2021 SUMMER SCHOOL IN

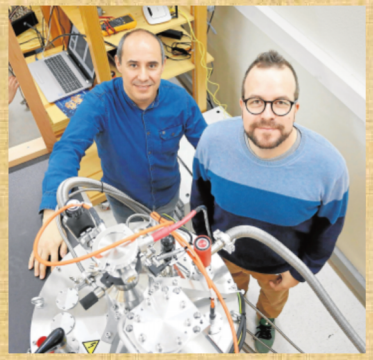
BASICS AND APPLICATIONS OF NANOLITHOGRAPHY

(University of Salamanca, June 28th to July 1st)

LOCAL ORGANIZERS

*MARIO AMADO: mario.amado@usal.es

*ENRIQUE DÍEZ: enrisa@usal.es



University of Salamanca, founded in 1218

NANOLITO NETWORK

rednanolito

Spanish network of excellence on Nanolithography, funded by the Ministry of Science (started in 2007)

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rednanolito

OBJECTIVES of NANOLITO: to foster the interaction between groups in the area of nanolithography, to share capacities, and to provide formation to new researchers in the field

Coordinating node: Zaragoza (INMA)

Other nodes: Madrid (ISOM, UCM, ICMM, IMDEA, IMN), Barcelona (CNM, UB, ICN2, ICFO, ICMAB), San Sebastián (Nanogune), Eibar (Tekniker), Oviedo (UNIOVI), Valencia (ICMOL)

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

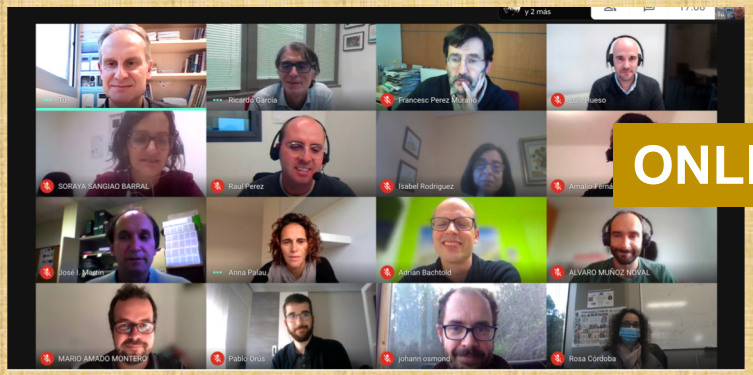
ACTIVITIES of NANOLITO

JACA-2016
JACA-2018

SAN SEBASTIAN-2016

MADRID-2017

SALAMANCA-2017



ONLINE-2020

WEBPAGE of NANOLITO

rednanolito

Español

NANOLITO Introduction

What is the network Nanolito?
Organizations and Partners
Scientific Committee

NANOLITO Activities

Meetings
Workshops
Summer School

Documents of interest

Highlights
Presentations

Links

Nanolithography laboratories Services
Masters
Related events

What is the network Nanolito?

Nanolito is the *Spanish Network on Nanolithography*. The Nanolithography comprises the set of techniques that allow the creation of nanodevices and thus is a key element in Nanotechnology.

Nanolito is funded since 2009 by the Ministry of Science in Spain to form a national network on Nanolithography that would foster scientific exchange and knowledge transfer between the national agents in this field (research groups, institutions and companies).

With Nanolito, it is aimed to optimise and coordinate the use of the national scientific resources in the area of Nanolithography. The obtained funding supports Nanolito for the organization of meetings and workshops, summer schools and short-term visits.

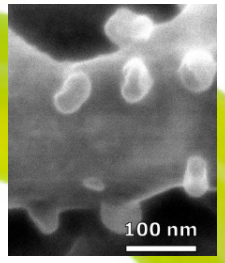
Introduction to Nanolithography techniques

MICRO WORLD

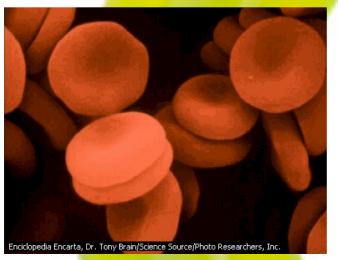
100 nm

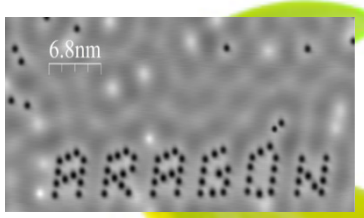
NANO WORLD

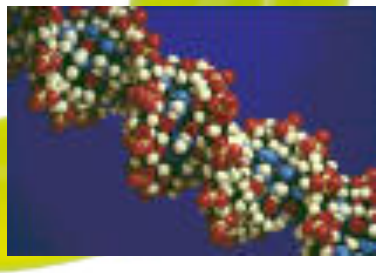
1 μm



10 nm



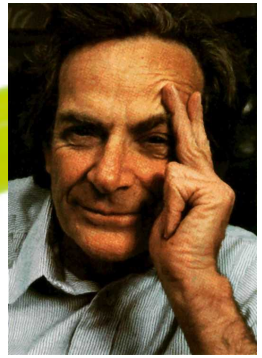




1 nm

1 mm

1 m



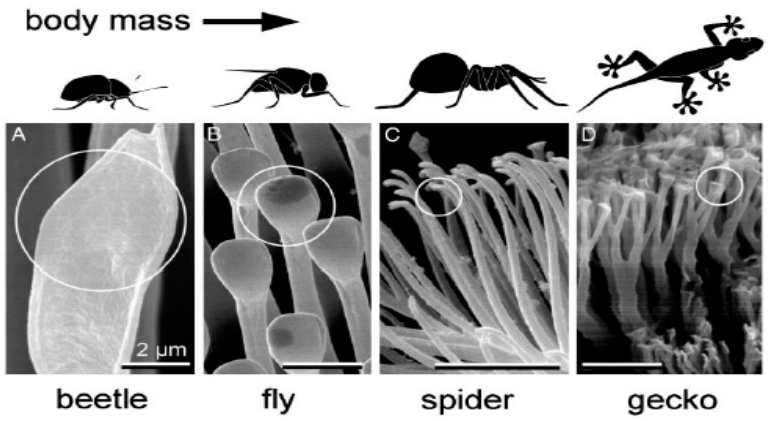
MACRO WORLD

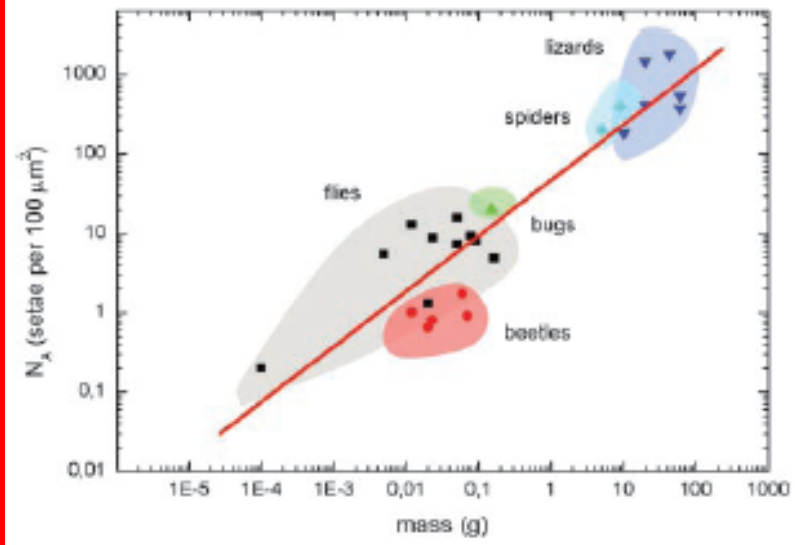
NANOTECHNOLOGY EXISTS IN NATURE

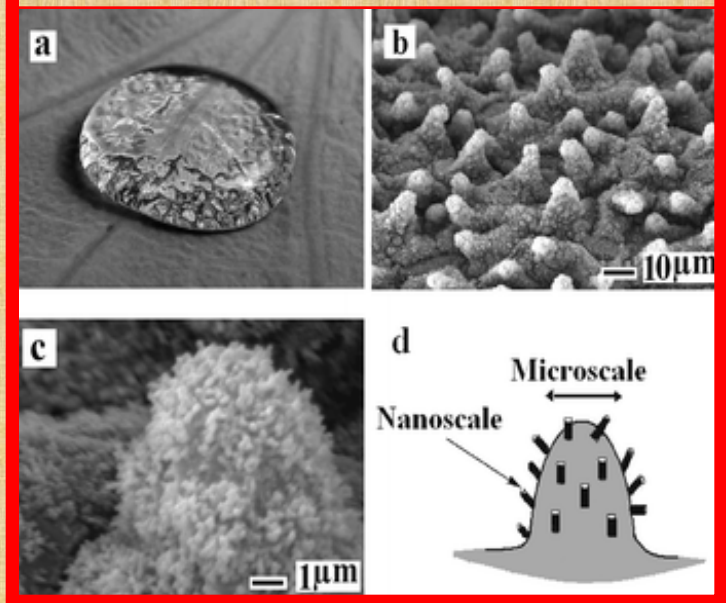
From micro to nano contacts in biological attachment devices

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!

1 **Introduction to nanolithography techniques and their applications** 1-1
José María De Teresa

2 **Optical lithography** 2-1
Francesc Perez-Murano, José Ignacio Martín and José María De Teresa

3 **Electron beam lithography and its use on 2D materials** 3-1
Vito Clericò, Mario Amado and Enrique Diez

4 **Focused electron beam induced deposition** 4-1
Javier Pablo-Navarro, Soraya Sangiao, César Magén and José María De Teresa

5 **Focused ion beam induced processing** 5-1
Pablo Orús, Rosa Córdoba and José María De Teresa

6 **Scanning probe lithography** 6-1
Ricardo Garcia

7 **Soft thermal nanoimprint and hybrid processes to produce complex structures** 7-1
Isabel Rodríguez and Jaime Hernández

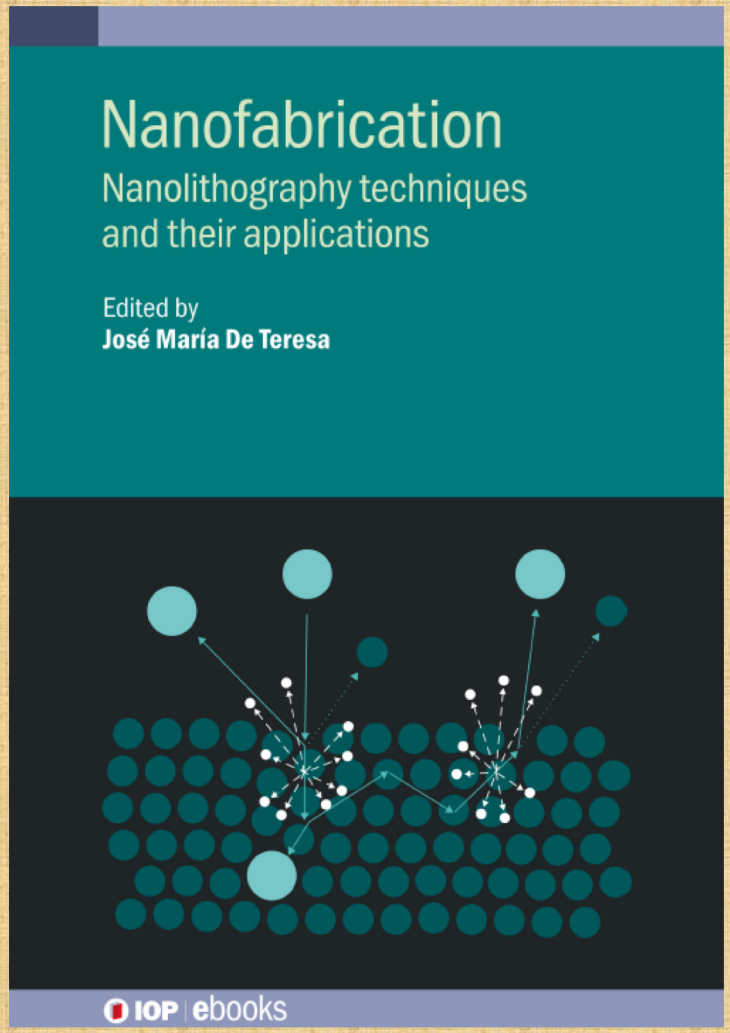
8 **Stencil lithography** 8-1
Oscar Vazquez-Mena and Luis Guillermo Villanueva

9 **Ice lithography** 9-1
Anpan Han, Ding Zhao and Min Qiu

10 **Magnetic nanopatterning via thermal scanning probe lithography** 10-1
Edoardo Albisetti, Daniela Petti, Riccardo Bertacco and Elisa Riedo

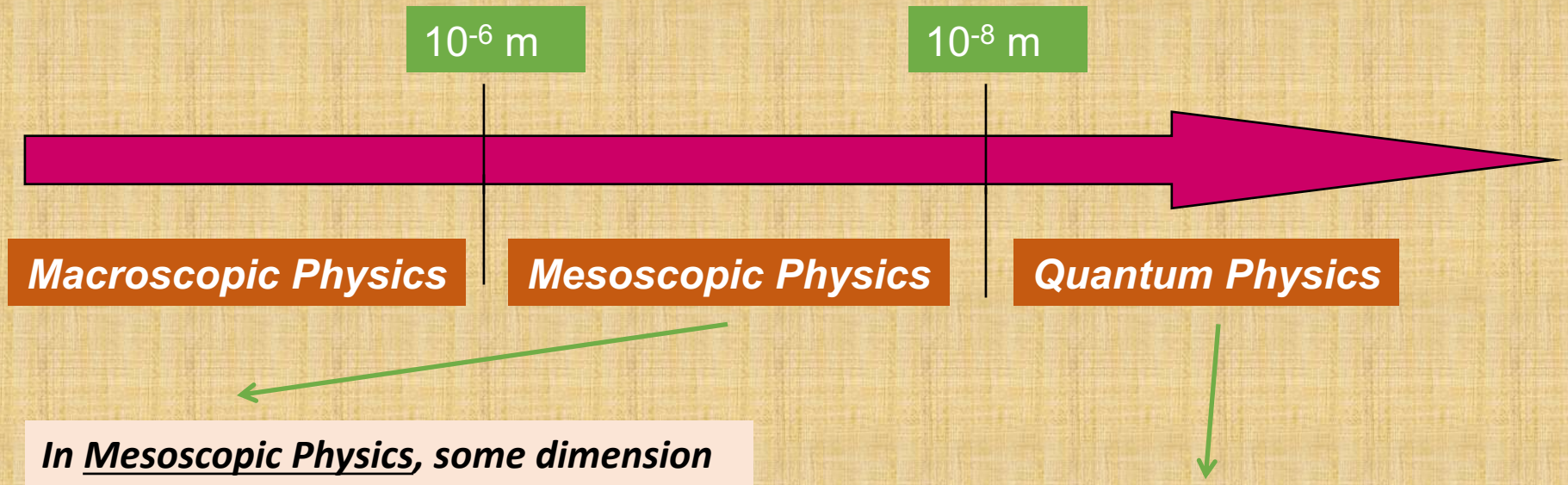
11 **Nanofabrication of three-dimensional magnetic structures** 11-1
Dédalo Sanz-Hernández, Claire Donnelly, Lucas Pérez and Amalio Fernández-Pacheco

12 **FEBIP for functional nanolithography of 2D nanomaterials** 12-1
Songkil Kim and Andrei G Fedorov



https://iopscience.iop.org/book/978-0-7503-2608-7

***BONUS*: 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… In addition, 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.

