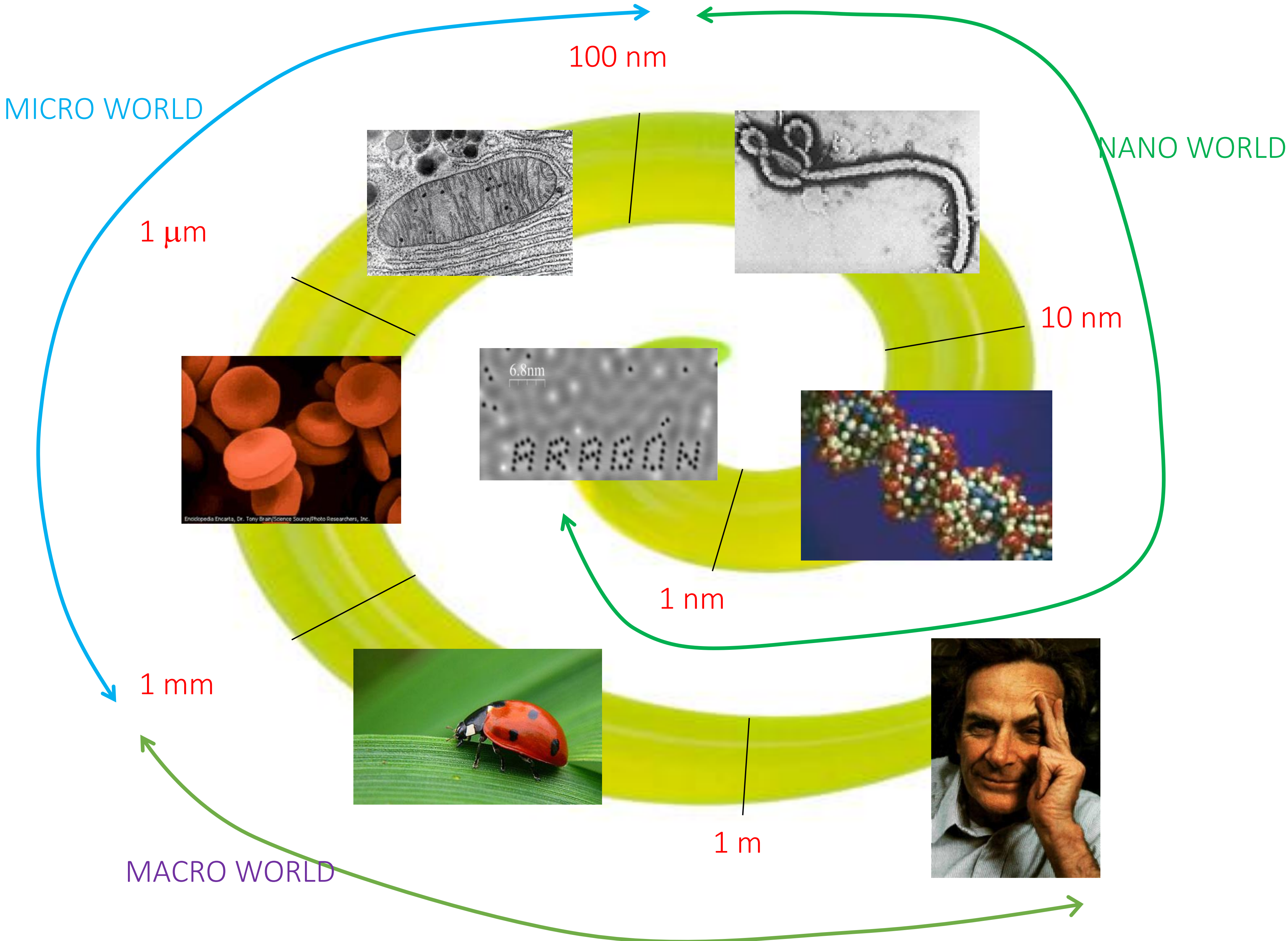
JACA-2016

SAN SEBASTIAN-2016

SALAMANCA-2017

MADRID-2017

Introduction to Nanolithography

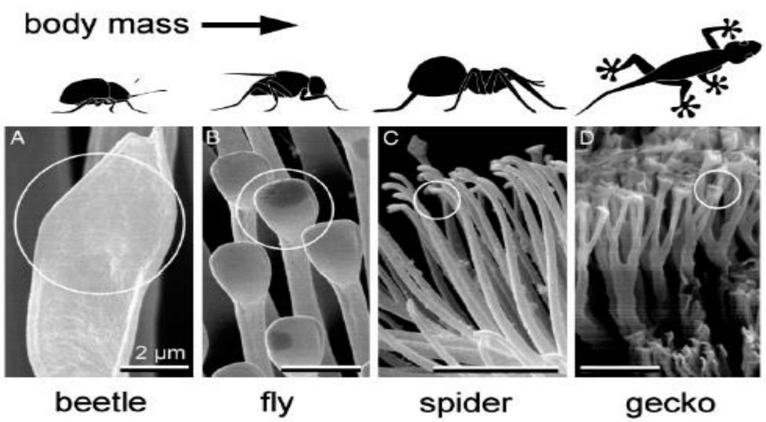

MICRO WORLD
100 nm
NANO WORLD
1 μm
10 nm
6.8nm
ARAGÓN
Enciclopedia Encarta, Dr. Tony Brain/Science Source/Photo Researchers, Inc.
1 nm
1 mm
1 m
MACRO WORLD

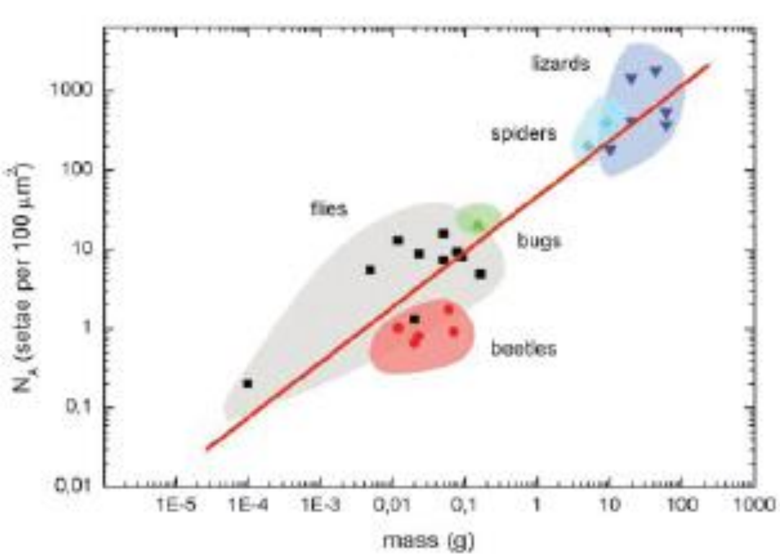
NANOTECHNOLOGY EXISTS IN NATURE

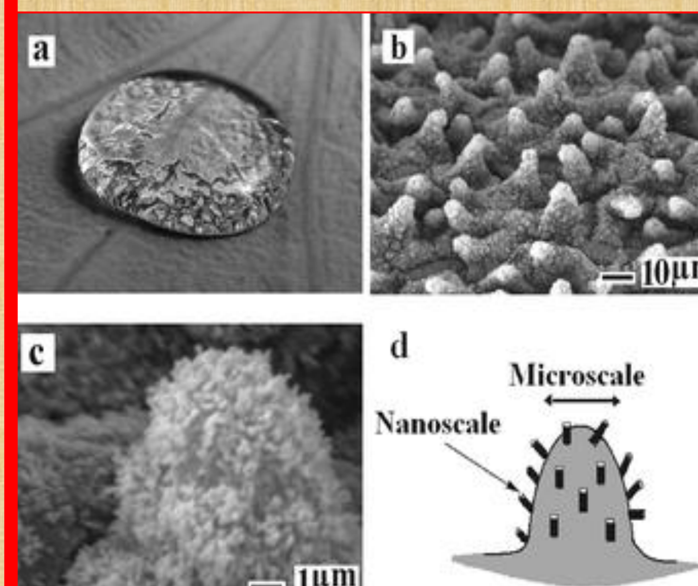
From micro to nano contacts in biological attachment devices

Eduard Arzt[†‡], Stanislav Gorb[†§], and Ralph Spolenak[†]

[†]Max Planck Institute for Metals Research, Heisenbergstrasse 3, 70569 Stuttgart, Germany; and [§]Biological Microtribology Group, Max Planck Institute of Developmental Biology, Spemannstrasse 35, 72076 Tübingen, Germany

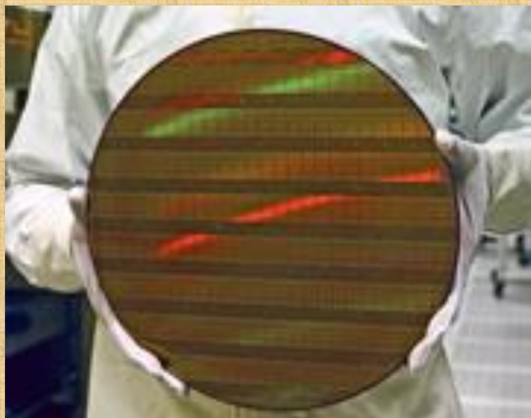


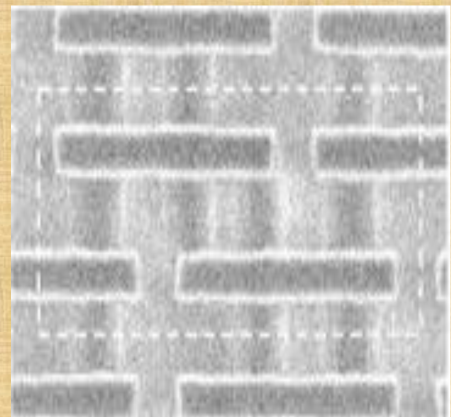




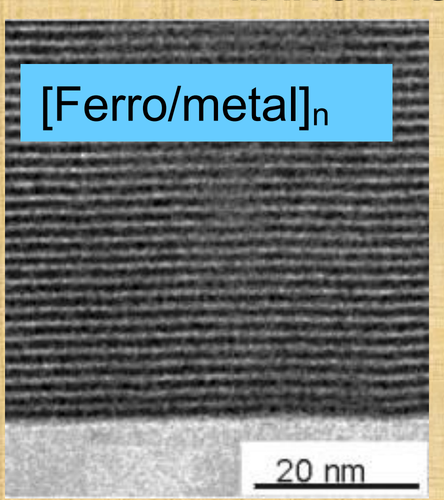
CAN WE CREATE ARTIFICIAL PROCESSES TO PATTERN MATERIALS AND DEVICES TO THE NANOSCALE? YES!

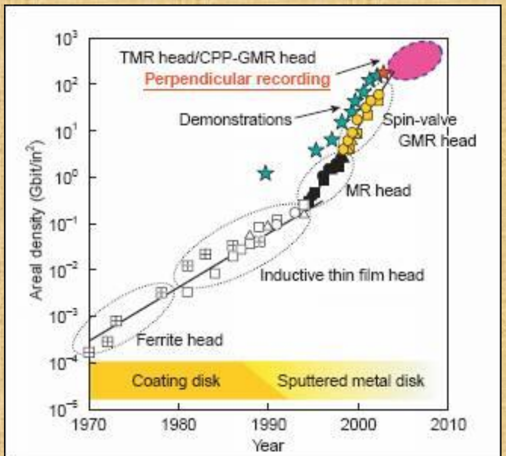
TRANSISTORS IN MICROPROCESSORS:
current node= 14 nm

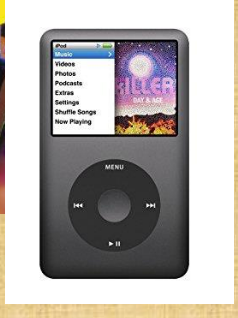




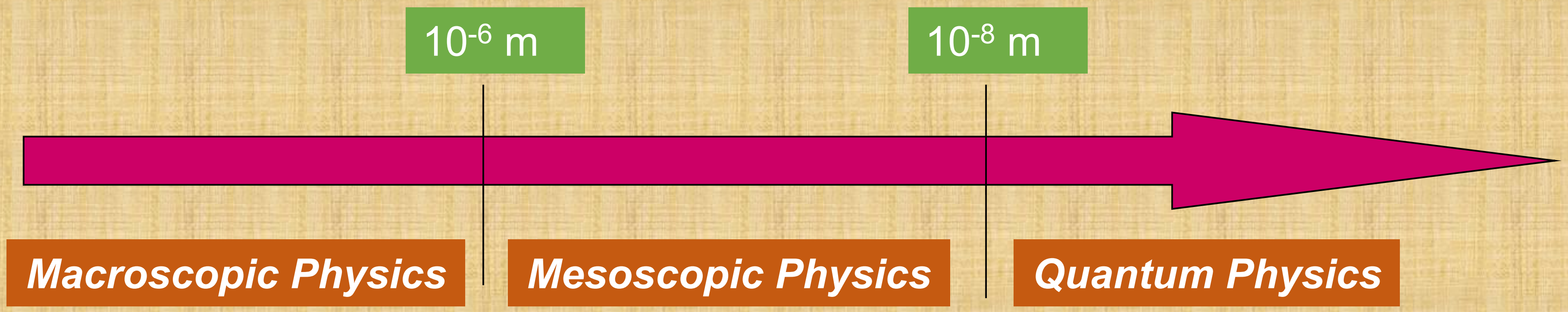
MEMORIES AND READING HEADS BASED ON NANOMAGNETIC ELEMENTS







PHYSICAL PHENOMENA CAN ALSO CHANGE AT THOSE DIMENSIONS!



In Mesoscopic Physics, some dimension of the material/device is comparable or smaller than some relevant length, such as the mean free path in metals, the exchange length and the spin diffusion length in magnetic materials, the coherence length and the magnetic field penetration length in superconductors…Besides, fluctuations become more important.

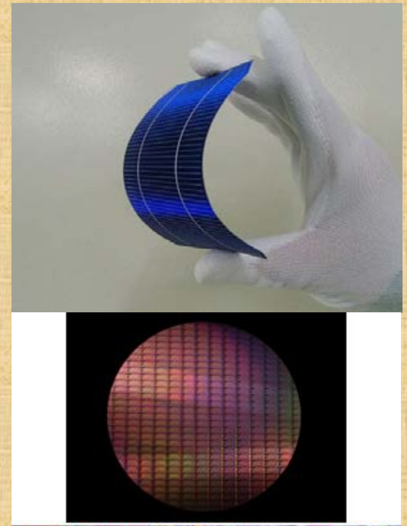
When dimensions are small enough, the discretization of the energy states becomes relevant and the system needs to be described by means of Quantum Physics.
$\Delta E_K/K_BT \approx 1$ (at RT, K_BT=25 meV and ΔE_K=25 meV, typically for L<10 nm)

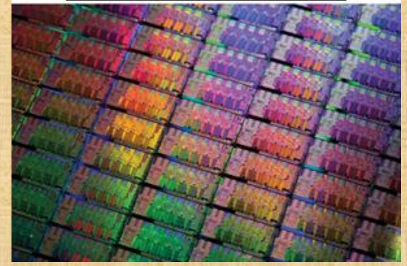
INTRODUCTION TO NANOLITHOGRAPHY (I)

TOP-DOWN APPROACH

Thin-film growth technology
+
Lithography techniques

If lateral dimensions are smaller than 1 μm, we talk about "nanolithography"





Thin-film growth technology

Physical vapour deposition (sputtering, evaporation), chemical vapour deposition, liquid-phase deposition (electrodeposition, spin coating), Langmuir-**Blodgett...**

Lithography techniques

Optical lithography, electron beam lithography, focused ion beam, scanning probe lithography, **nanoimprinting, nanostencil,...**

INTRODUCTION TO NANOLITHOGRAPHY (II)

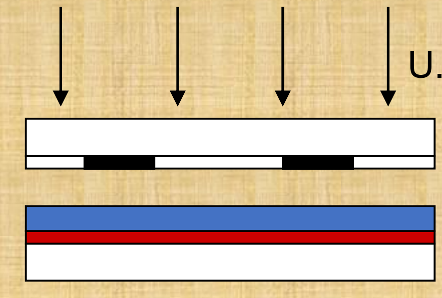
⇒ THE LITHOGRAPHY IS THE SET OF TECHNIQUES ALLOWING THE TRANSFER OF PATTERNS TO A SAMPLE. THE TYPICAL MINIMUM SIZE IN THE TRANSFERED PATTERNS IS MICROMETRIC OR NANOMETRIC.

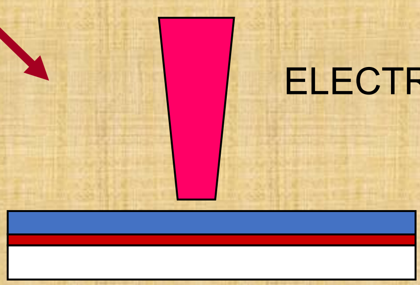
⇒ THE PATTERNS CAN:

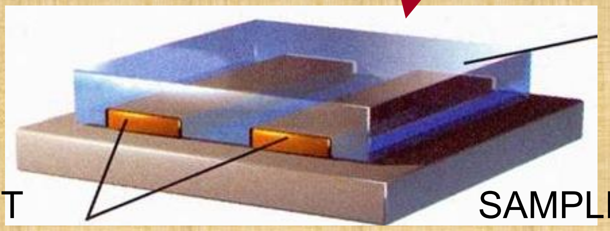
-<u>BE PREVIOUSLY DESIGNED ON A MASK</u>: Optical UV or EUV lithography

-<u>BE GENERATED BY MEANS OF A SCANNING ELECTRON OR ION BEAM</u>: Electron-beam lithography, ion-beam lithography, local probe scanning

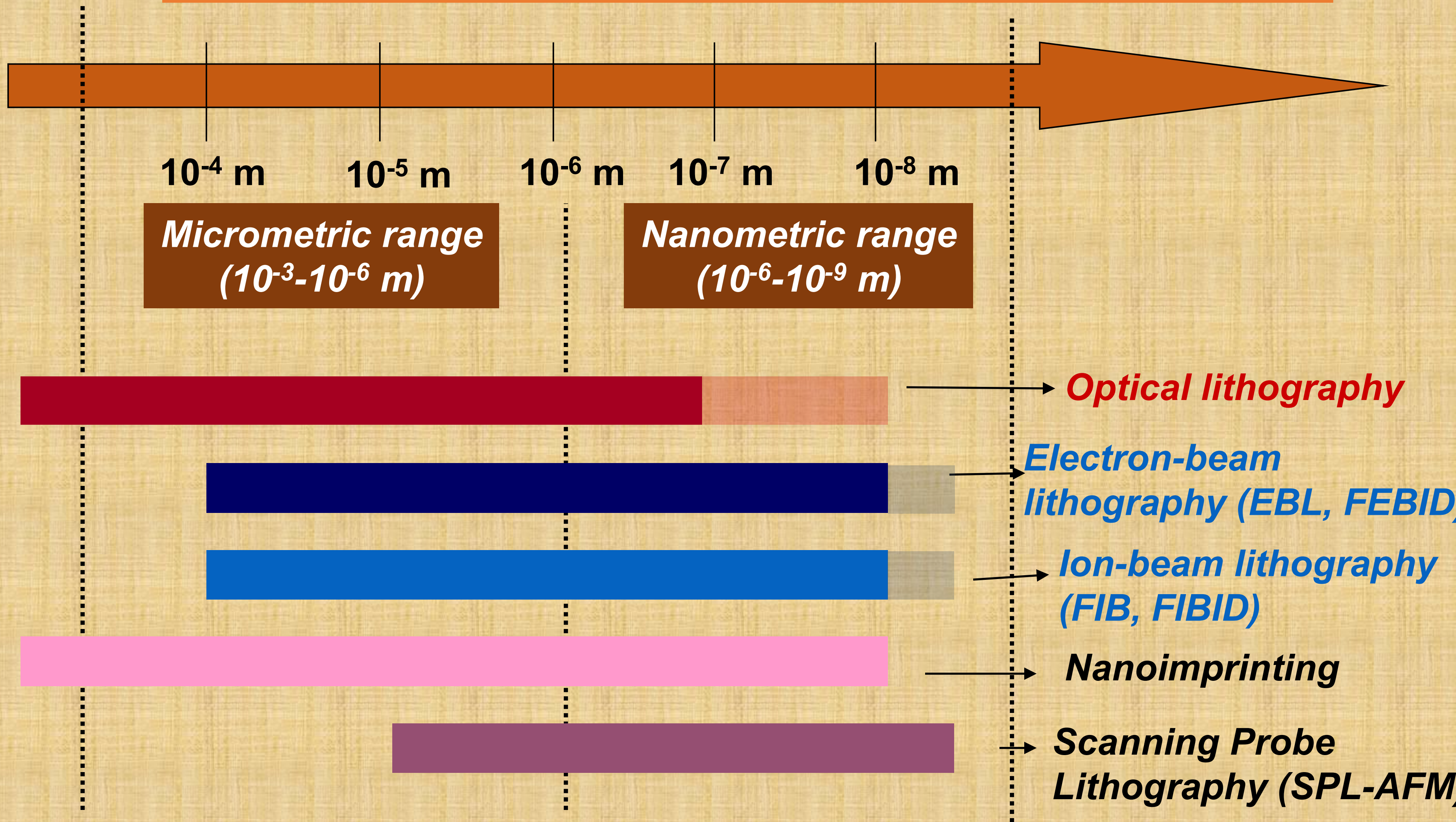
-<u>BE PREVIOUSLY AVAILABLE ON A MOULD</u>: Nanoimprinting







INTRODUCTION TO NANOLITHOGRAPHY (III)



⇒ Besides resolution, other important aspects to consider are: speed, cost, reproducibility, possibility to develop complex patterns, accessibility to the technique...

INTRODUCTION TO NANOLITHOGRAPHY (IV)

⇒ LITHOGRAPHY PROCESSES SHOULD BE PERFORMED IN CLEAN ROOMS

-A Clean Room is a space with controlled environmental conditions, keeping low levels of contamination (dust, particles, microbes…)

-In a Clean Room the following parameters are controlled:

- -Number and dimensions of the particles present in the air
- -Temperature
- -Humidity
- -Differential pressure and flow of air
- -Illumination
- -Electrostatic protection

ISO RULE 14644

***APPLICATIONS AREAS*:**

-MICRO- AND NANO-ELECTRONICS

-FARMACEUTICS

-FOOD INDUSTRY

-MICROSYSTEMS

-HOSPITALS AND CLINICS

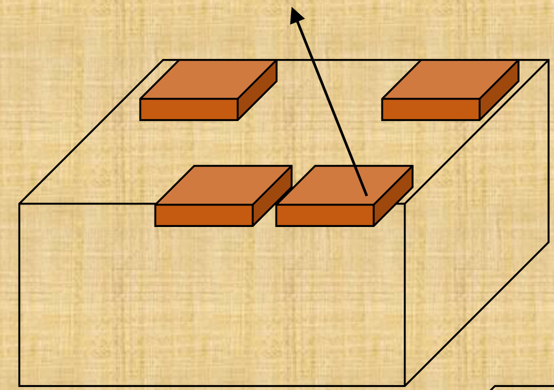
-PLASTICS AND CHEMISTRY INDUSTRY

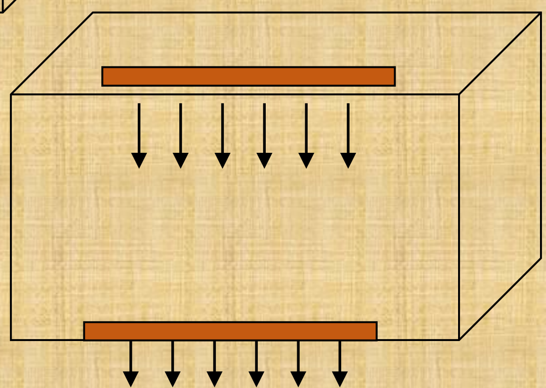
INTRODUCTION TO NANOLITHOGRAPHY (V)

⇒ *HOW CAN WE KEEP A ROOM CLEAN?*

INTRODUCTION TO NANOLITHOGRAPHY (VI)

FFU (filter/fan unit)





⇒ *HOW CAN WE KEEP A ROOM CLEAN?*

-HEPA (High-efficiency particulate air) FILTER: 99.97% - 99.99% (0.3μm)

-ULPA (Ultra high-efficiency particulate air) FILTER :99.9995% (0.12μm)

Class	maximum particles/m^3						FED STD 209E equivalent
	≥0.1 μm	≥0.2 μm	≥0.3 μm	≥0.5 μm	≥1 μm	≥5 μm	
ISO 1	10	2.37	1.02	0.35	0.083	0.0029	
ISO 2	100	23.7	10.2	3.5	0.83	0.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	1,020	352	83	2.9	Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1.0×10^6	237,000	102,000	35,200	8,320	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352,000	83,200	2,930	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832,000	29,300	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293,000	Room air

Class	Air flow speed	Renovations per hour	Percentage of ceiling covered
10000	0.05-0.08 m/s	60-90	15-20%
1000	0.13-0.2 m/s	150-240	25-40%
100	0.2-0.4 m/s	240-280	35-70%

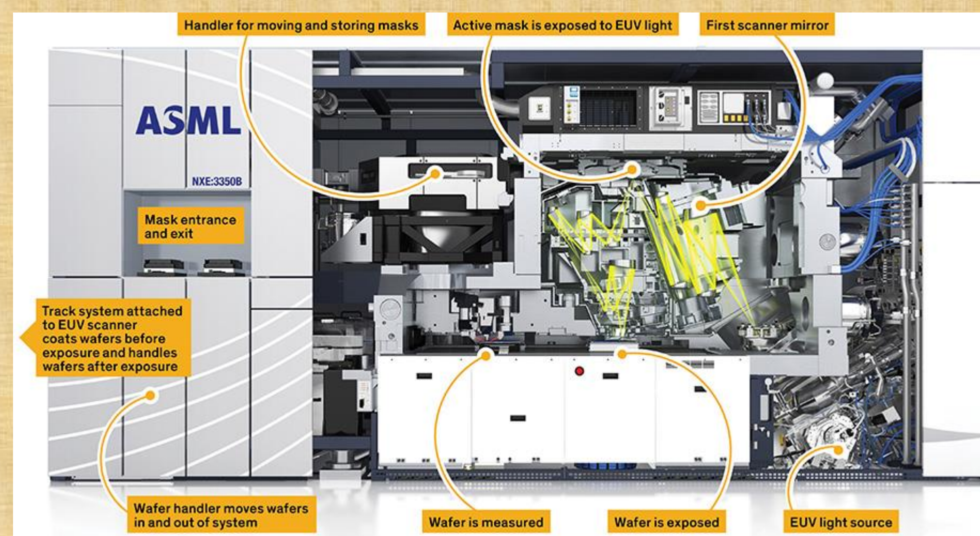
Optical Lithography

TECHNOLOGICAL EVOLUTION IN OPTICAL LITHOGRAPHY

UV MASK ALIGNER
(lab technology)

