Nanofabrication methods for Plasmonics

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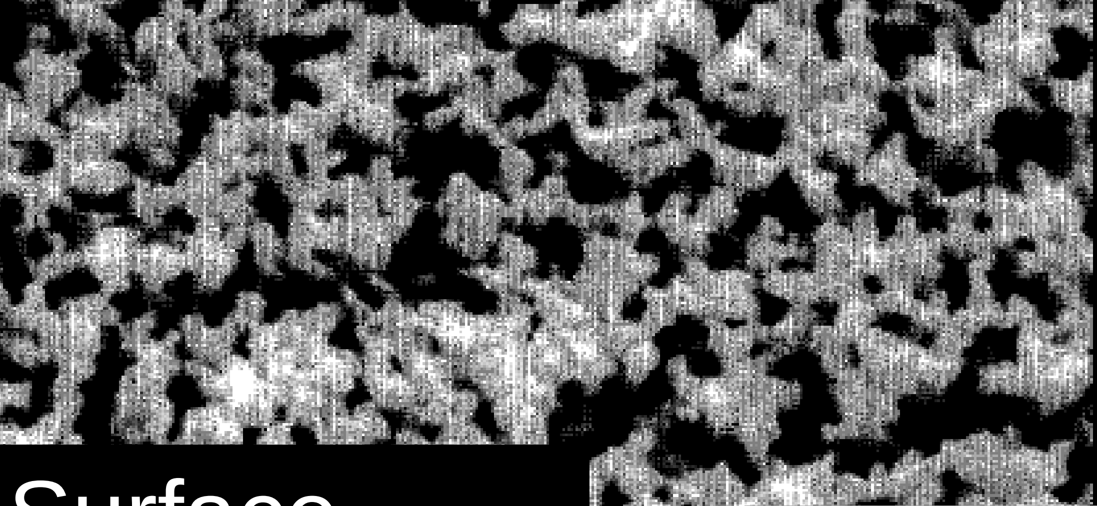
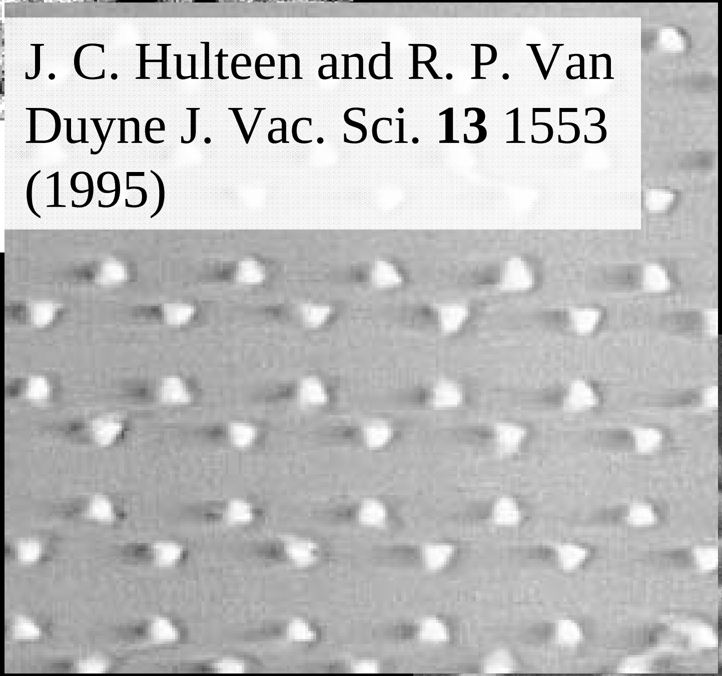
ICD

Histor



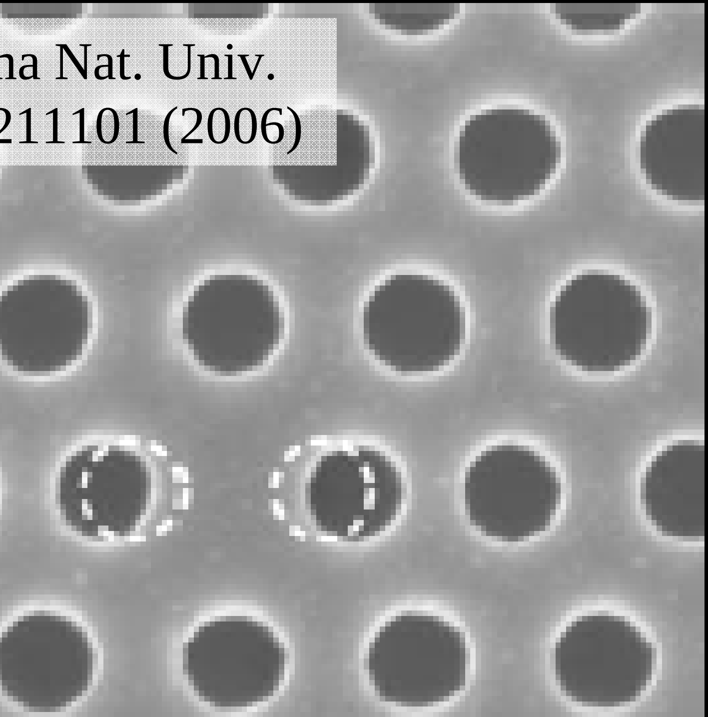
Surface
ructuration



J. C. Hulteen and R. P. Van Duyne J. Vac. Sci. **13** 1553 (1995)

Lithography

Nanofabricatio



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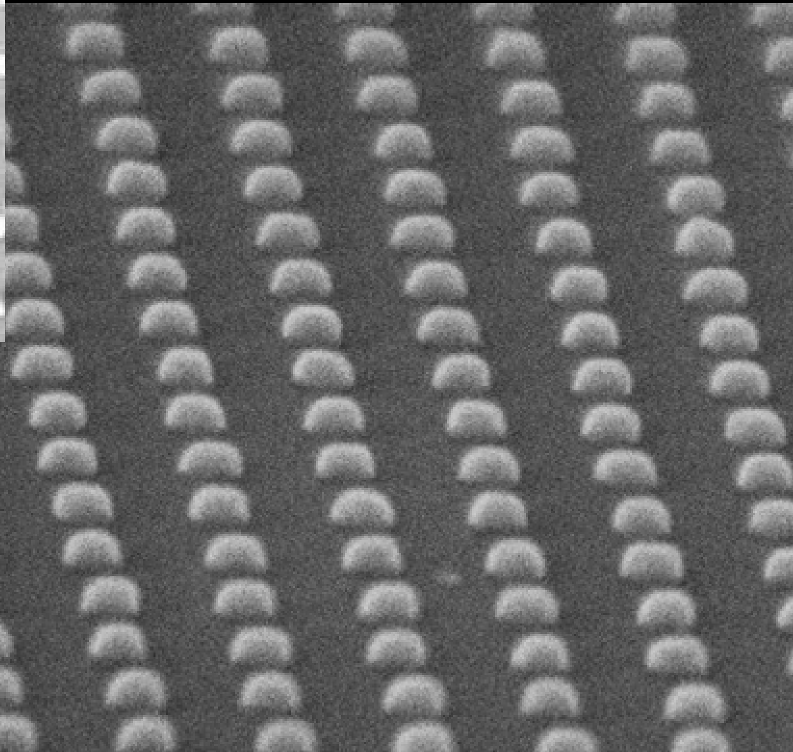
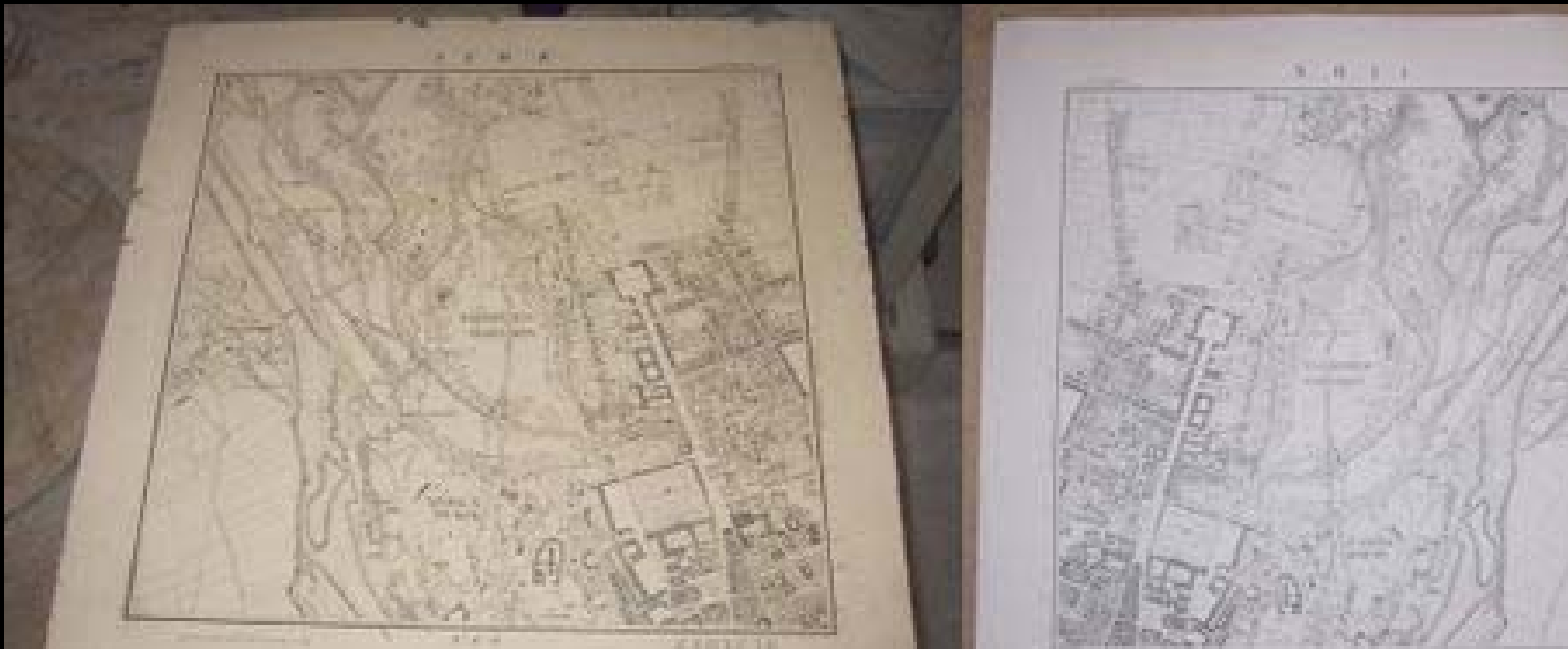


Lithograph

edia :