INTRODUCTION TO NANOLITHOGRAPHY (I)

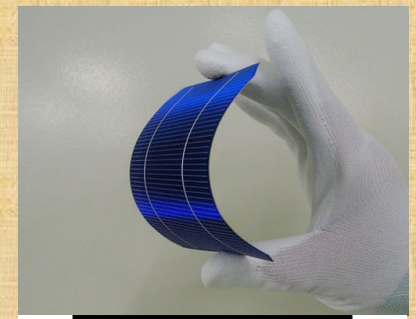
TOP-DOWN APPROACH

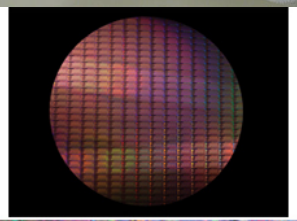
Thin-film growth technology
+
Lithography techniques

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

Thin-film growth technology

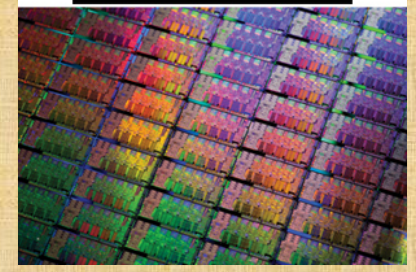
Physical vapour deposition (sputtering, evaporation), chemical vapour deposition, liquid-phase deposition (electrodeposition, spin coating), Langmuir-Blodgett…





Lithography techniques

Optical lithography, electron beam lithography, focused ion beam, scanning probe lithography, nanoimprinting, nanostencil,…



INTRODUCTION TO NANOLITHOGRAPHY (II)

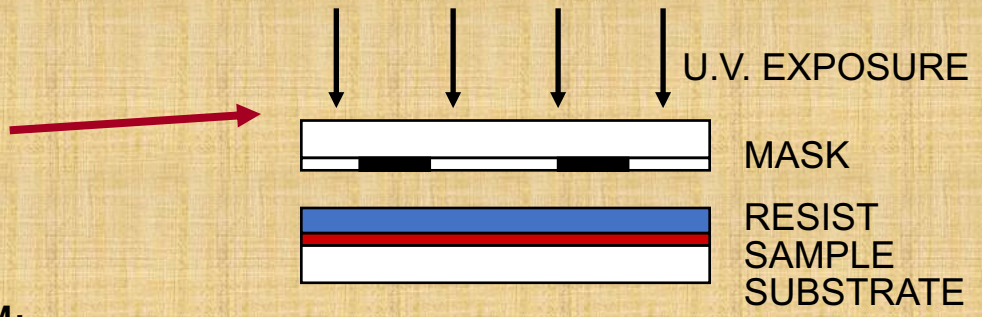
⇒ THE LITHOGRAPHY IS THE SET OF TECHNIQUES ALLOWING THE TRANSFER OF PATTERNS TO A SAMPLE. THE TYPICAL MINIMUM SIZE IN THE TRANSFERED PATTERNS IS MICROMETRIC OR NANOMETRIC.

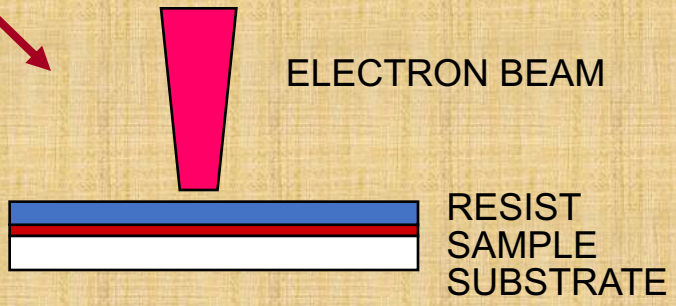
⇒ THE PATTERNS CAN:

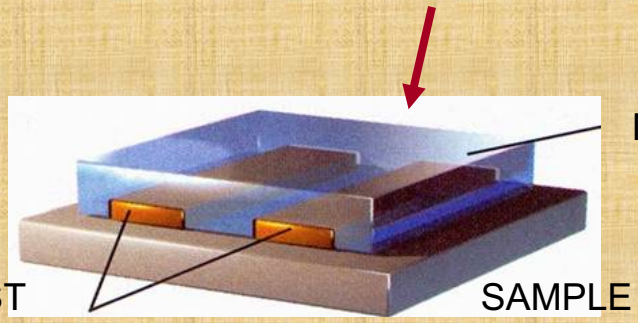
-<u>BE PREVIOUSLY DESIGNED ON A MASK</u>: Optical UV or EUV lithography

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

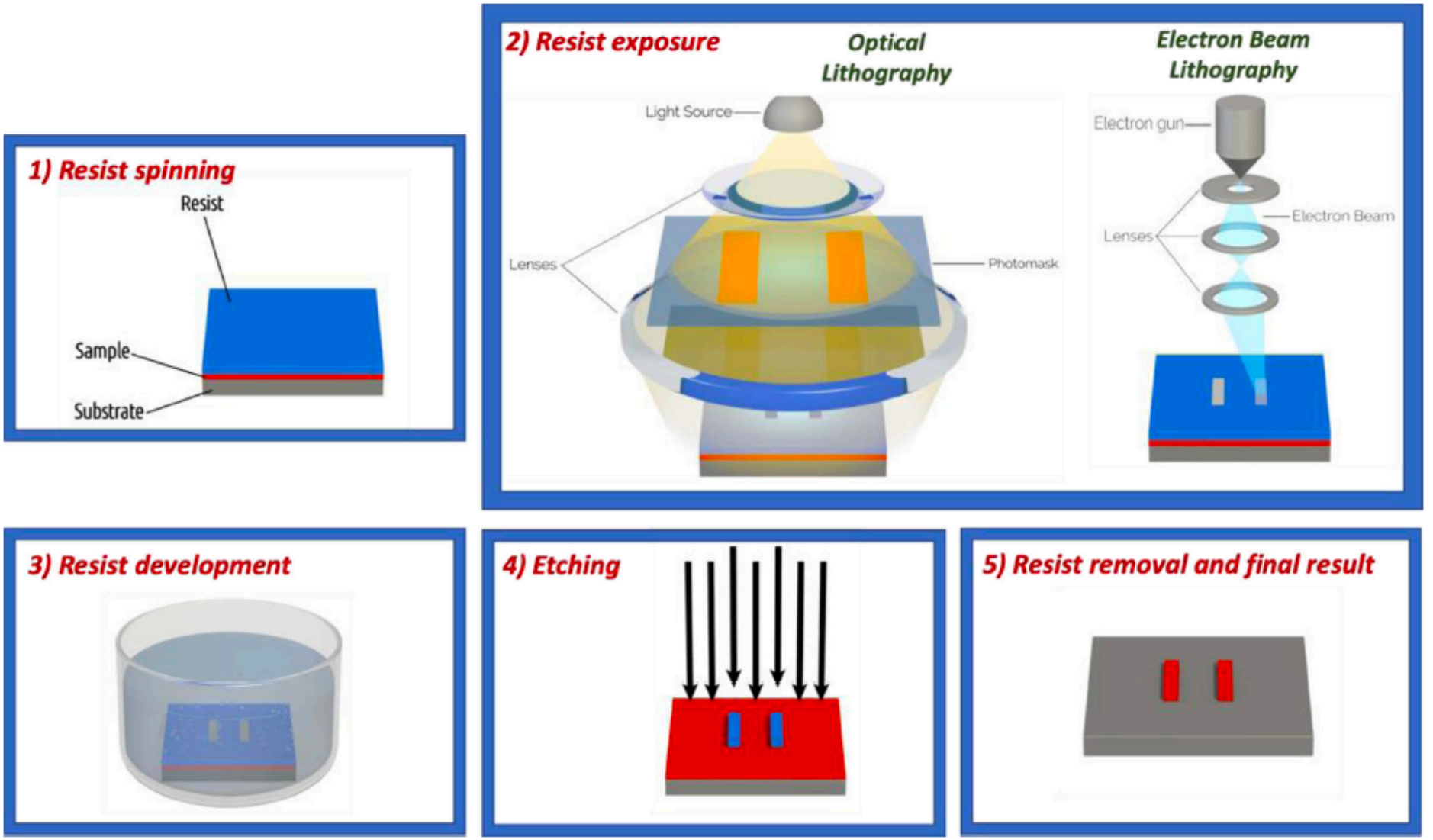
-<u>BE PREVIOUSLY AVAILABLE ON A MOULD</u>: Nanoimprinting



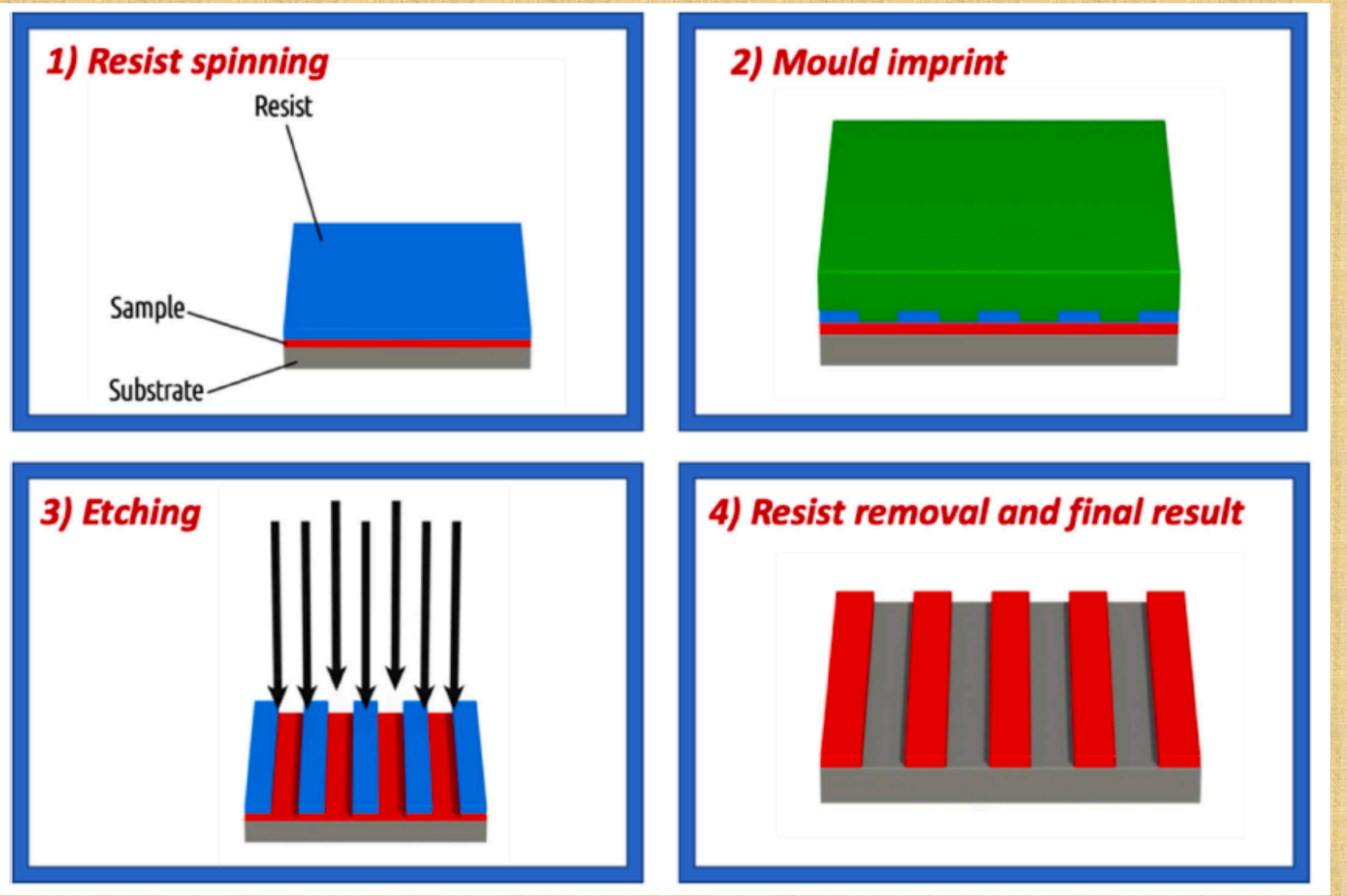




OPTICAL AND ELECTRON BEAM LITHOGRAPHY



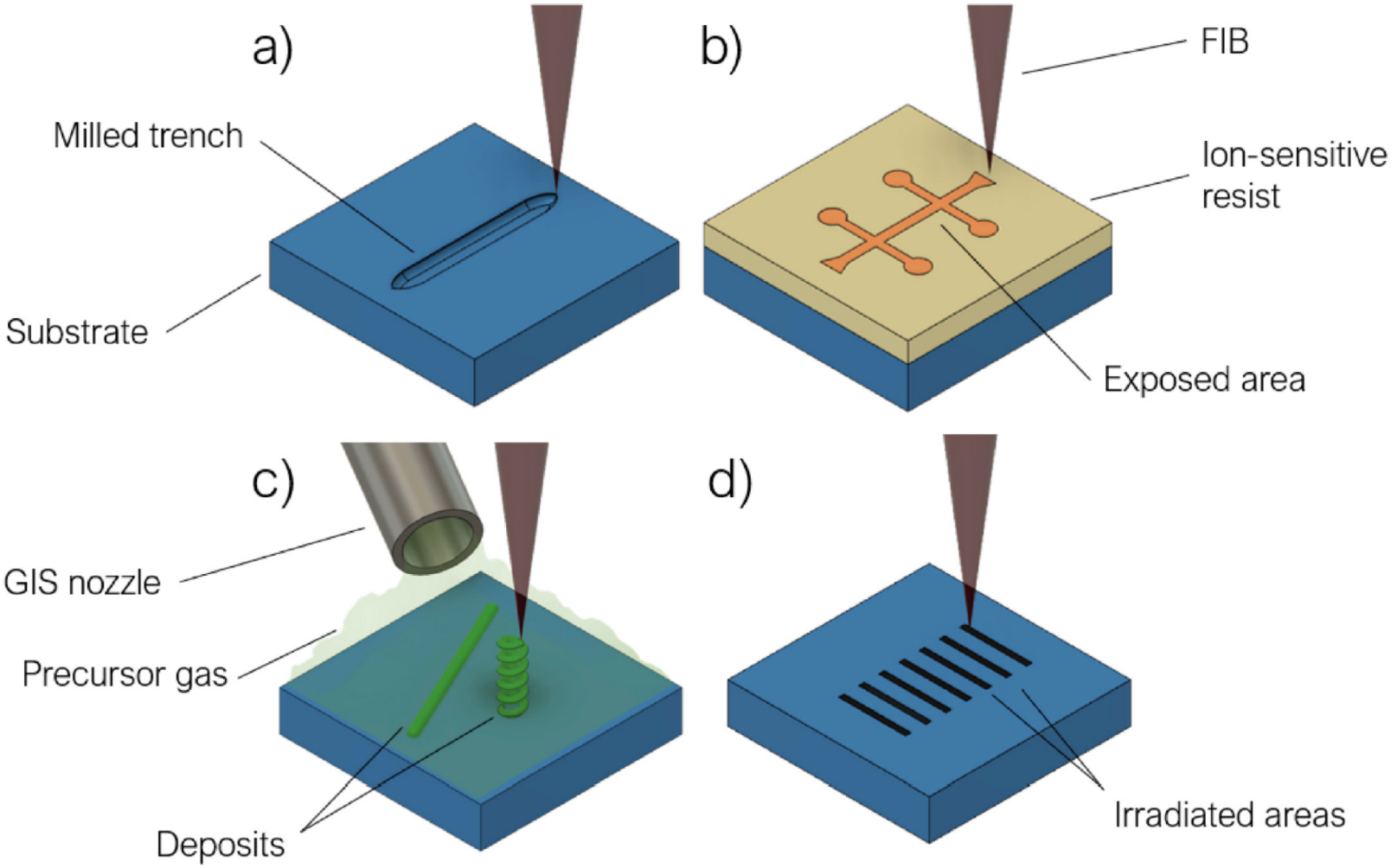
NANOIMPRINT LITHOGRAPHY



FOCUSED ION BEAM LITHOGRAPHY

Milling (FIB milling)