UV STEPPER
(semicon industry, today)

EUV STEPPER
(semicon industry, tomorrow)



BASIC PROCESS

1) GROWTH OF THE MATERIAL
2) BASIC LITHOGRAPHY PROCESS

TWO APPROACHES TO WORK WITH RESISTS (in optical and electron-beam lithographies)

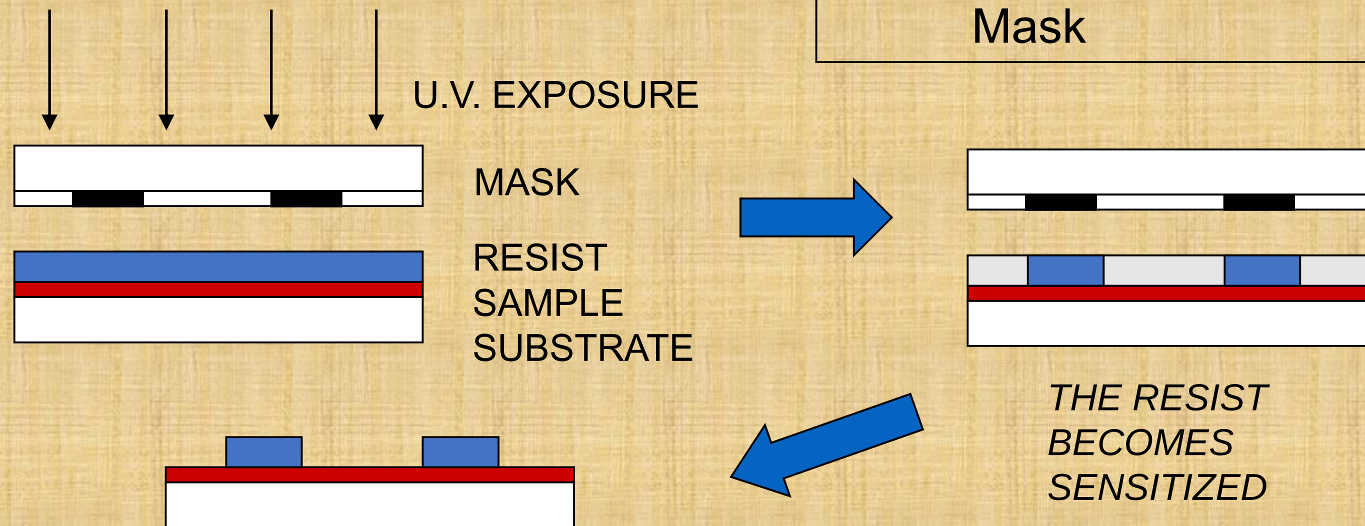
LIFT-OFF PROCESS

1) BASIC LITHOGRAPHY PROCESS
2) GROWTH OF THE MATERIAL IN AN INTERMEDIATE STEP OF THE LITHOGRAPHY PROCESS

⇒ AN ACTUAL FULL LITHOGRAPHY PROCESS INVOLVES MANY BASIC AND LIFT-OFF PROCESSES ONE AFTER THE OTHER

OPTICAL LITHOGRAPHY

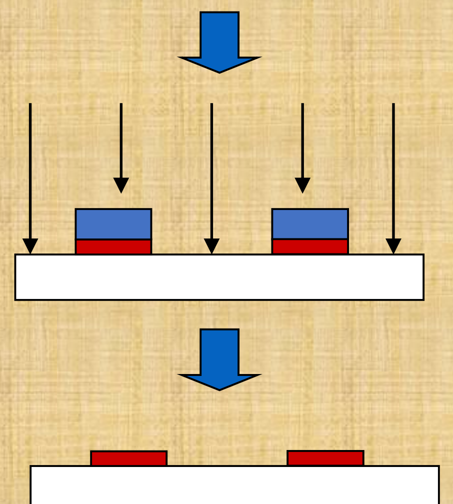
BASIC PROCESS



1) EXPOSURE

2) DEVELOPMENT

IMMERSION IN DEVELOPING FLUID



3) ETCHING

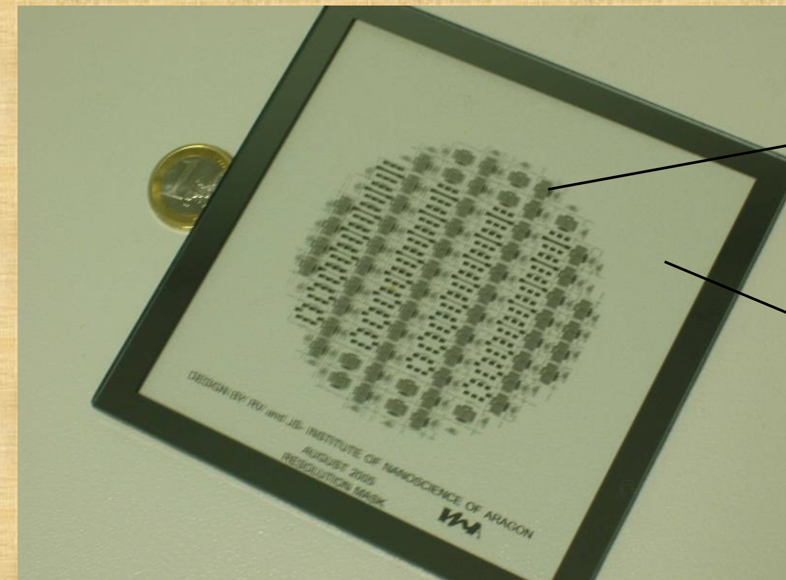
(DRY OR WET ETCHING)

4) RESIST REMOVAL

TYPICALLY, ACETONE

***RESULT*: SAMPLE WITH THE SAME PATTERN OF THE MASK**

OPTICAL LITHOGRAPHY MASKS

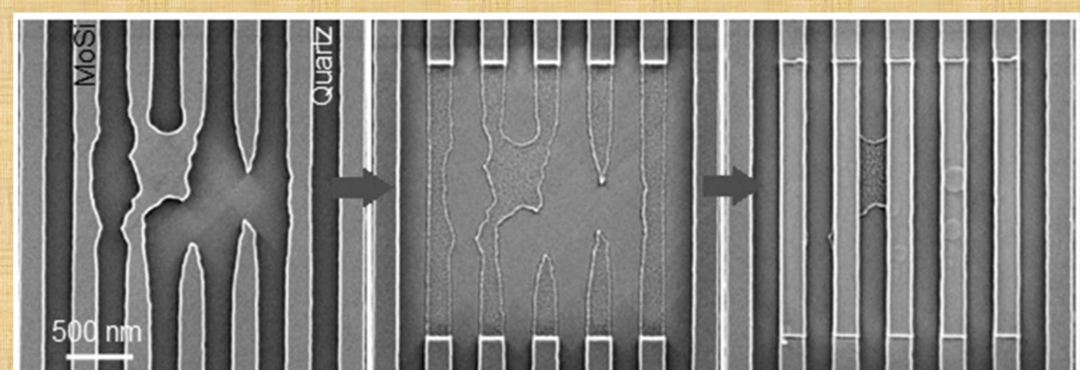


CHROMIUM MOTIFS (absorbers of the U.V. light)

QUARTZ SUBSTRATE (transparent at UV wavelenghts)

MASK REPAIR TOOLS

a) b) c)



RESISTS: VISCOUS FLUID FORMED BY A POLYMER, A PHOTOSENSITIVE COMPONENT AND A SOLVENT

POSITIVE RESIST

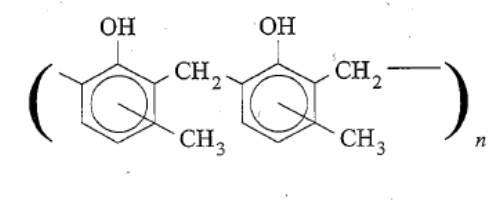
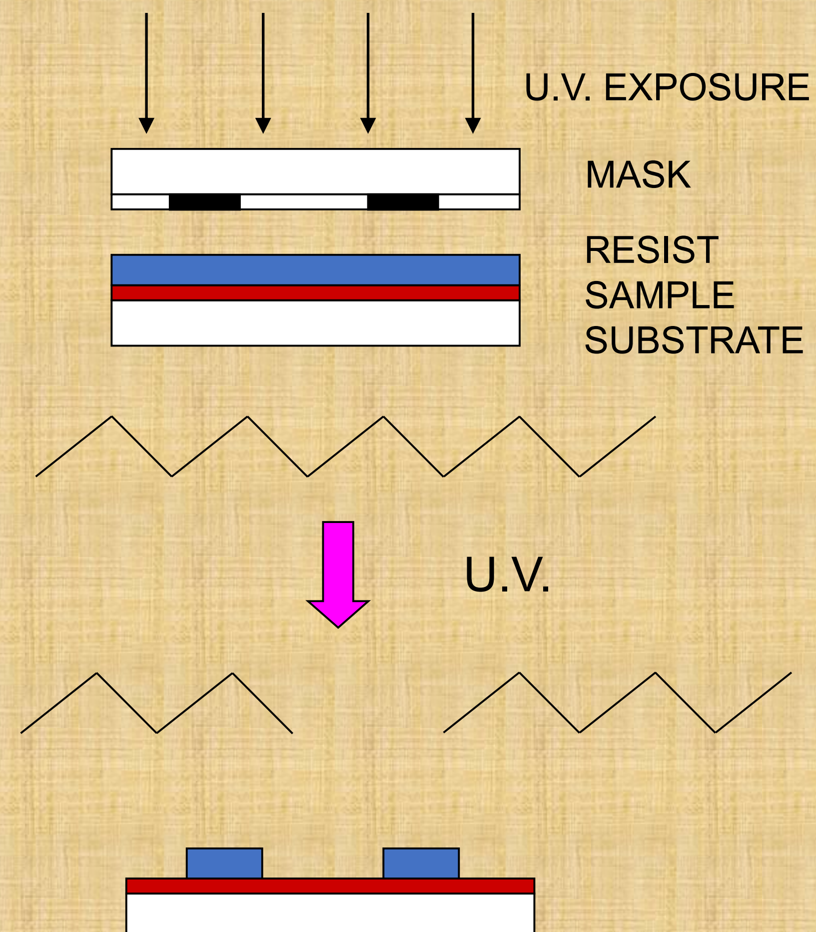


Figure 3.17 Novolak resin (ortho-ortho coupling).



NEGATIVE RESIST

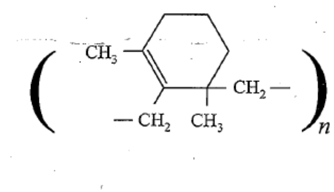
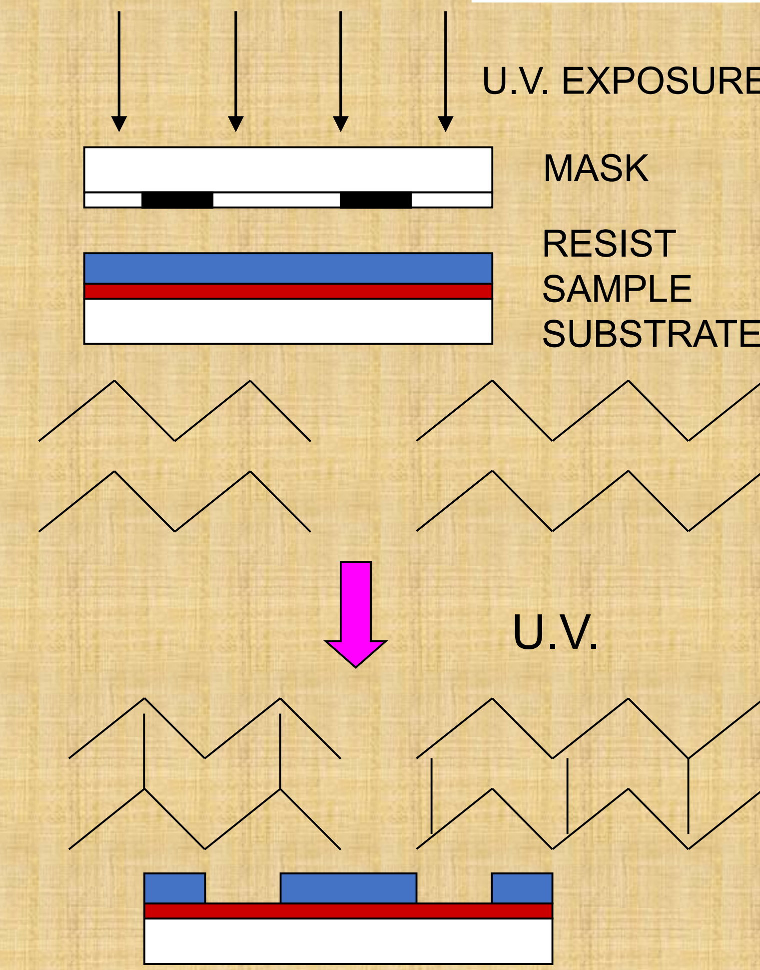
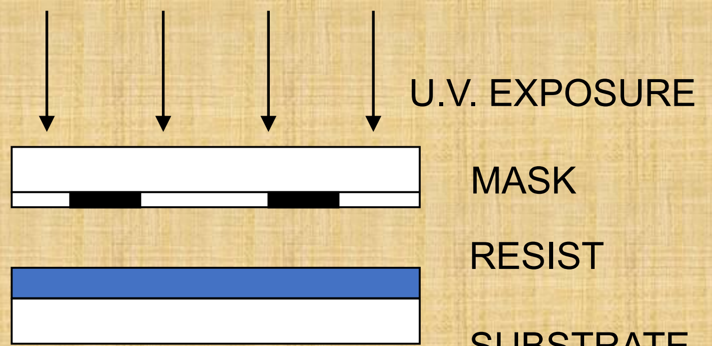


Figure 3.1 Cyclized poly-isoprene.[1]



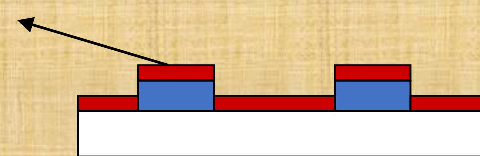
LIFT-OFF PROCESS (WITH POSITIVE RESIST)

1) EXPOSURE



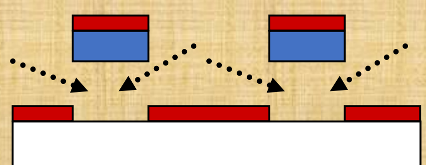
2) DEVELOPMENT

3) **SAMPLE GROWTH**



$$e_{resist} > 1.5 \times e_{sample}$$

4) IMMERSION IN ACETONE



FINAL RESULT

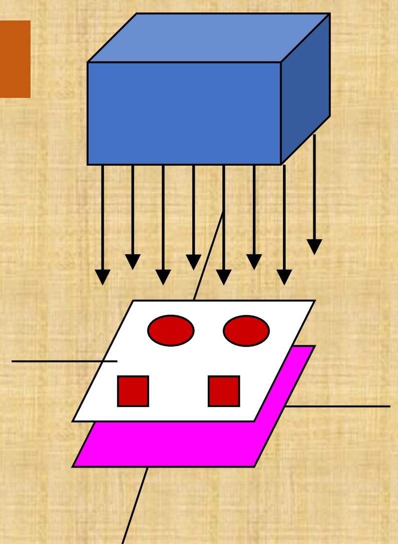
***RESULT*: SAMPLE WITH PATTERN SUPPLEMENTARY TO THAT OF THE MASK ACHIEVED WITHOUT ETCHING STEP!!**

DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (I)

RESIST SPIN COATING

A subsequent soft bake (90-100ºC) eliminates the solvent, improves the adhesion and avoid strains. A primer substance improves the adhesion of the resist.

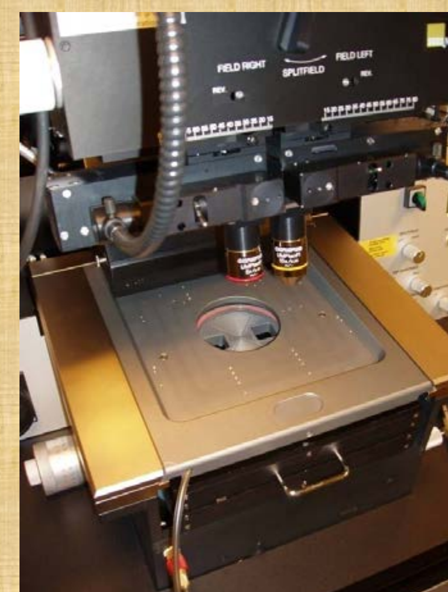
MASK ALIGNER



U.V. LAMP

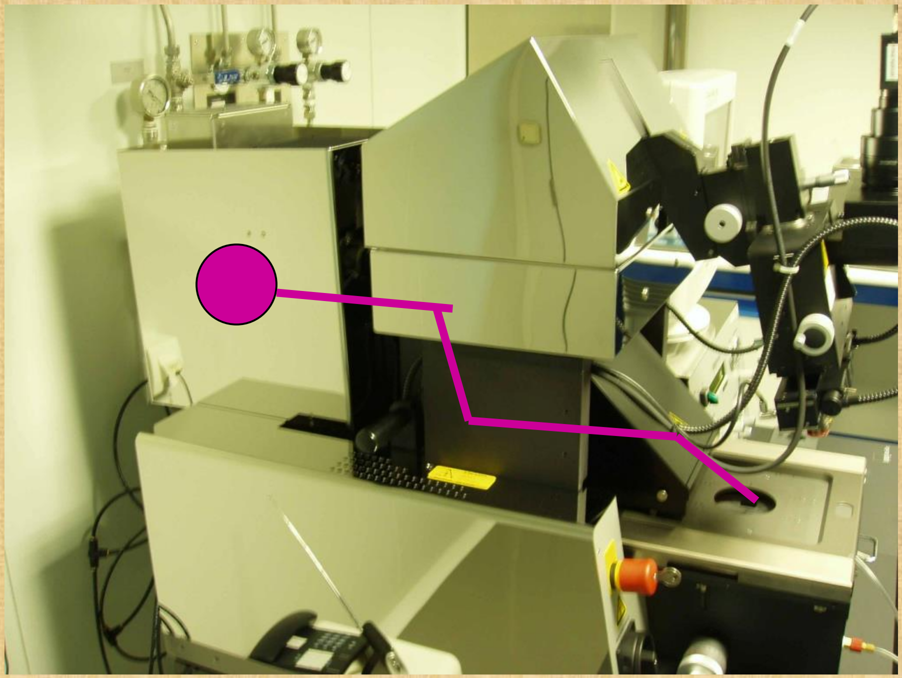
MASK

SAMPLE



DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (II)

MASK ALIGNER



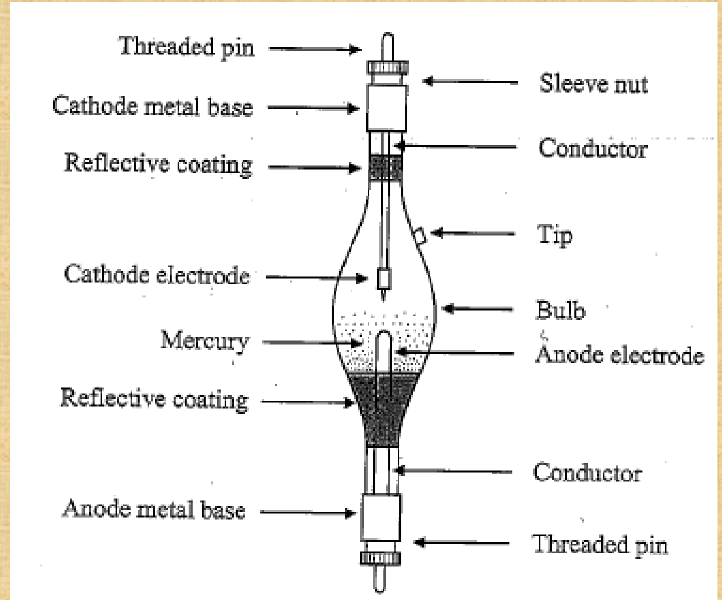
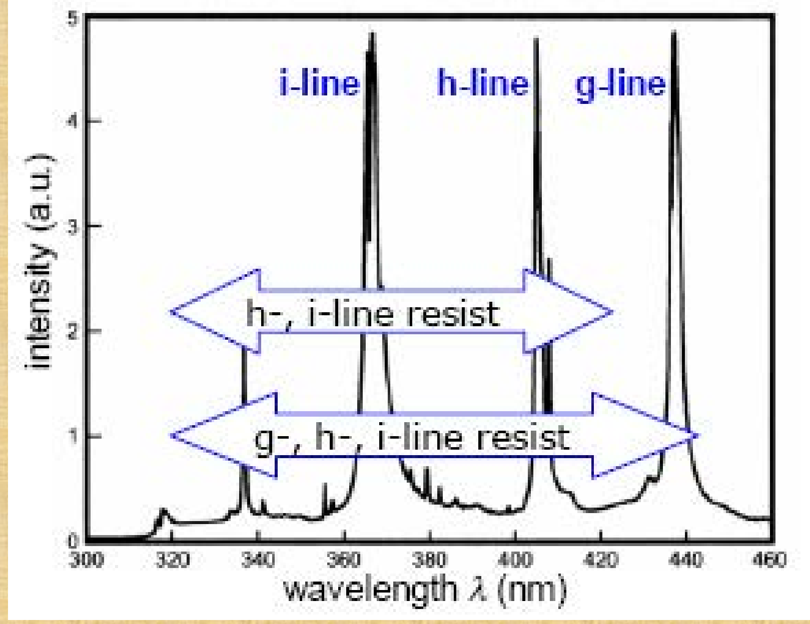


Figure 5.4 Mercury-arc lamp.

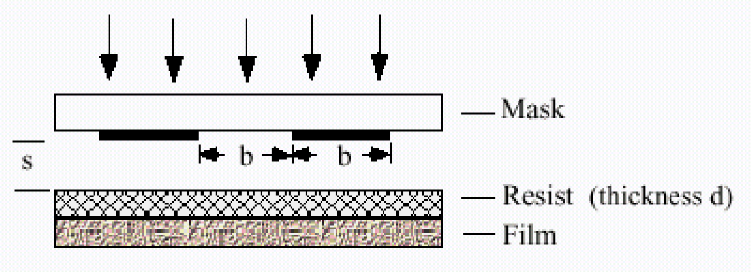


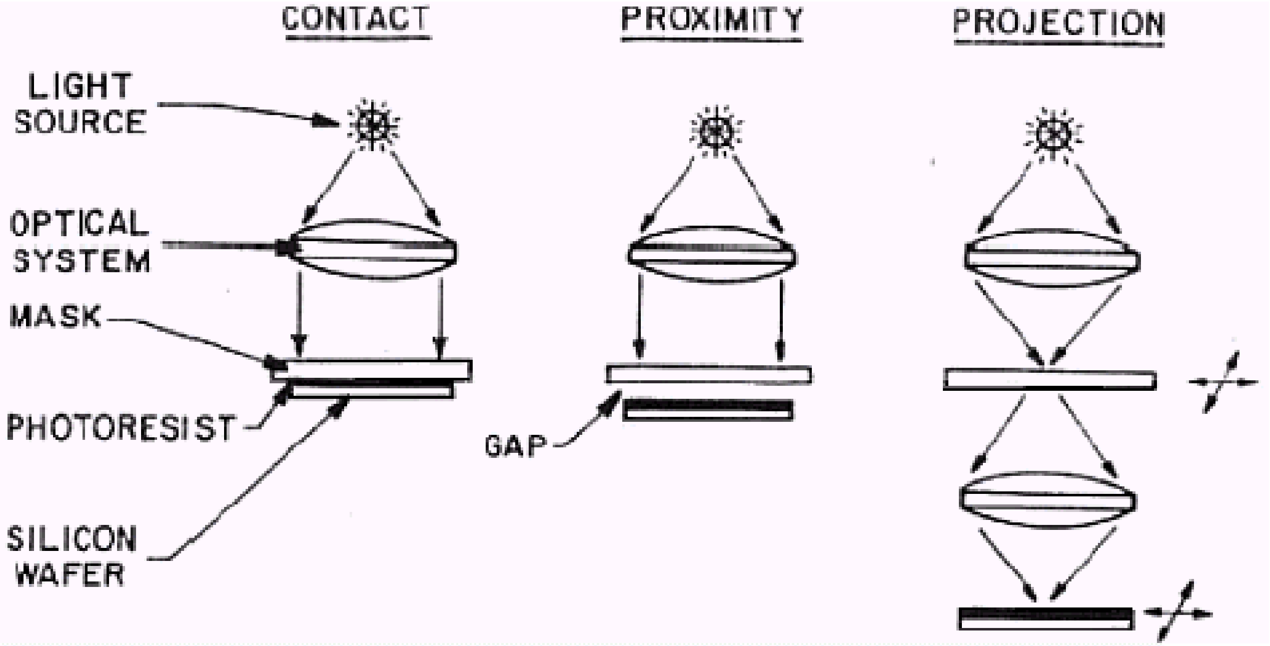
-By means of optical filters, the working wavelength can be selectioned

-*LAMP*: Hg (emission lines: G at 436 nm, H at 405 nm, I at 365 nm)

DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (III)