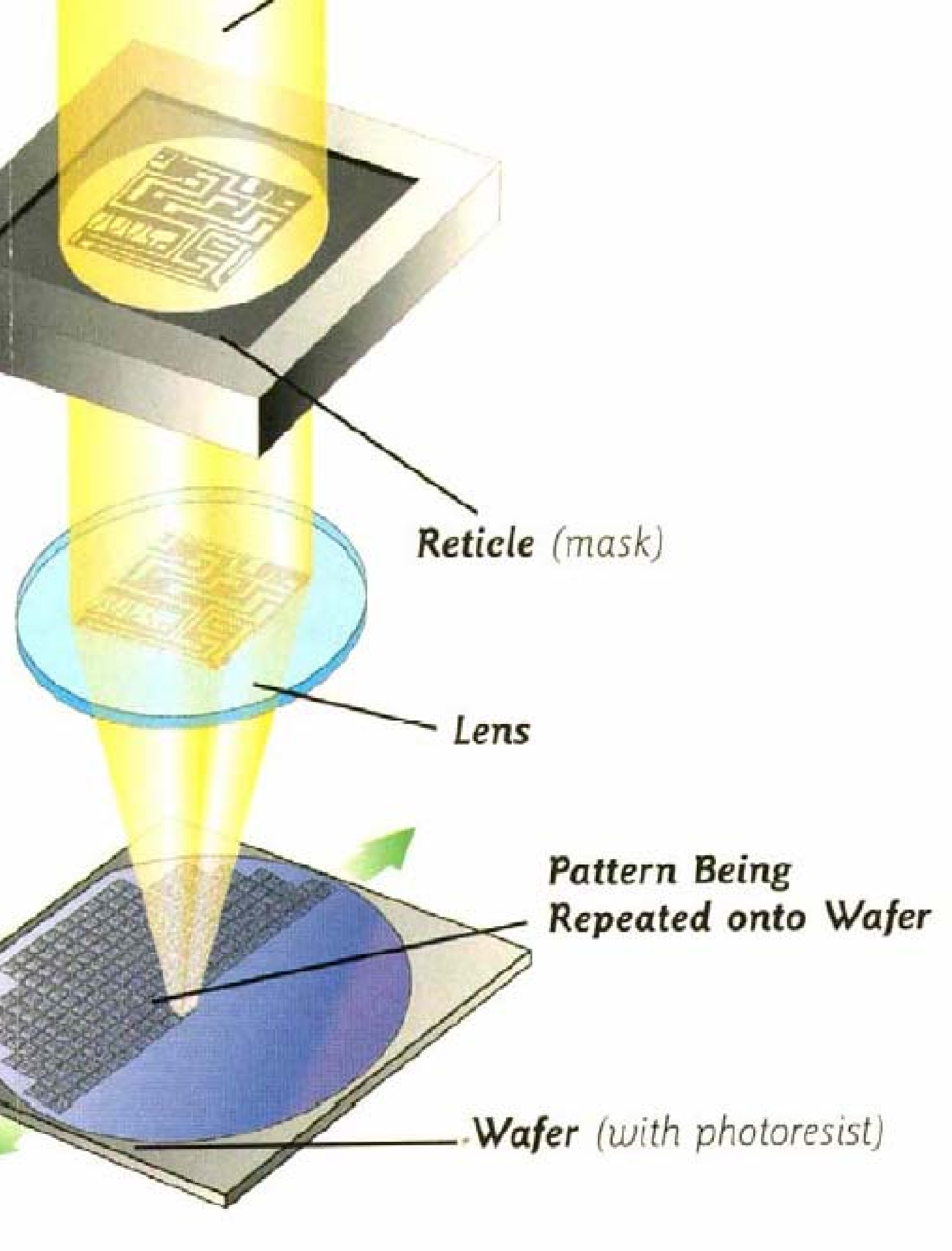
Lithography is a printing process that uses **chemical processes** to **create an mage (inv. 1796)**.

Lithography stone and mirror-image print of a map of Munich.



Lithograph

Micro and nanoelectronics



Gate width

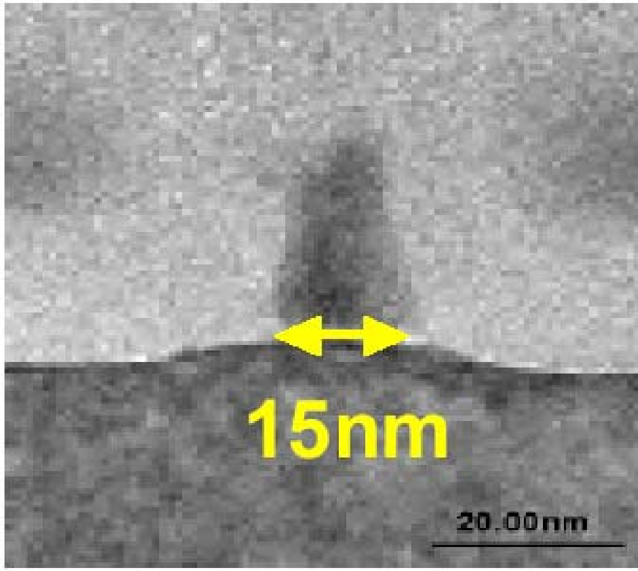
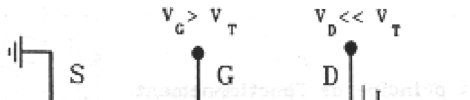


Figure 5: TeraHertz transistor with 15nm



1mm in 1970

Lithograph glossary

Photolithography

E-beam lithography

I-beam lithography

Laser writing

terference lithography

Self assembling

NA assisted lithography

Dip pen lithography

SNOM lithography

Embossing

Imprint

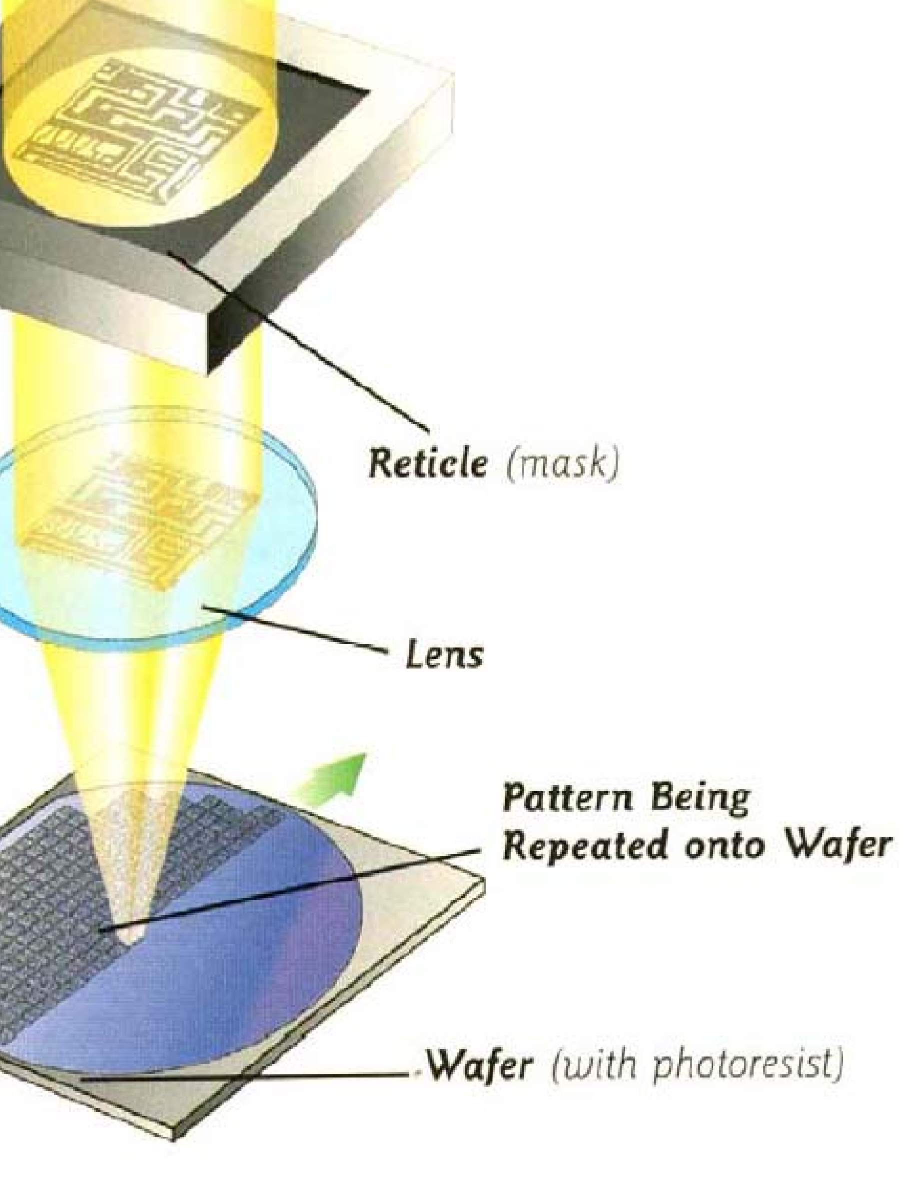
RIE, CAIBE, IBE

Content

- Introduction
- Conventional techniques
- Alternative techniques
- Emerging techniques and fourth coming issues
- Plasmonics for nanofabrication