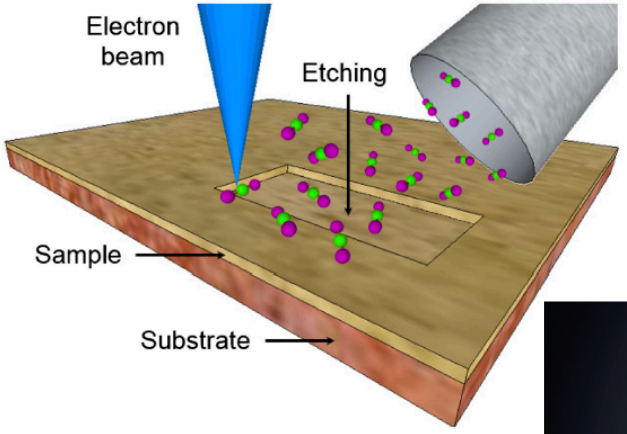
Resist lithography (FIBL)



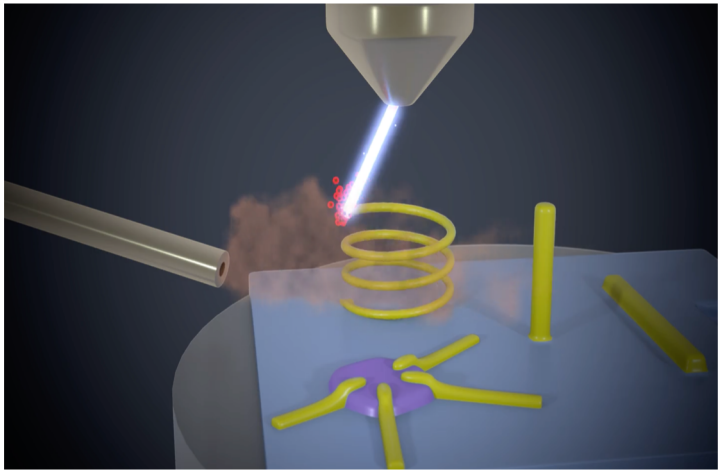
Deposition (FIBID)

Irradiation

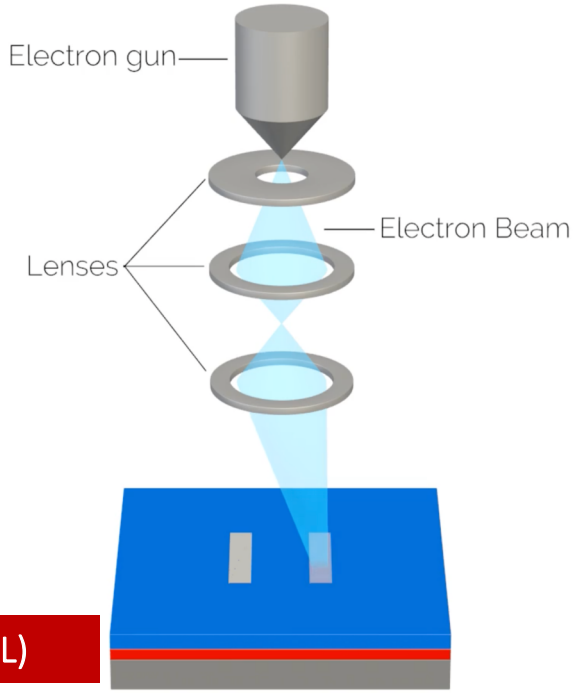
FOCUSED ELECTRON BEAM LITHOGRAPHY



Etching (FEBIE)

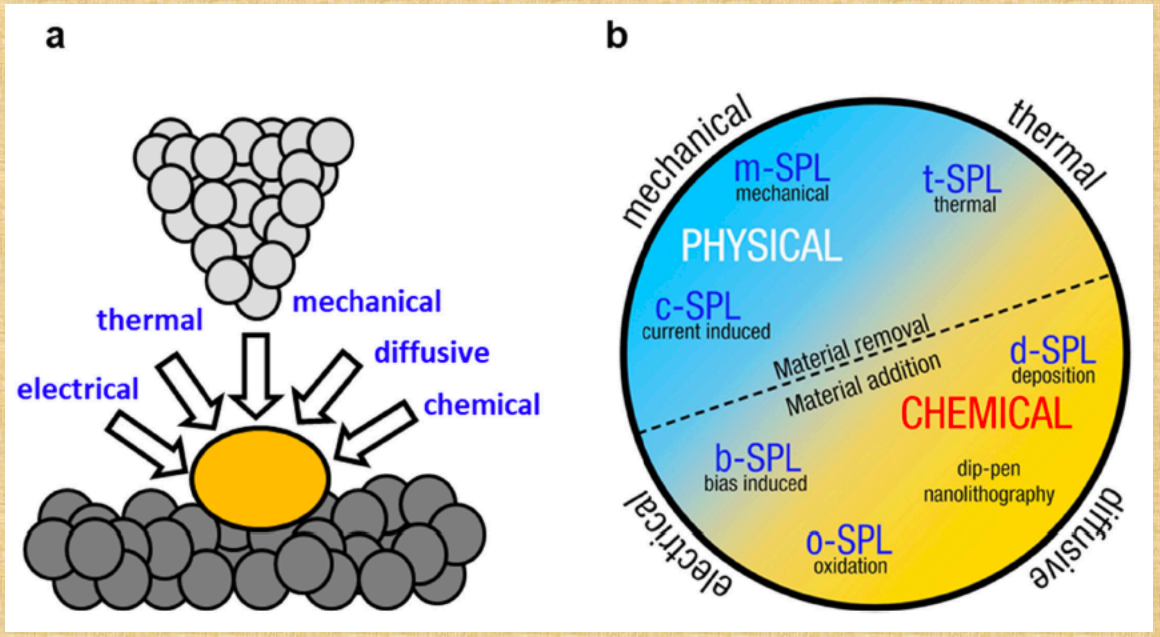


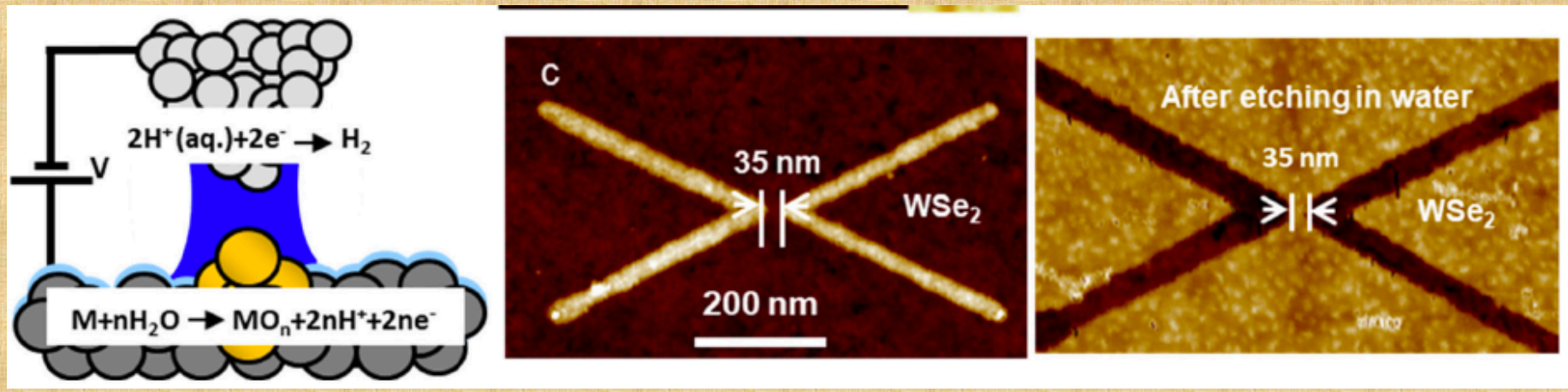
Deposition (FEBID)



Resist lithography (EBL)

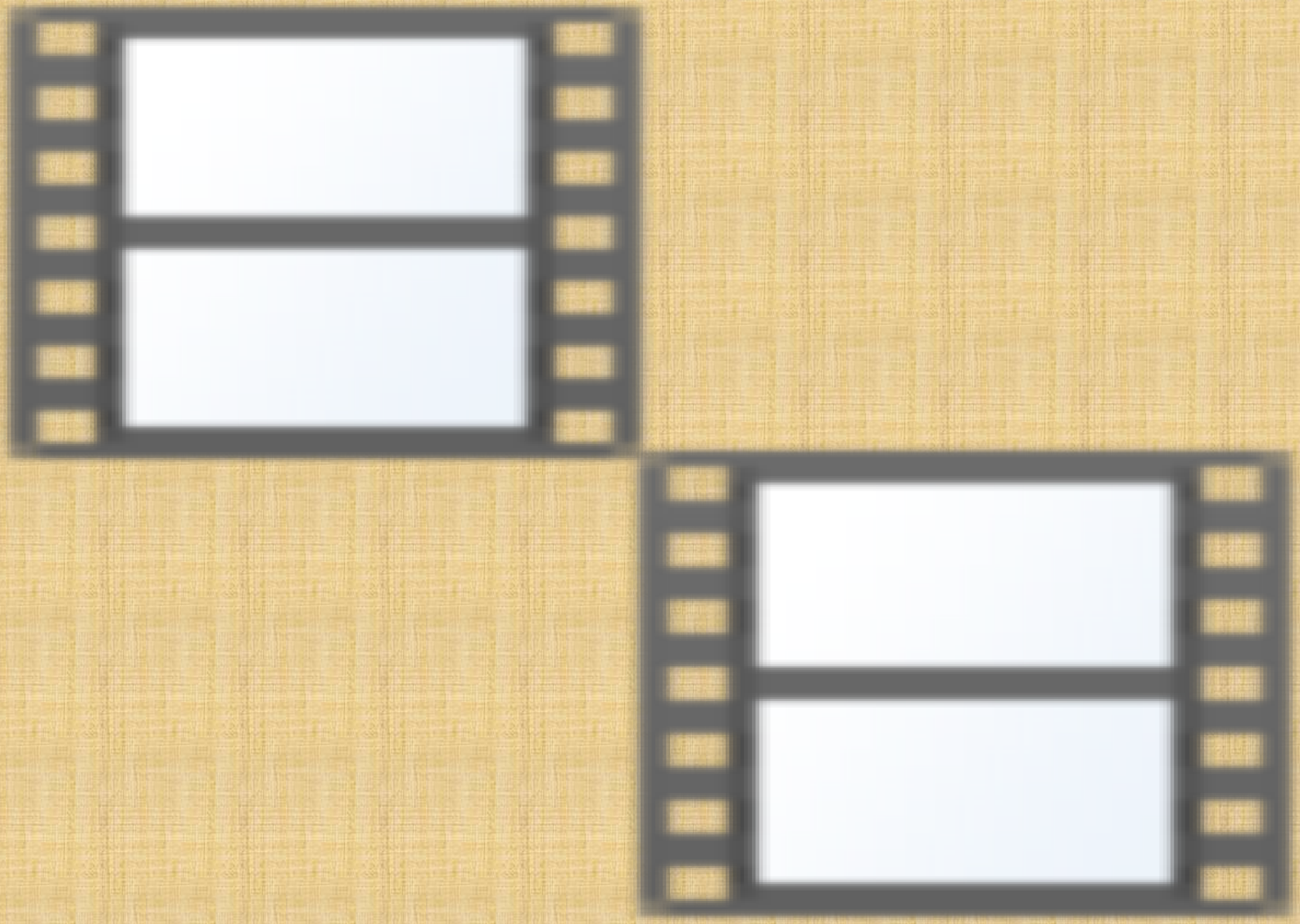
SCANNING PROBE LITHOGRAPHY





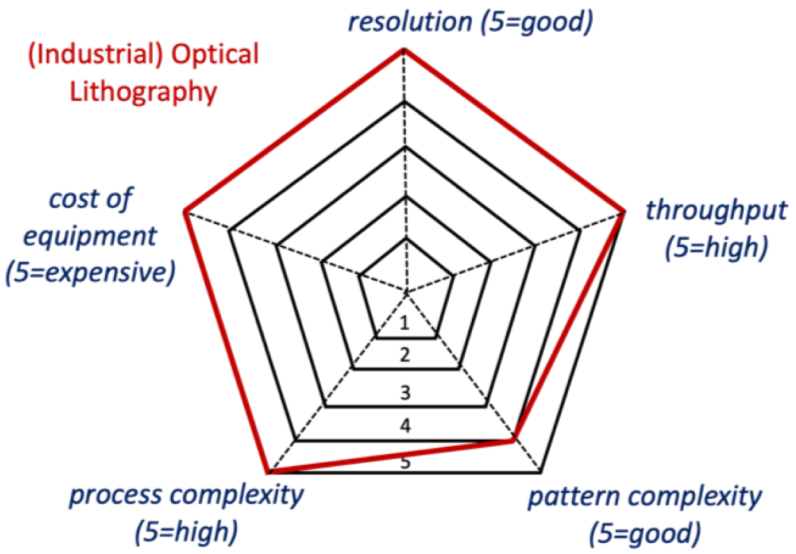
Dago et al., Appl. Phys. Lett. 109, 163103 (2016)