EXPOSURE MODES AND RESOLUTION



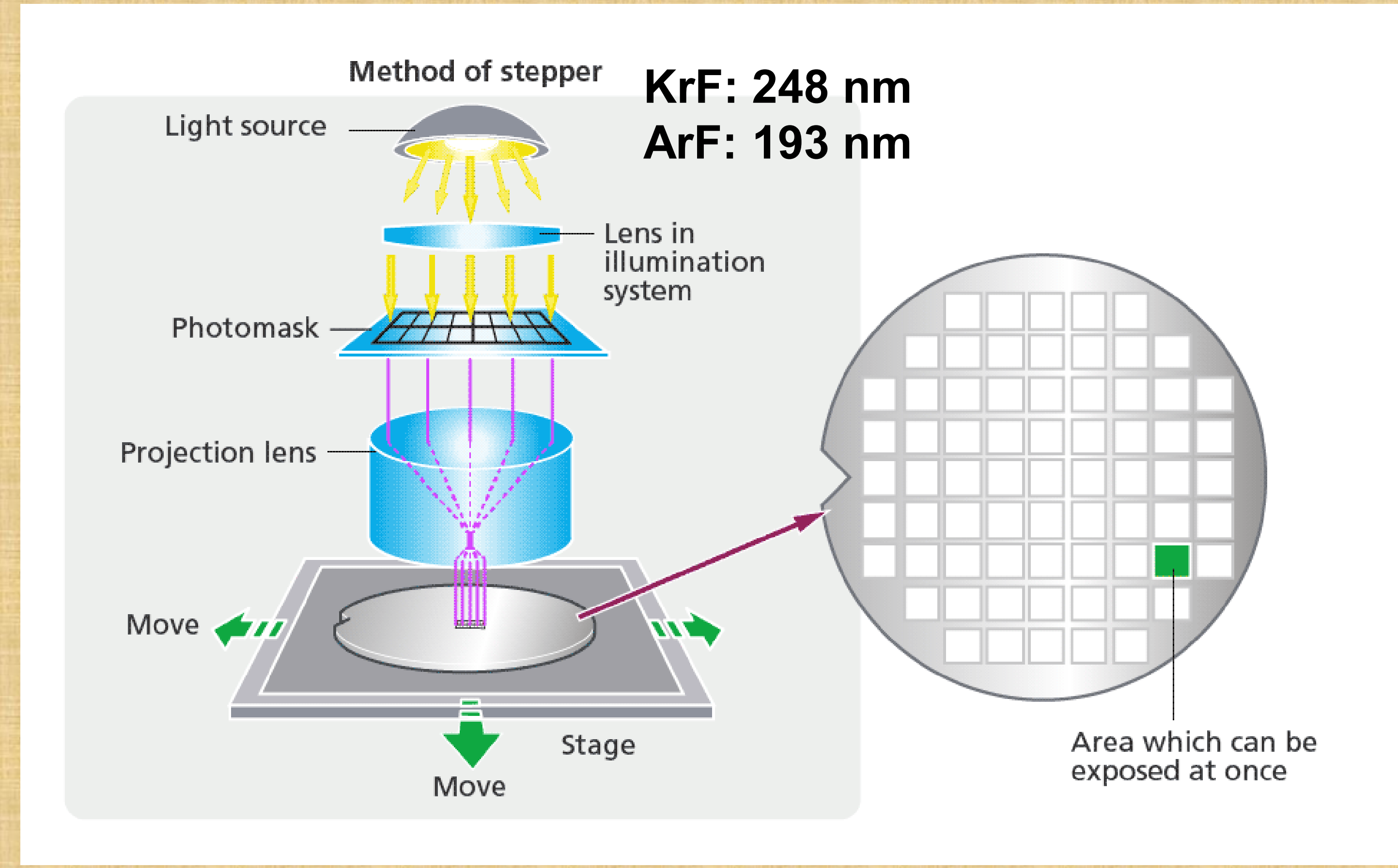


Resolution limit:

Contact	Proximity	Projection
$2b_{\min} = 3\sqrt{\lambda d / 2}$	$2b_{\min} \approx 3\sqrt{\lambda s}$	$b_{\min} = \dfrac{k\lambda}{NA}$
bmin≈0.5 µm	bmin≈3 µm	bmin≈10 nm

DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (IV)

STEPPERS IN SEMICON INDUSTRY



*Throughput: 200 wafers per hour

*Wafer diameter: up to 300 mm

*Tricks: immersion lens, phase-shift masks, double exposure

*Resolution:

0.35 μm (1997) →
0.18 μm (2002) →
90 nm (2007) →
30 nm (2013) →
10 nm (2017)

MINIMUM SIZE OF THE MOTIFS= K λ / (NA)

DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (V)

STEPPERS IN SEMICON INDUSTRY

https://www.youtube.com/watch?v=ShYWUIJ2FZs

DESCRIPTION OF THE STEPS IN OPTICAL LITHOGRAPHY (VI)

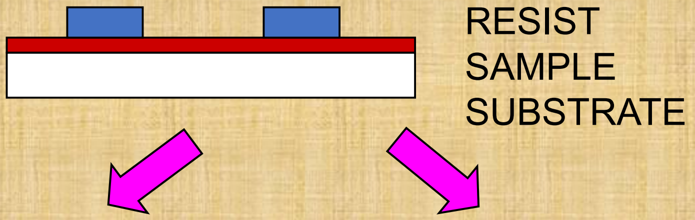
ETCHING PROCESSES

-WET ETCHING: BY MEANS OF REACTIVE LIQUIDS THAT PRODUCE A SOLUBLE BY-PRODUCT

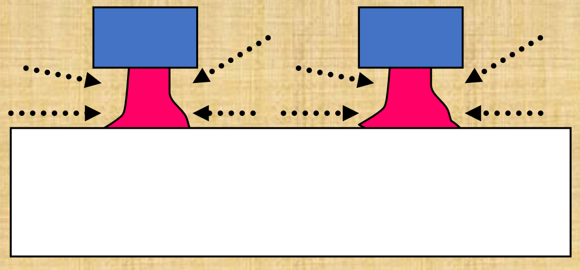
-DRY ETCHING: A VOLATILE COMPOUND IS FORMED

*PHYSICAL ETCHING: BY MEANS OF SPUTTERING AND IONIC BOMBARDEMENT (IBE)

*PHYSICAL/CHEMICAL ETCHING: BY MEANS OF PLASMA, REACTIVE ION ETCHING (RIE)…

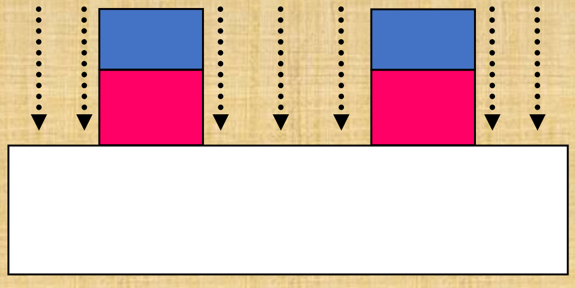


WET ECTHING



ISOTROPIC ETCHING PROFILE

DRY ETCHING



ANISOTROPIC ETCHING PROFILE

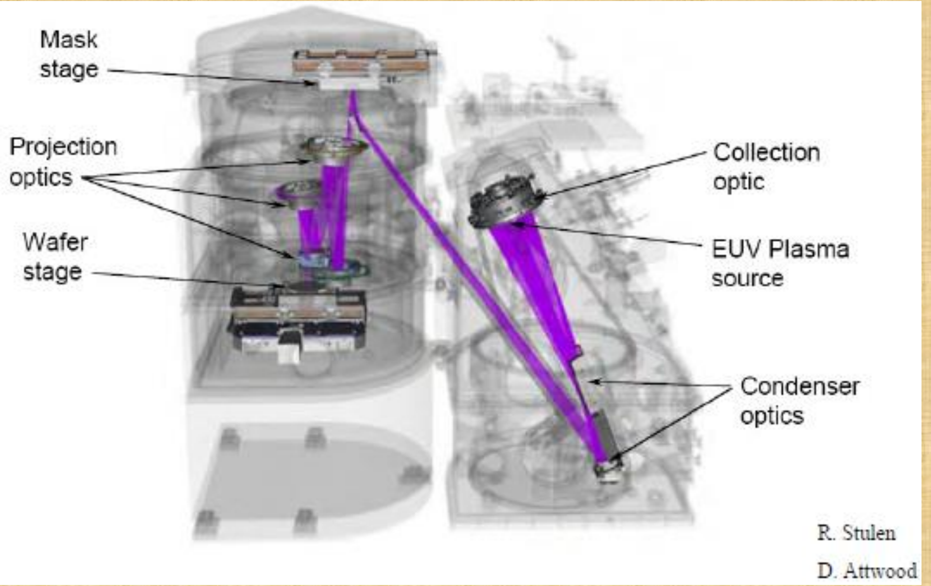
WHAT COMES NEXT?

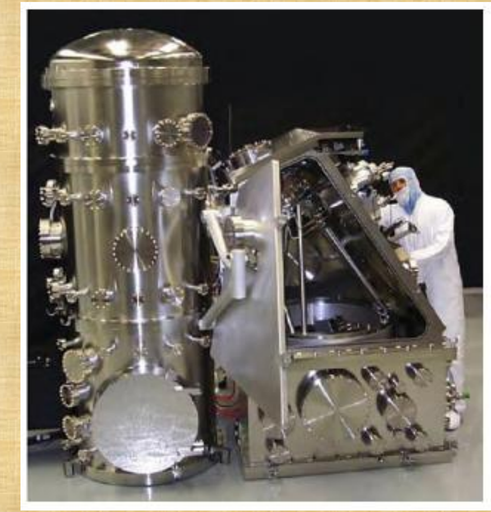
Wavelength (nm)	Source
436	G line of Hg lamp
365	I line of Hg lamp
248	KrF laser
193	ArF laser
157	F_2 laser
~10	Plasma (EUV)
~1	X-rays, synchrotron

PRODUCTION TO START IN 2020 TO REACH SUB-10 nm NODES

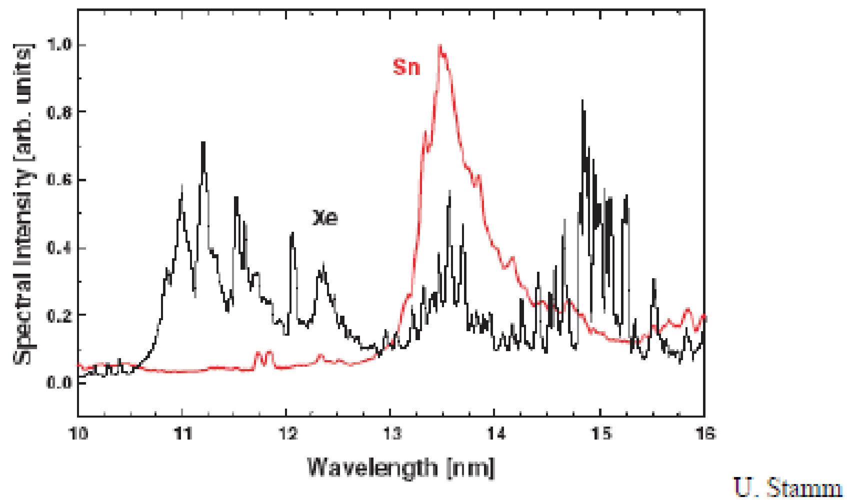
EUV LITHOGRAPHY (I)

CHANGE FROM REFRACTION OPTICS TO REFLECTION OPTICS





SELECTED SOURCE: Sn PLASMA



Difficulties:

*Low-efficiency energetic process

*Short lifetime of the elements

*Suitable resists needed

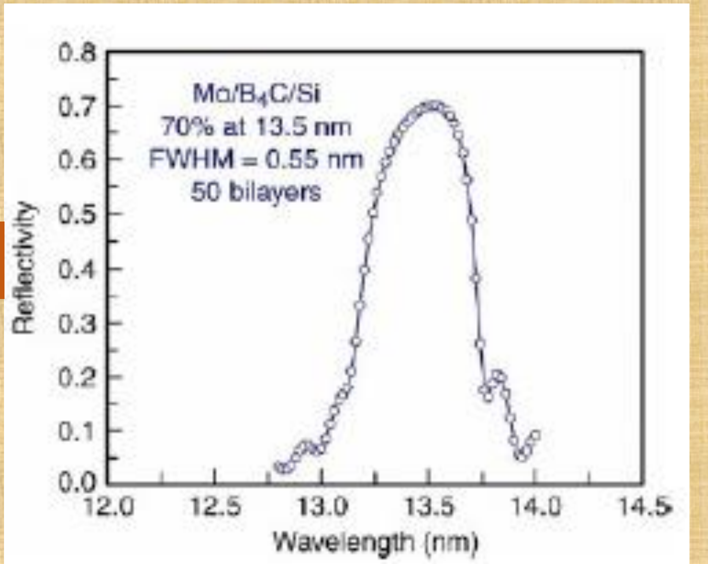
*Suitable masks needed

*Suitable mirrors needed

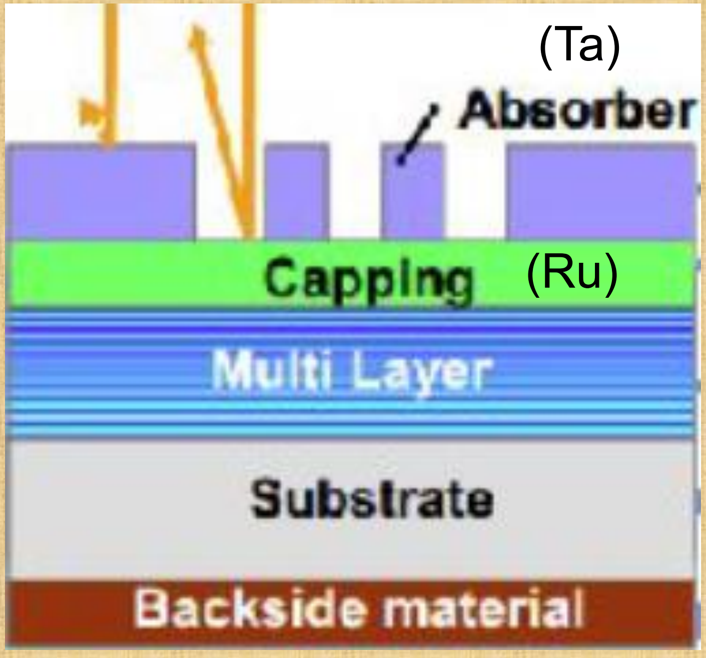
EUV LITHOGRAPHY (II)

MIRRORS: Mo/Si multilayers

MIRRORS



MASKS



RESISTS

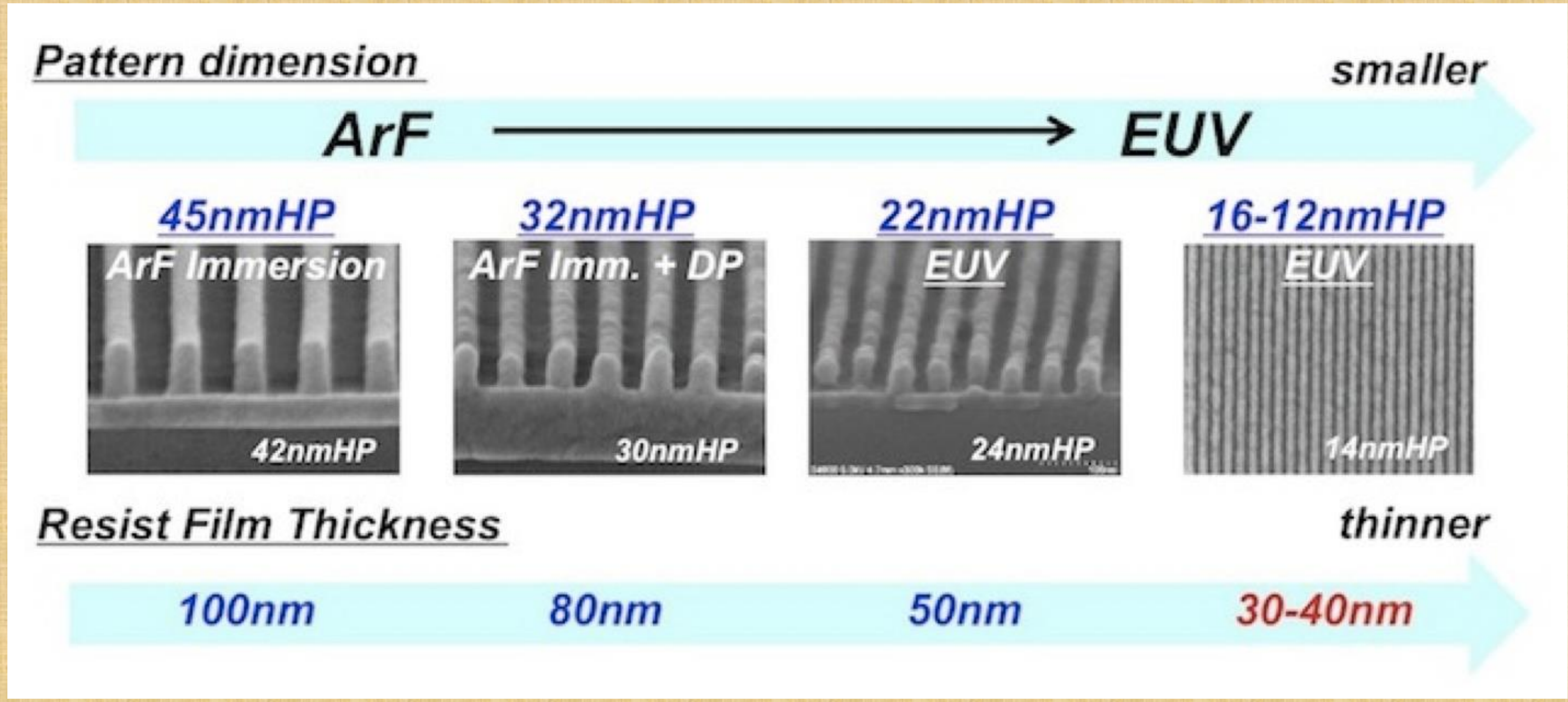
*Chemically-amplified resists

*Polymers with metal particles

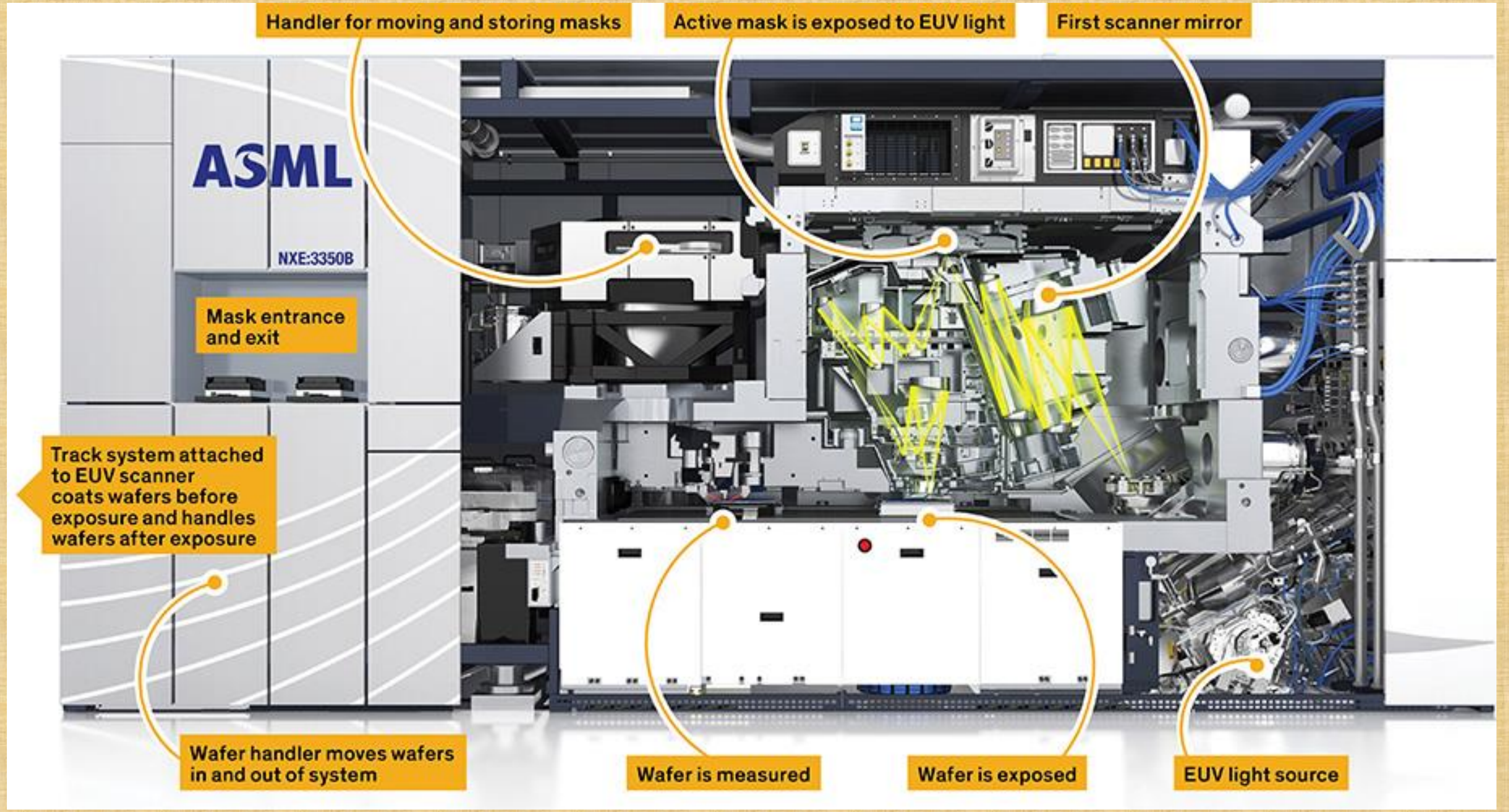
*Multi-trigger resists

→ Sensitivity versus linewidth roughness

TECHNOLOGICAL EVOLUTION IN OPTICAL LITHOGRAPHY



EUV IS THE NEXT STEP IN OPTICAL LITHOGRAPHY



ASML SELLS THE NEW EUV MACHINES for 100 MILLION EURO EACH

COMPANIES SUCH AS INTEL AND GLOBAL FOUNDRIES TO PRODUCE 7 nm CHIPS SINCE 2020

Introduction to Nanofabrication techniques

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Universidad Zaragoza

1542

Outline

- Introduction:
  - Nanotechnology.
  - Length scales.
  - Applications.
  - Nanolithography techniques.
- Optical lithography.
- Scanning Electron Microscopy (SEM).
- Electron Beam Lithography (EBL).
- Focused Electron Beam Induced Deposition (FEBID).

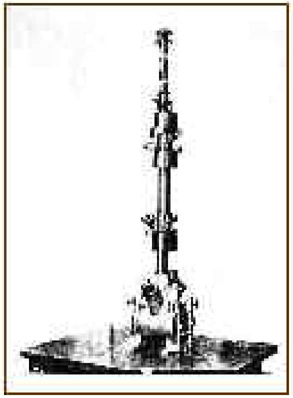
Scanning Electron Microscopy

Electron microscopy: science that allows us to visualize objects in magnified way by using an electron beam.

- 1924. Louis de Broglie proposed that all particles behave to an extent like waves, and have properties such as wavelength and frequency:

$$\lambda \sim h / mv$$

- As a consequence, electron microscopes can have much higher resolution than optical microscopes: an electron accelerated at 25 kV has an associated wavelength of 0.008 nm.



- 1933: Manufacturing of the first Transmission Electron Microscope (TEM) by Ernst Ruska and Max Knoll.

- 1935: Developing of the concept of Scanning Electron Microscope (SEM) by Max Knoll.

- 1938: Manufacturing of a high resolution SEM by Manfred von Ardenne (resolution of 50 nm).