Conventional Techniques

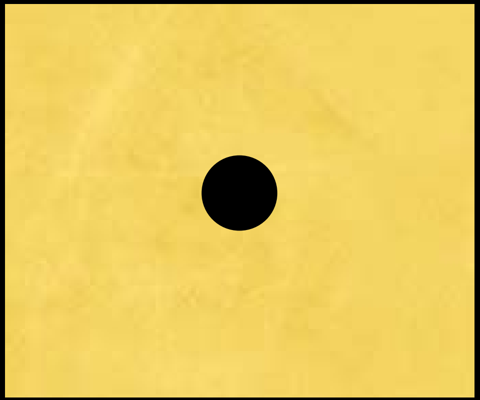
Photolithograp



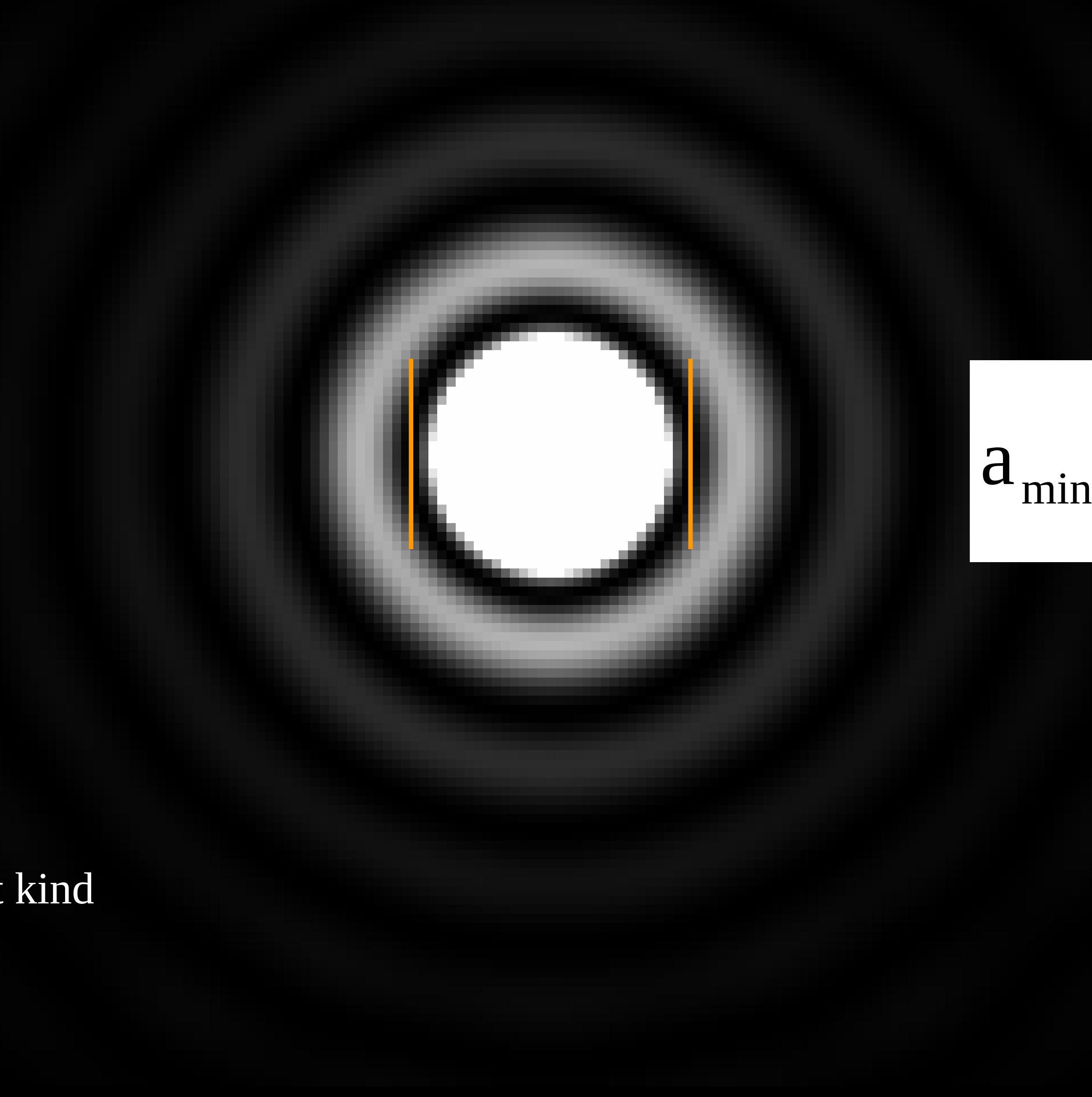
Projection type

⇒

Diffraction limited



Resolution



on theory for a pinhole

$$E_0\left(\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right)^2$$

Bessel function of the first kind

$$a_{\min} = 1.22\,\frac{\lambda}{n\,\mathrm{si}}$$

How to reduce $a_{\min}$?

Solution

What is the smallest aperture you can obtained exposing in air a photoresist using a green laser (λ=515nm) and a microscope objective of NA=0.5?

$a_{min} = 1.24\ \mu m$!!!

Reduce Wavelength

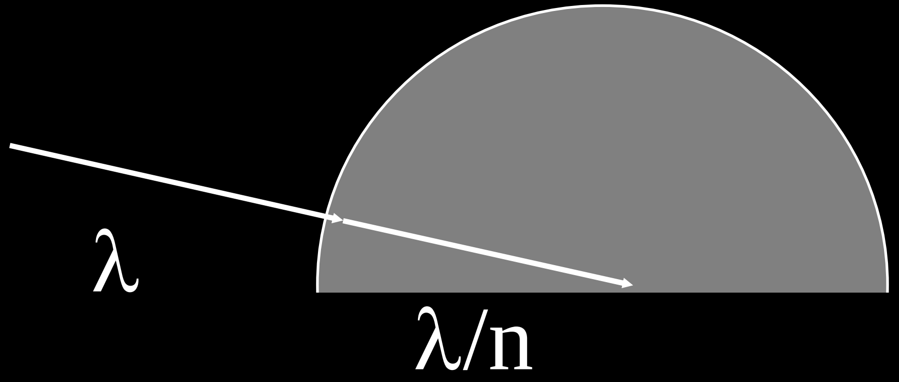
$$a_{min} = 1.22 \frac{\lambda}{n \sin \theta}$$

Immersion lithography

Increase $\theta \sim \pi/2$ ($a_{min} = 0.62\ \mu m$)

Liquid… water ($a_{min} = 0.47\ \mu m$)

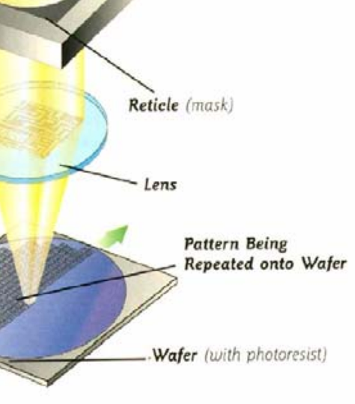
Solid Immersion Lenses (SIL)

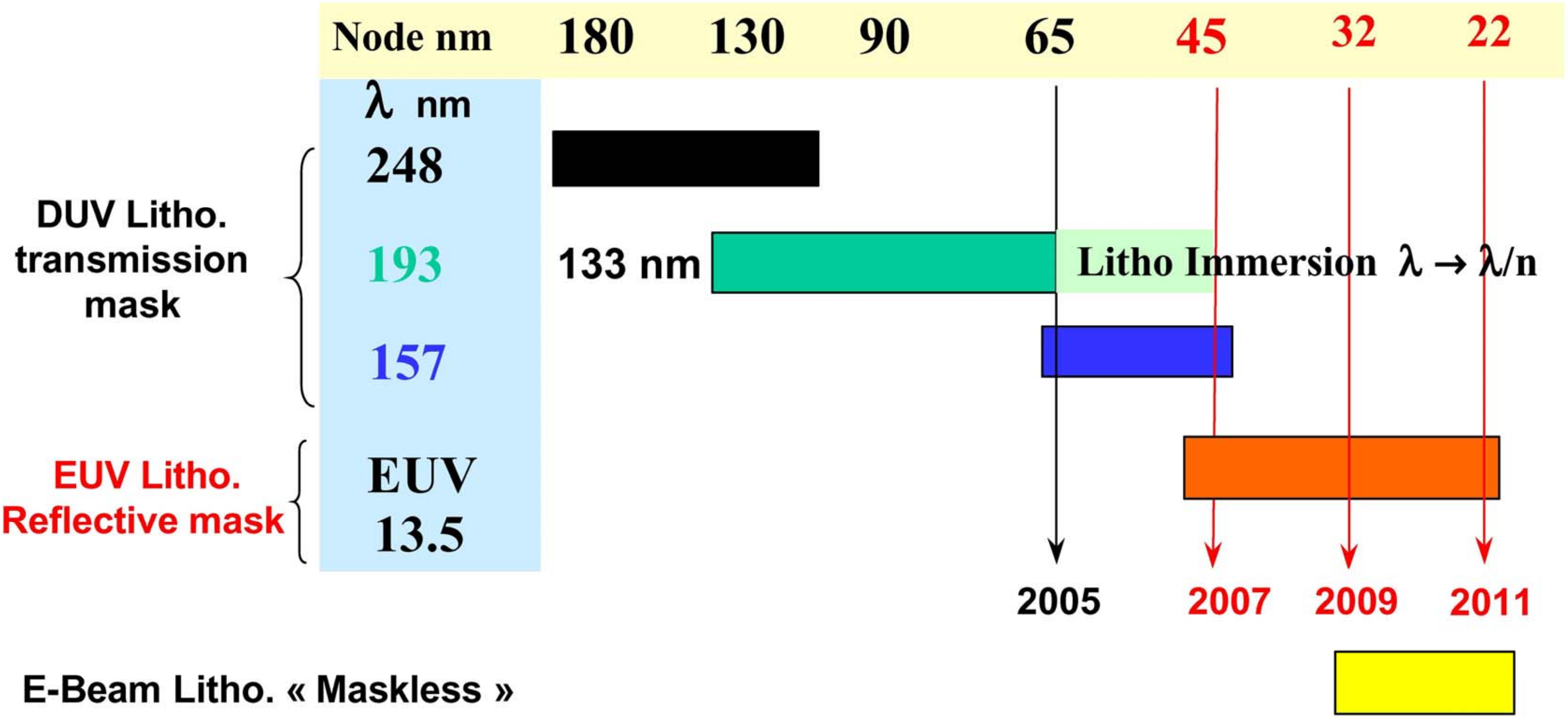


(Si_3N_4 n = 2.5)

$a_{min} = 0.19$

Photolithography
UV, DUP, EUV (X rays)..





EUV lithograph

http://www.xraylith.wisc.edu/ngl/in

Soft X rays (10nm) a_{min} = 10nm !!