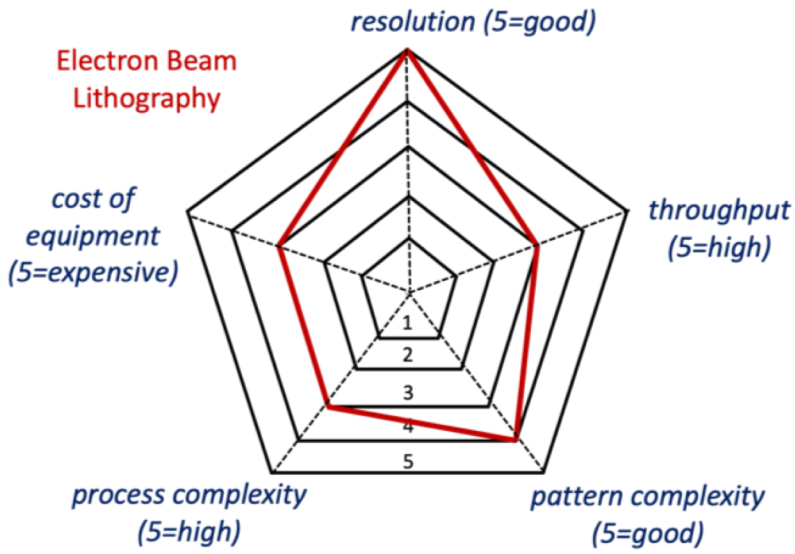
STENCIL LITHOGRAPHY

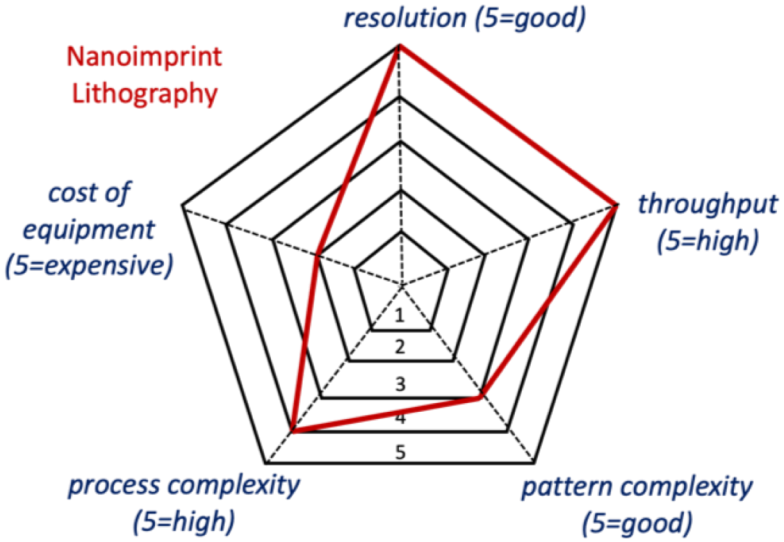


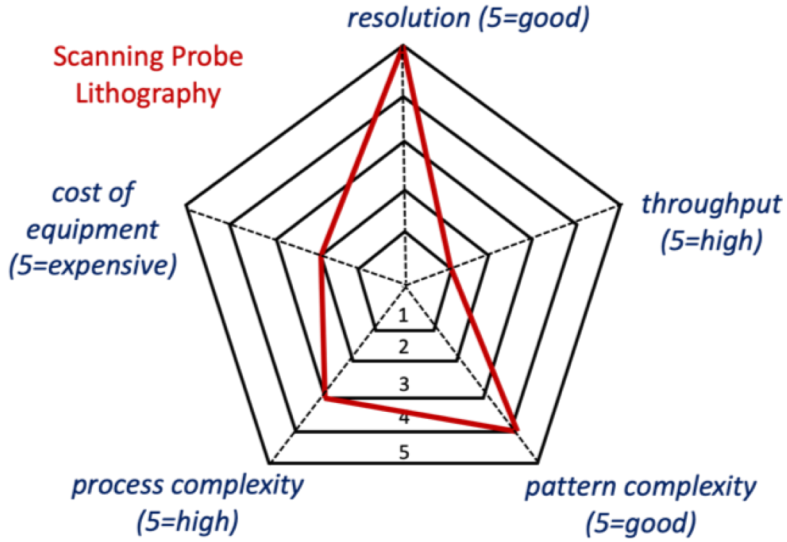
G. Villanueva et al., EPFL

COMPARISON OF NANOLITHOGRAPHY TECHNIQUES









NANOLITHOGRAPHY IS PERFORMED IN A CLEAN ROOM

-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

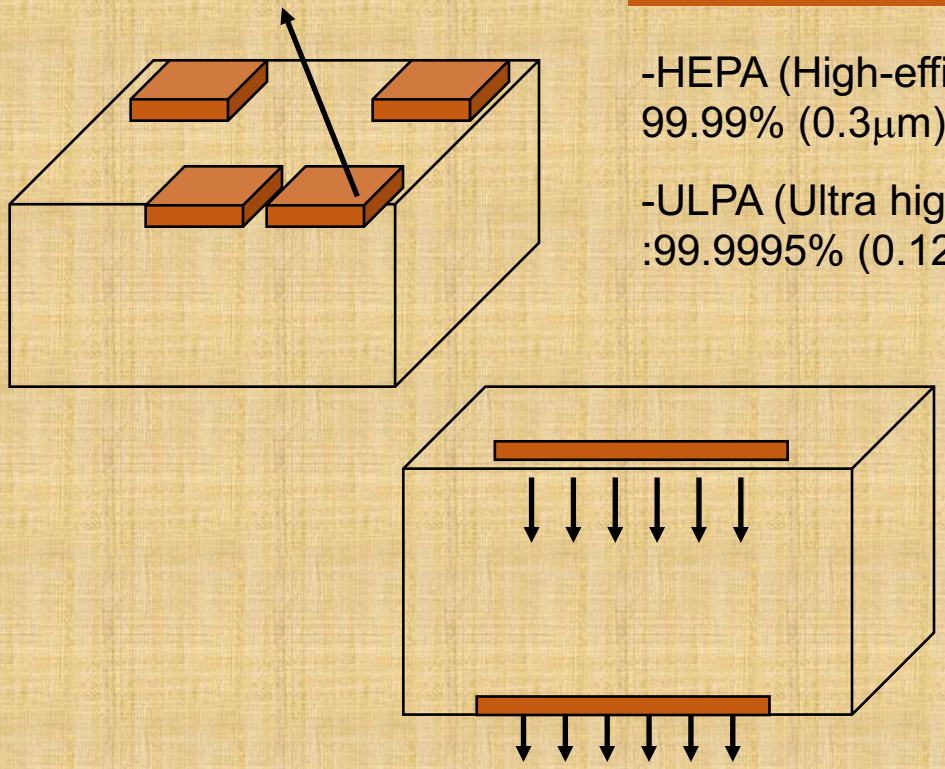
-HOSPITALS AND CLINICS

-PLASTICS AND CHEMISTRY INDUSTRY

NANOLITHOGRAPHY IS PERFORMED IN A CLEAN ROOM

NANOLITHOGRAPHY IS PERFORMED IN A CLEAN ROOM

FFU (filter/fan unit)



⇒ *HOW CAN WE KEEP A ROOM CLEAN?*

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

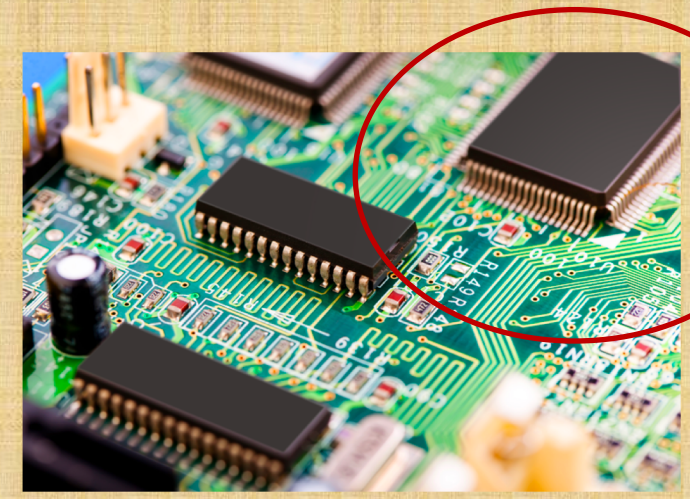
-ULPA (Ultra high-efficiency particulate air) FILTER :99.9995% (0.12μm)

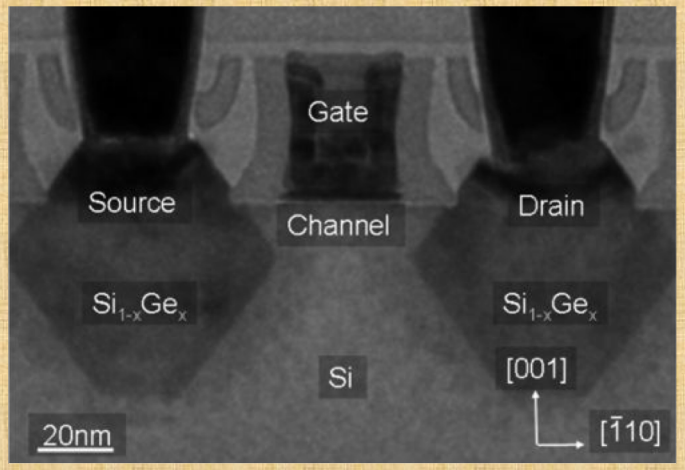
Class	maximum particles/m^3						FED STD 209E equivalent
	≥0.1 μm	≥0.2 μm	≥0.3 μm	≥0.5 μm	≥1 μm	≥5 μm	
ISO 1	10	2.37	1.02	0.35	0.083	0.0029	
ISO 2	100	23.7	10.2	3.5	0.83	0.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	1,020	352	83	2.9	Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29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

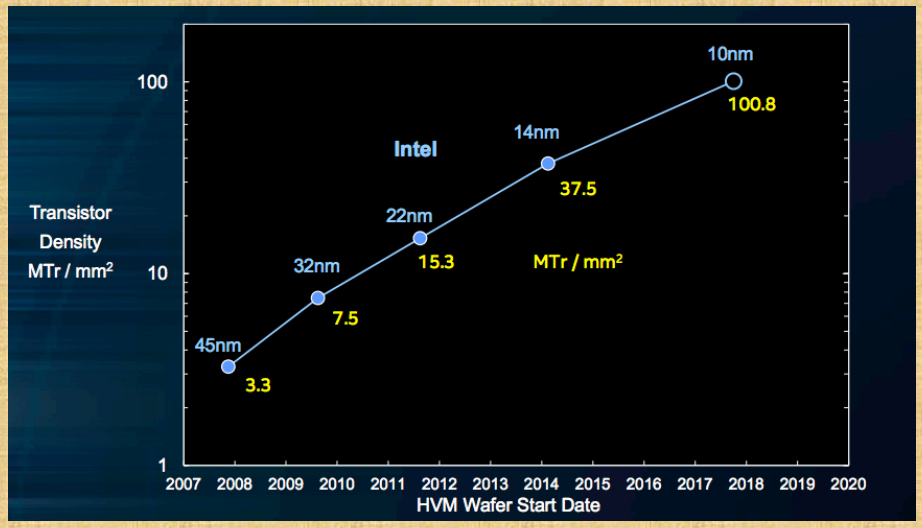
DRIVING FORCE: FABRICATION OF INTEGRATED CIRCUITS



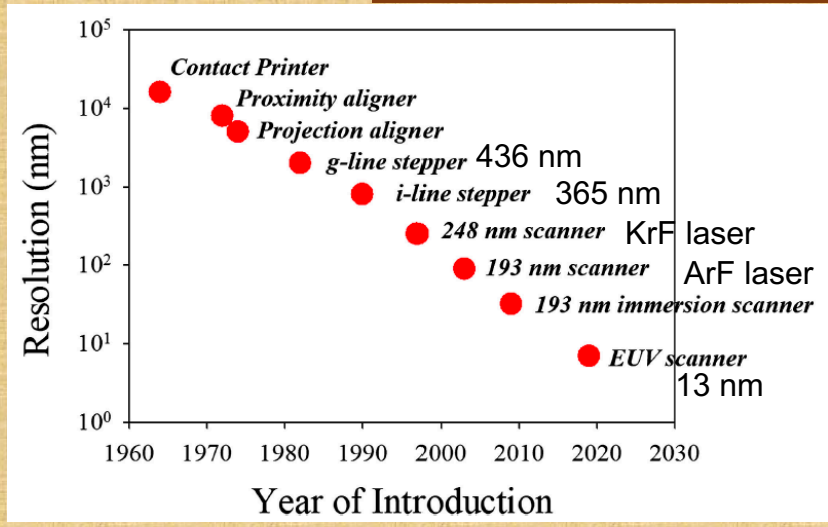


MOORE'S LAW…indeed…MOORE'S PROPHECY

(doubling of number of transistors every 1.5 years)

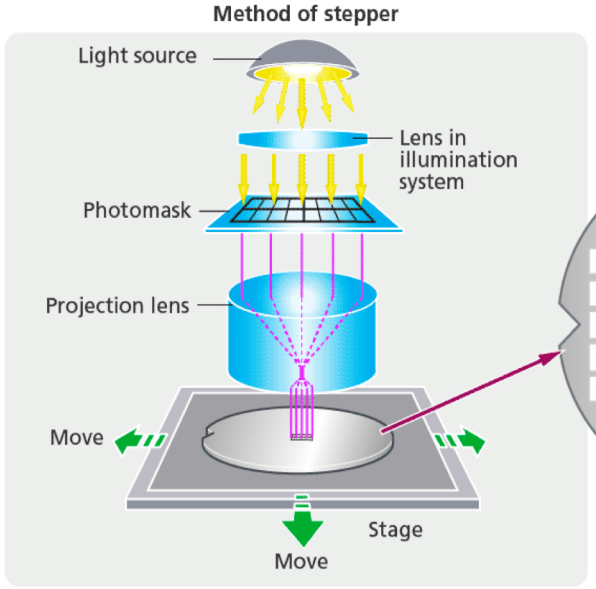


MINIMUM SIZE OF THE PATTERNS= K λ / (NA)



TECHNOLOGICAL EVOLUTION IN OPTICAL LITHOGRAPHY

UV MASK ALIGNER (lab technology)

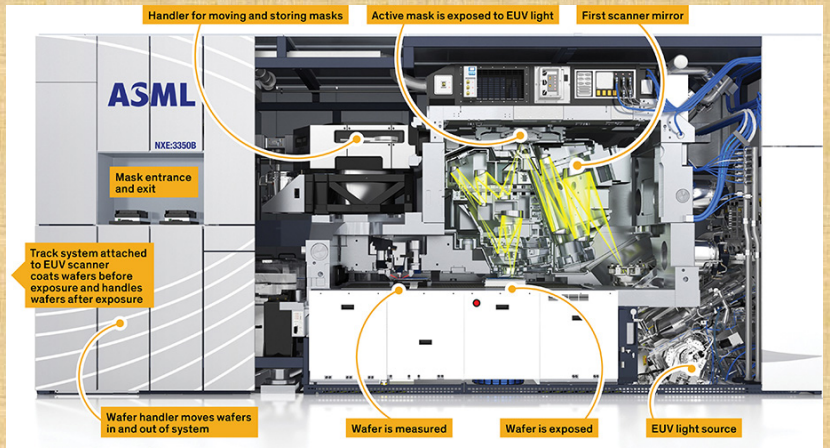


*Throughput: 200 wafers per hour

*Wafer diameter: up to 300 mm

UV STEPPER (semicon industry, today)

EUV STEPPER (semicon industry, today)



BASIC PROCESS

1) **GROWTH OF THE MATERIAL**
2) **BASIC LITHOGRAPHY PROCESS**

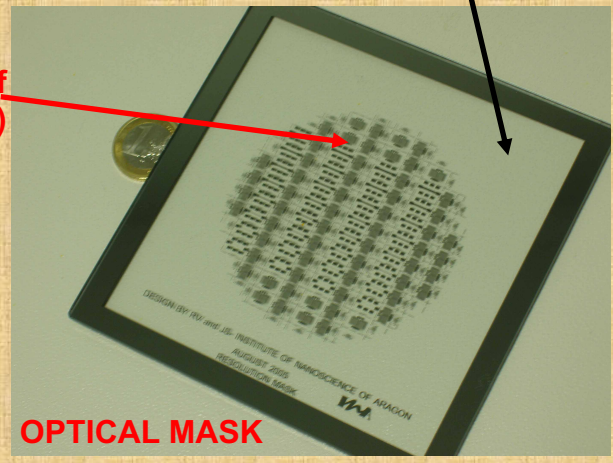
TWO APPROACHES TO WORK WITH RESISTS (in optical and electron-beam lithographies)

LIFT-OFF PROCESS

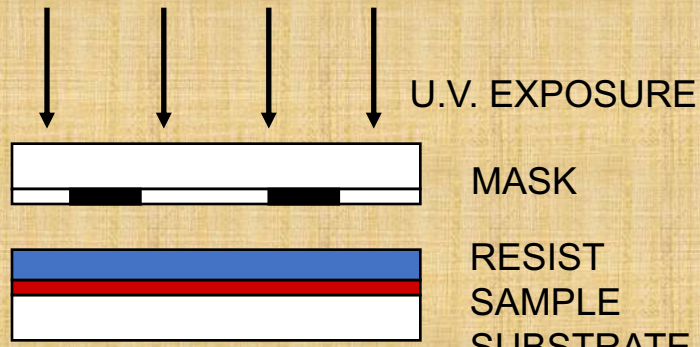
1) **BASIC LITHOGRAPHY PROCESS**
2) **GROWTH OF THE MATERIAL IN AN INTERMEDIATE STEP OF THE LITHOGRAPHY PROCESS**