Scanning Electron Microscopy

Description of a SEM

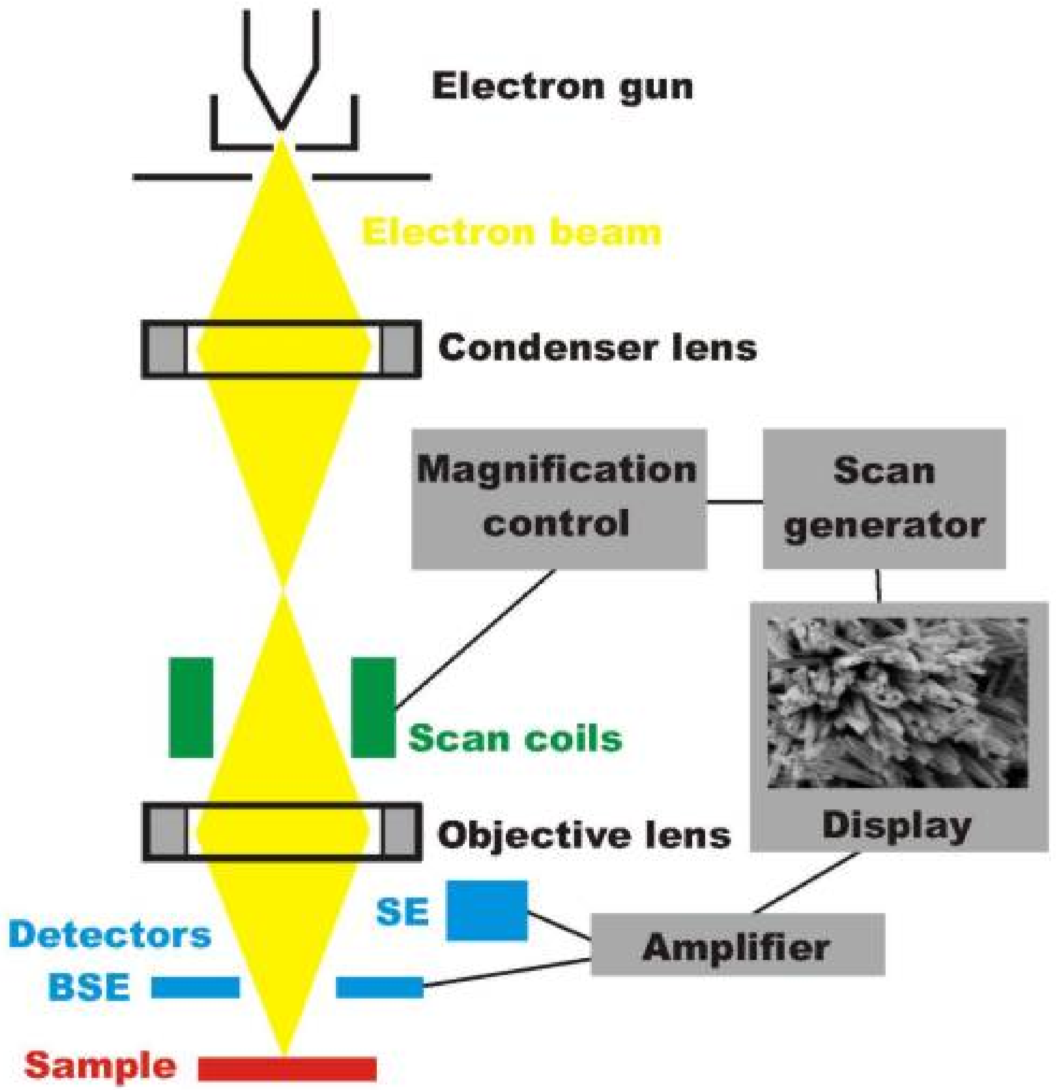
-UNDERLYING CONCEPT OF EBL:

$\lambda \sim h/mv$

Which implies that electron acceleration to high speed produces short wavelengths, applicable in lithography:

-For example:

λ = 0.008 nm at 25 kV



Scanning Electron Microscopy

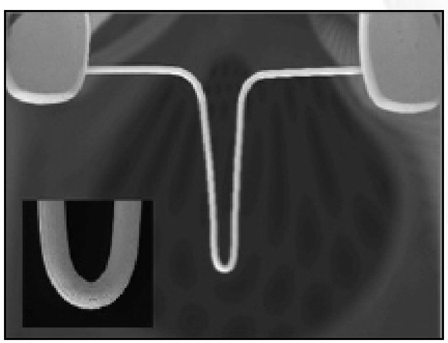
Description of a SEM

EMITTER

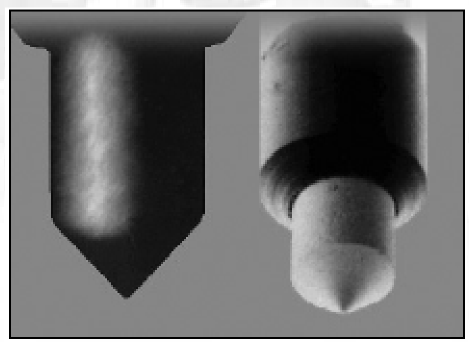
LENSES

BEAM DEFLECTOR

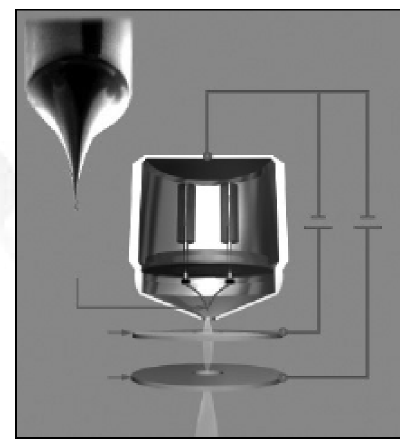
Source type / Working principle	Filament material	Brightness ($A/cm^2/rad$)	Source size	Energy dispersion (eV)	Vacuum level (Torr)	Filament temperature (K)
Tungsten thermoionic	W	$\sim 10^5$	25 µm	2-3	10^{-6}	~3000
LaB_6 thermoionic	LaB_6	$\sim 10^6$	10 µm	2-3	10^{-8}	~2000-3000
Thermic field emission (Schottky)	Zr/O/W	$\sim 10^8$	20 nm	0.9	10^{-9}	~1800
Cold field emission	W	$\sim 10^9$	5 nm	0.22	10^{-10}	Ambience



W filament



LaB_6 crystal



Field emission

Scanning Electron Microscopy

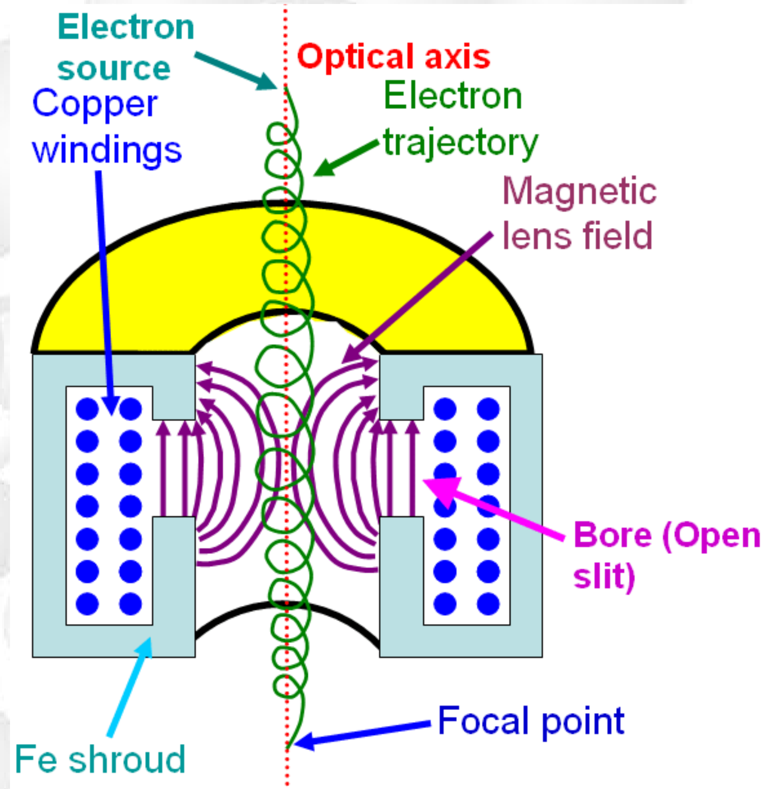
Description of a SEM

EMITTER

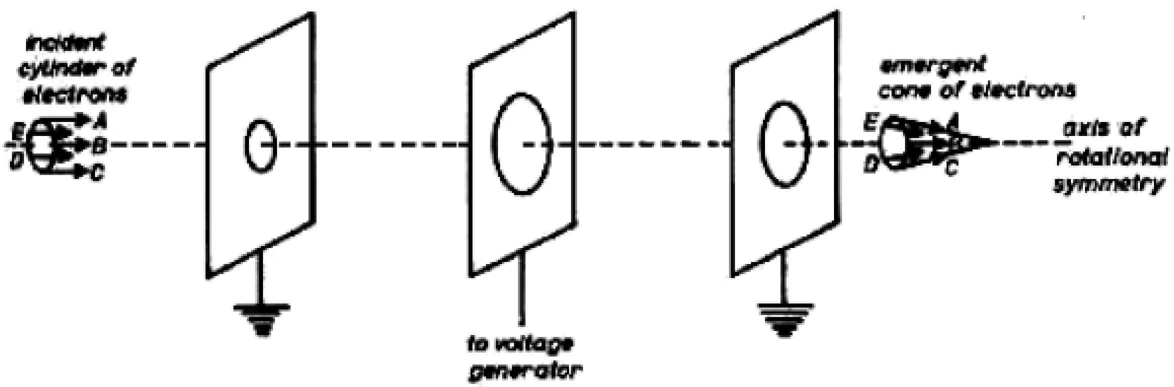
LENSES

BEAM DEFLECTOR

MAGNETIC



ELECTROSTATIC



The lenses are not perfect and give rise to optical aberrations (spherical, chromatic, astigmatism…)

ues

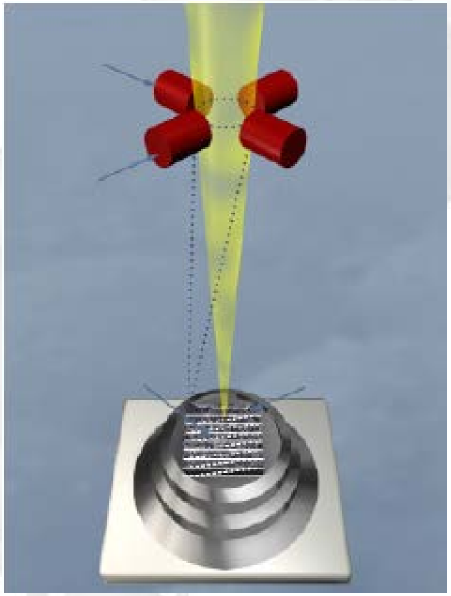
Scanning Electron Microscopy

Description of a SEM

EMITTER

LENSES

BEAM DEFLECTOR



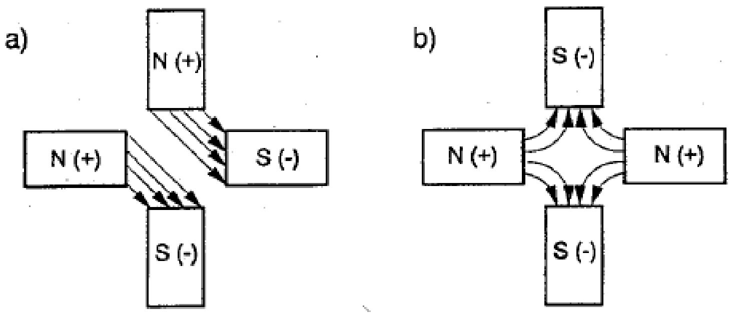


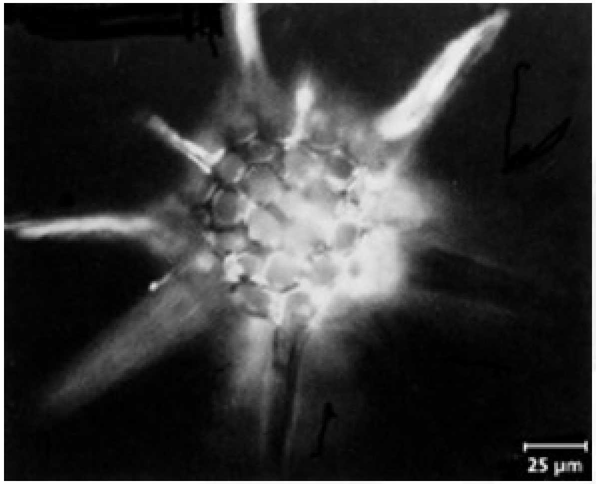
FIG. 2.8. Schematic showing the magnetic (electrostatic) field distribution for a) a simple beam deflector or alignment device energized for diagonal deflection and b) a stigmator. The optical axis is perpendicular to the plane of the page.

Scanning Electron Microscopy

Description of a SEM

SEM vs optical microscope:

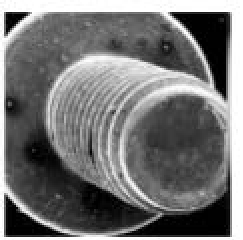
Optical microscope:



Lower resolution: 200x

Lower depth of focus: 15 μm

SEM:



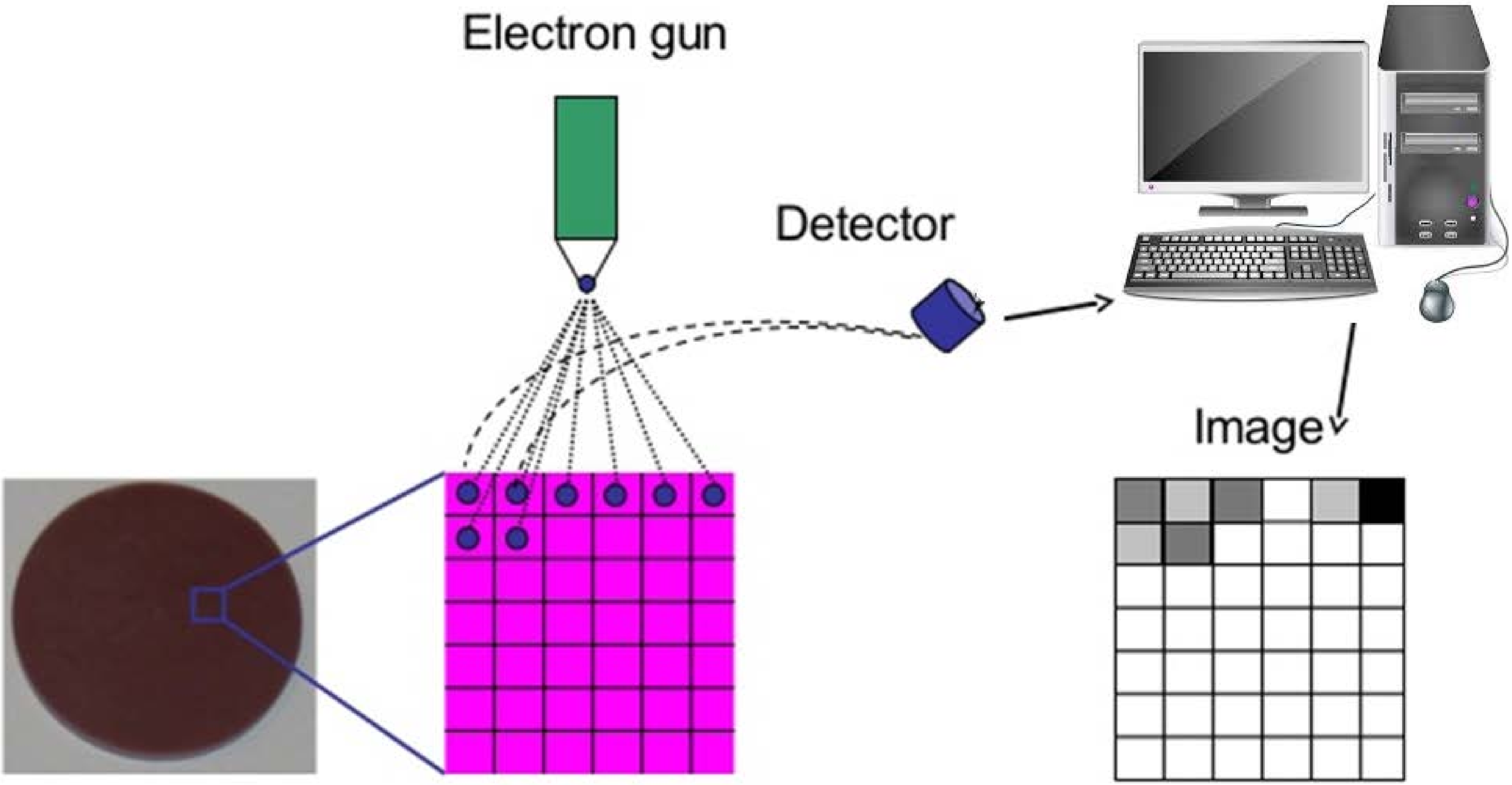
Higher resolution: 500,000x

Higher depth of focus: 4 mm

Much higher contrast, compositional information, etc.