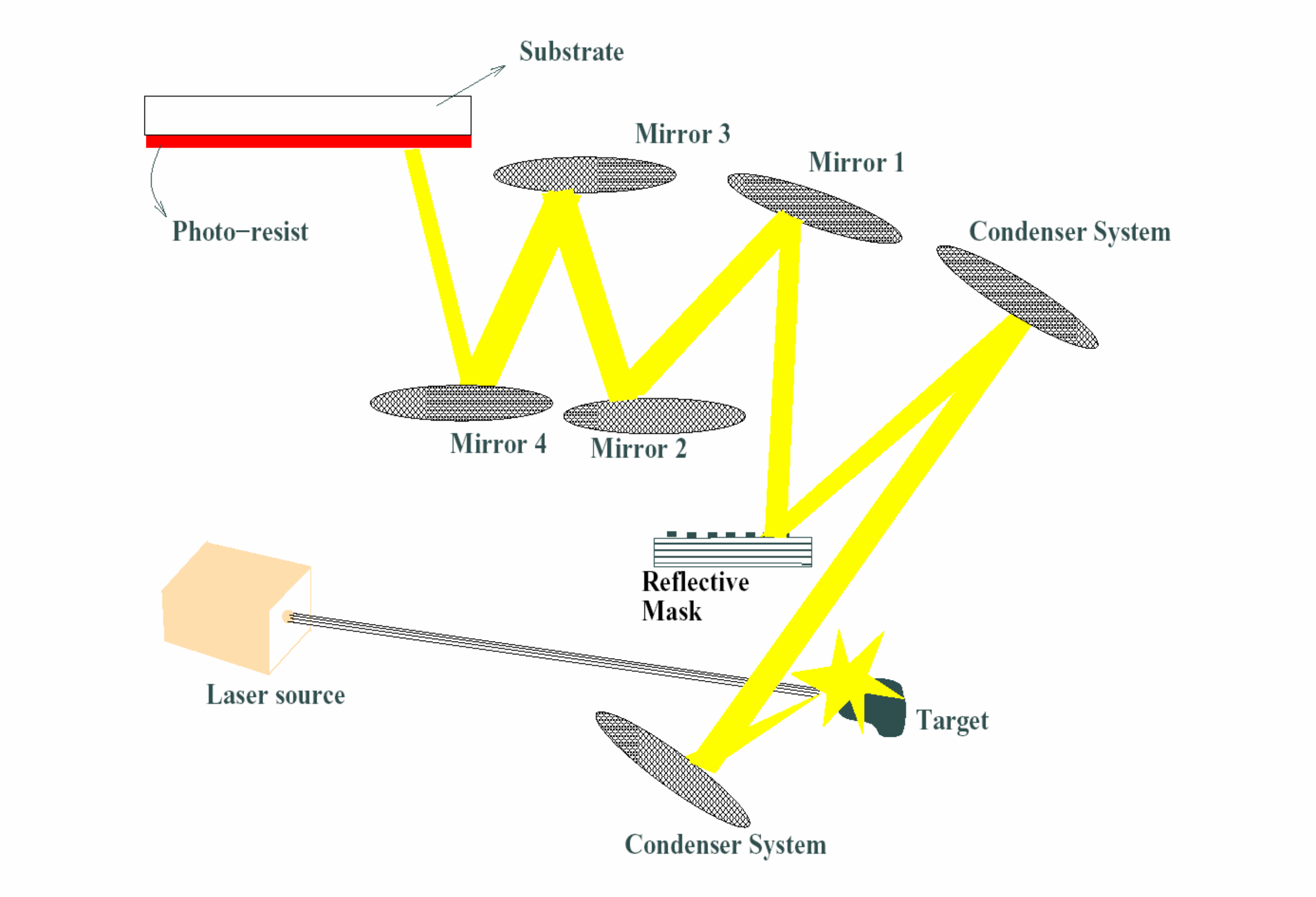
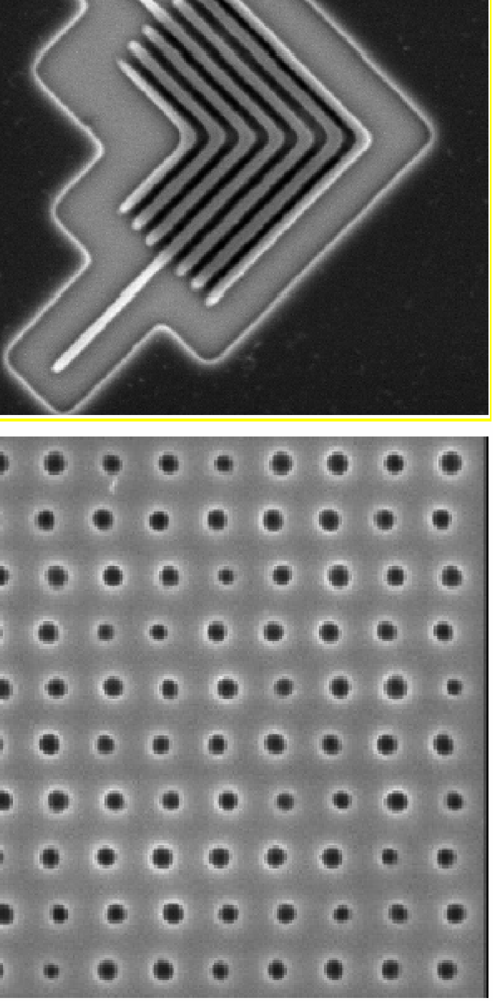
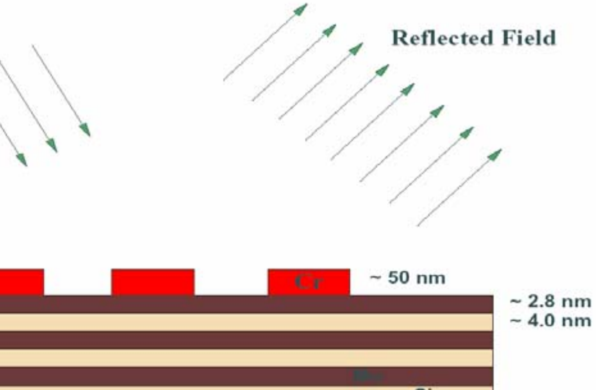


Figure 1: *An artist's rendition of the proposed EUVL system (after Hawryluk A.M [7])*

Issues: Reflection



m lines and contacts patterned with a 0.1NA
prototype EUV exposure tool



$$= \frac{h}{mV} = \left(\frac{h}{p}\right)$$

photons

Wave-particle duality

e^{-}: alternative to light i.e. photon

NR $\lambda = \frac{1.226}{\sqrt{E}}$ with E in eV and λ in nm

$$\lambda = 1.2\,10^{-2}\ \mathrm{nm}\ (\mathrm{E} : 10\ \mathrm{keV}) < \mathrm{r}_0$$

$$\theta = 10mrad$$

R (E>100keV) $\lambda = \frac{1.226}{\sqrt{E(1+0.978\,10^{-6}E)}}$

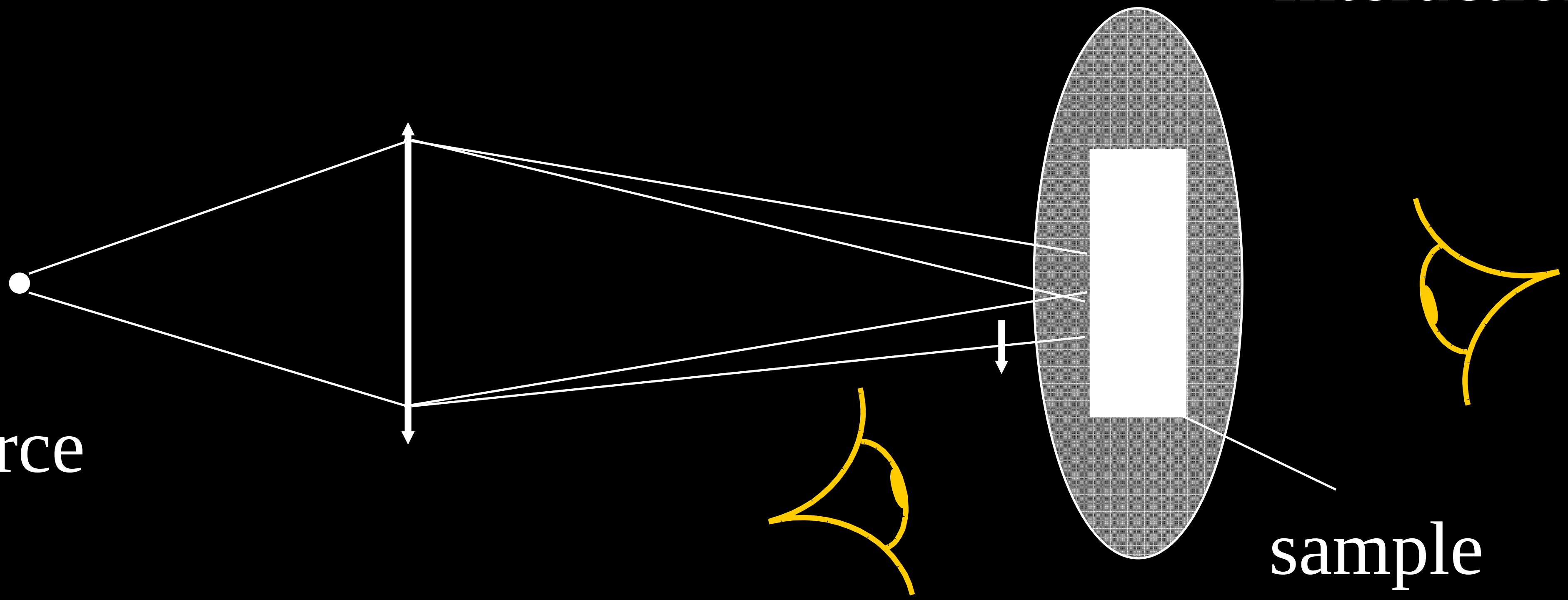
$$\lambda = 3.7\ \mathrm{pm}\ (\mathrm{E} : 100\ \mathrm{keV}$$

Instrumentation

Electron microscope
(Textbook material)
Electron beam lithography

Electron microscopy

Electron microscope : optical microscope



Interaction area

source

sample

Acceleration + Focalization

Blanker

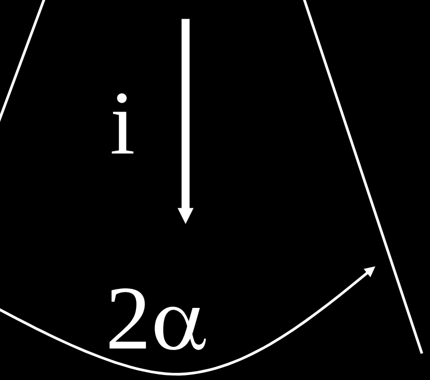
Source and e^- gun

Thermoelectronics emission - (heating: T)
Tungsten filament
Lanthanum Hexaboride LaB_6 filament