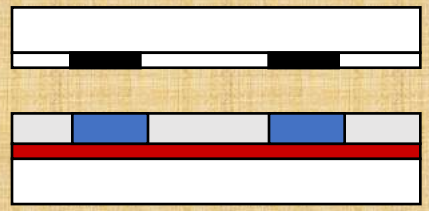
⇒ AN ACTUAL FULL LITHOGRAPHY PROCESS INVOLVES MANY BASIC AND LIFT-OFF PROCESSES ONE AFTER THE OTHER

BASIC PROCESS



1) EXPOSURE

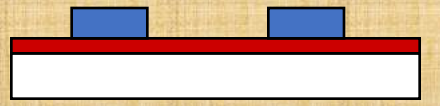




THE RESIST BECOMES SENSITIZED

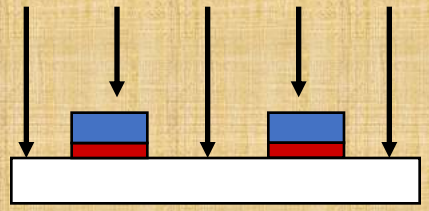
2) DEVELOPMENT

IMMERSION IN DEVELOPING FLUID



3) ETCHING

(DRY OR WET ETCHING)



4) RESIST REMOVAL

TYPICALLY, ACETONE

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

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

POSITIVE RESIST

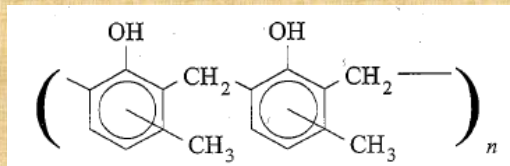
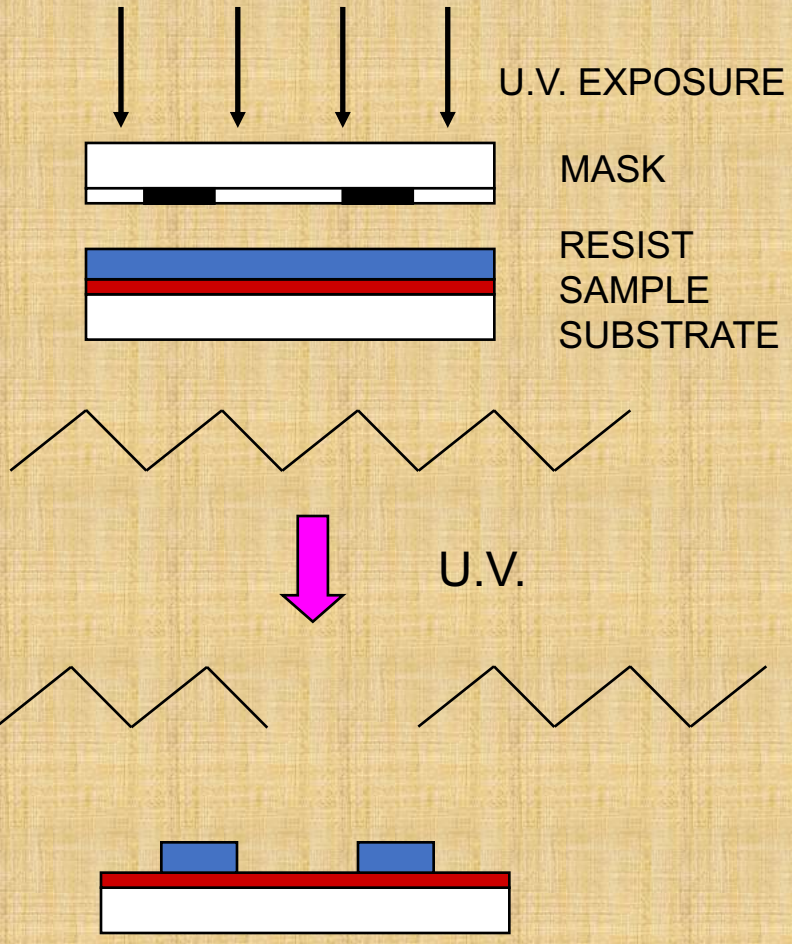


Figure 3.17 Novolak resin (ortho-ortho coupling).



NEGATIVE RESIST

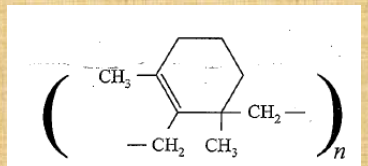
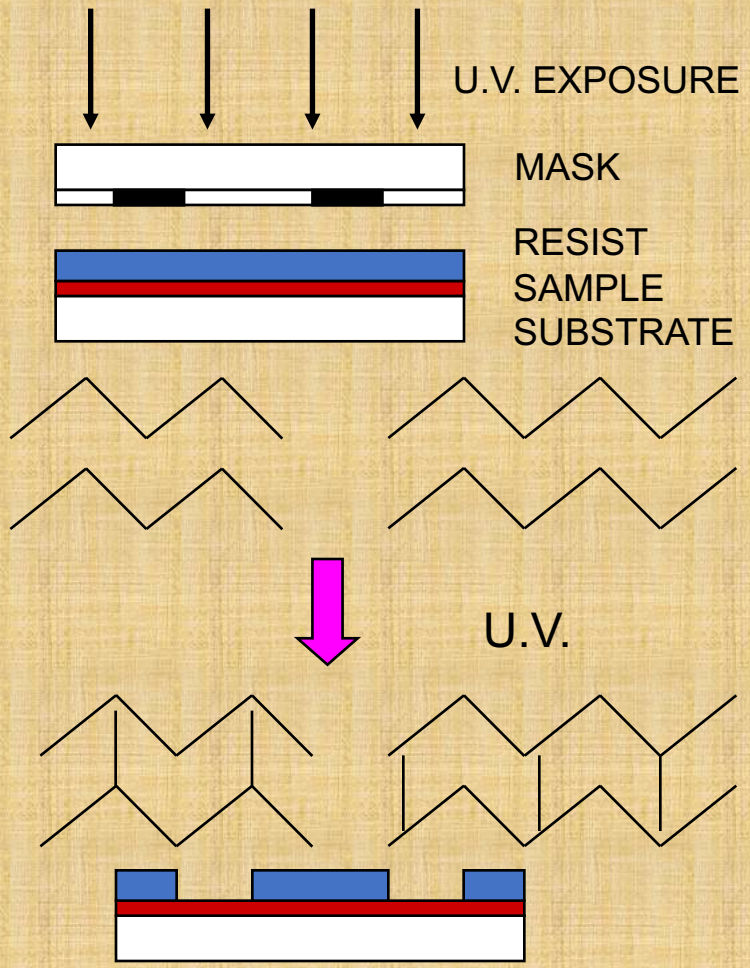
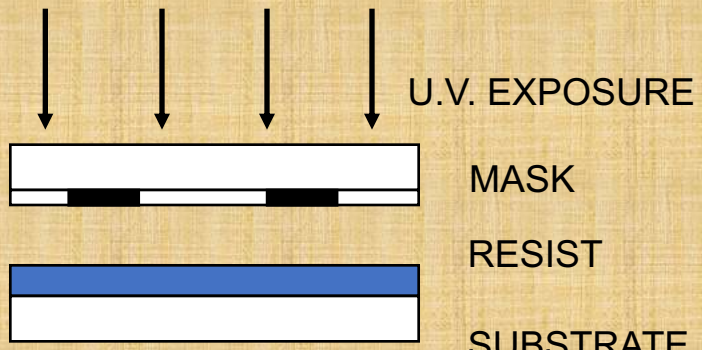


Figure 3.1 Cyclized poly-isoprene.[1]

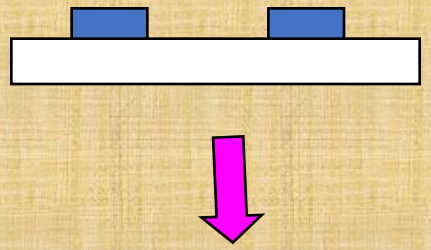


LIFT-OFF PROCESS (WITH POSITIVE RESIST)

1) EXPOSURE



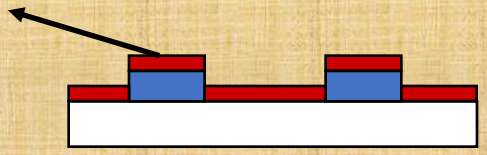
2) DEVELOPMENT



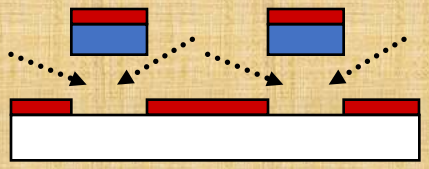
3) **SAMPLE GROWTH**

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

SAMPLE



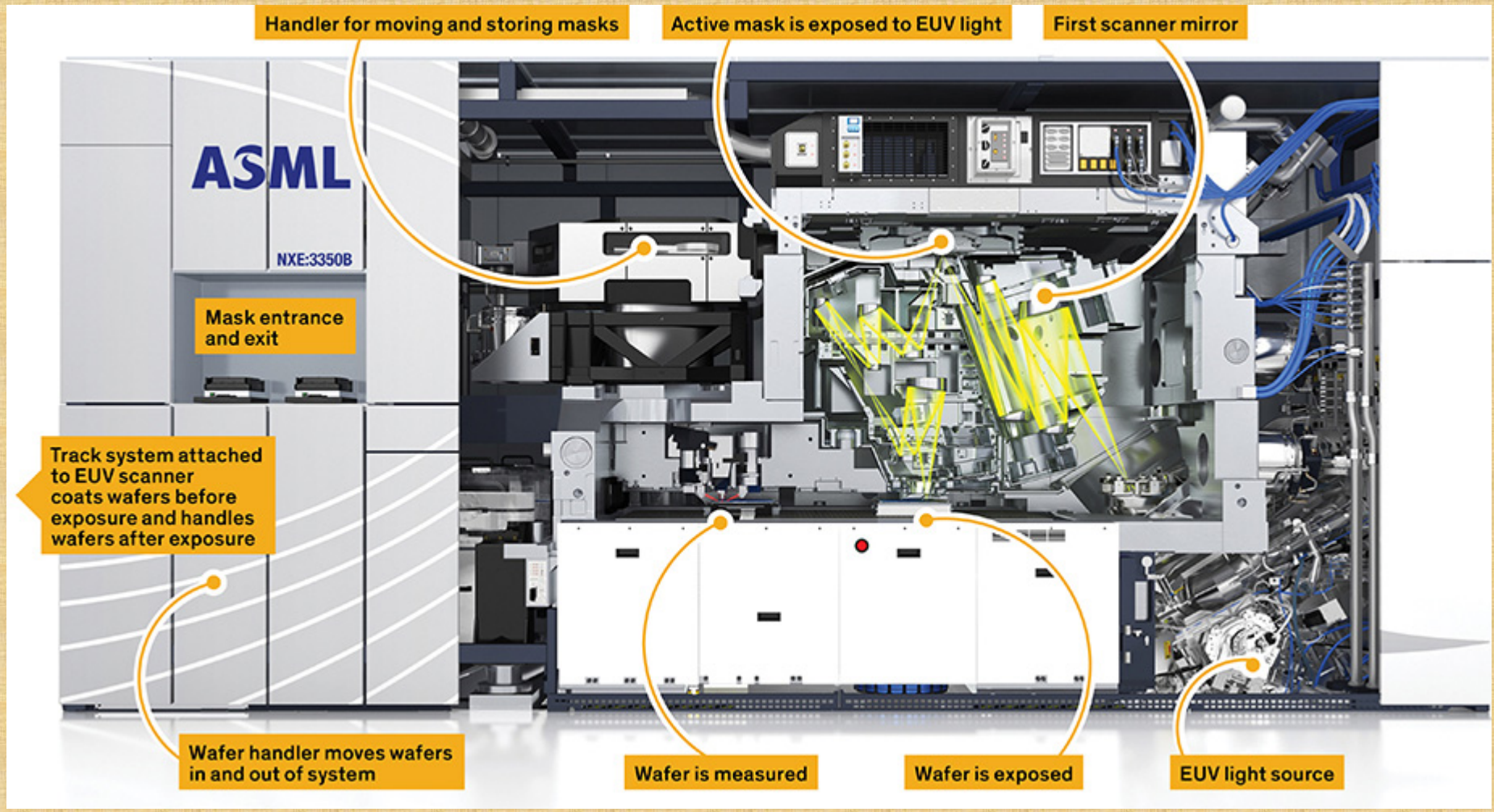
4) IMMERSION IN ACETONE



FINAL RESULT

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

EUV IS THE STATE-OF-THE-ART IN OPTICAL LITHOGRAPHY



ASML SELLS THE NEW EUV MACHINES for 100 MILLION EURO EACH

STEPPERS IN SEMICONDUCTOR INDUSTRY

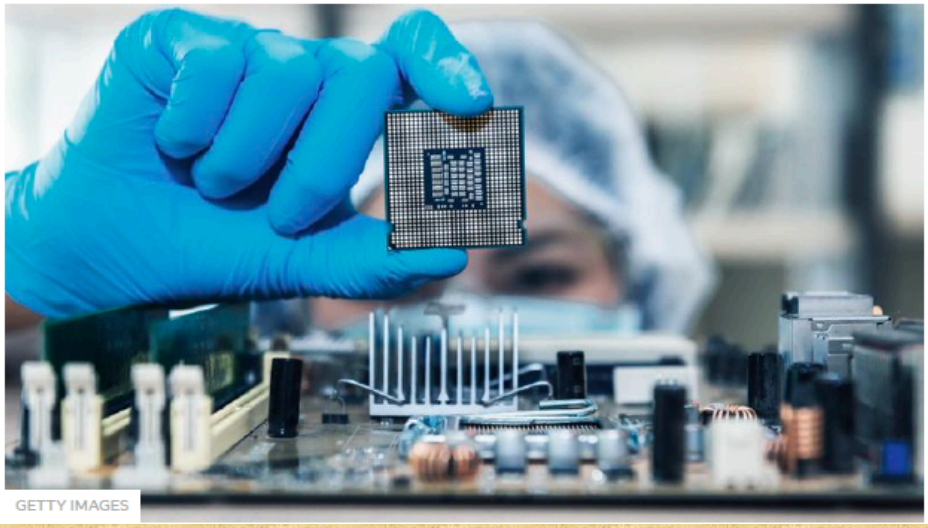
https://www.youtube.com/watch?v=ShYWUlJ2FZs

Number of Semiconductor Manufacturers with a Cutting Edge Logic Fab										
SilTerra										
X-FAB										
Dongbu HiTek										
ADI	ADI									
Atmel	Atmel									
Rohm	Rohm									
Sanyo	Sanyo									
Mitsubishi	Mitsubishi									
ON	ON									
Hitachi	Hitachi									
Cypress	Cypress	Cypress								
Sony	Sony	Sony								
Infineon	Infineon	Infineon								
Sharp	Sharp	Sharp								
Freescale	Freescale	Freescale								
Renesas (NEC)	Renesas	Renesas	Renesas	Renesas						
SMIC	SMIC	SMIC	SMIC	SMIC						
Toshiba	Toshiba	Toshiba	Toshiba	Toshiba						
Fujitsu	Fujitsu	Fujitsu	Fujitsu	Fujitsu	Huali					
TI	TI	TI	TI	TI	SMIC					
Panasonic	Panasonic	Panasonic	Panasonic	Panasonic	Panasonic					
STMicroelectronics	STM	STM	STM	STM	STM					
UMC	UMC	UMC	UMC	UMC	UMC					
IBM	IBM	IBM	IBM	IBM	IBM	IBM	SMIC	One fab=10.000 M€		
AMD	AMD	AMD	GlobalFoundries	GF	GF	GF	GF			
Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung	Samsung
TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC	TSMC
Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel	Intel
180 nm	130 nm	90 nm	65 nm	45 nm/40 nm	32 nm/28 nm	22 nm/20 nm	16 nm/14 nm	10 nm	7 nm	5 nm