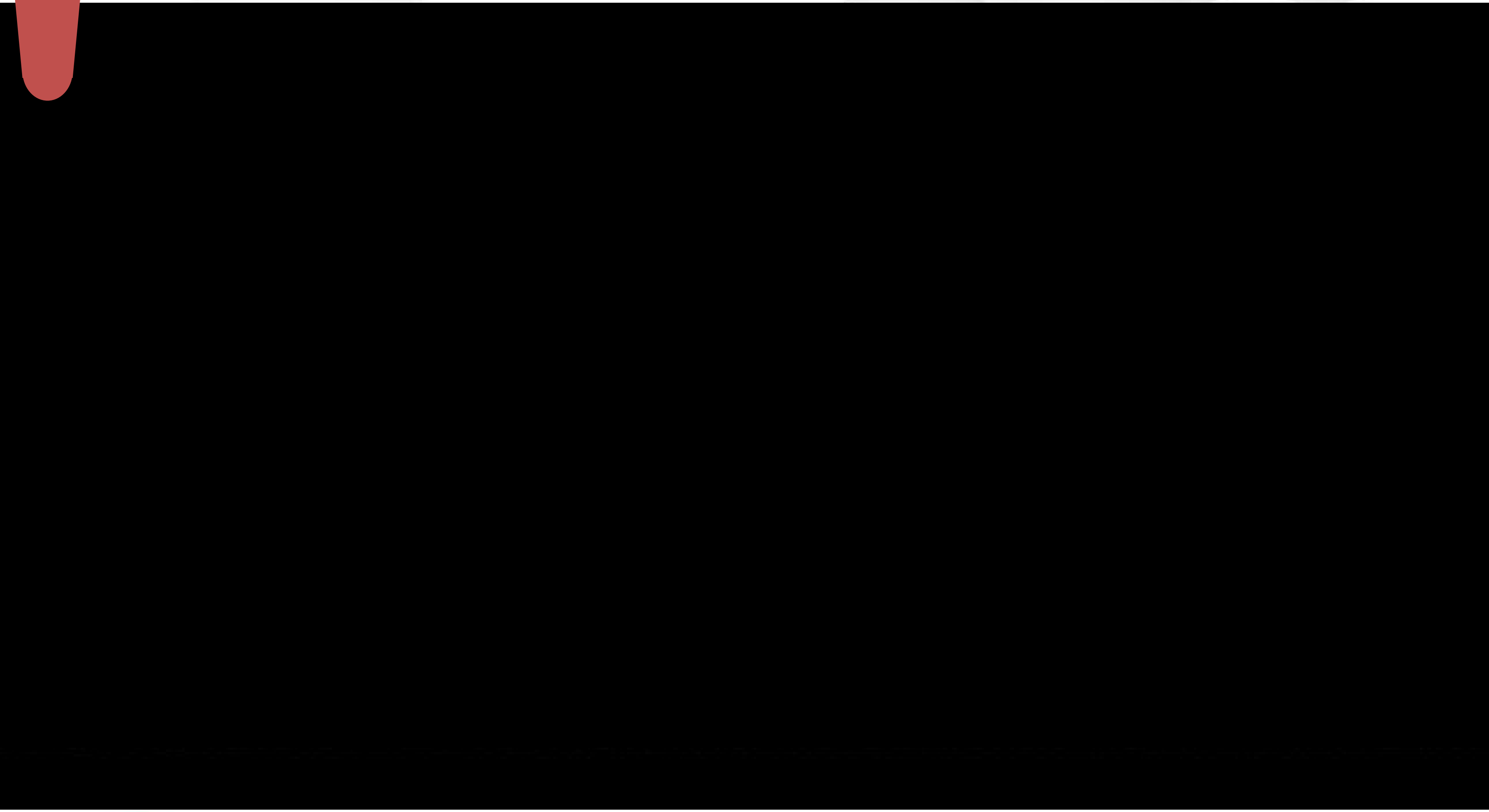
Scanning Electron Microscopy

Image formation in a SEM



Scanning Electron Microscopy

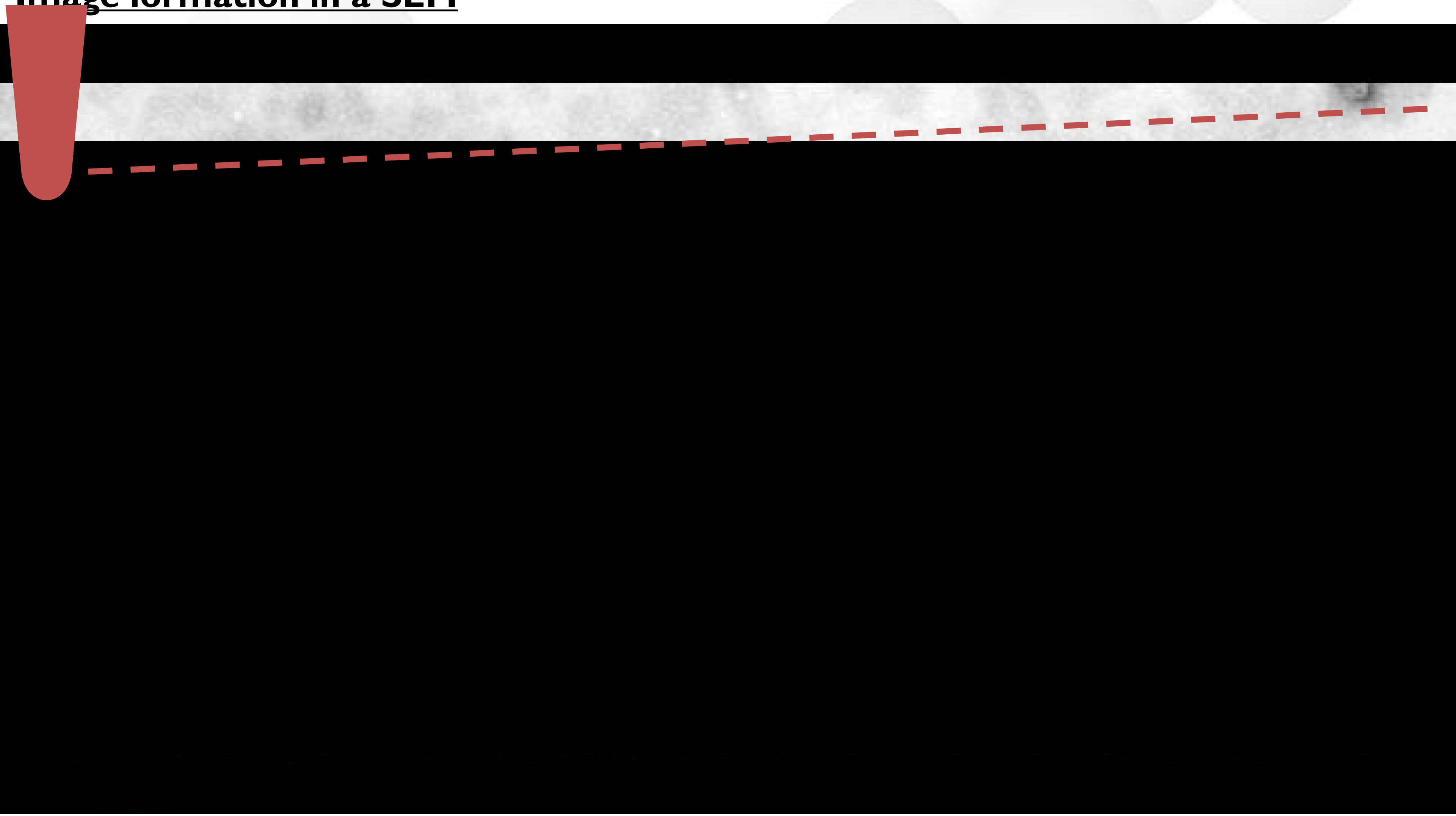
ge formation in a SEM



Scanning Electron Microscopy

Image formation in a SEM

Image formation in a SEM

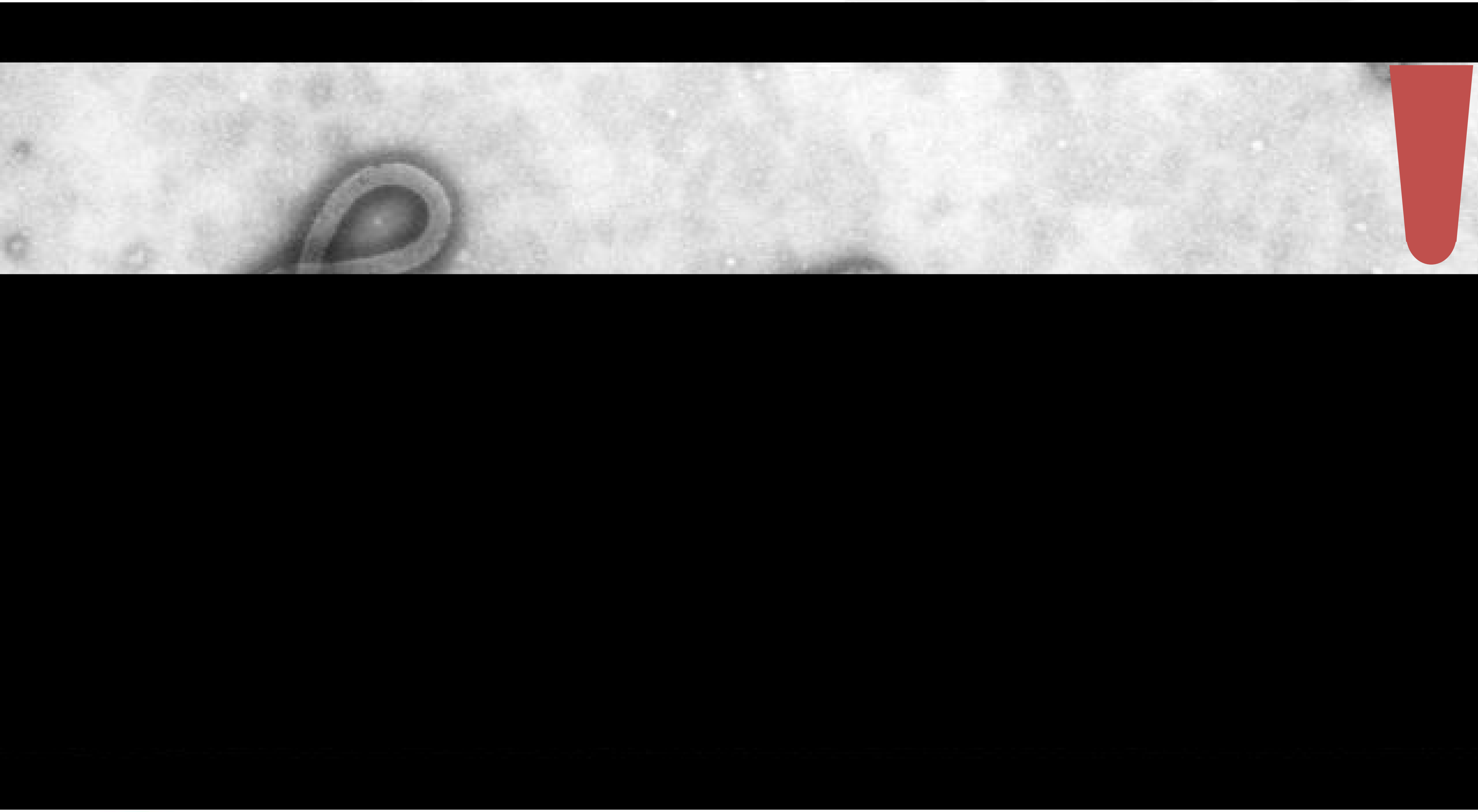


Scanning Electron Microscopy

Image formation in a SEM

Scanning Electron Microscopy

Image formation in a SEM

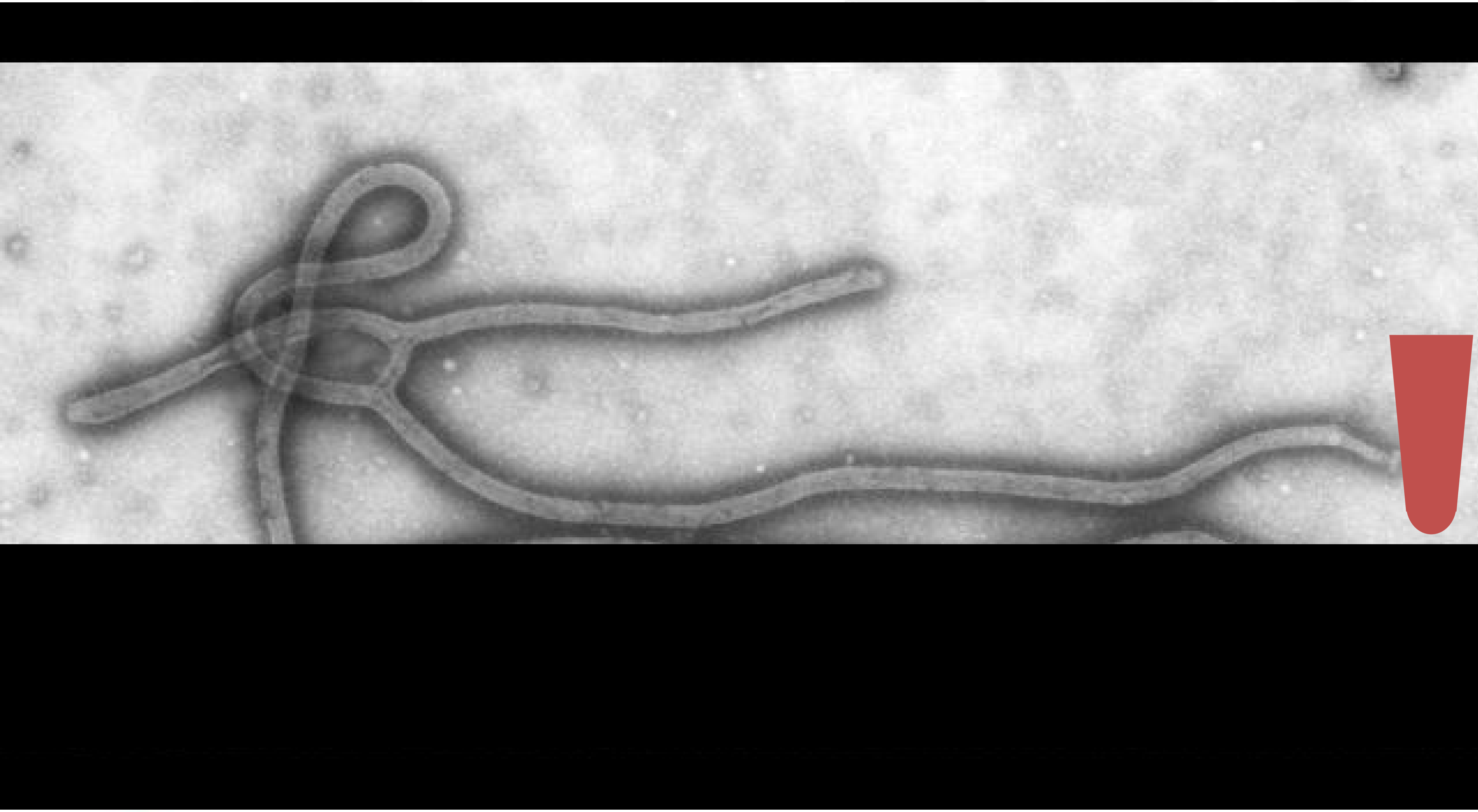


Scanning Electron Microscopy

Image formation in a SEM

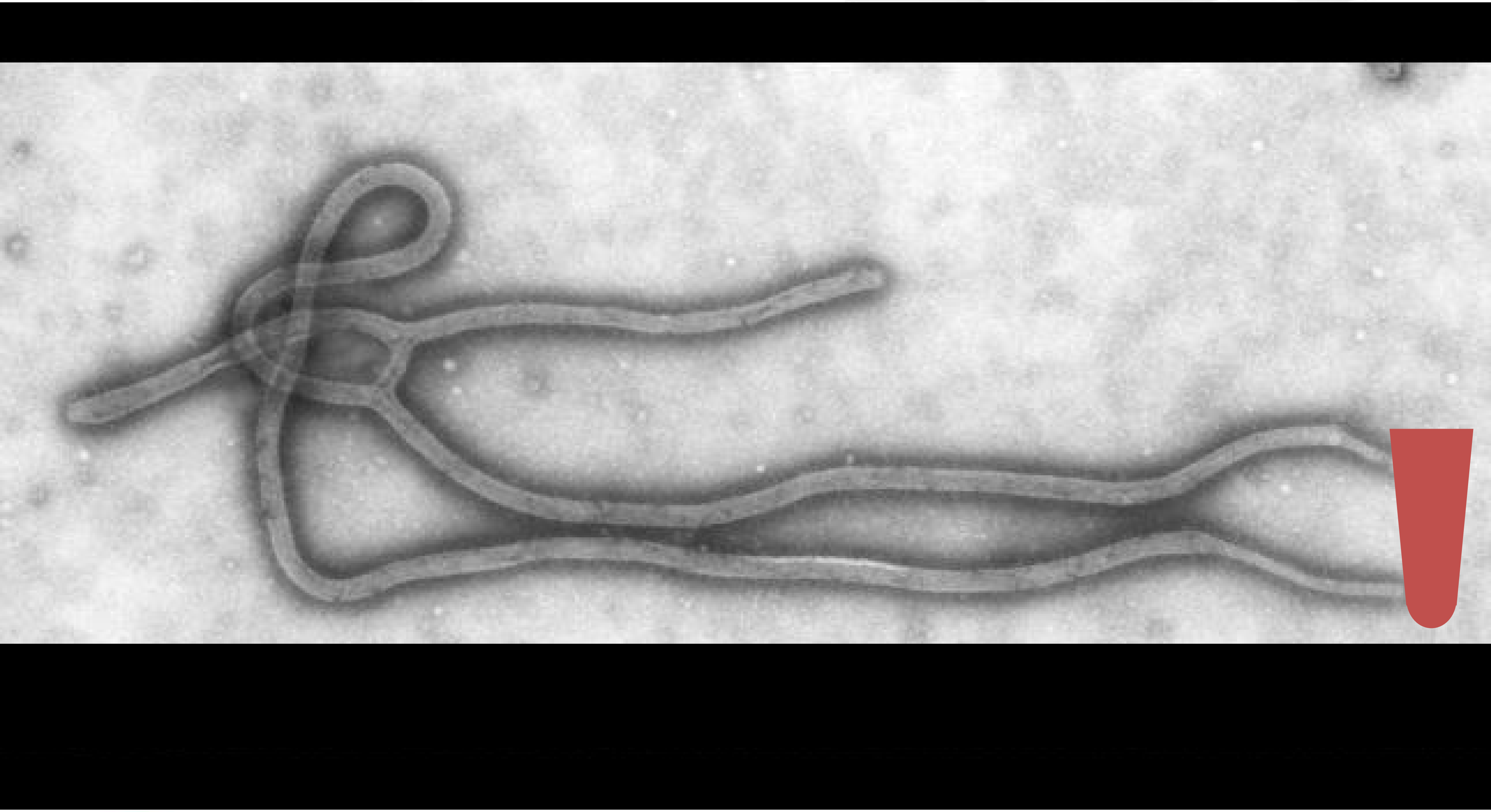
Scanning Electron Microscopy

Image formation in a SEM



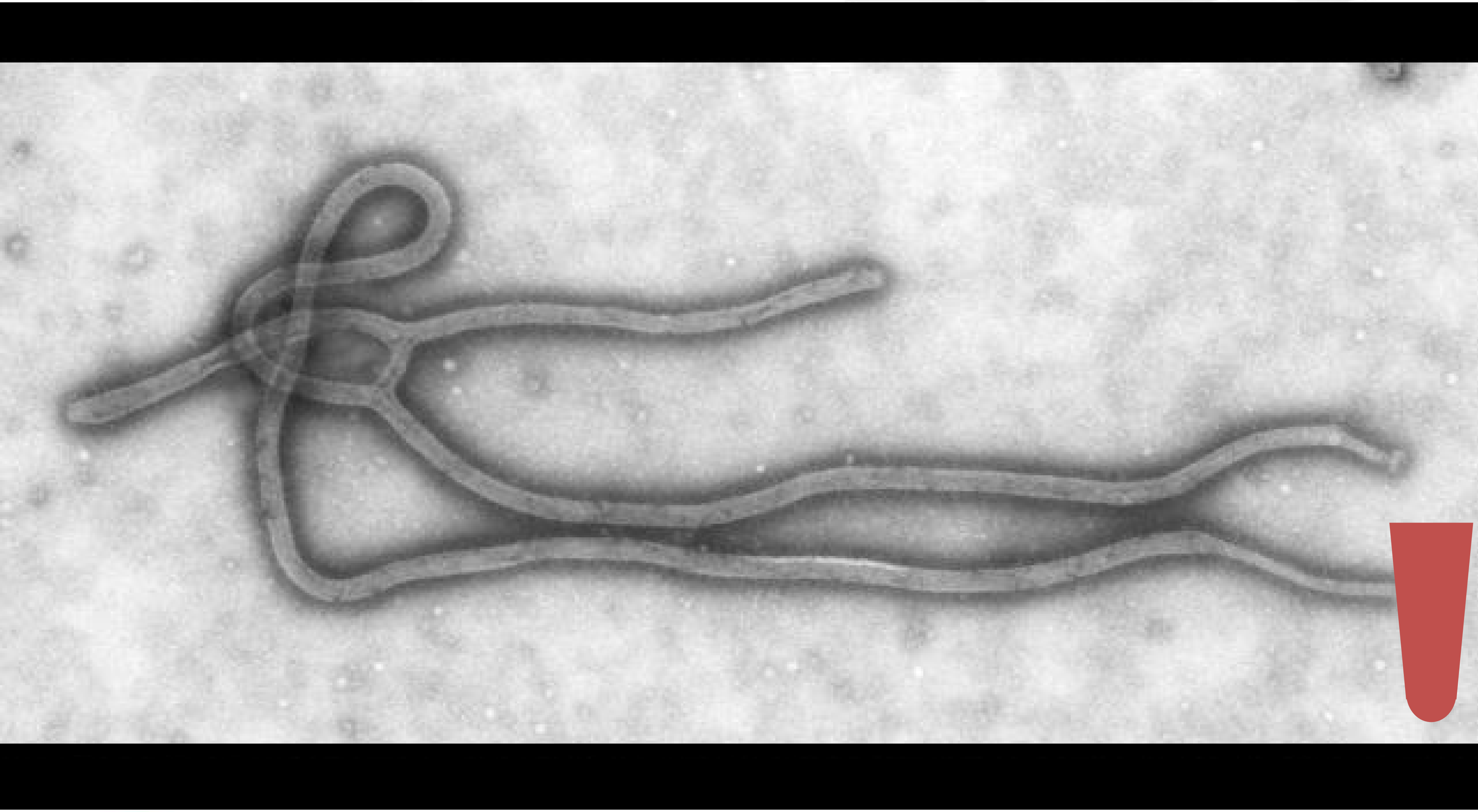
Scanning Electron Microscopy

Image formation in a SEM



Scanning Electron Microscopy

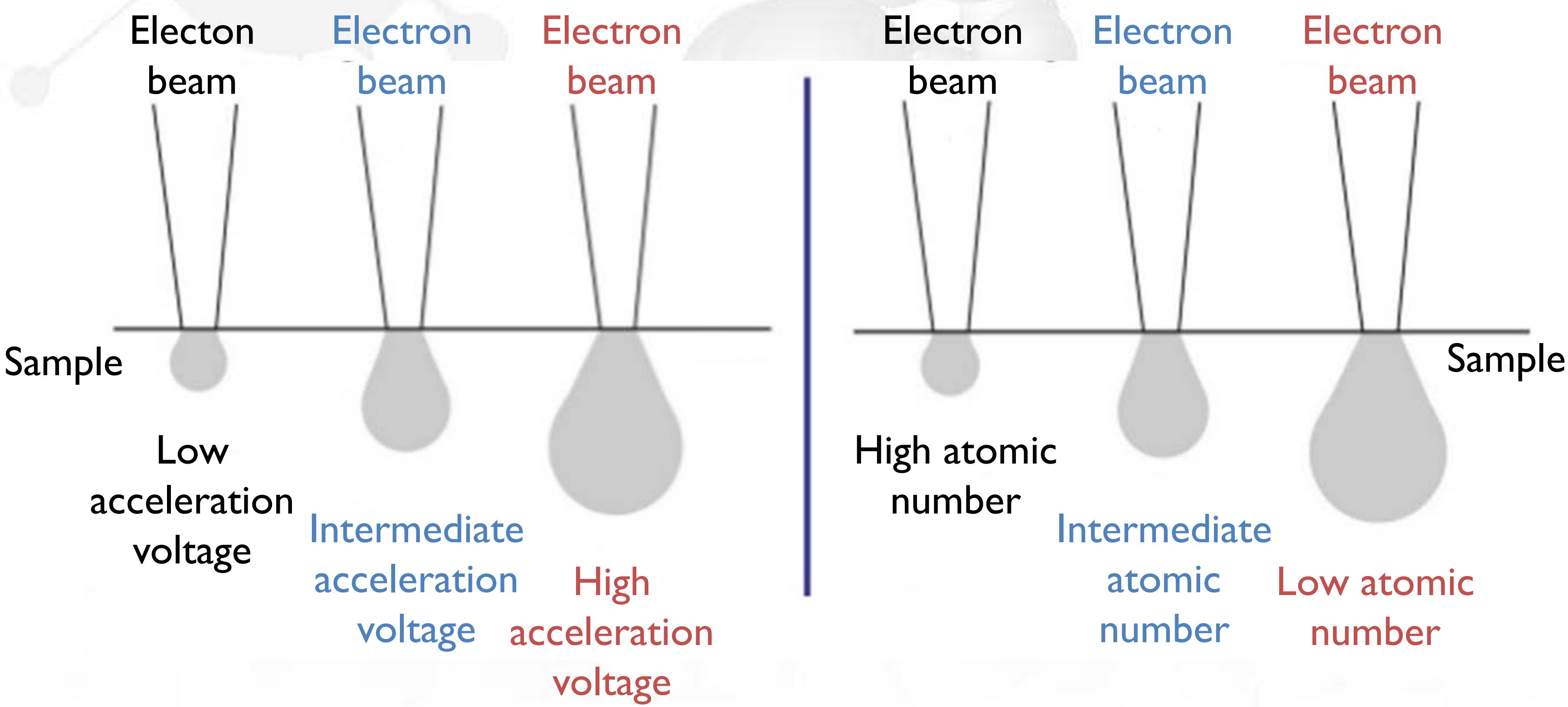
Image formation in a SEM



Scanning Electron Microscopy

<u>Image formation in a SEM</u>

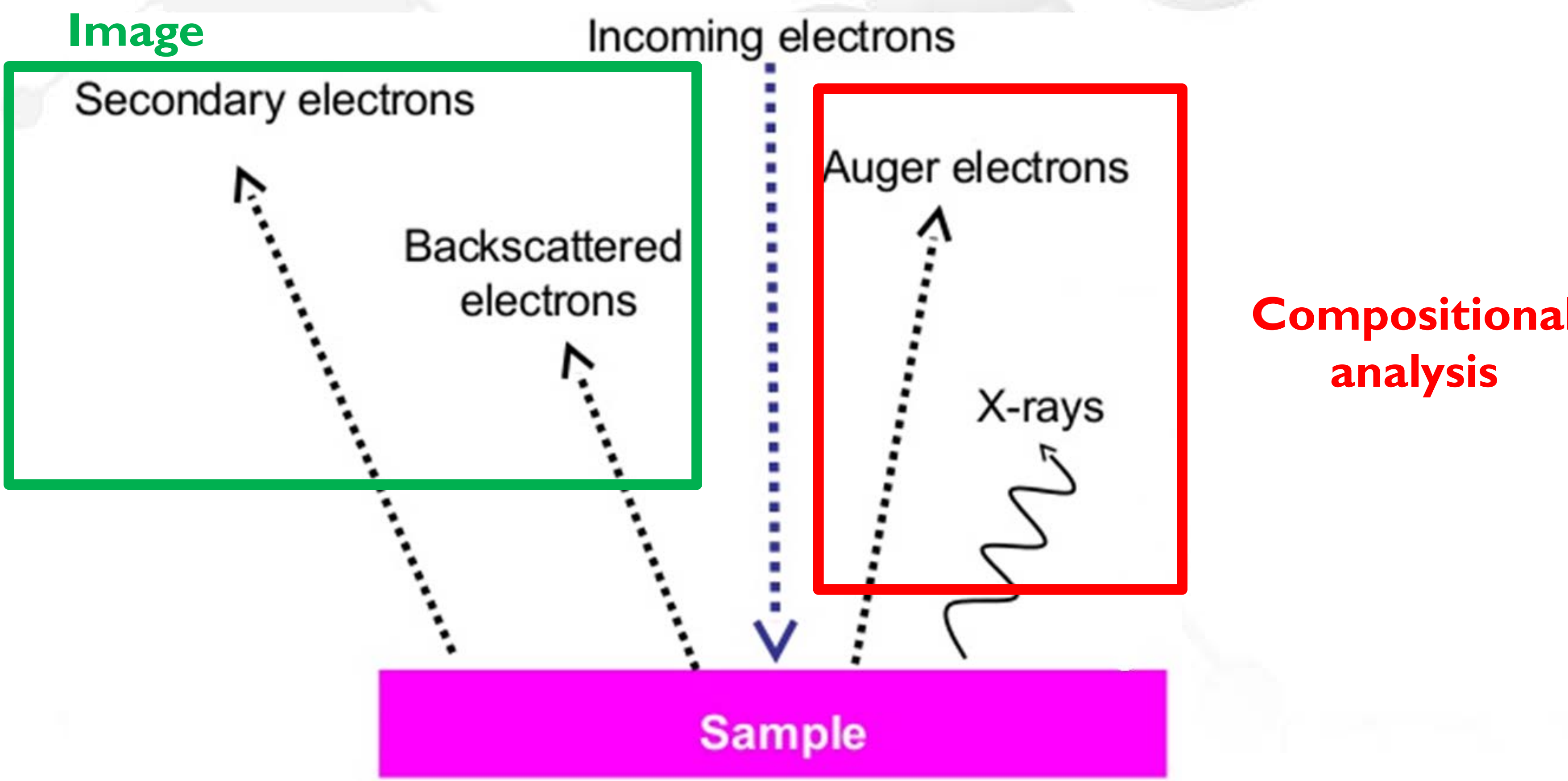
> Electron beam – sample interaction:



Scanning Electron Microscopy

Image formation in a SEM

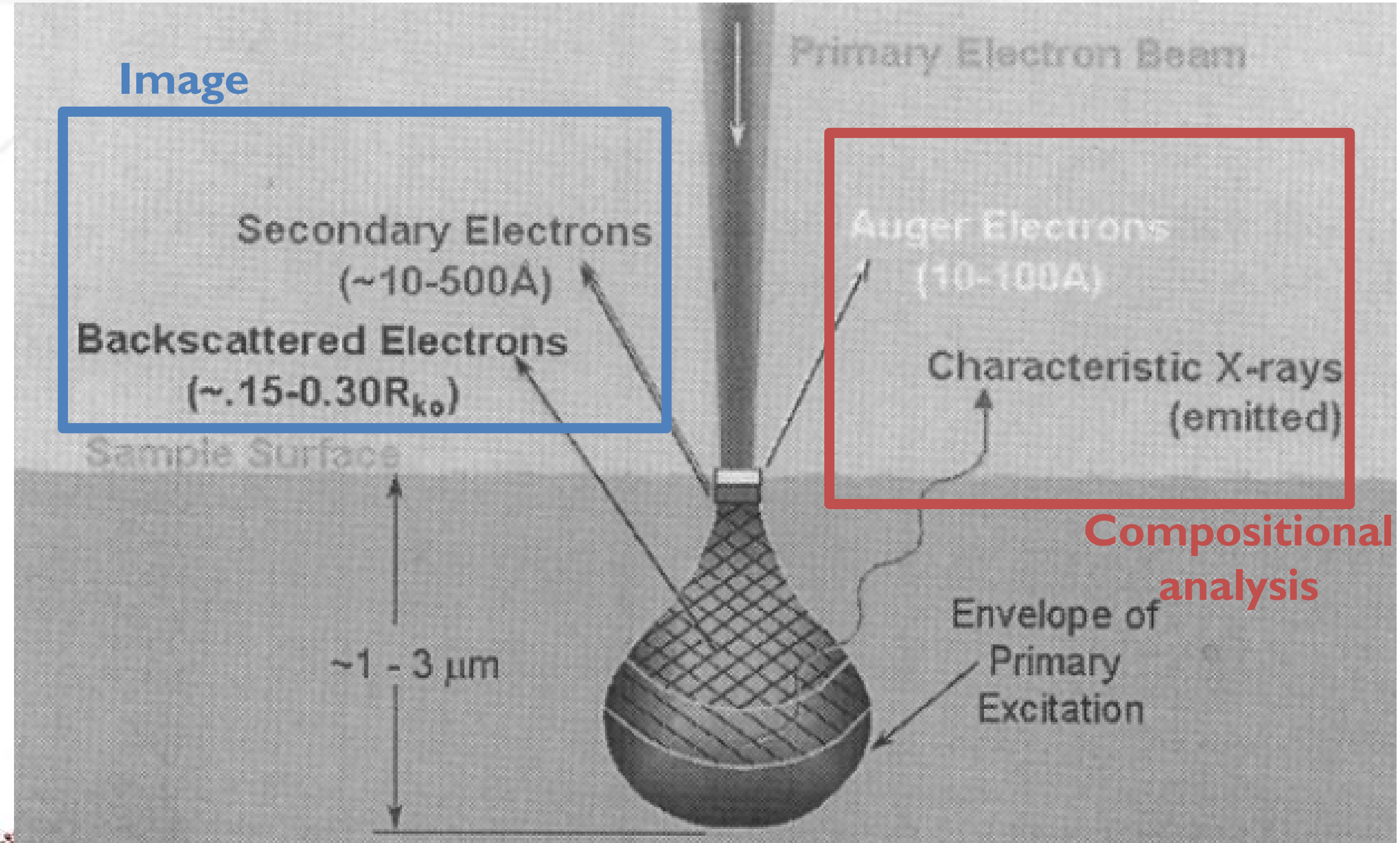
> Signals originated in the sample:



Scanning Electron Microscopy

Image formation in a SEM

> Signals originated in the sample:

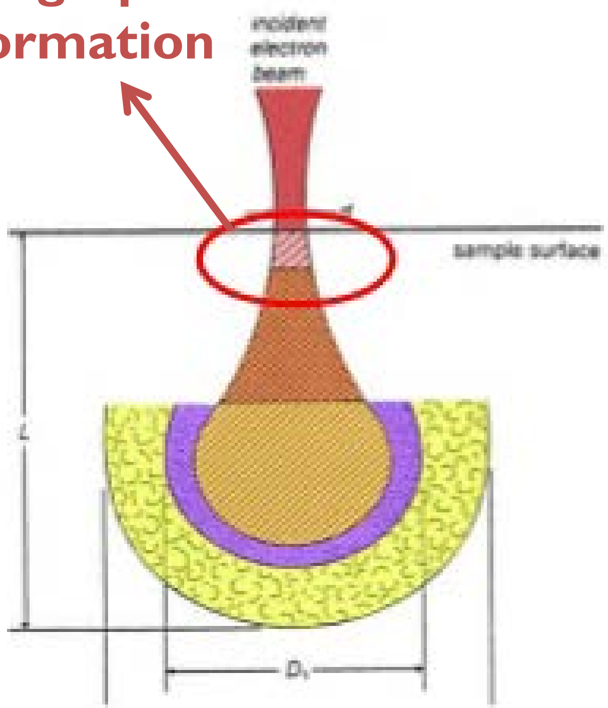


Scanning Electron Microscopy

Image formation in a SEM

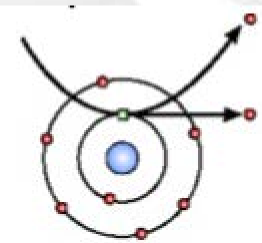
> Secondary electrons:

Topographic information



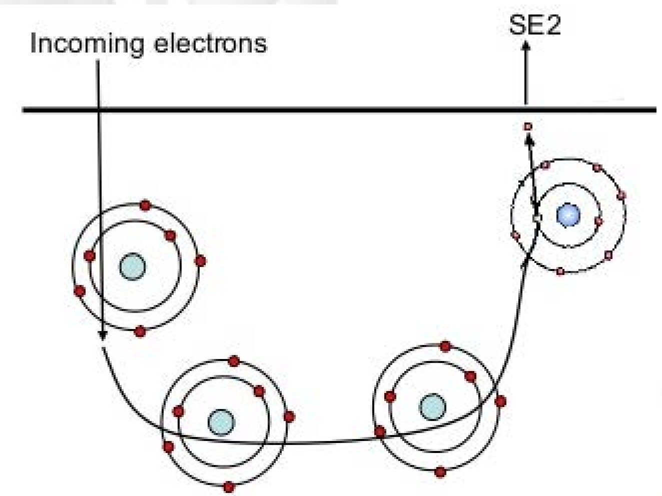
E ≈ (10 – 50) eV

SE1



Higher resolution

SE2

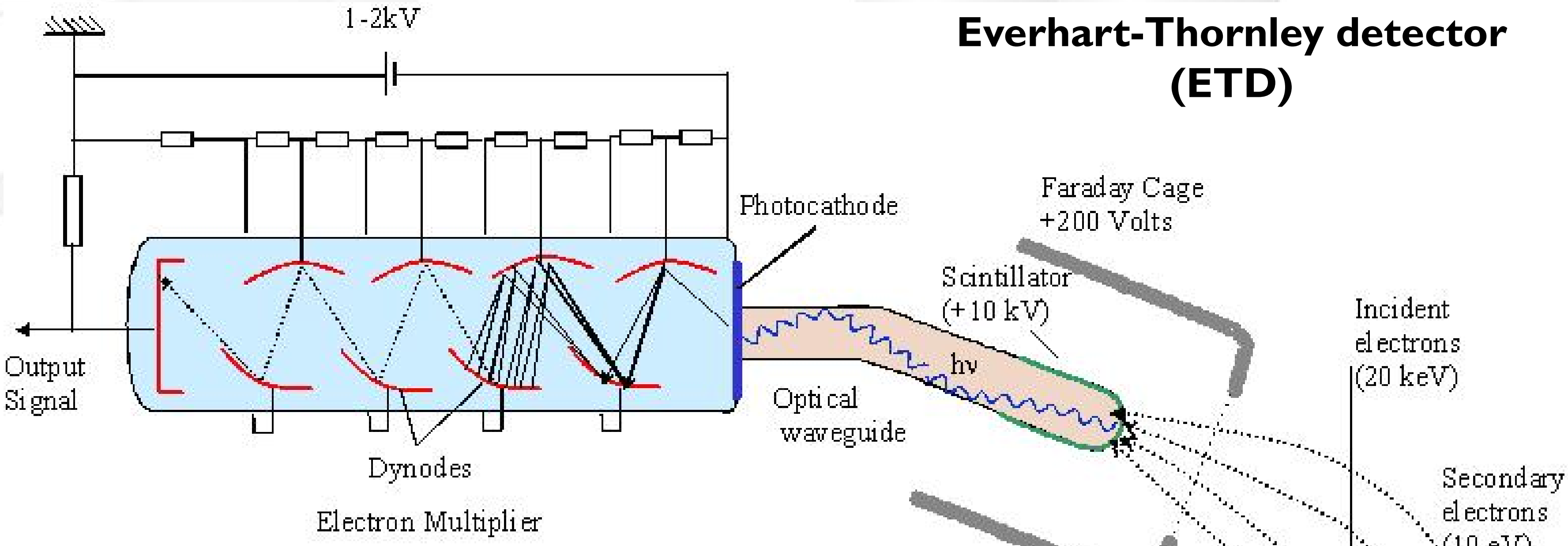


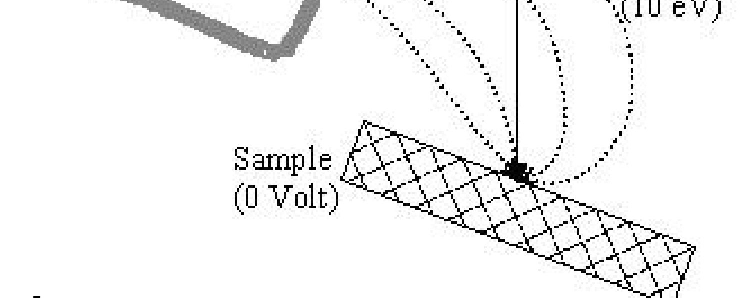
Scanning Electron Microscopy

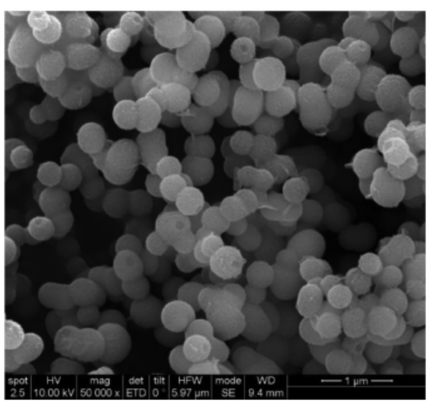
Image formation in a SEM

> Detector of secondary electrons:

Everhart-Thornley detector (ETD)





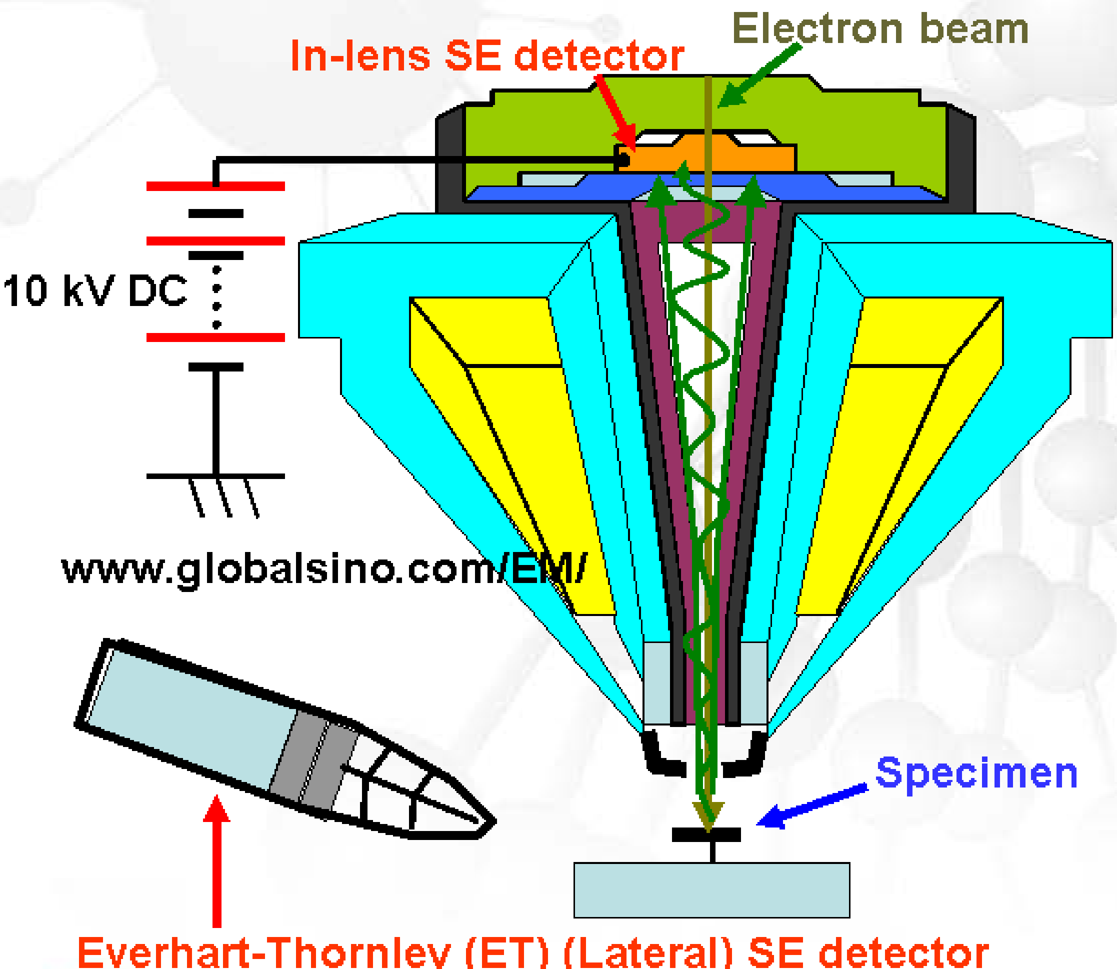


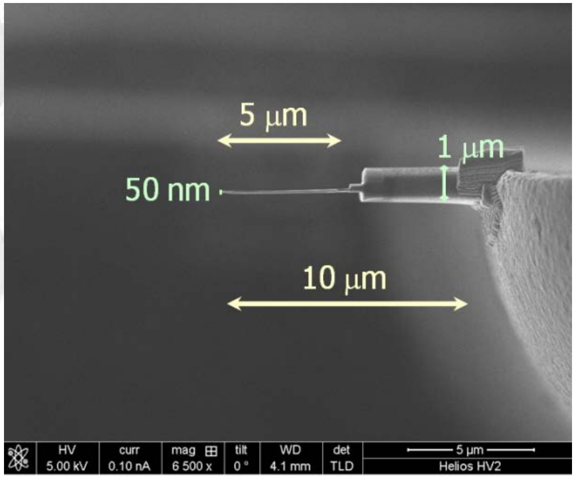
>> Very sensitive to the topography.

Scanning Electron Microscopy

Image formation in a SEM

> In-lens secondary electrons detector:



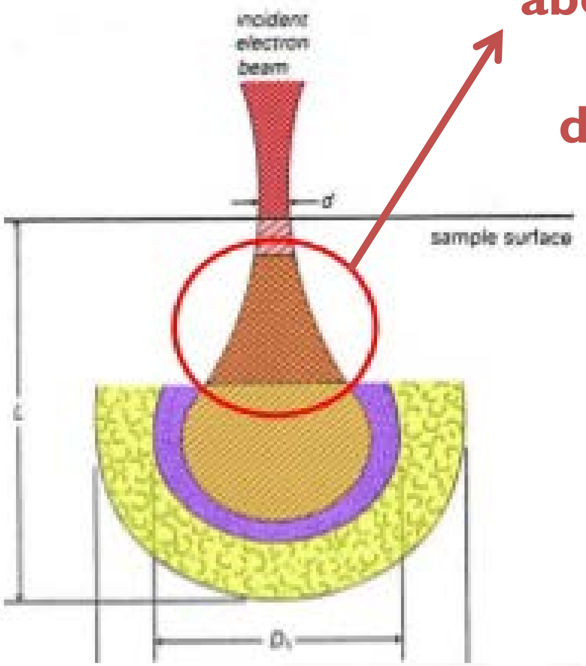


>> It only detects SE1: Very high resolution.

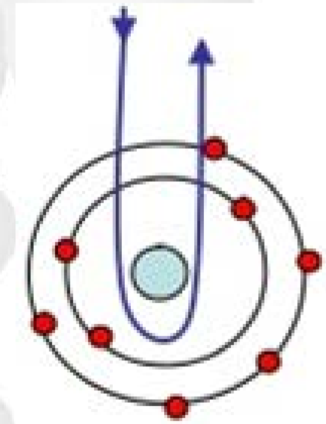
Scanning Electron Microscopy

Image formation in a SEM

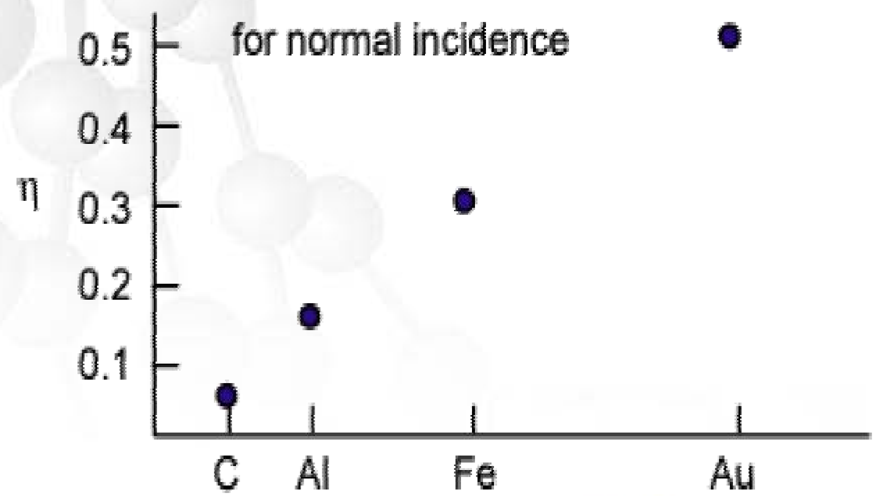
> Back-scattered electrons:



Information about chemical elements distribution.



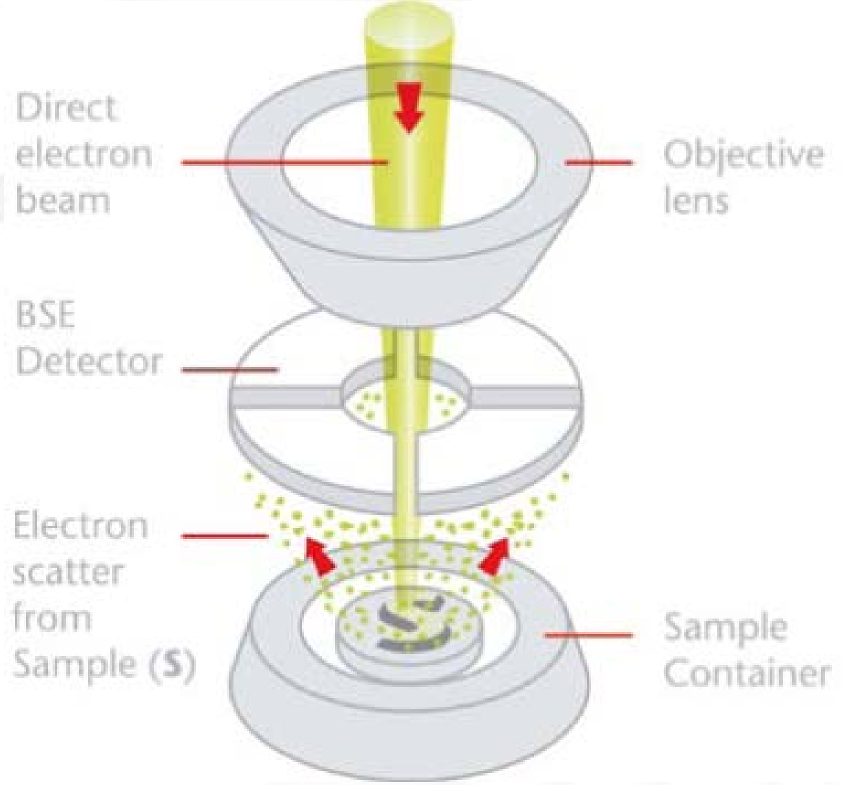
$$i_{backscatt.} = \eta \times i_{beam}$$



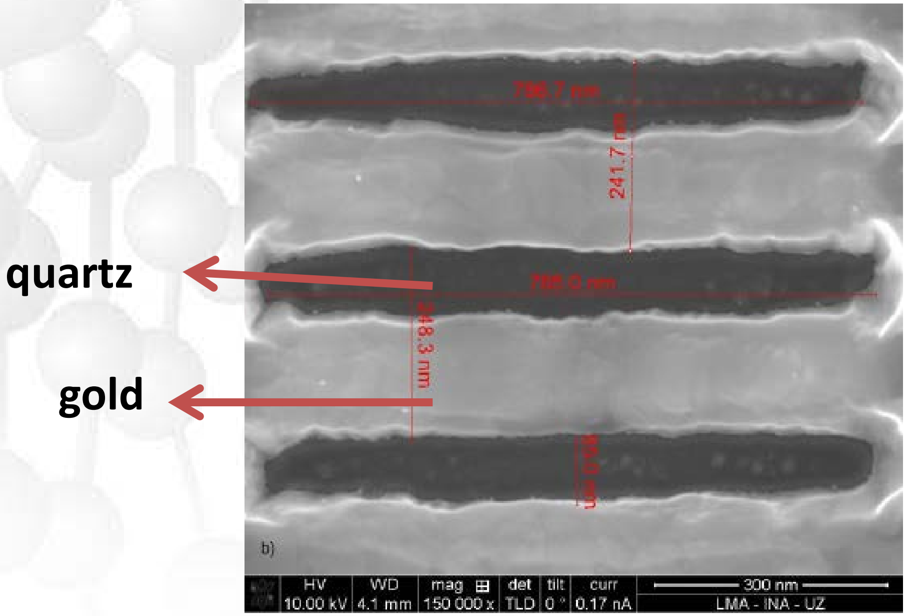
Scanning Electron Microscopy

Image formation in a SEM

> Back-scattered electrons detector:



>> Very sensitive to differences in composition (depending on Z).

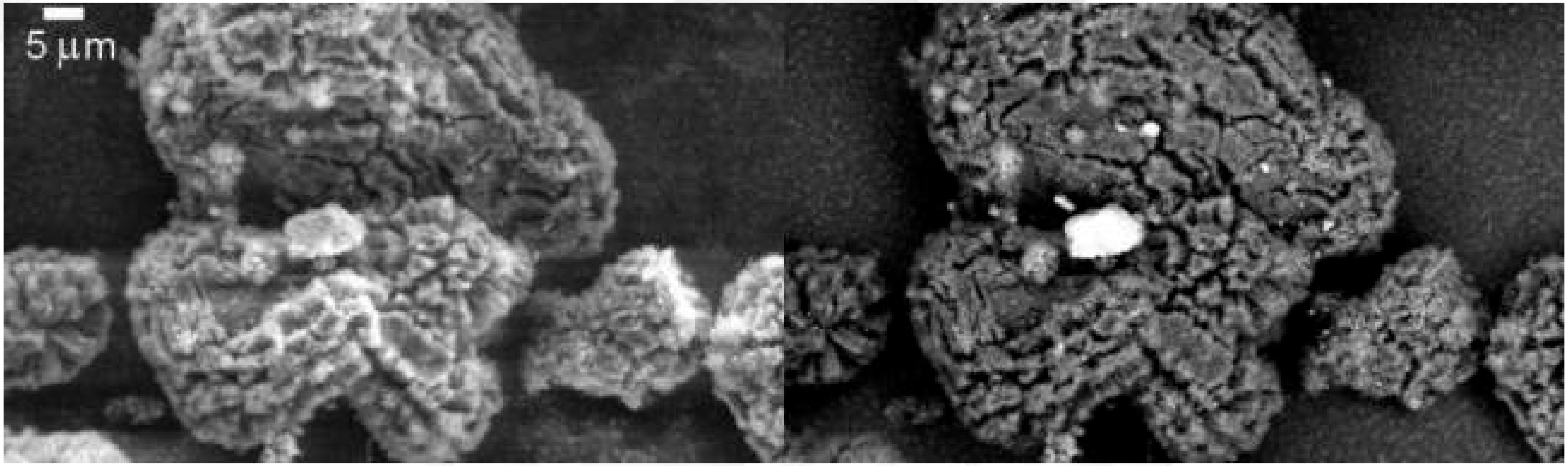


Scanning Electron Microscopy

Image formation in a SEM

> Secondary electrons image vs. Back-scattered electrons image:

Fe particles on carbon:



Secondary electrons

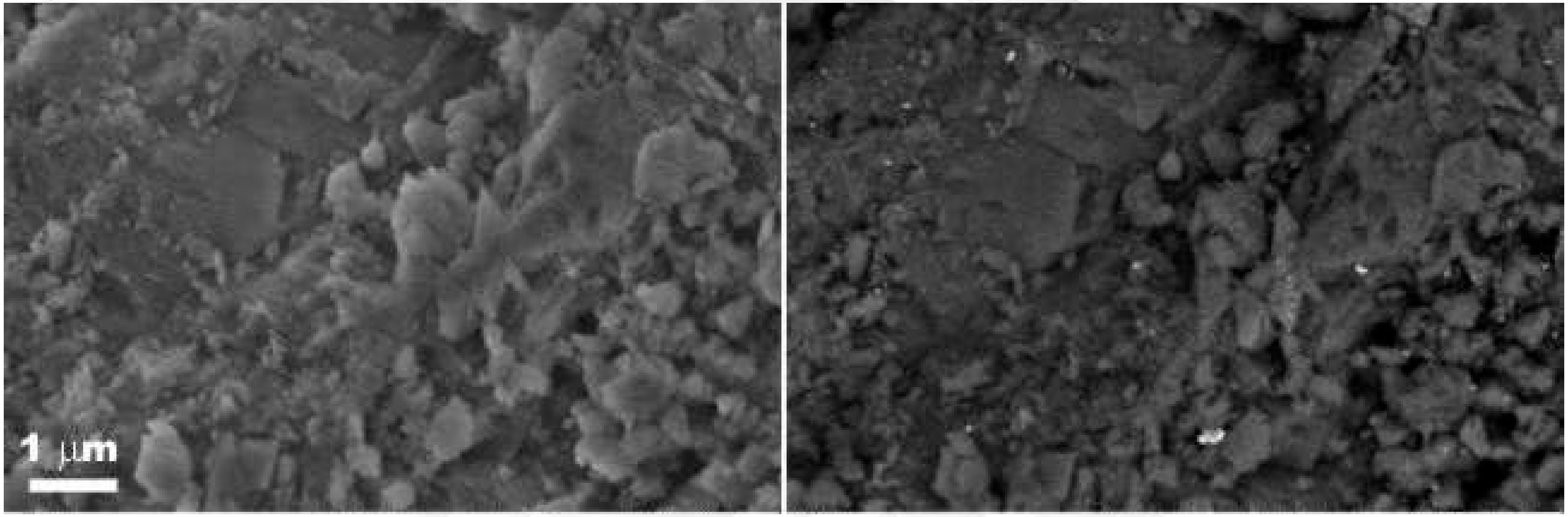
Back-scattered electrons

Scanning Electron Microscopy

Image formation in a SEM

> Secondary electrons image vs. Back-scattered electrons image:

Pt particles on alumina:



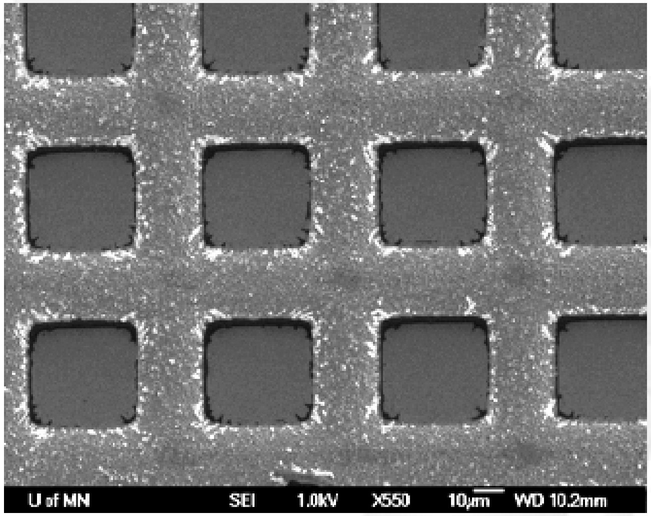
Secondary electrons **Back-scattered electrons**

Scanning Electron Microscopy

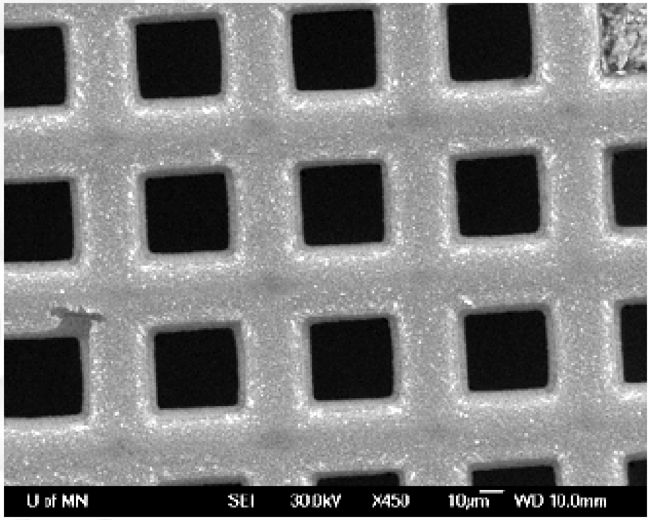
Image formation in a SEM

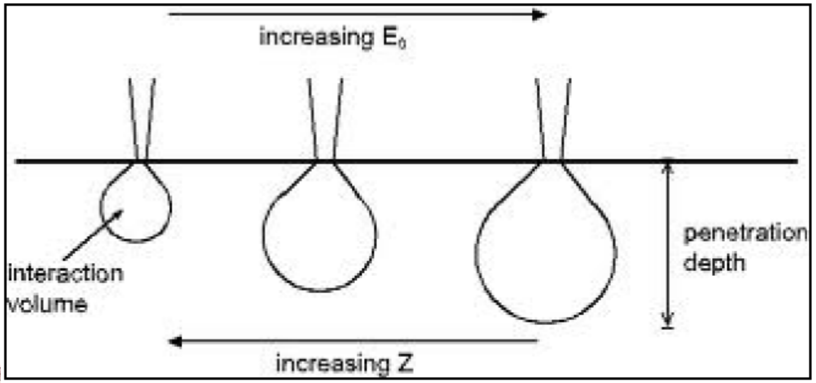
> Importance of the acceleration voltage:

2 keV



20 keV



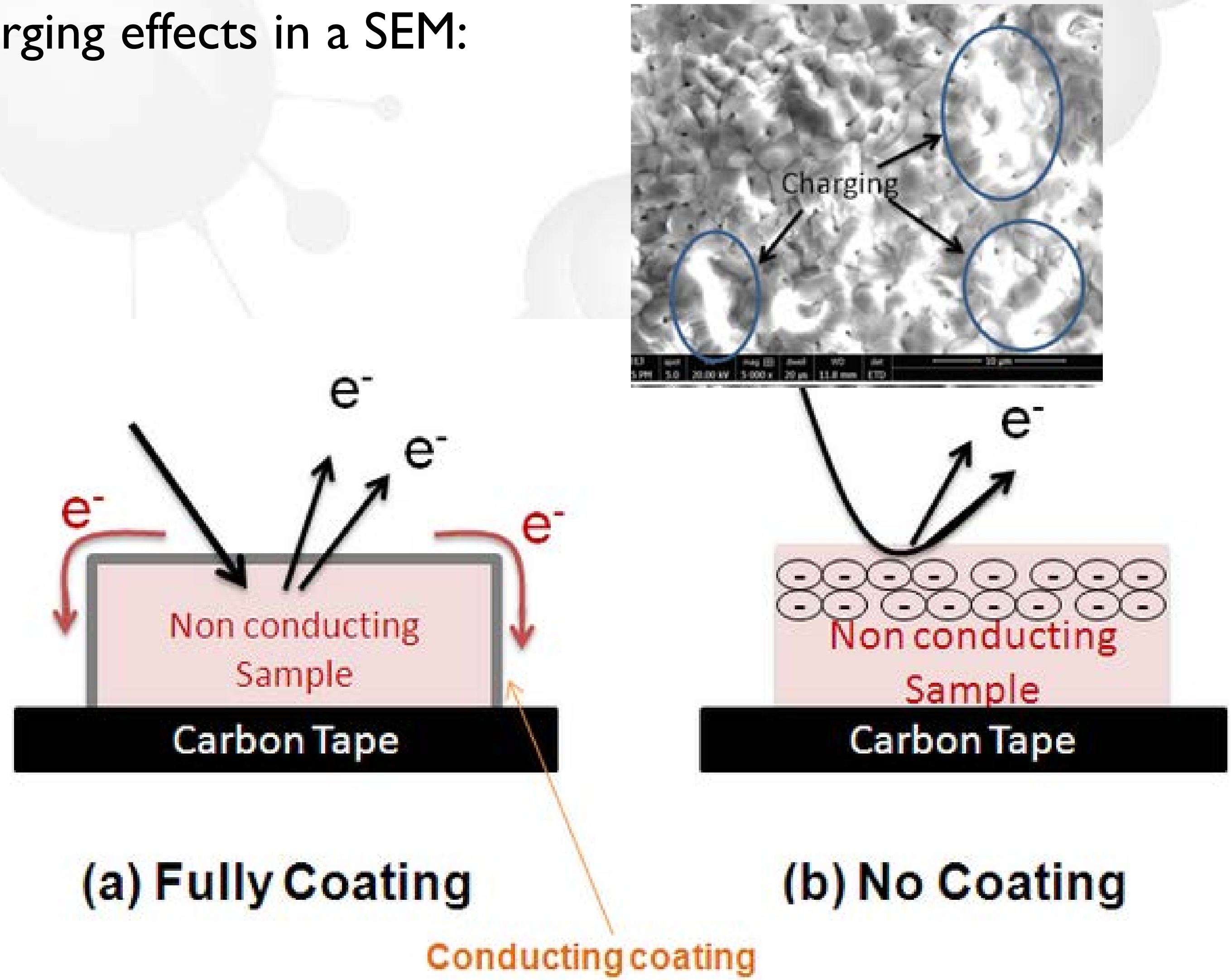


>> At low voltage it is more sensitive to the surface because the penetration depth is lower.