Field emission (electric field induced) – cold emission
Combined

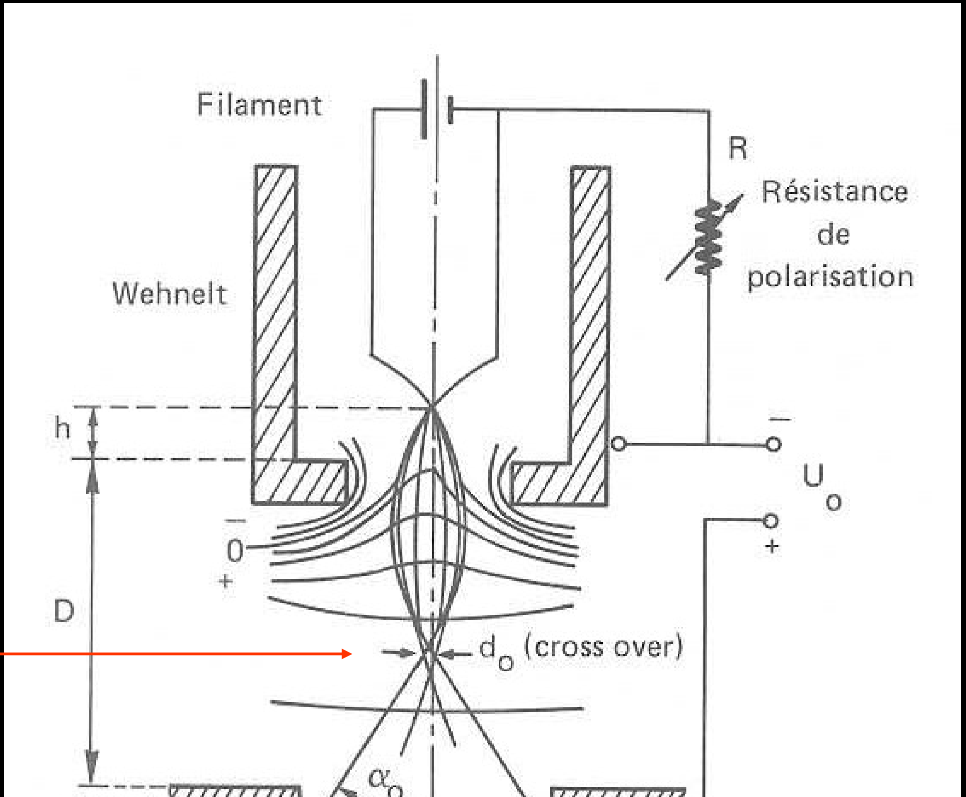
Objective: create an e^- pencil that will be then used to
image (expose) the sample surface:
Probe (brightness and size)

and e$^-$ g



$$\beta = \frac{4i}{\pi^2 \alpha^2 d^2}$$

Thermoelectronic emission

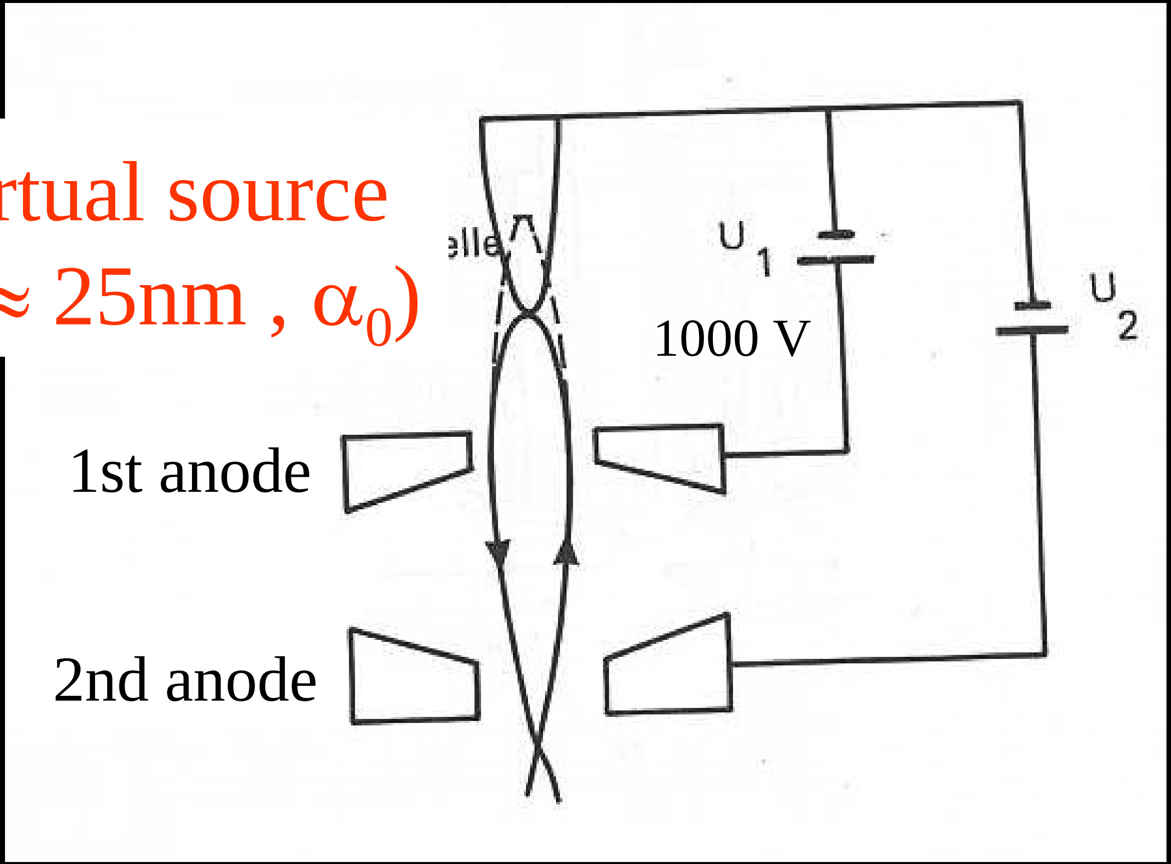


Real source

Field emissio

Tungsten monocrystalline tip (r=0.1µm)

Emission through tunn



Virtual source
($d_0 \approx 25$nm , α_0)

1000 V

1st anode

2nd anode

e⁻ density
(Fowler-Nordheim)

$$J = A\frac{E^2}{W_s}\exp(-B\frac{W$$

A=1.4 10^{-6} B=4.5$10^{7}$ et E=10

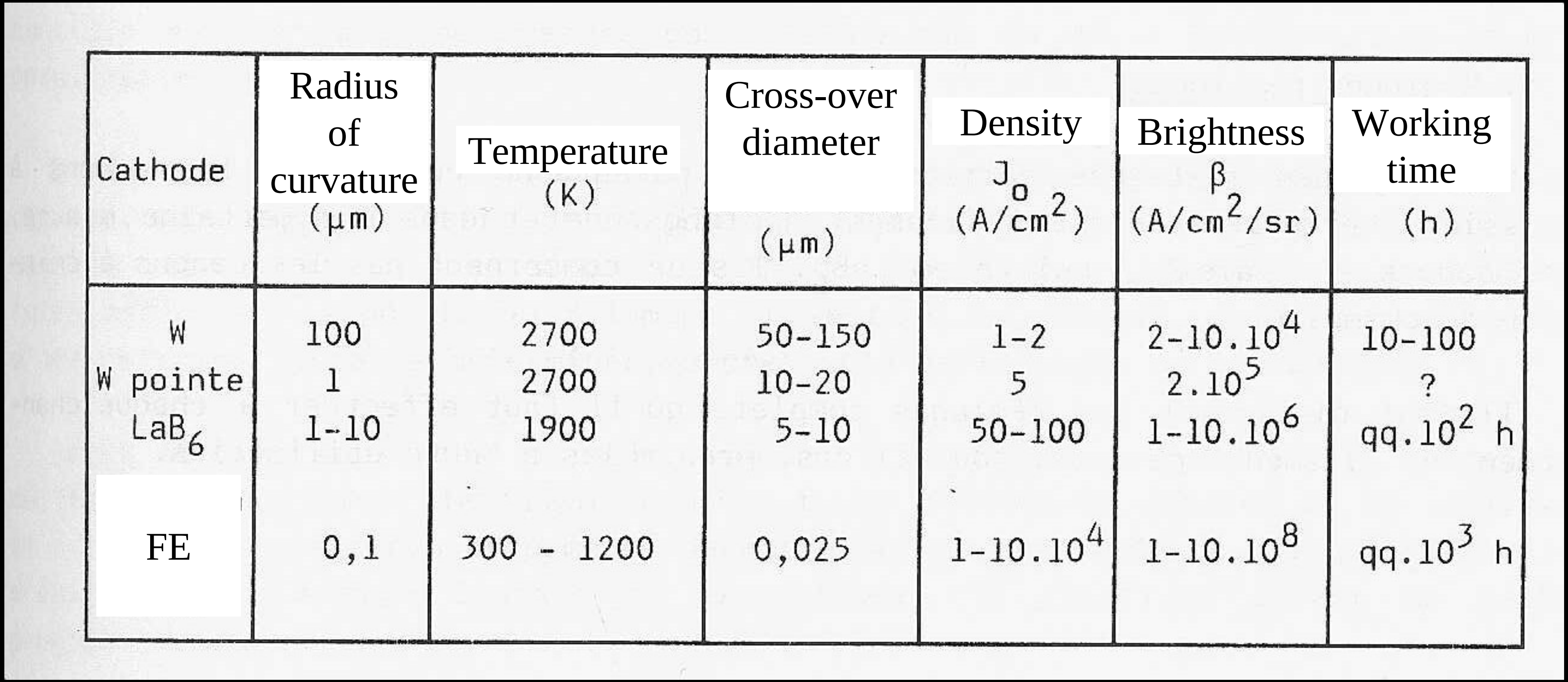
Brightness

$$\beta = \frac{J_0 e U_1}{\pi\Delta}$$

10^9 A

$\Delta = 0.3$ eV

Different types of gun



Cathode	Radius of curvature (μm)	Temperature (K)	Cross-over diameter (μm)	Density J_o (A/cm^2)	Brightness β ($A/cm^2/sr$)	Working time (h)
W	100	2700	50-150	1-2	$2\text{-}10.10^4$	10-100
W pointe	1	2700	10-20	5	2.10^5	?
LaB_6	1-10	1900	5-10	50-100	$1\text{-}10.10^6$	$qq.10^2$ h
FE	0,1	300 - 1200	0,025	$1\text{-}10.10^4$	$1\text{-}10.10^8$	$qq.10^3$ h

W

LaB_6 (high vacuum)

FE (weak probing intensity, ultra - vacuum)

(electro-)magnetic lenses

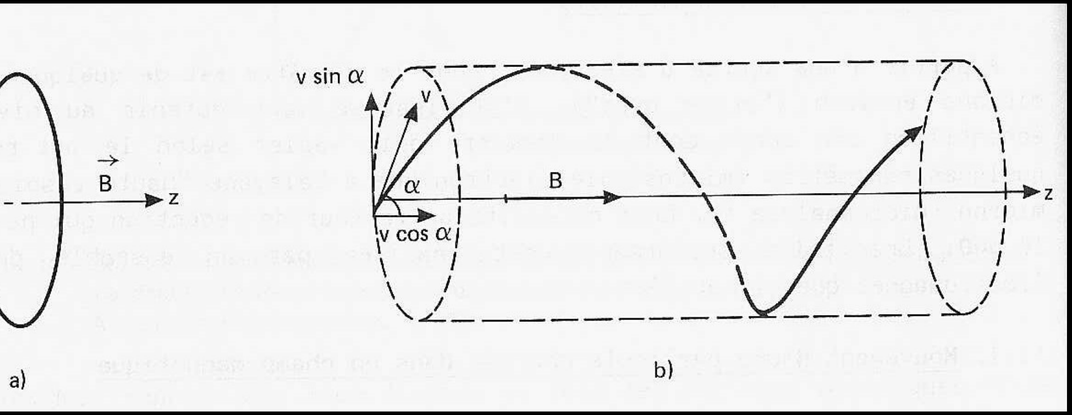
$$\vec{F} = -e\,\vec{v} \wedge \vec{B}$$