Escasez de microchips: por qué hay una crisis de semiconductores y cómo puede afectarte

Leo Kelion
Editor de Tecnología de BBC

10 febrero 2021



GETTY IMAGES

EL SECTOR DEL AUTOMÓVIL

La escasez de microchips pone en riesgo unos 250 empleos de Figuerueleas

Peligra la continuidad del segundo turno de noche, que se reactivó en octubre con trabajadores eventuales. La planta volverá a la actividad en la madrugada del martes al miércoles tras llevar ocho días parada

J. HERAS PASTOR

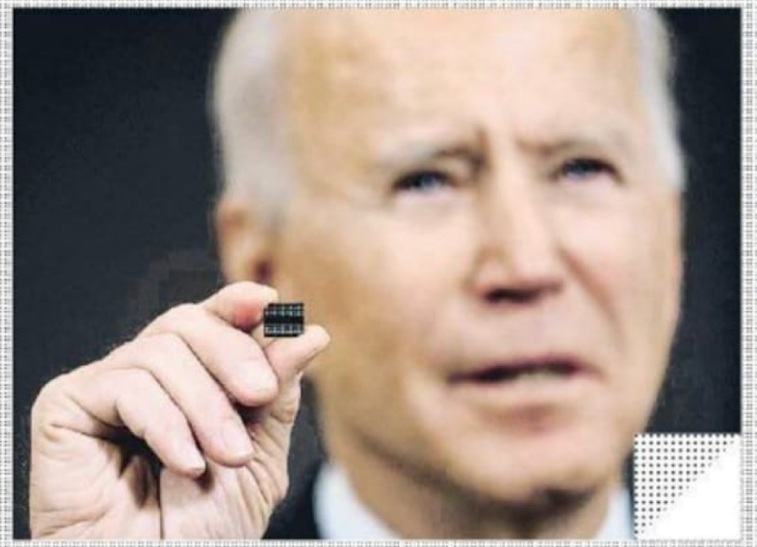
ZARAGOZA | 27·04·21 | 03:30

La guerra de los chips

El mundo se ha quedado seco de semiconductores. Los procesadores y las memorias electrónicas, esas pequeñas pastillas de silicio que nos permiten ejecutar operaciones digitales a la velocidad de la luz y memorizar millones de bits de información empiezan a escasear. La covid generó interrupciones en su cadena de suministro, a la vez que las empresas automovilísticas suspendieron sus compras al inicio de la pandemia. Hoy, todos hemos intensificado nuestro consumo digital. La *stay-at-home-economy* saturó el ciberespacio de videoconferencias masivas. Actualizamos nuestros PC, nuestros portátiles y nuestros móviles. Incrementamos el volumen de nuestros archivos digitales y exigimos más memoria en la nube. Nos bajamos más apps, vemos ahora más series de Netflix y pasamos más horas en nuestra PlayStation. Queremos mejores comunicaciones 5G. Pero todo ello no es gratuito: los chips de silicio, bloques constituyentes básicos de la economía digital, se han vuelto omnipresentes. Se encuentran en los robots industriales, en nuestros electrodomésticos (desde la nevera hasta Alexa, pasando por el televisor o el microondas), en los automóviles (cada vez más repletos de sensores y controles digitales), en los dispositivos médicos y hospitalarios, o en los servidores de los sistemas financieros. También en los satélites y en las antenas de comunicación. Y sus tensionadas cadenas de suministro, finalmente, se han colapsado. La manufactura global se está ralentizando. Apple, Microsoft, Nintendo o Sony están sin chips. El último en llegar, quien fabrica *just in time*, la industria del automóvil, es la gran perjudicada. Las pérdidas de facturación se estiman en 60.000 millones. Volkswagen producirá 100.000 vehículos menos este año por la falta de semiconductores. La caída combinada de Honda y Nissan puede ser de 250.000 coches. Ford, General Motors y Fiat Chrysler tienen líneas paradas. Tesla acaba de anunciar la suspensión temporal de operaciones en una de sus plantas. Como una mancha de aceite, la falta de chips se extiende por la totalidad de cadenas productivas y amenaza la recuperación mundial

Los líderes de la industria norteamericana de semiconductores enviaron una carta al presiden-

Dependencia
La falta de estos componentes se extiende por las cadenas productivas y amenaza la recuperación mundial

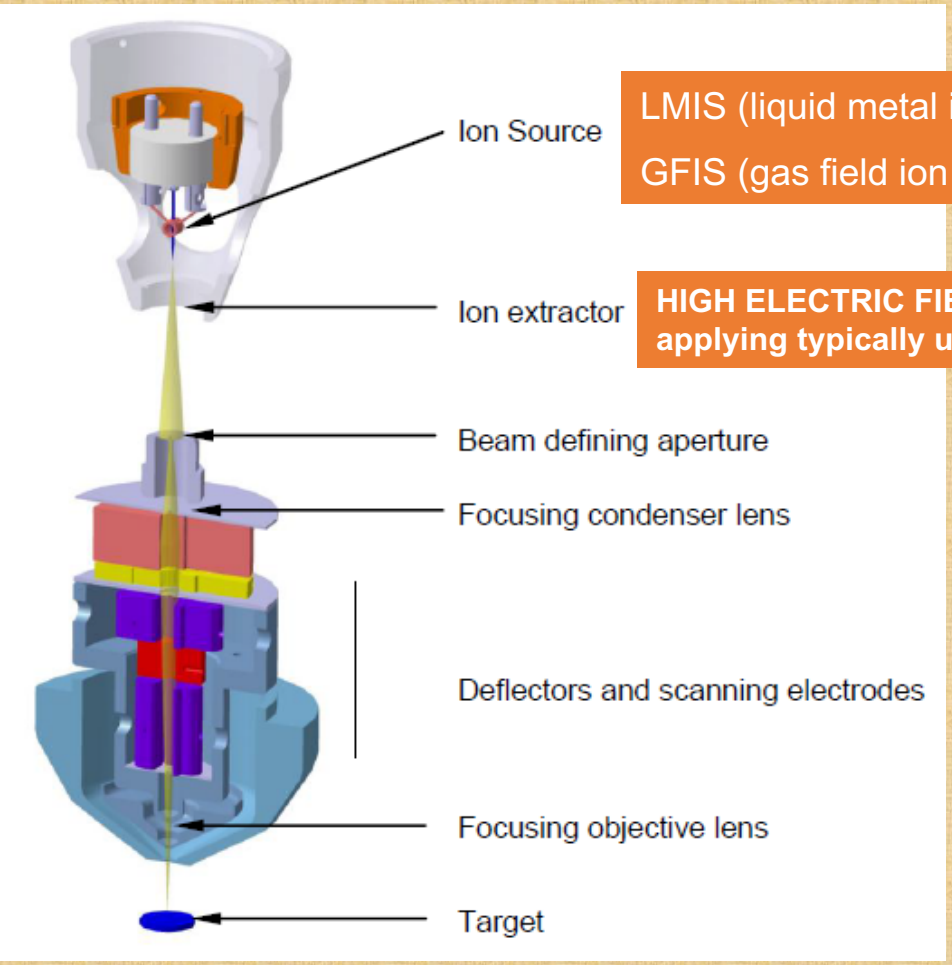


DOUG MILLS / EFE

Semiconductores
La nueva globalización consistirá en desarrollar clústeres locales de I+D y producción integrada, en sectores estratégicos, capaces de competir globalmente

FOCUSED ION BEAM (FIB) and FIB-SEM

FOCUSED ION BEAM (FIB)