Scanning Electron Microscopy

Image formation in a SEM

> Charging effects in a SEM:

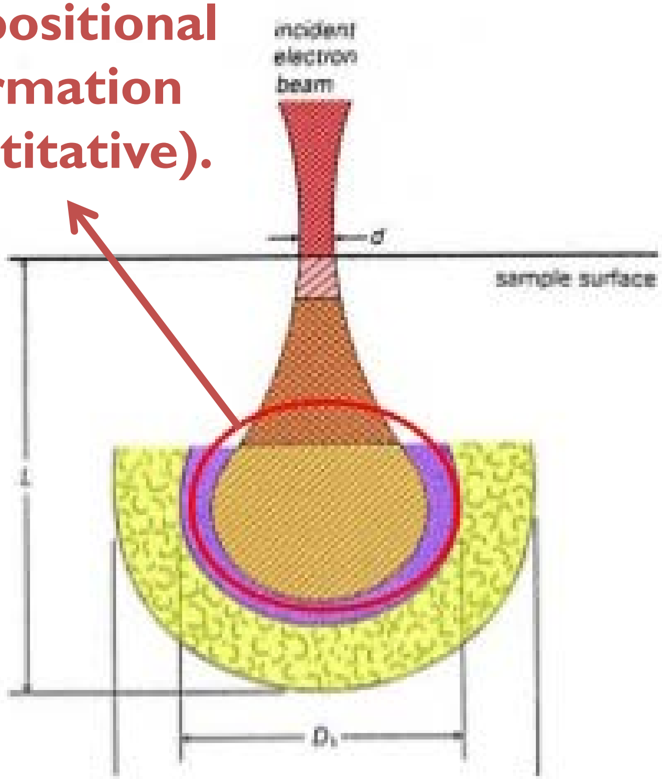


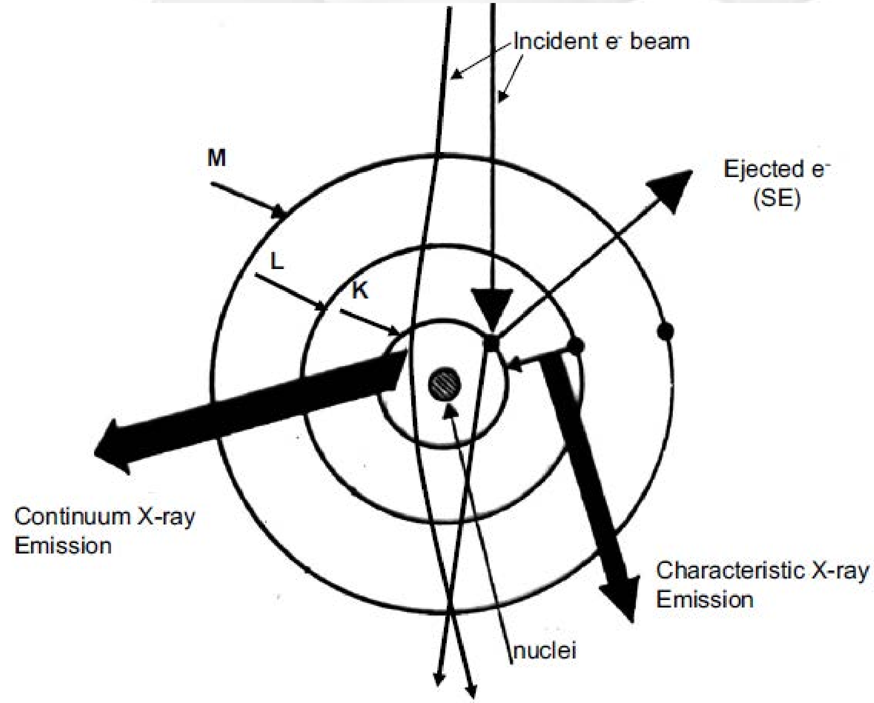
Scanning Electron Microscopy

Compositional analysis in a SEM

> X-rays:

Compositional information (quantitative).



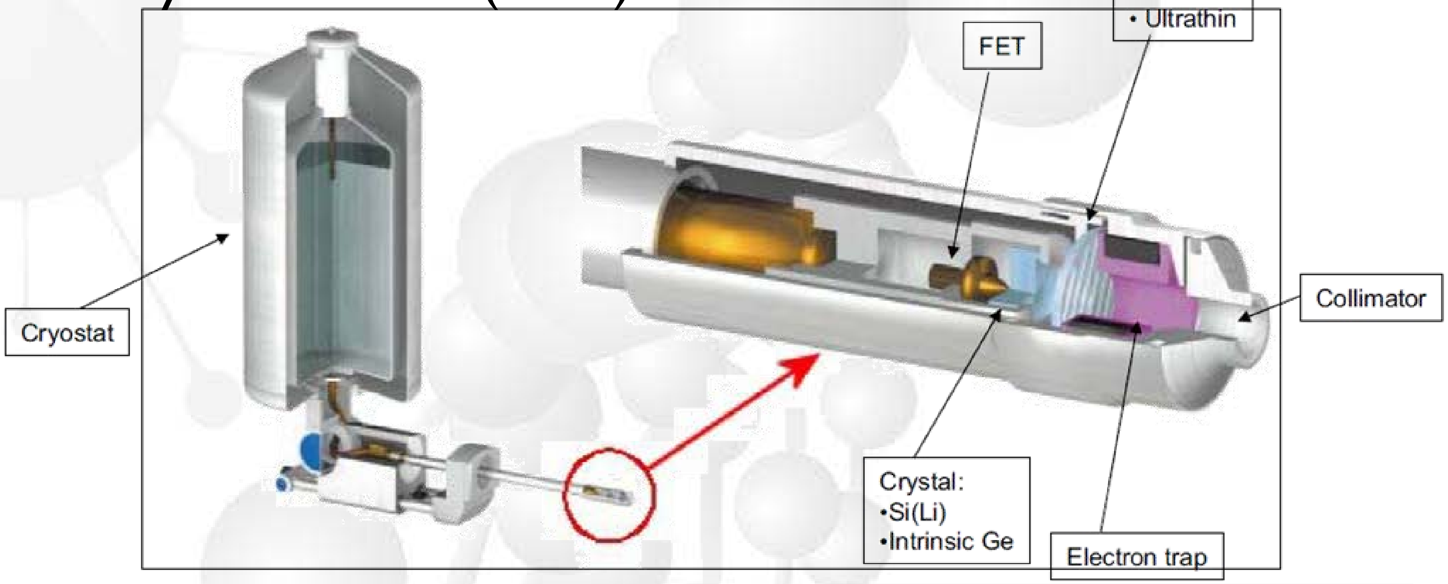


>> The energy of the X-rays generated is characteristic of each element, so one can performed a quantitative compositional analysis.

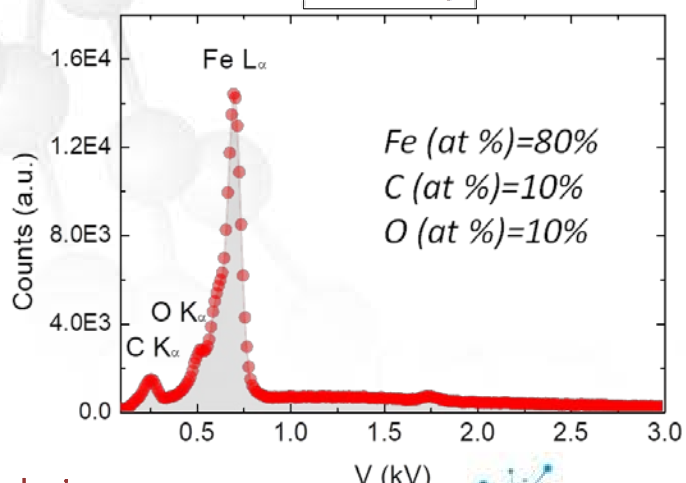
Scanning Electron Microscopy

Compositional analysis in a SEM

> X-ray microanalysis in a SEM (EDX):



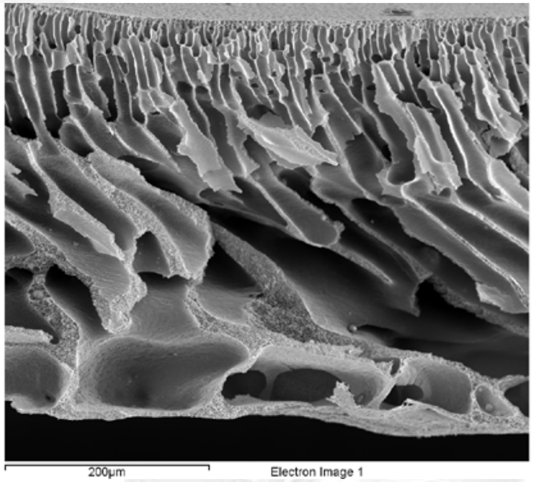
>> The analysis is semi-quantitative (energy resolution of 125 eV) and the emissions of several elements overlap. Light elements (H, He, Li, Be) are not efficiently detected.



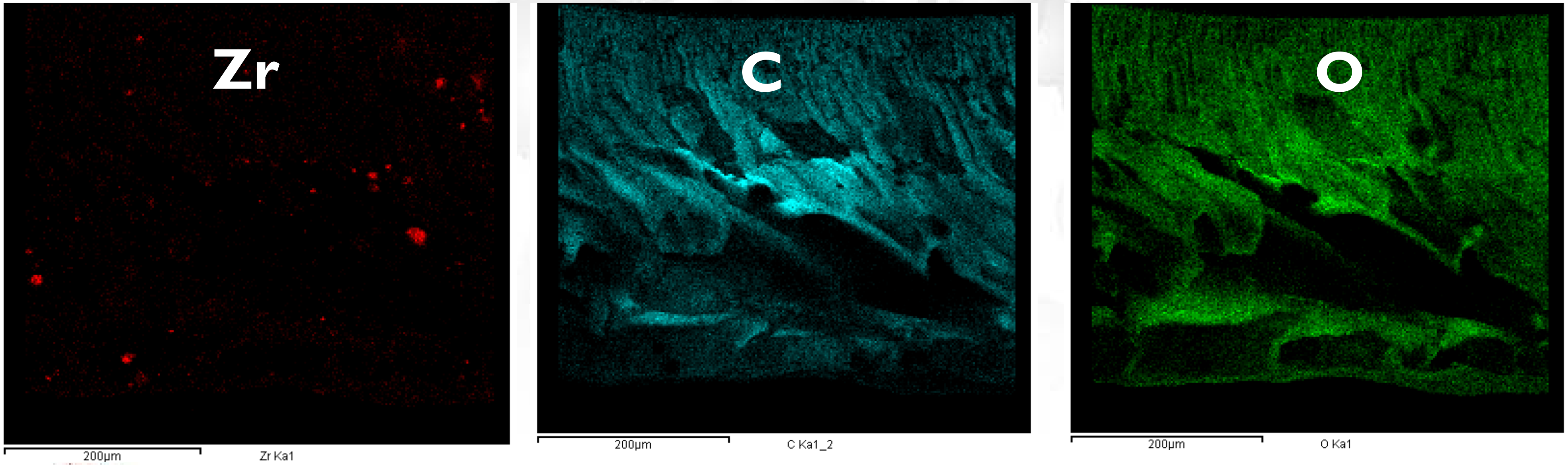
Scanning Electron Microscopy

Compositional analysis in a SEM

> X-ray microanalysis in a SEM (EDX):



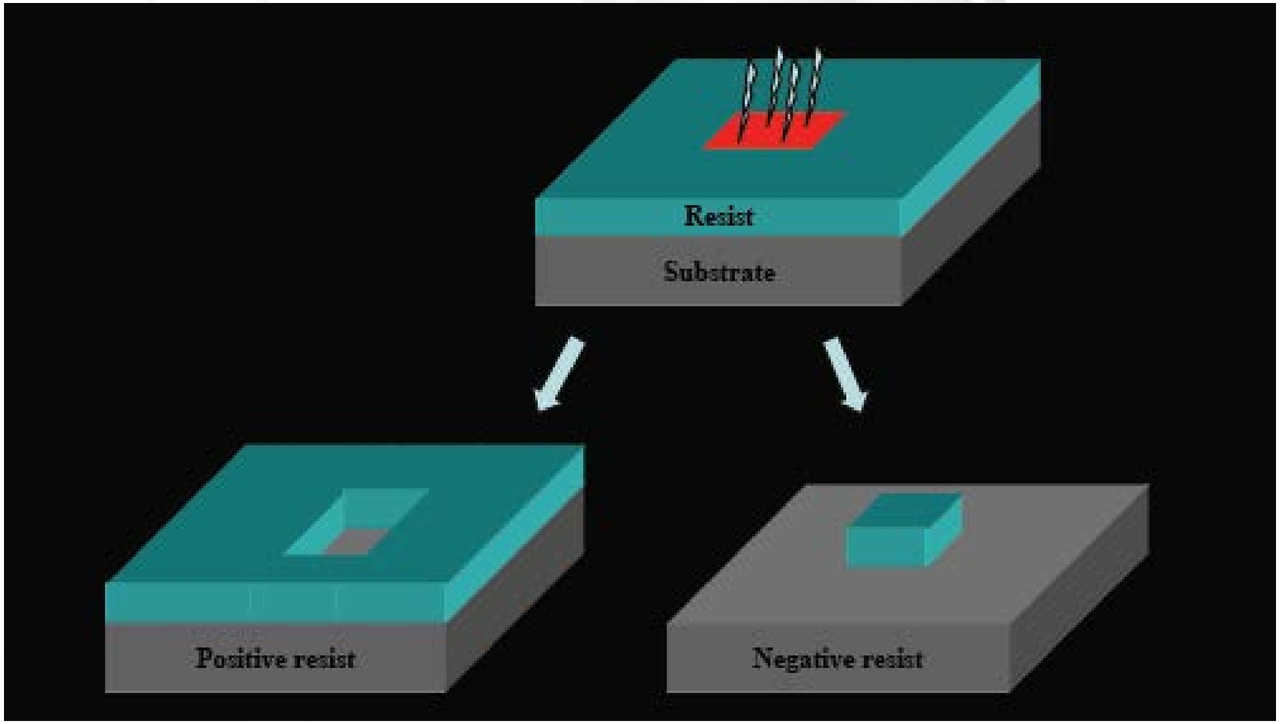
>> Chemical mapping:



Electron Beam Lithography

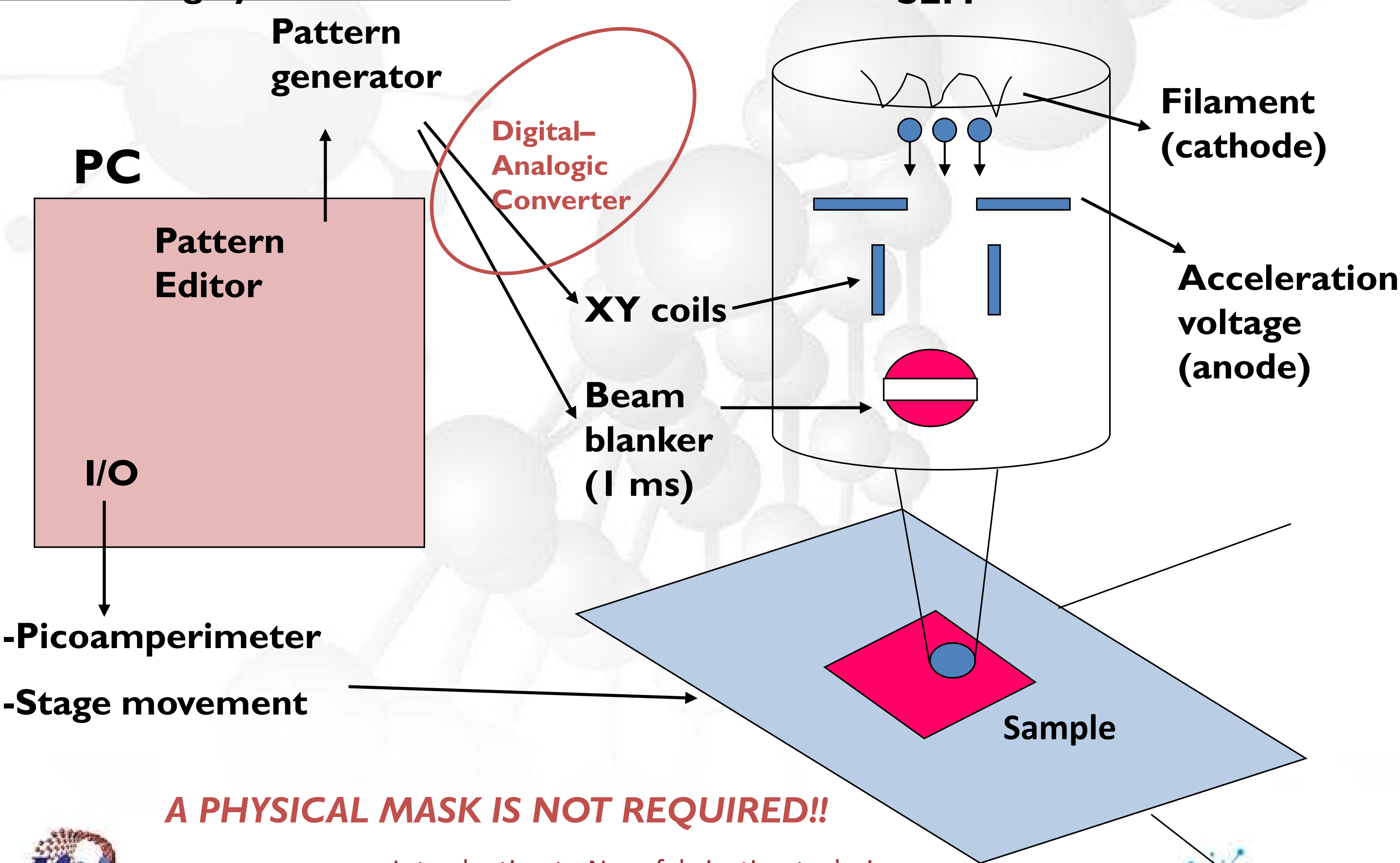
Concept:

Definition of submicrometric patterns by means of the electron beam scanning on a material (resist) sensitive to electronic irradiation



Electron Beam Lithography

Direct writing by means of EBL:



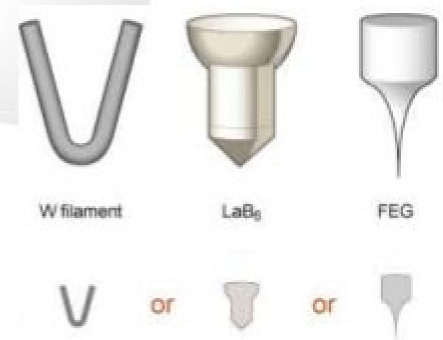
A PHYSICAL MASK IS NOT REQUIRED!!

Electron Beam Lithography

Aspects of the SEM to consider for the application in EBL:

SEM emitter:

*-The brightness of the electron emission is important, so, **field-emission sources are better than thermionic sources.***



- The stability is also important, so because of the current instability, **cold FEG is not good choice for EBL, though it is the best for SEM imaging applications**.

Emission	Thermoionic		Field emission
	W	LaB_6	FE
Brightness ($A/cm^2/sr$)	$10^4 – 10^5$	$10^5 – 10^6$	$10^7 – 10^9$
Energy spread (eV)	1 – 5	0.5 – 3.0	0.2 – 0.9
Lifetime (h)	>20	>100	>300
Vacuum (torr)	$10^{-4} – 10^{-5}$	$10^{-6} – 10^{-7}$	$10^{-9} – 10^{-10}$

Electron Beam Lithography

Aspects of the SEM to consider for the application in EBL:

Acceleration voltage and electron column quality:

- *The acceleration voltage and the microscope resolution are relevant parameters.*

- $\lambda = 1.2 / (V_a)^{1/2}$; for example $\lambda = 0.008$ nm at 25 kV.

- The acceleration voltage is important for the resolution because of the optical aberrations and the interaction of the electron beam with the resist and the sample.

Emission	Thermoionic		Field emission
	W	LaB_6	FE
Source size	25 μm	10 μm	5 – 20 nm
Energy spread (eV)	1 – 5	0.5 – 3.0	0.2 – 0.9

- The energy spread of the electron emission combined with the collimation, focusing and the column chromatic aberration will be important to determine the process maximum resolution.

Electron Beam Lithography

Aspects of the SEM to consider for the application in EBL:

Electron beam size on the resist:

Beam size (d)

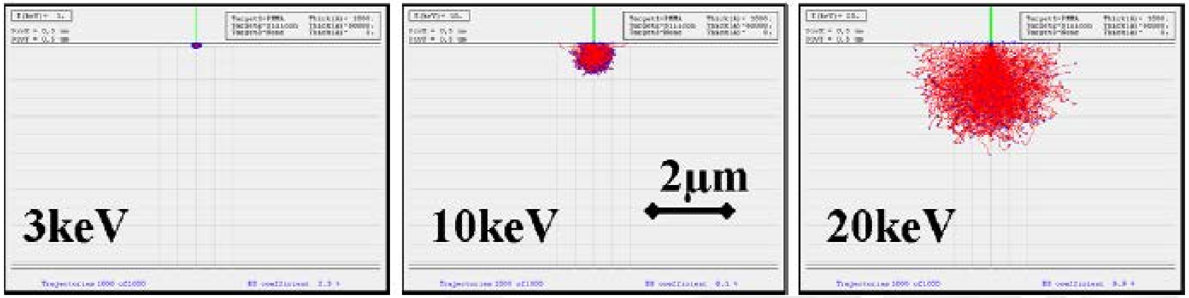
$$d = (d^2_g + d^2_s + d^2_c + d^2_d)^{1/2}$$

• **virtual source**, $d_g = d_f/M$	d_f, source size; M, magnification
• **spherical aberration**, $d_s = \frac{1}{2} C_s \alpha^3$	C_s, spherical aberration; α, beam convergence angle; C_s proportional to f, where f, focal distance
• **chromatic aberration**, $d_c = Cc\, \alpha\, \Delta E / V_e$	Cc, chromatic aberration; ΔE, energetic dispersion and V_e beam acceleration voltage
• **diffraction limit**, $d_d = 0.6\, \lambda/\alpha$	$\lambda = 1.2 / \sqrt{V_e}$, electronic wave length

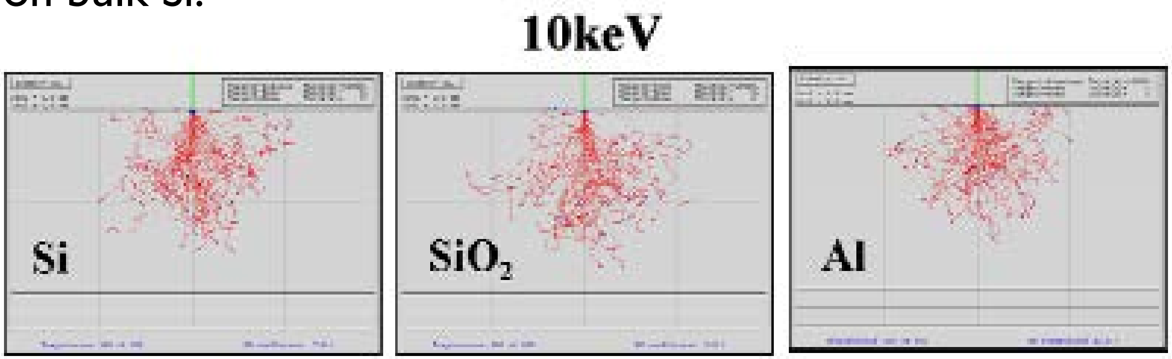
Electron Beam Lithography

Aspects of the SEM to consider for the application in EBL:

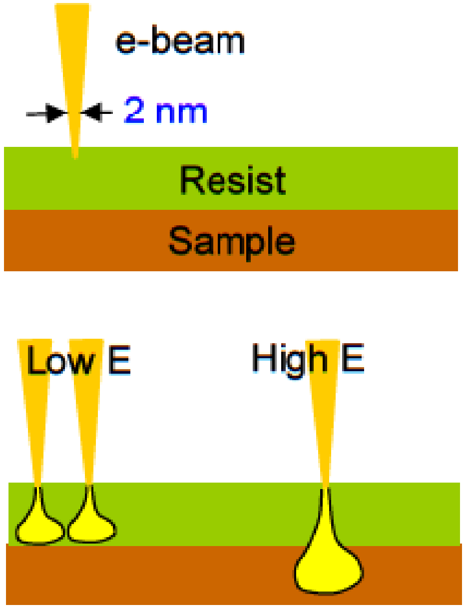
Electron penetration in the sample: The acceleration voltage is important for the resolution and for the proximity effect.



Effect of beam energy for exposure of 100 nm of PMMA on bulk Si.



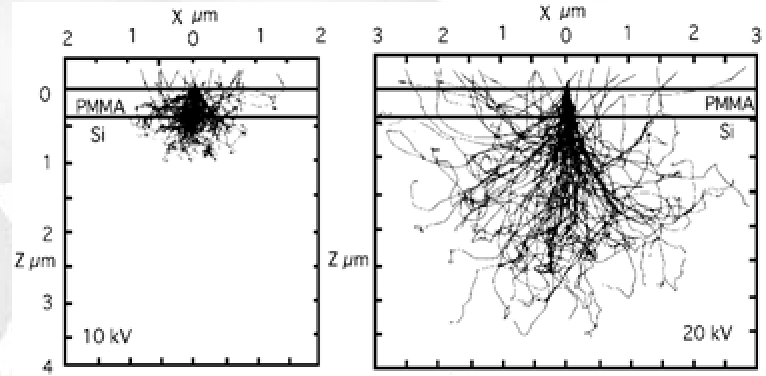
The electron penetration depends on the material below the resist too.

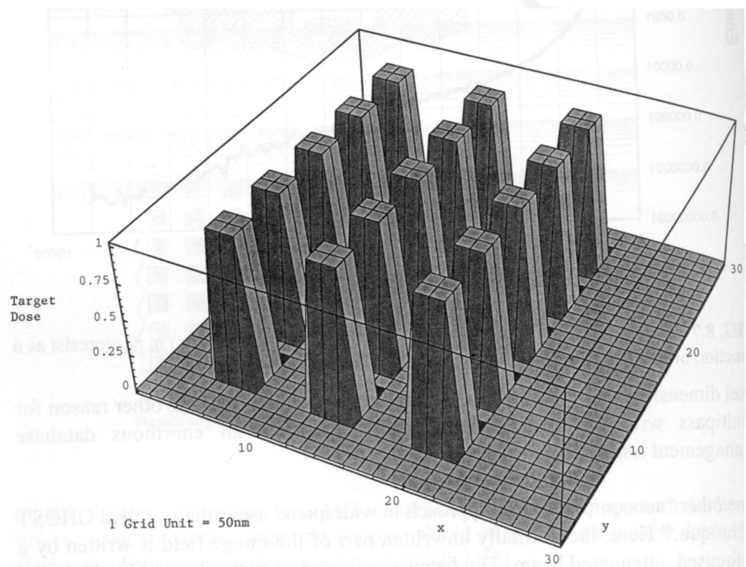


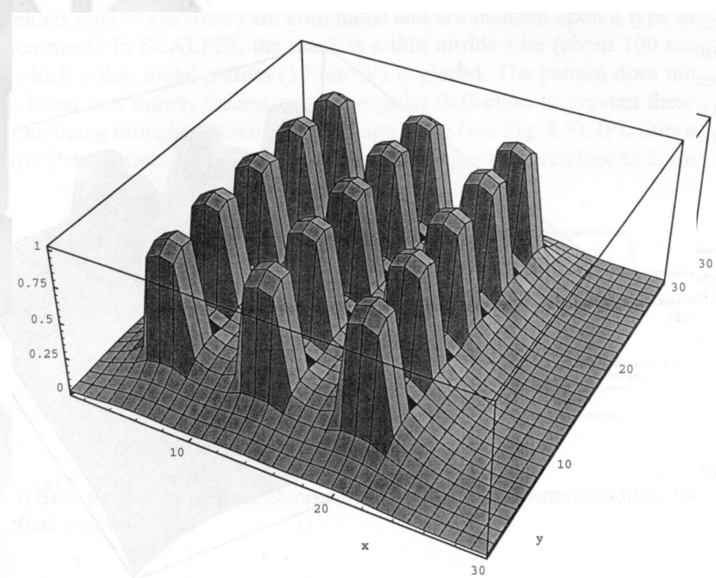
Electron Beam Lithography

Aspects of the SEM to consider for the application in EBL:

Proximity effect: Dense patterns worsen the resolution because of unintentional changes in the actual electro dose.