Goal : image the « cross over » on the sample (size reduction 10 000)

Magnetic field

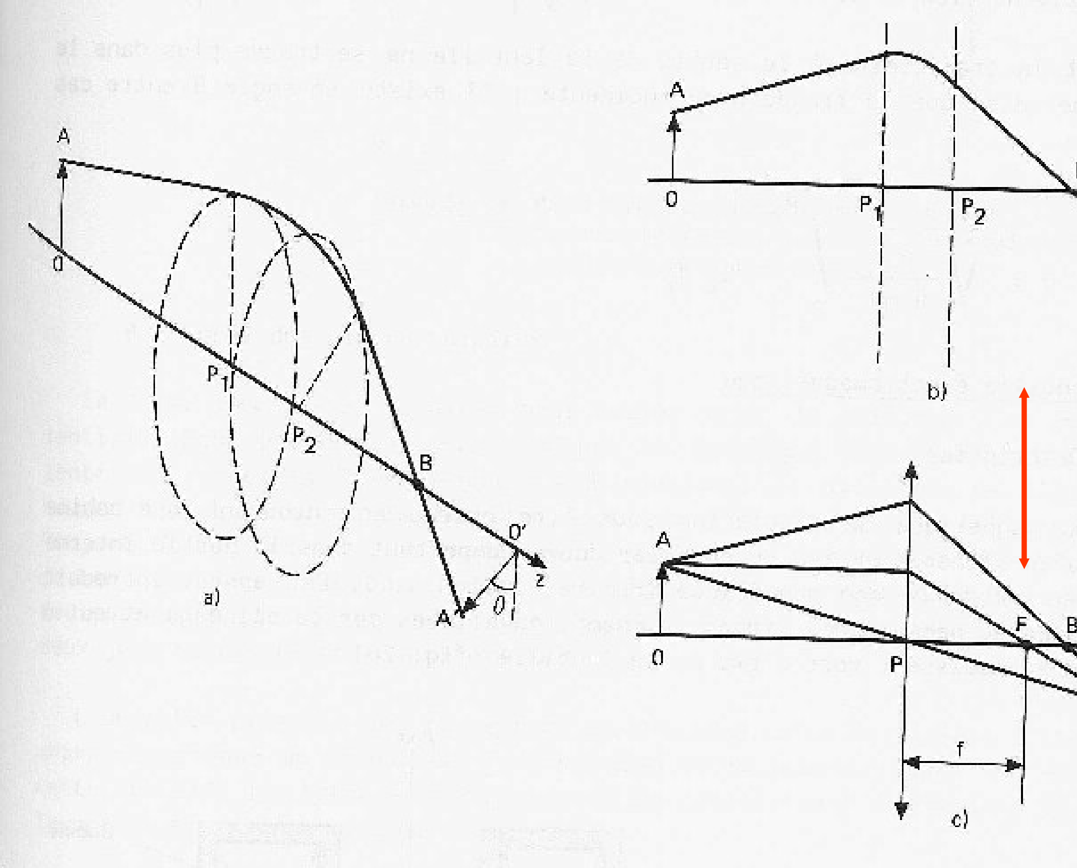
e^- speed module and energy are constant, only their trajectory varies

e$^-$ in a magnetic field



Uniform field

$$R = \frac{mv\sin\alpha}{eB}$$



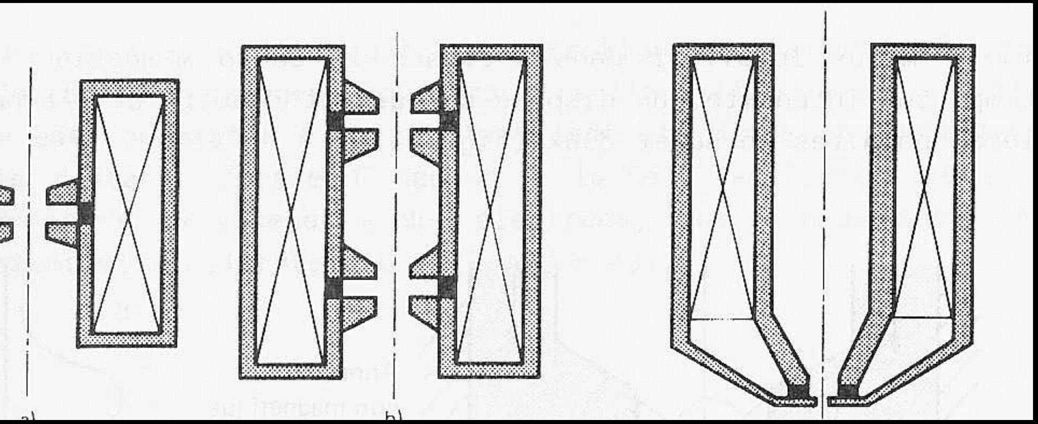
Rapid variation of radial component of the field

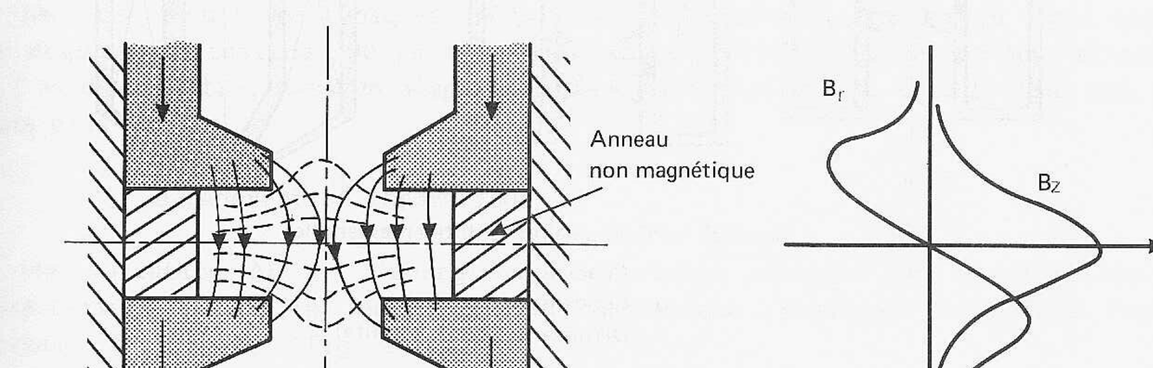
$$\frac{1}{f} = \frac{e}{8mU}\int_{P_1}^{P_2} B^2{}_z dz \approx \frac{e}{8mU} B^2 L$$

(electro-)magnetic lenses

olenoid surrounding by pure Iron

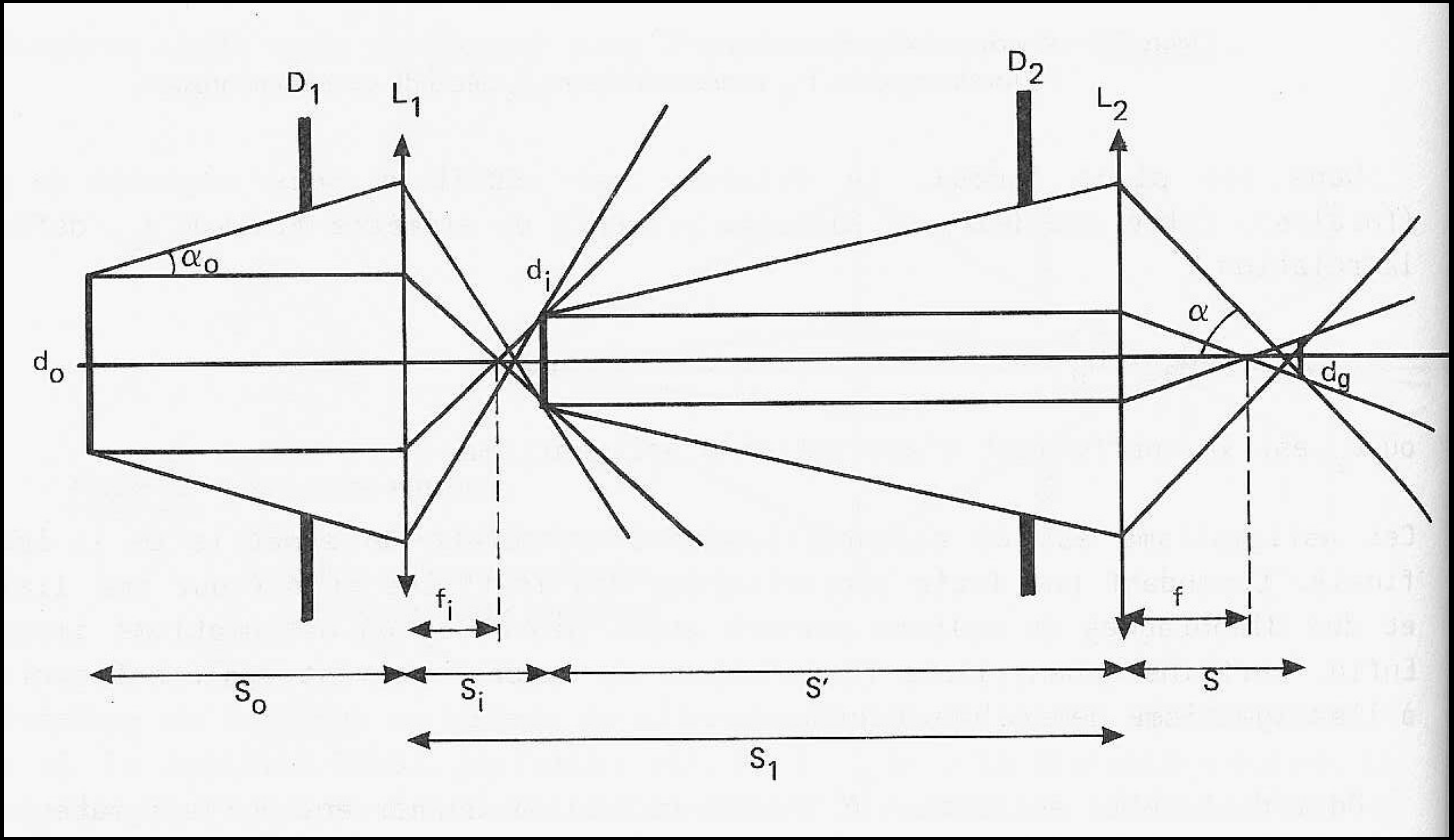
$$\frac{1}{f} \approx K = \frac{N^2 I^2}{V^*}$$