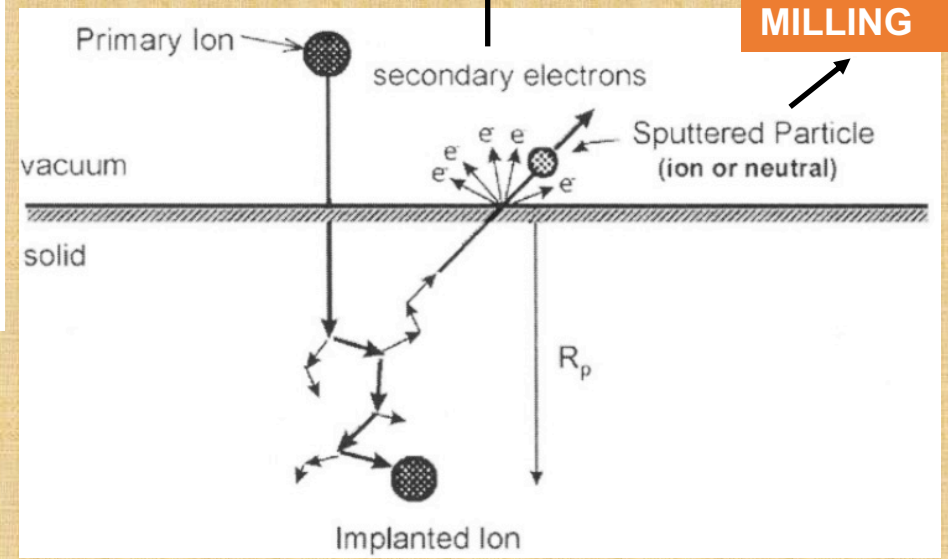
LMIS (liquid metal ion source): Ga^+

GFIS (gas field ion source): He^+, Ne^+

HIGH ELECTRIC FIELD (FIELD EMISSION) applying typically up to 50 kV

IMAGE AND DEPOSITION

MILLING

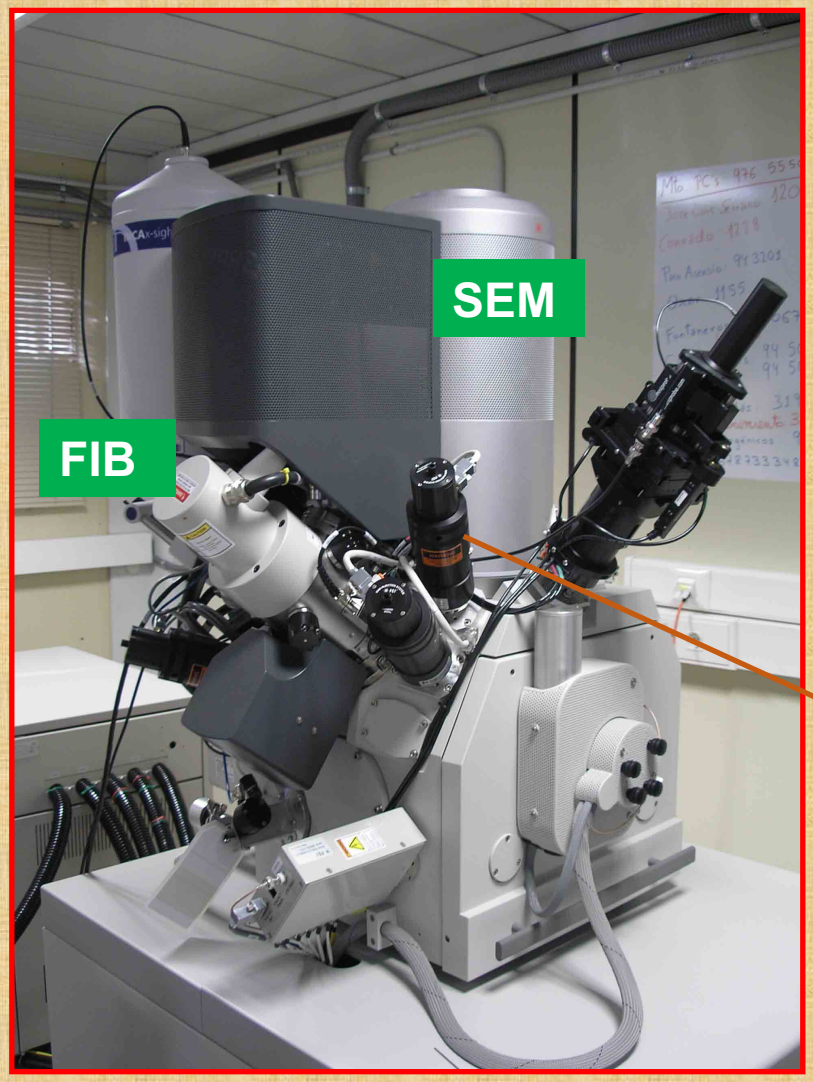


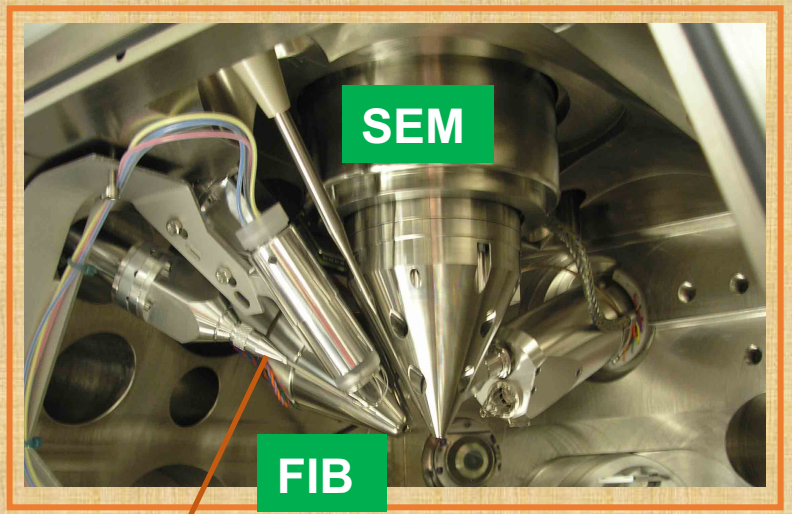
J. Gierak, Nanofabrication 1 (2014) 35

FOCUSED ION BEAM (FIB) TECHNIQUES

Focused Ion Beam milling and
Focused Ion Beam Induced Deposition

FIB-SEM EQUIPMENT: A NANOLABORATORY

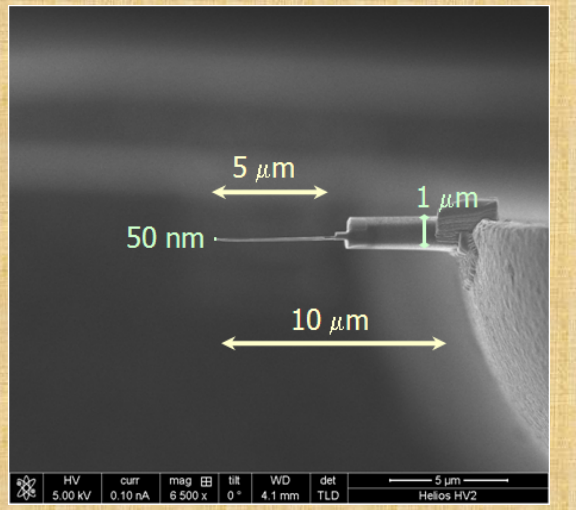




Gas injectors with the precursor molecules

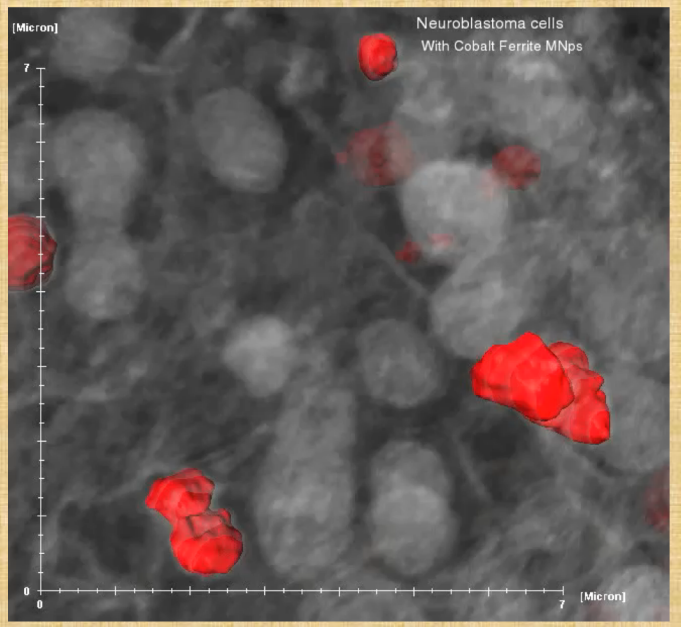
FIB-SEM APPLICATIONS

Lamellae preparation

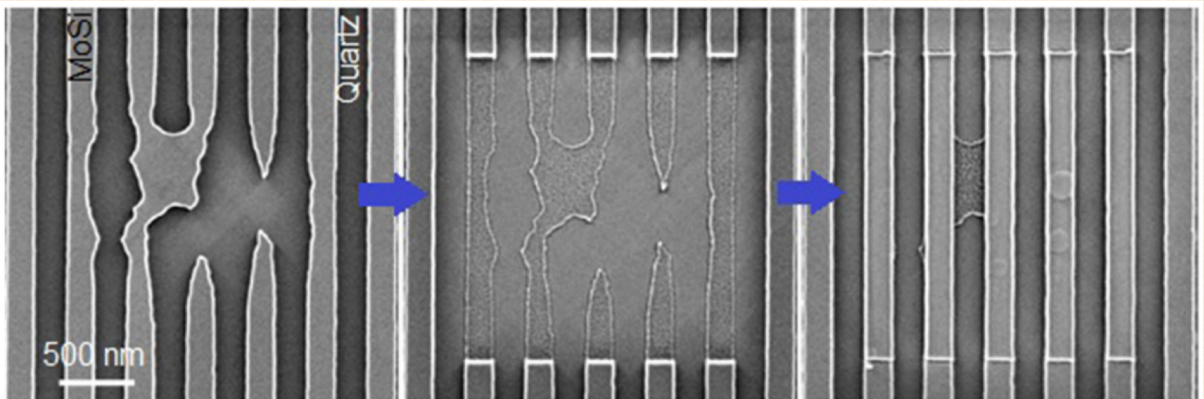


Circuit edit

3D reconstruction of cells and materials



Mask repair

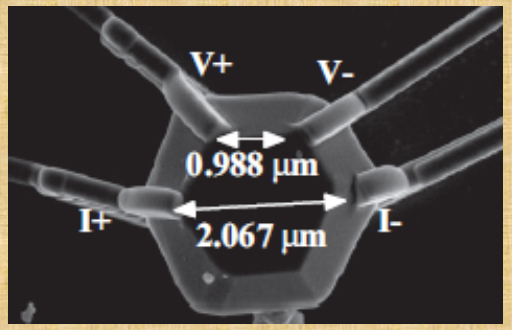


Challenge:

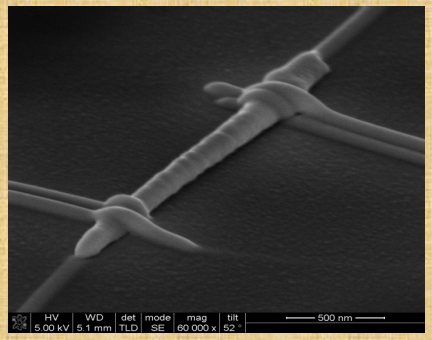
to find new applications

SOME APPLICATIONS OF FOCUSED ELECTRON/ION BEAM INDUCED DEPOSITION (FEBID and FIBID)

Electrical contacts to micro/nano-objects

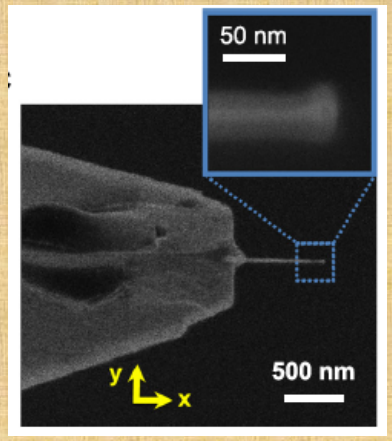


C. Hiley et al., Phys. Rev. B 92, 104413 (2015)



Marcano et al., Appl. Phys. Lett. 96, 082110 (2010)

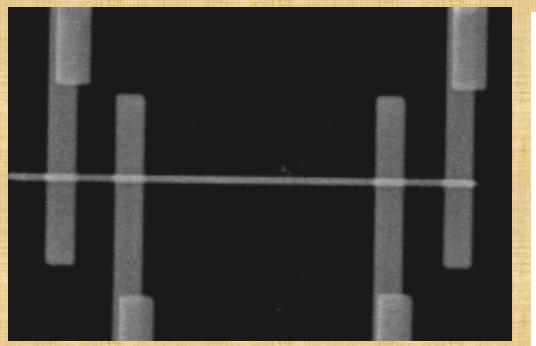
Pt-C and W-C sharp tips for AFM

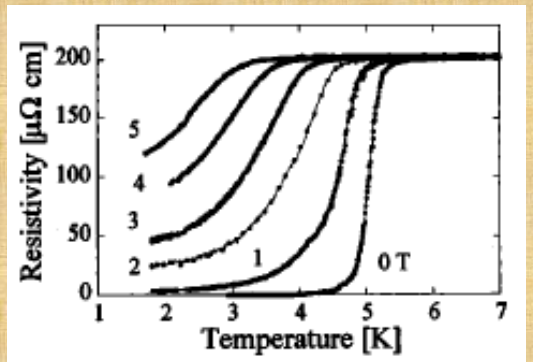


Nanda et al., J. Vac. Sci. Technol. B 33, 06F503 (2015)

Allen et al., unpublished

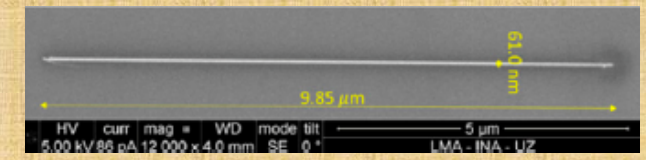
Growth of W-C superconductors

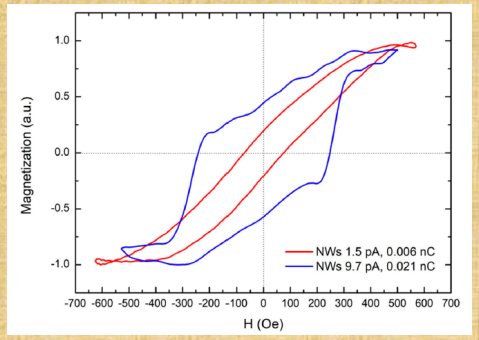




Sadki et al., Appl. Phys. Lett. 85, 6206 (2004)

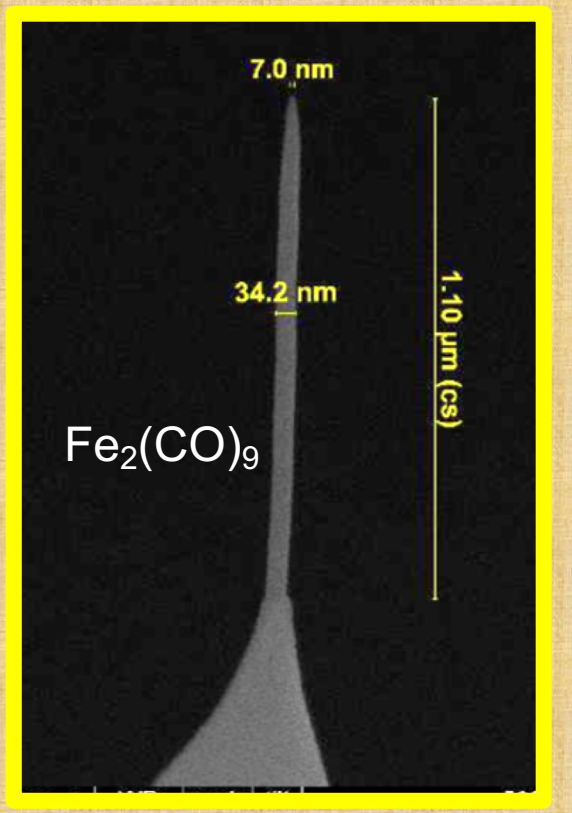
Growth of ferromagnetic Co nanowires





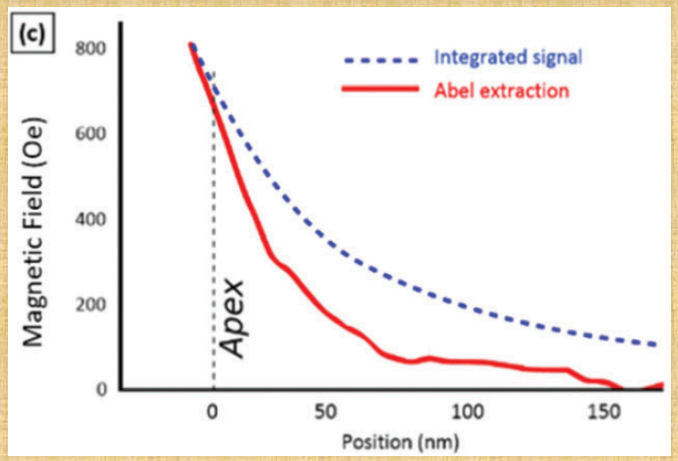
Sanz et al., Nanomaterials 9, 1715 (2019)

Ferromagnetic deposits by FEBID



>> To get rid of non-magnetic interactions
>> High lateral resolution
>> Low invasiveness (magnetic interaction tip-sample)
>> Extraction of quantitative information (quantitative MFM)
>> High coercive field of the magnetic tip (> 600 Oe)
>> Liquid environment

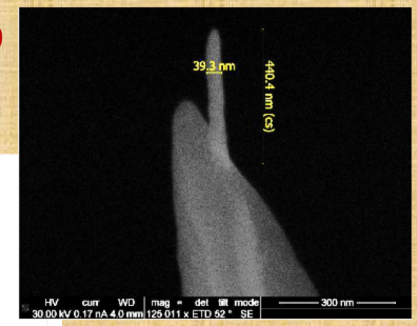
Electron holography measurements of the magnetic stray field



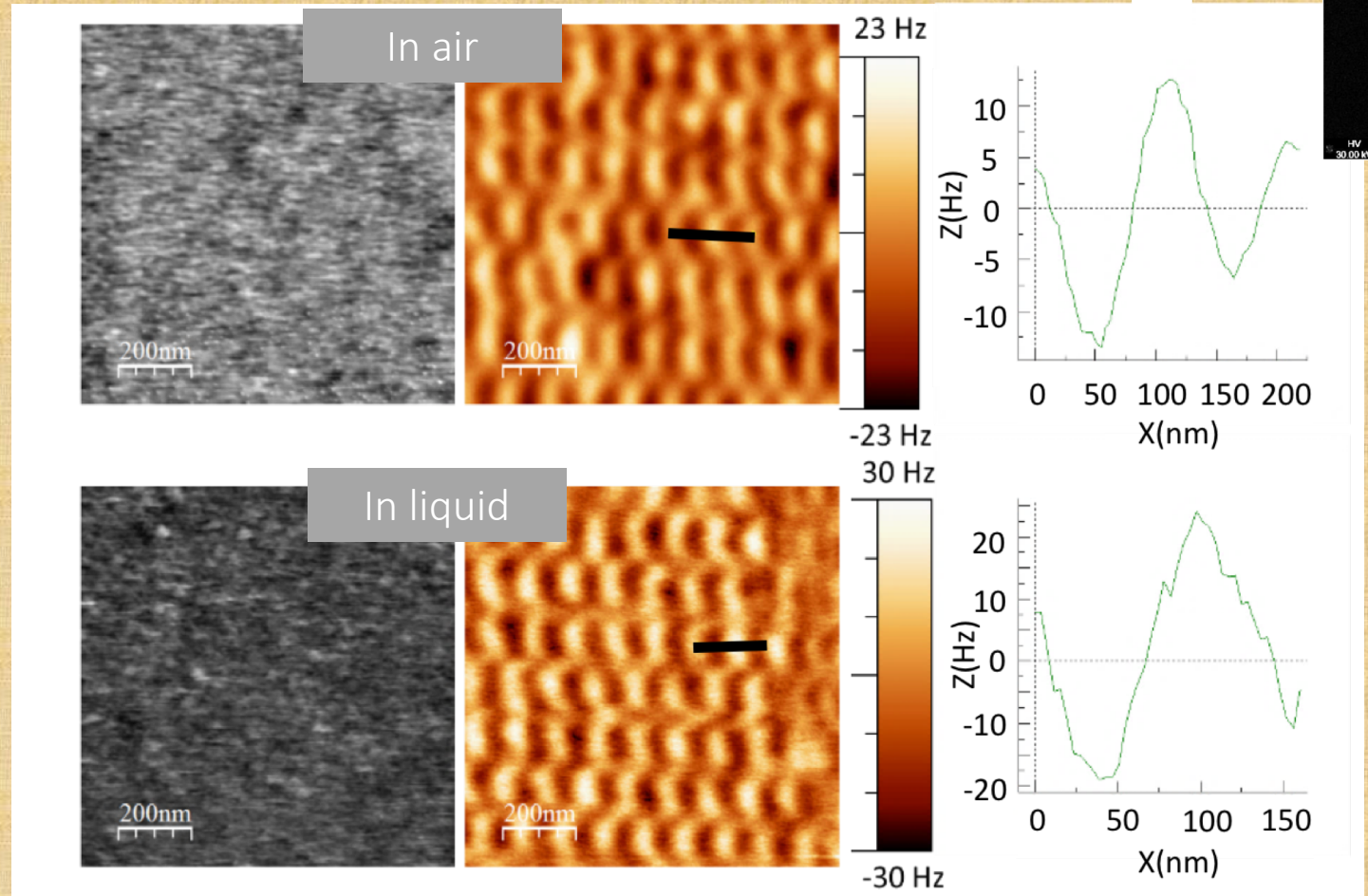
M. Jaafar et al., Nanoscale 12, 10090 (2020)

Ferromagnetic deposits by FEBID

$Fe_2(CO)_9$

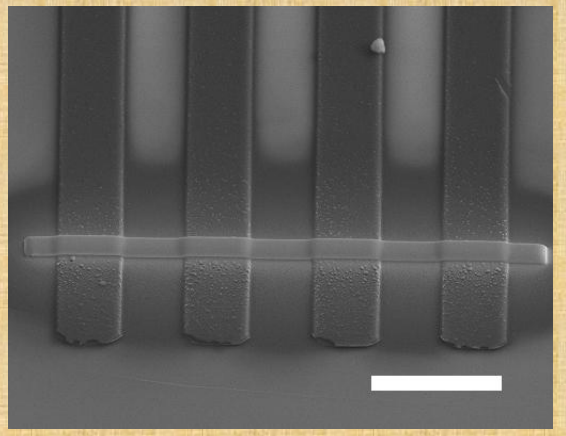


FEBID tips behave well in liquid environment



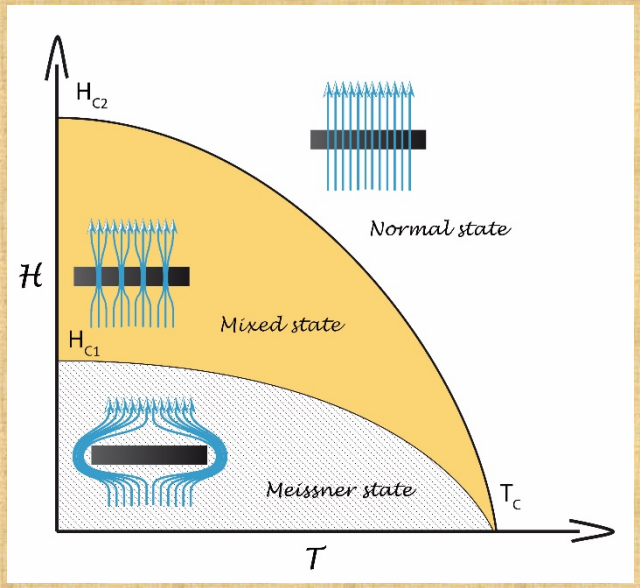
M. Jaafar et al., Nanoscale 12, 10090 (2020)