Expected dose without proximity effect.

Real dose due to the proximity effect.

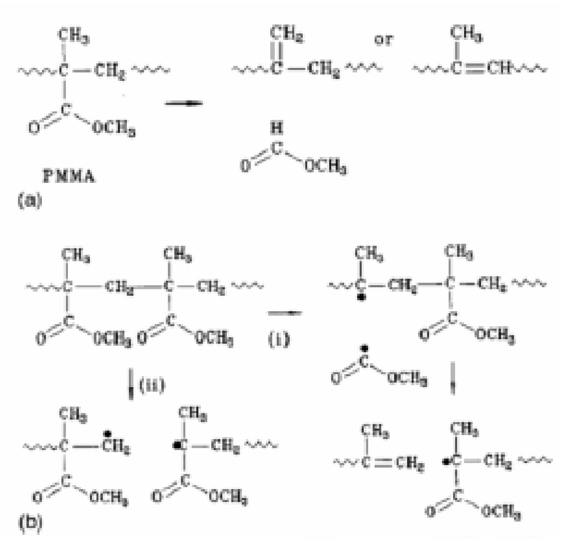
Electron Beam Lithography

Resists for EBL:

- Most of resists are organic and can be positive or negative.

- The secondary electrons produced by the primary electron beam induce the break of the polymers (positive resist) or the cross-link (negative resist).

- **PMMA, poly(methyl methacrylate):** it is a positive electron-beam-sensitive resist widely used due to the good resolution achievable**.**



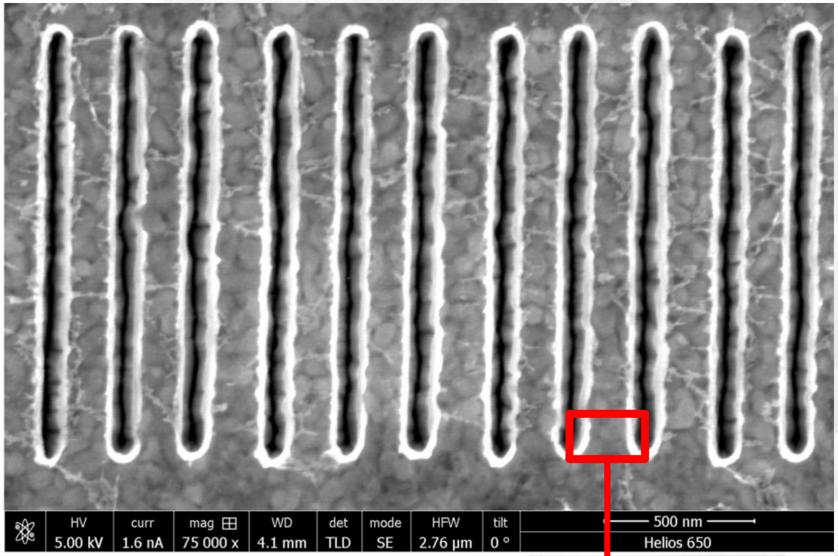
PMMA MW	Beam energy (keV)	Dose ($\mu C/cm^2$)	Thickness (nm)
950 k	3	25 / ---	100 / 400
	10	55 / 85	
	20	100 / 180	
495 k	3	20 /---	100 / 350
	10	40 / 90	
	20	105 / 200	
35 k	3	---	350
	10	50	
	20	100	

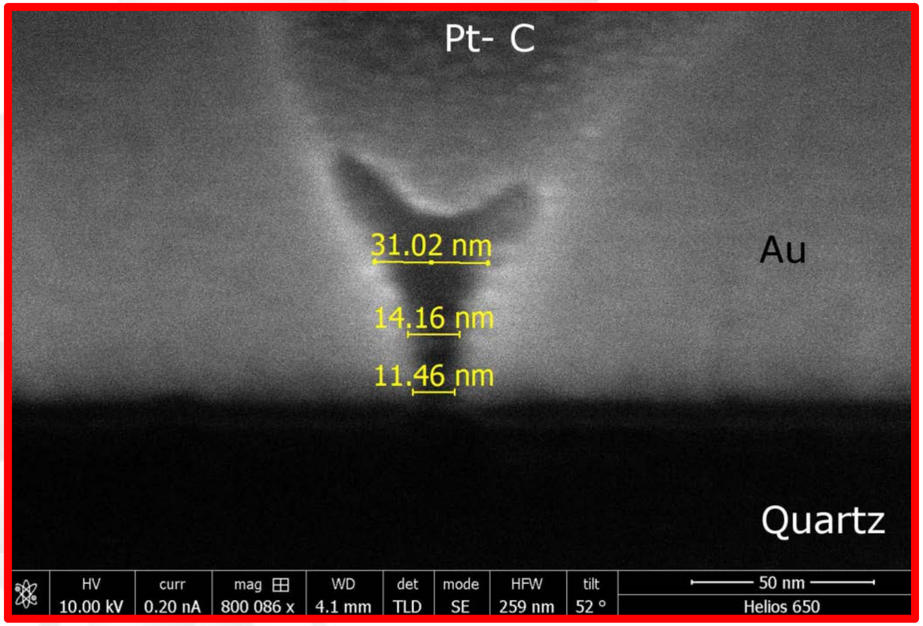
Generic reaction paths caused by EBL on PMMA.

Electron Beam Lithography

Resolution limit of EBL:

≈ 10 nm on insulating substrates:





Cross- section image.

The lithography is possible on the resist… and the transfer?

This is more complex due to the etching or the lift-off

S. Sangiao, J. M. De Teresa et al., *Nanotechnology* **27**, 505202 (2016).

Focused Electron Beam Induced Deposition

Fundamentals of FEBID:

FEBID: It is based on the electron-induced dissociation of a molecular precursor previously adsorbed on a substrate surface and constantly replenished by a gas-injection system (GIS).

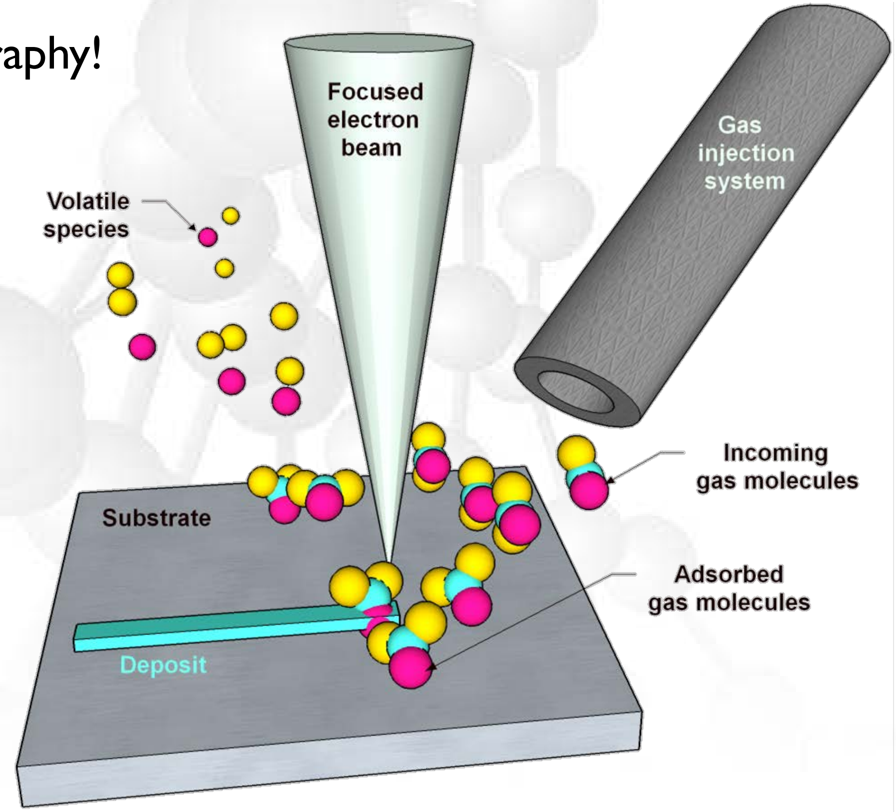
It is a **direct-writing technique** in which the electron beam is provided by a SEM:

- No resist layer prior to lithography!

- No masks!

- No reactive gases or liquids!

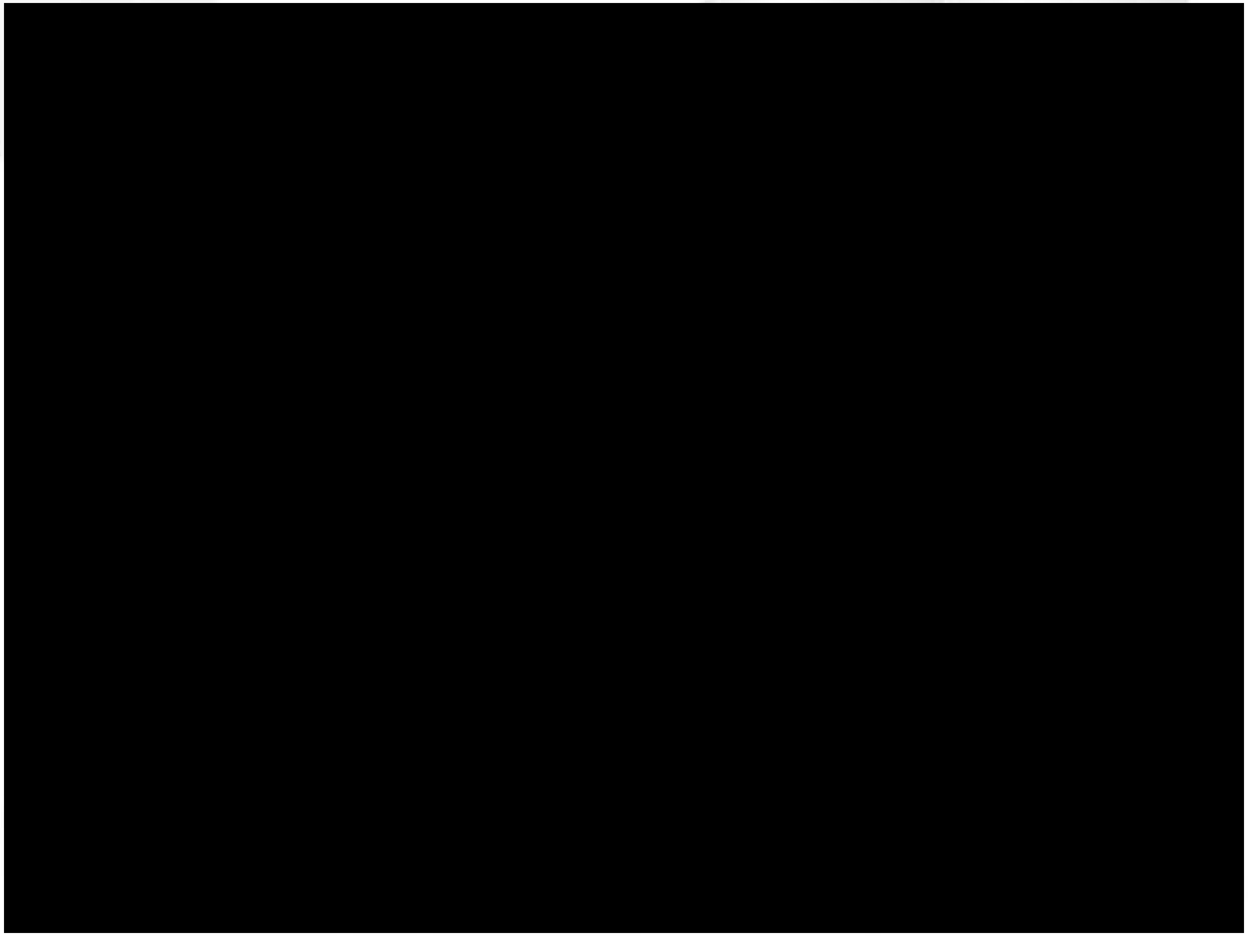
- 3D capabilities!



Focused Electron Beam Induced Deposition

3D capabilities of FEBID:

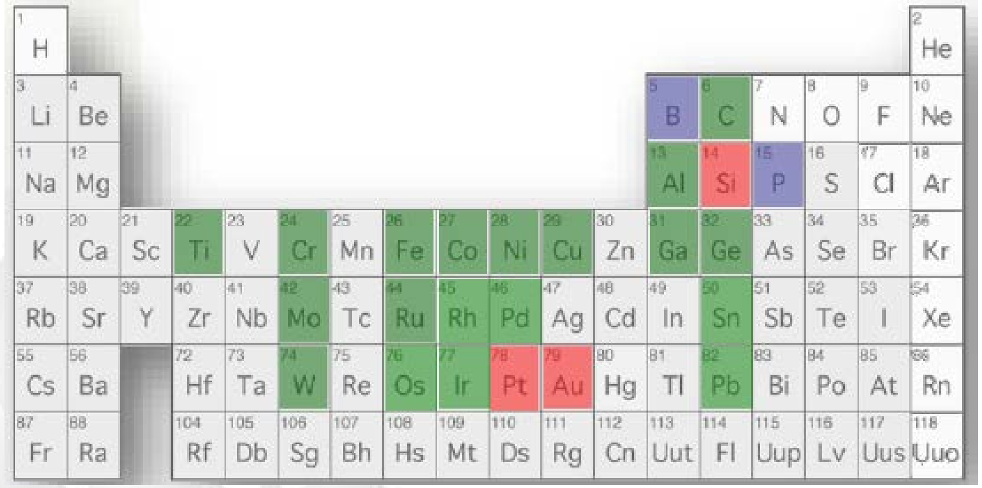
True 3D Nanoprinting!



Focused Electron Beam Induced Deposition

Available precursors for FEBID:

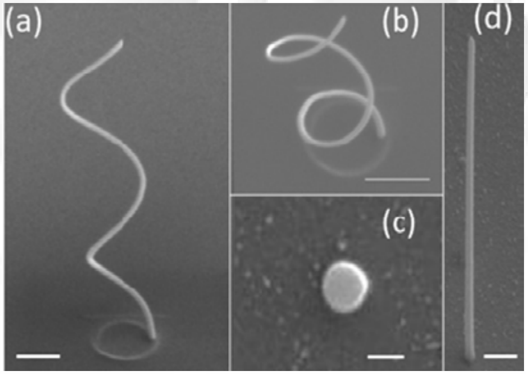
Elements that can be deposited by FEBID:

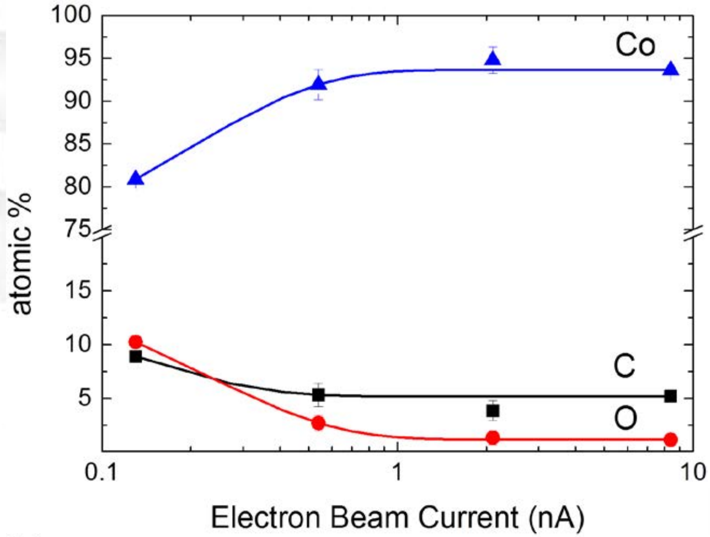


Main **drawback**: Purity of the deposits grown by FEBID.

Most of FEBID materials reveal metal-matrix composition (metallic nano-grains in carbon matrix).

Purest FEBID material: FEBID-Co grown by using the $Co_2(CO)_8$ precursor gas.





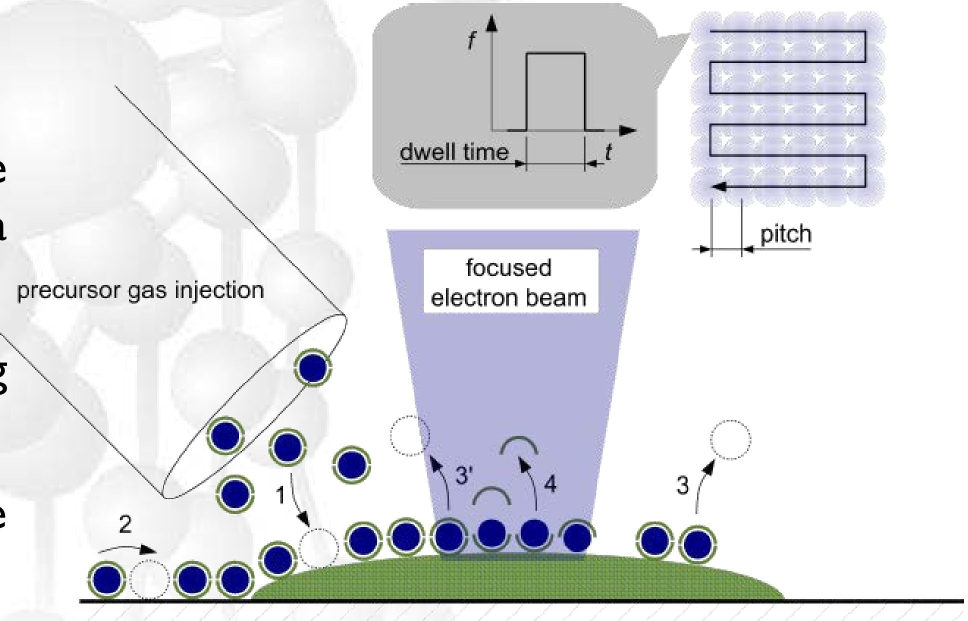
M. Huth et al., *Beilstein J. Nanotechnol.* **3**, 597 (2012). J. M. De Teresa et al., *J. Phys. D:Appl. Phys.* **49**, 243003 (2016).

Focused Electron Beam Induced Deposition

FEBID parameters:

Main parameters that govern the writing process:

- **Primary-beam energy**.
- **Beam current**.
- **Dwell time**: time for which the electron beam is held constant on a particular point on the surface.
- **Pitch**: distance between neighboring dwell points.
- **Loops**: Number of loops for which the writing pattern is repeated.
- **Replenishment time**: Period for which the writing is paused between two successive loops.

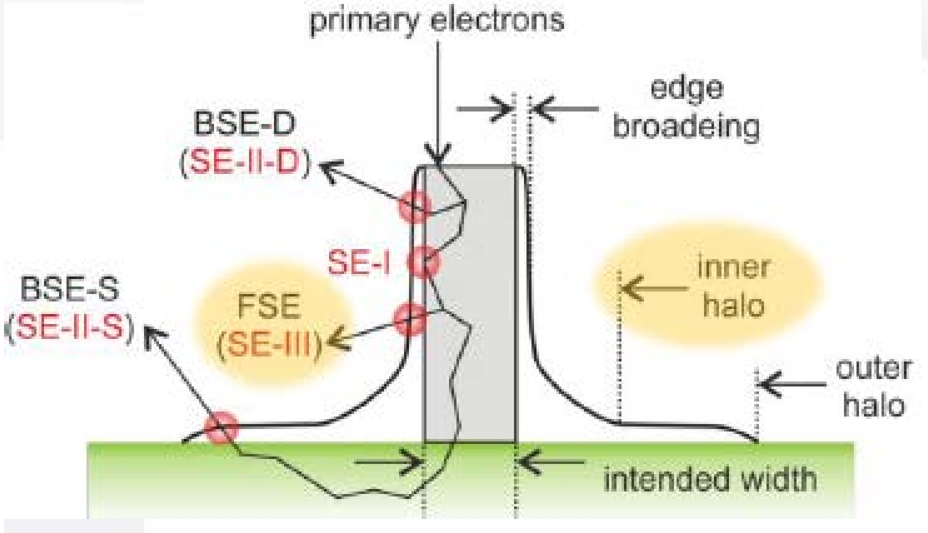


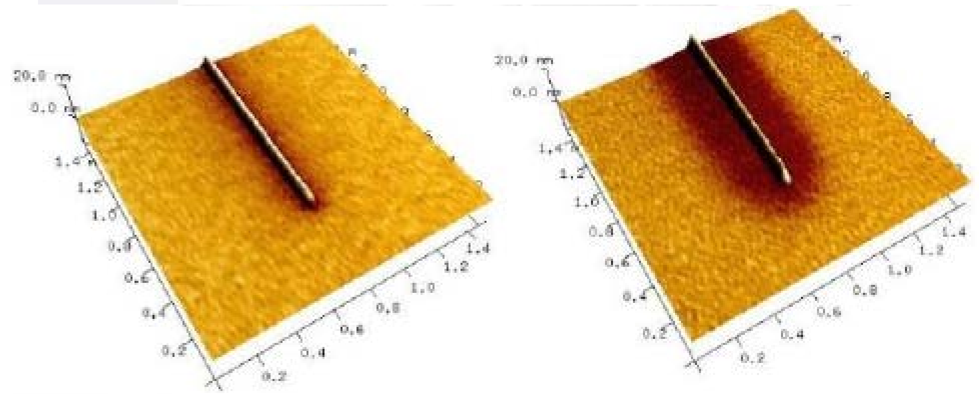
M. Huth et al., *Beilstein J. Nanotechnol.* **3**, 597 (2012).

Focused Electron Beam Induced Deposition

Lateral resolution of FEBID:

FEBID deposits are broader than the electron beam profile because of the electron interaction volume:



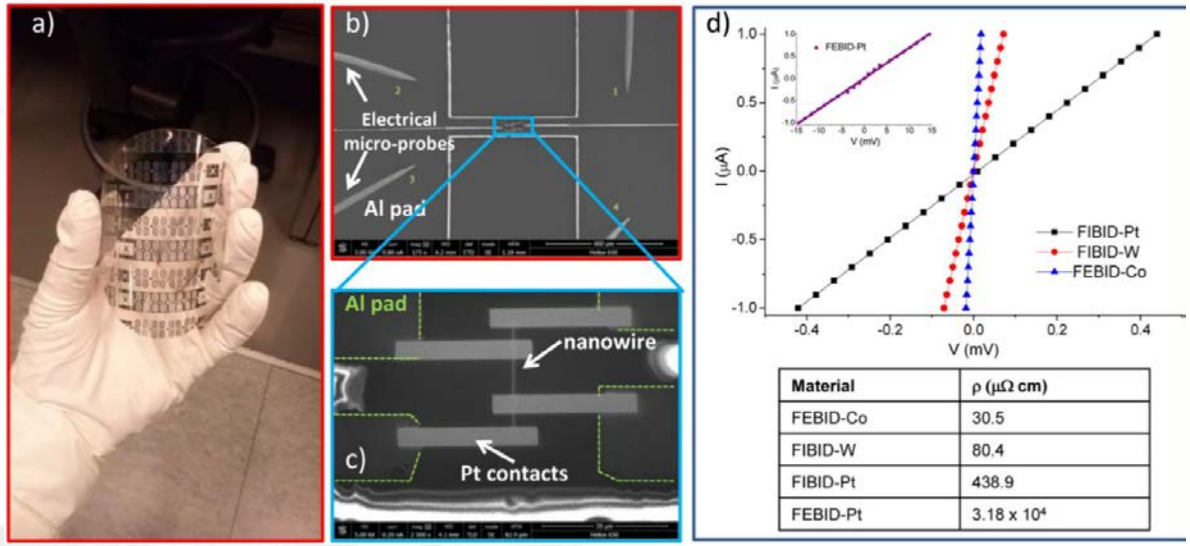


Harald Plank, Institute for Electron Microscopy, Graz University of Technology.

Focused Electron Beam Induced Deposition

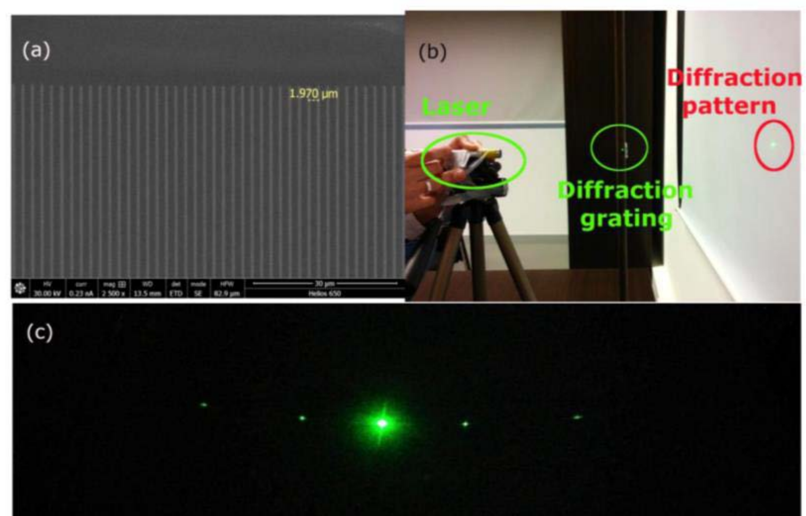
Applications: FEBID on insulating flexible substrates:

FEBID can be performed on insulating and FLEXIBLE polymer substrates.



Material	ρ (μΩ cm)
FEBID-Co	30.5
FIBID-W	80.4
FIBID-Pt	438.9
FEBID-Pt	3.18 x 10⁴

The functionality of FEBID nanodeposits on flexible substrates is maintained over a huge range of bending angles! New applications, such as nano-optics, become possible!



P. Peinado, S. Sangiao and J. M. De Teresa, *ACS Nano* **6**, 6139 (2015).

Thank you for your attention!