Beam diameter

Source + 2 electronic (magnetic) lenses



$$\frac{d_0}{d_g} = M_1 M_2 =$$

M = 50 and 10

S_0=20cm, S_1=30cm and

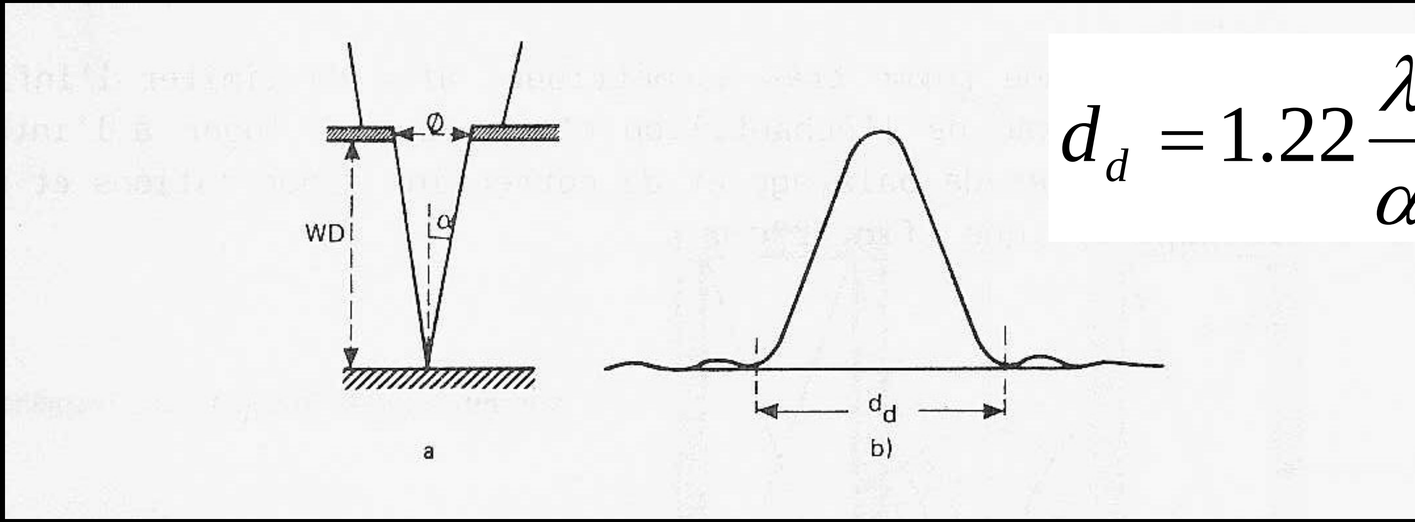
d_g=0.5µm

with a 3rd lens

⇒ M=1000 et 10

Aberrations

Diffraction



$$d_d = 1.22 \frac{\lambda}{\alpha}$$

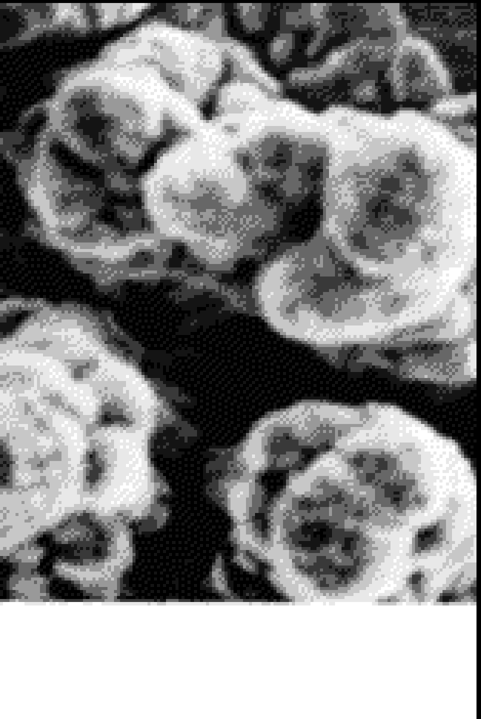
d_d=5.2nm with WD=25mm, λ=8.6 10^{-3}(E_0=20keV) et Φ=

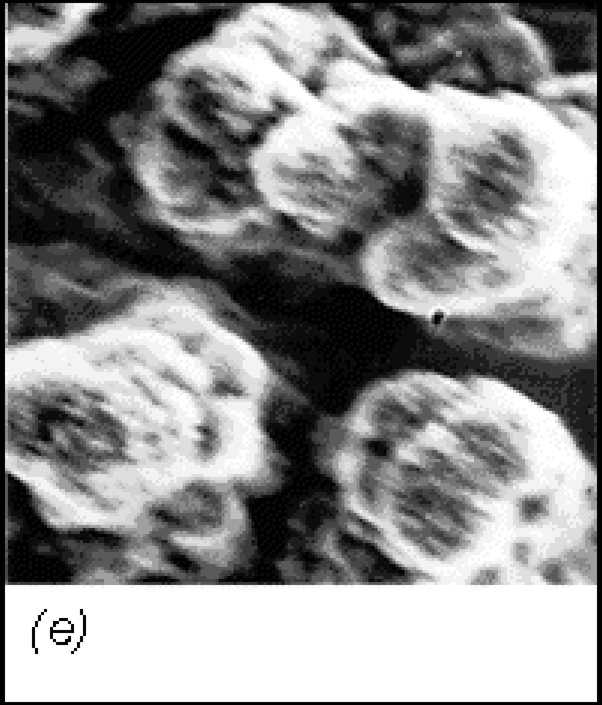
Chromatic (ΔE)

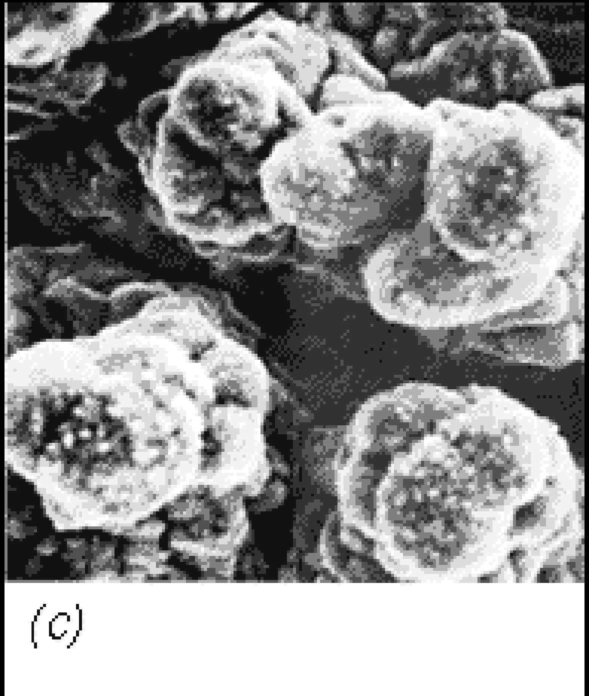
Large α = small

Spherical … small α !

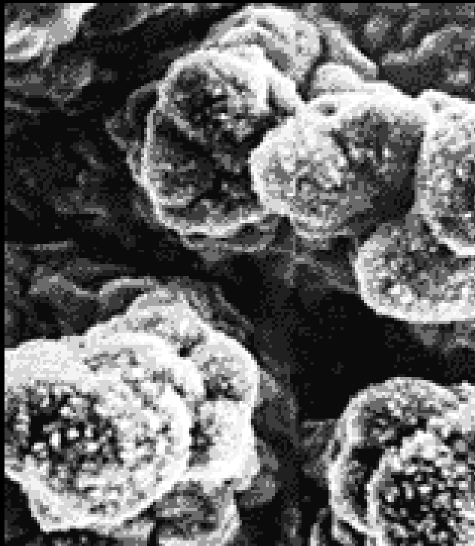
Stigmatism…







Focalized with correction
Focalized without correction
Unfocalized without correction
Unfocalized with correction



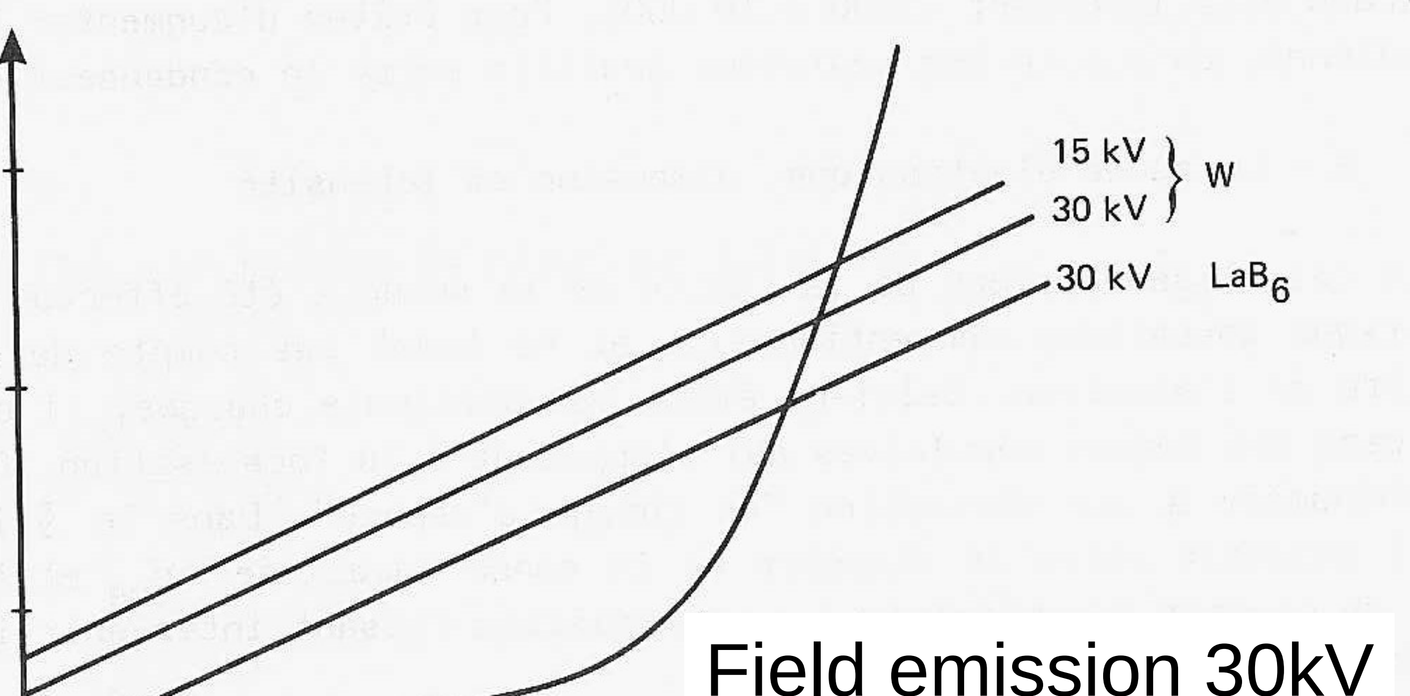
$${}^2 = \frac{\;_0}{\pi^2 \beta}\frac{}{\alpha^2} + \frac{}{4} C_s{}^2 \alpha^6 \; (+\,\mathrm{ast})$$

the beam

$d^2 = \Sigma_i \, d_i^2$ (independent phenomena)