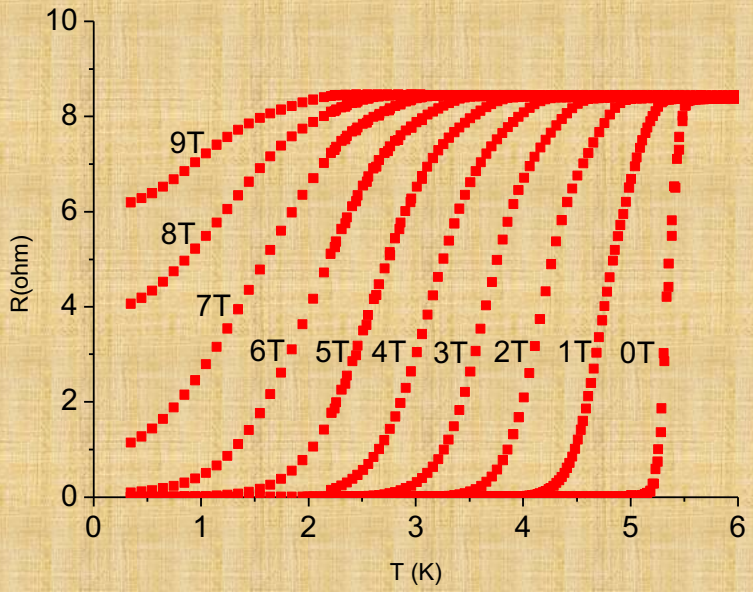
W-C superconducting deposits by FIBID

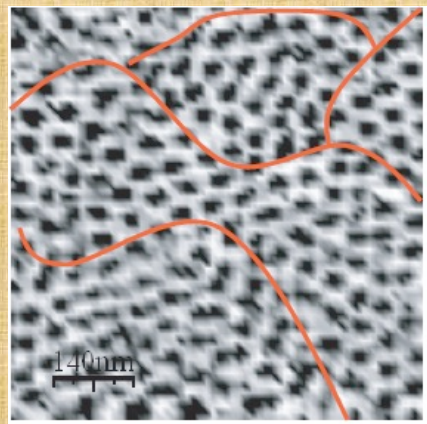


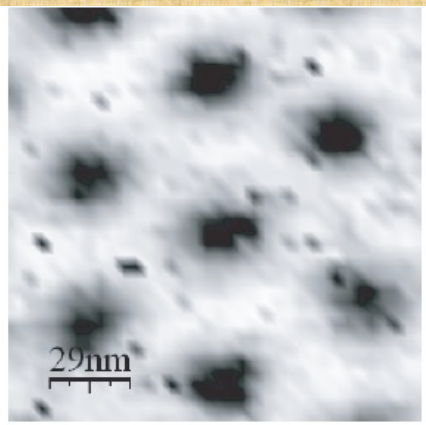
$W(CO)_6$

W: 40%
C: 40%
Ga: 10%
O: 10%



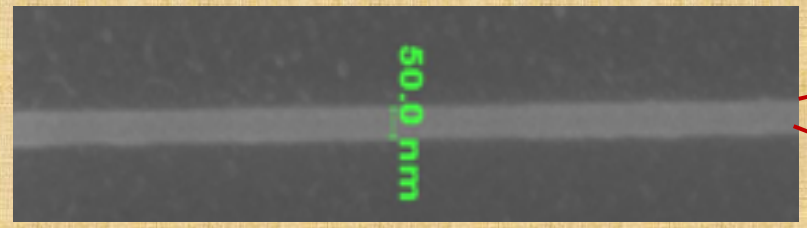


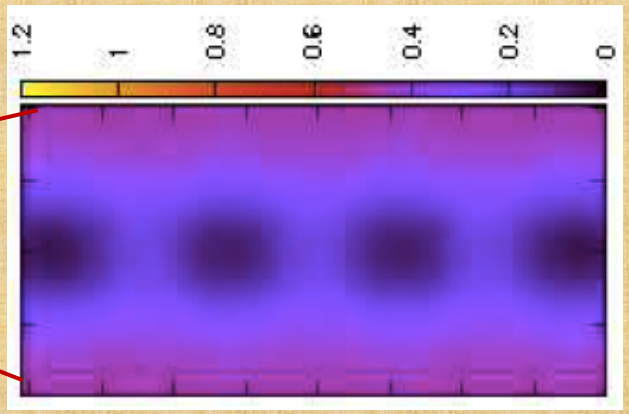


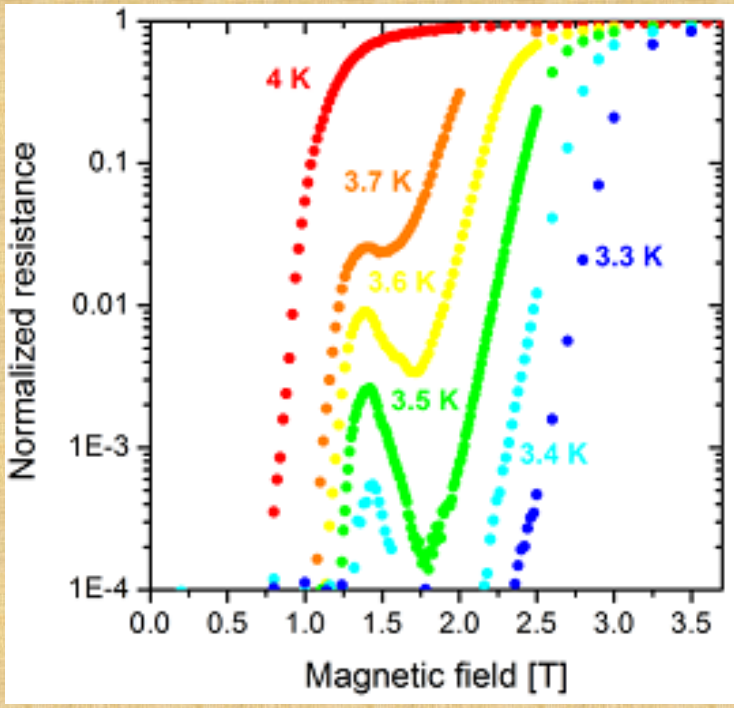


I. Guillamón et al., New Journal of Physics 10, 093005 (2008); Nature Physics 5, 651 (2009); Nature Physics 10, 851 (2014)

W-C superconducting deposits by FIBID





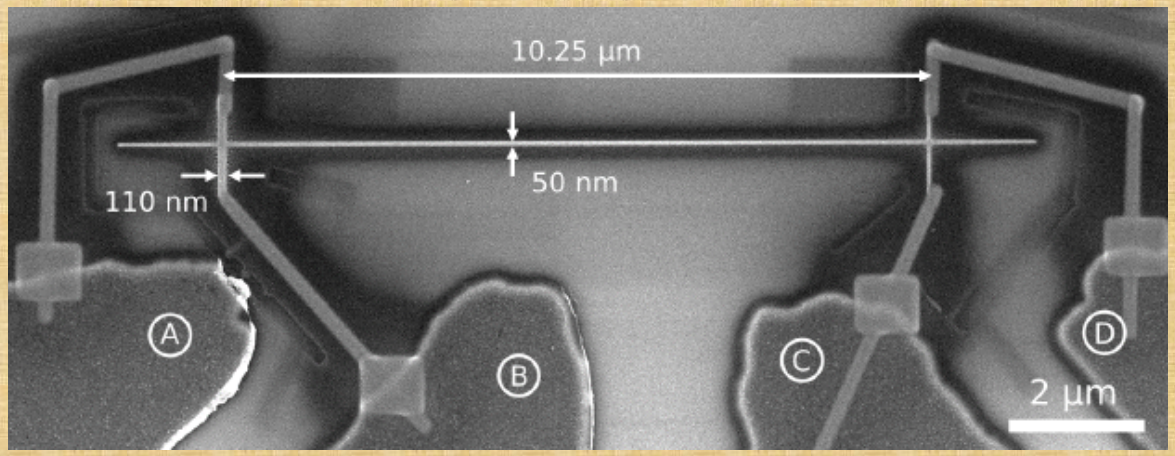


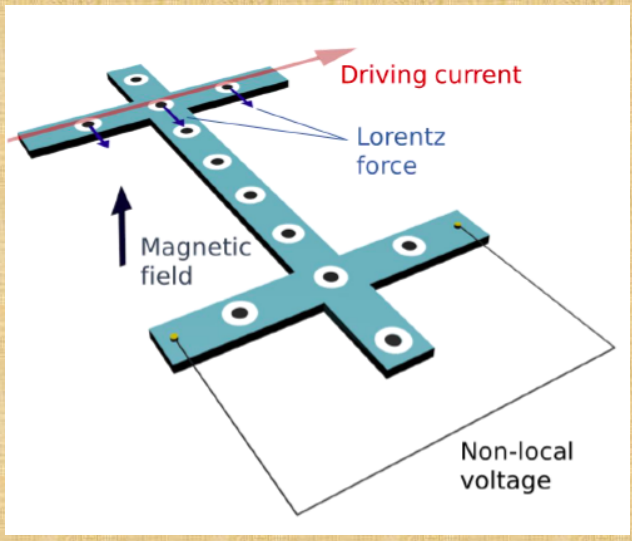
A single row of vortex is confined at the nanowire, giving rise to reentrant superconductivity effects

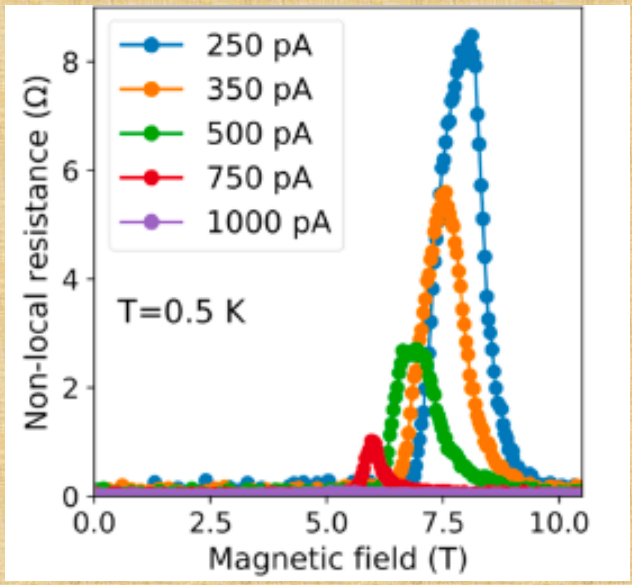
R. Córdoba et al., Nature Commun. 4 (2013) 1437

W-C superconducting deposits by FIBID

Long-range non-local vortex transport in W-C nanowires by Ga^+-FIBID

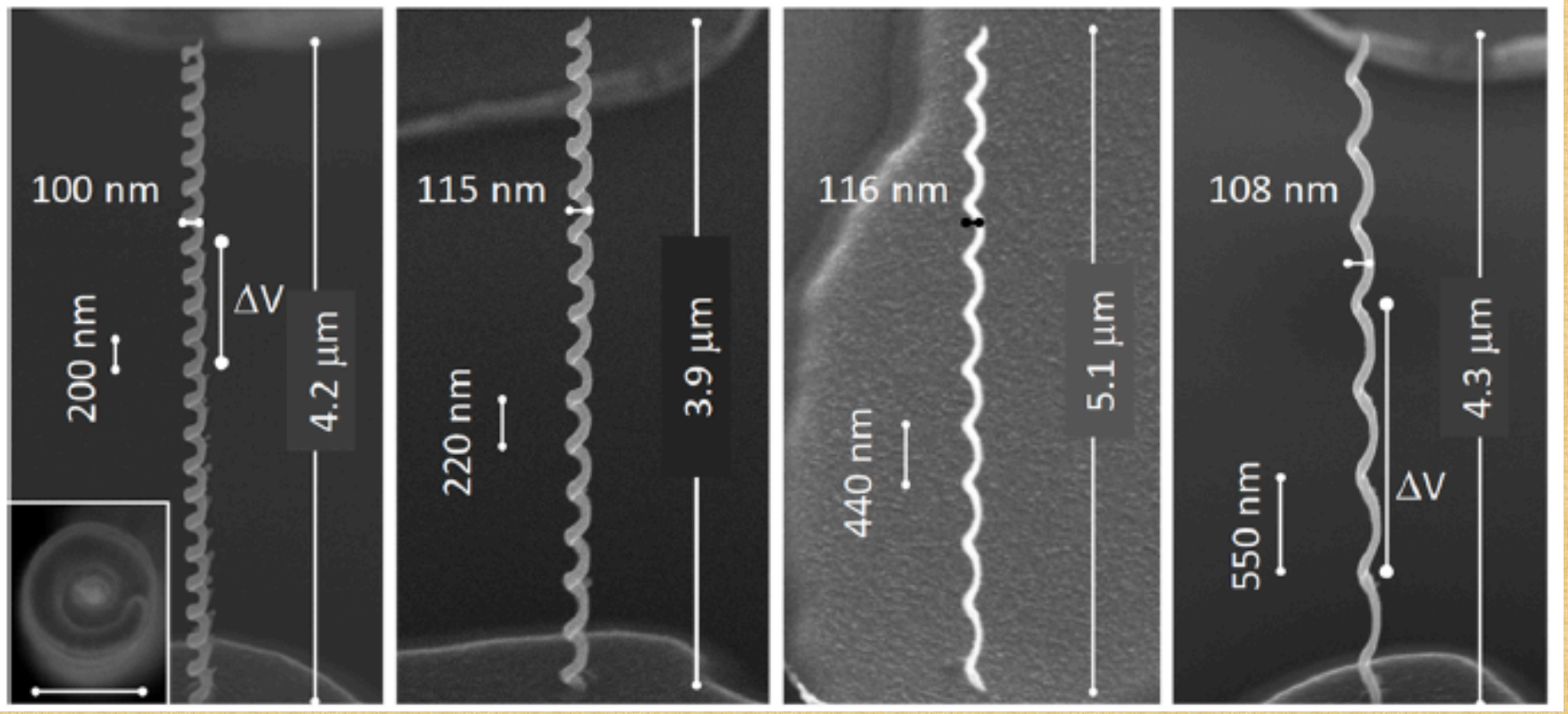






R. Córdoba et al., Scientific Reports 9, 12386 (2019)

W-C superconducting deposits by FIBID



R. Córdoba et al., Nano Letters 19, 8597 (2019)

LABORATORIO DE MICROSCOPIAS AVANZADAS (LMA)

https://elecmi.es/

National facility in Spain for electron microcopy and nanofabrication

9 electron and ion microscopes for advanced characterization and nanofabrication

200 m²
total CR area

12
dedicated staff

NANOMIDAS GROUP
Nanofabrication and Advanced Microscopies
CSIC-University of Zaragoza

https://nanofab-deteresa.com

+ past group members: A. Fernández-Pacheco, R. Córdoba and J. Pablo-Navarro

INMA
INSTITUTO DE NANOCIENCIA Y MATERIALES DE ARAGÓN

CSIC
Consejo Superior de Investigaciones Científicas

Universidad Zaragoza
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