Thermoelectronic Emission

d α i_0 (U and β)



Field emission 30kV

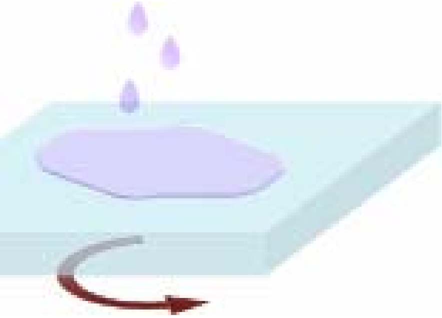
α_{optimum}

$d_{\text{opt.}}$ ~ a few nanom

Lithography

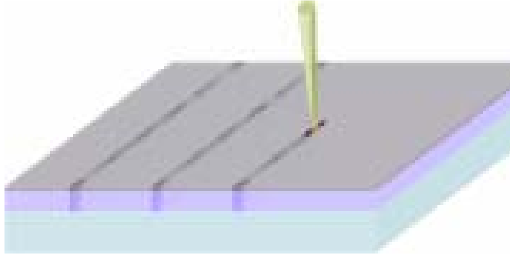
Electron beam lithography

EBL and lift-off proce



MMA spin-coating

Al evaporation

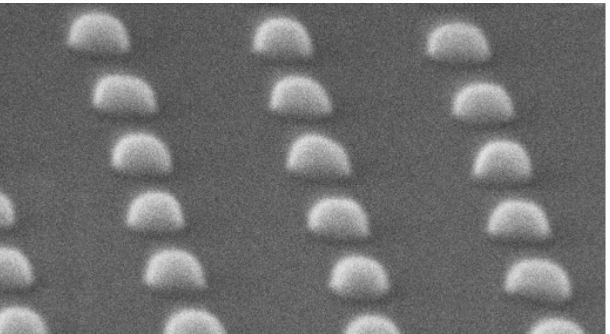


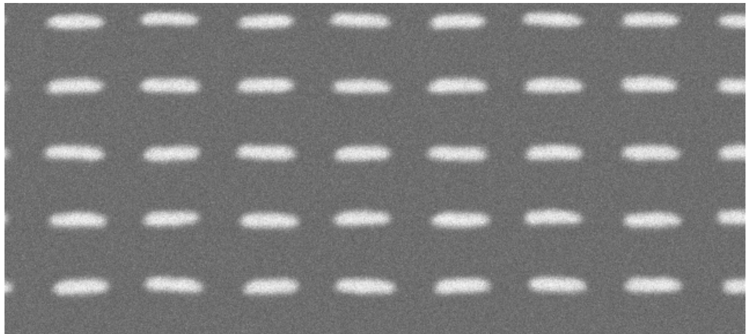
Exposure

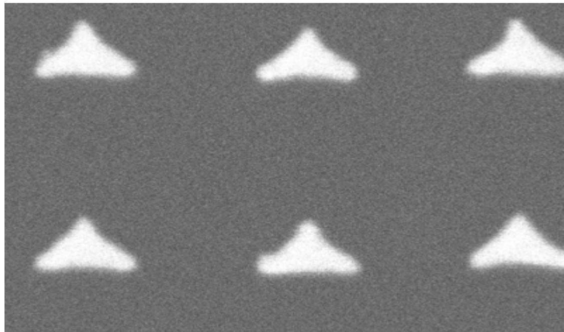
lopment (MIBK:IPA)

Metal evaporation

Lift-off (aceton)

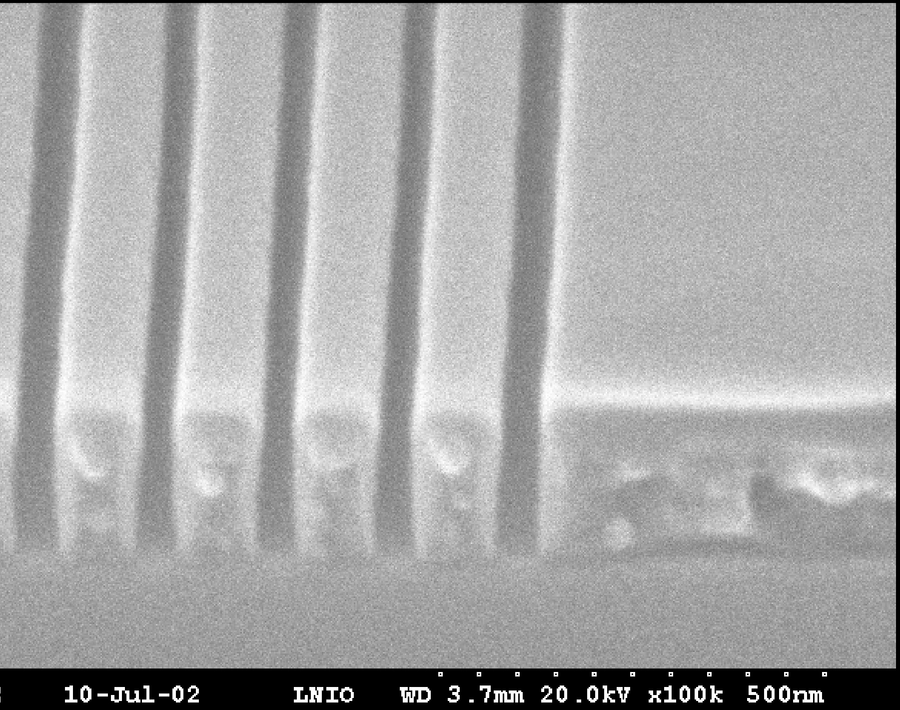


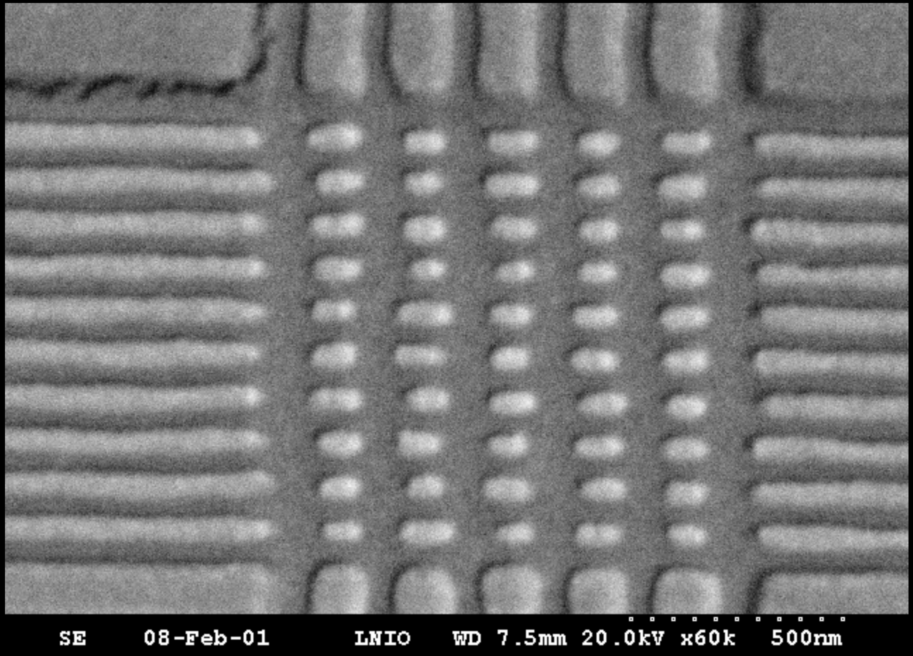




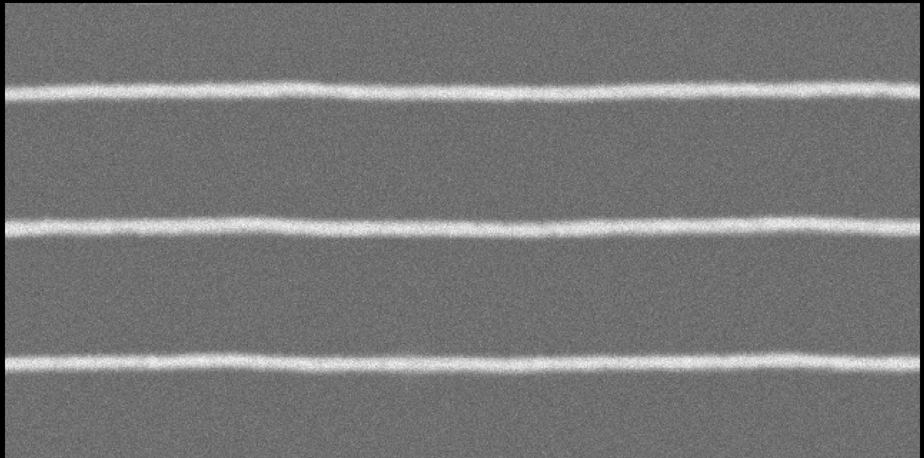
Test patterns

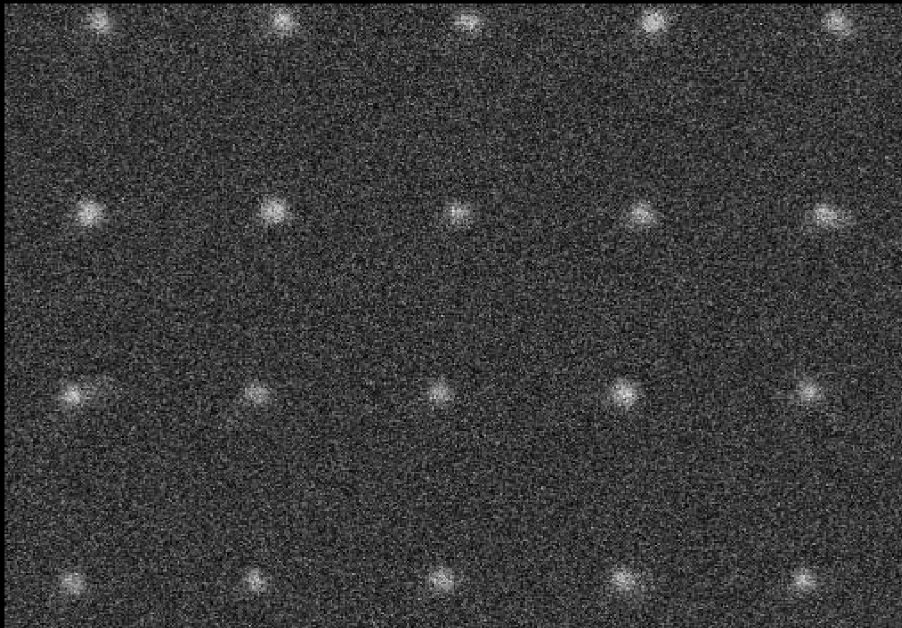
Lines and dots…





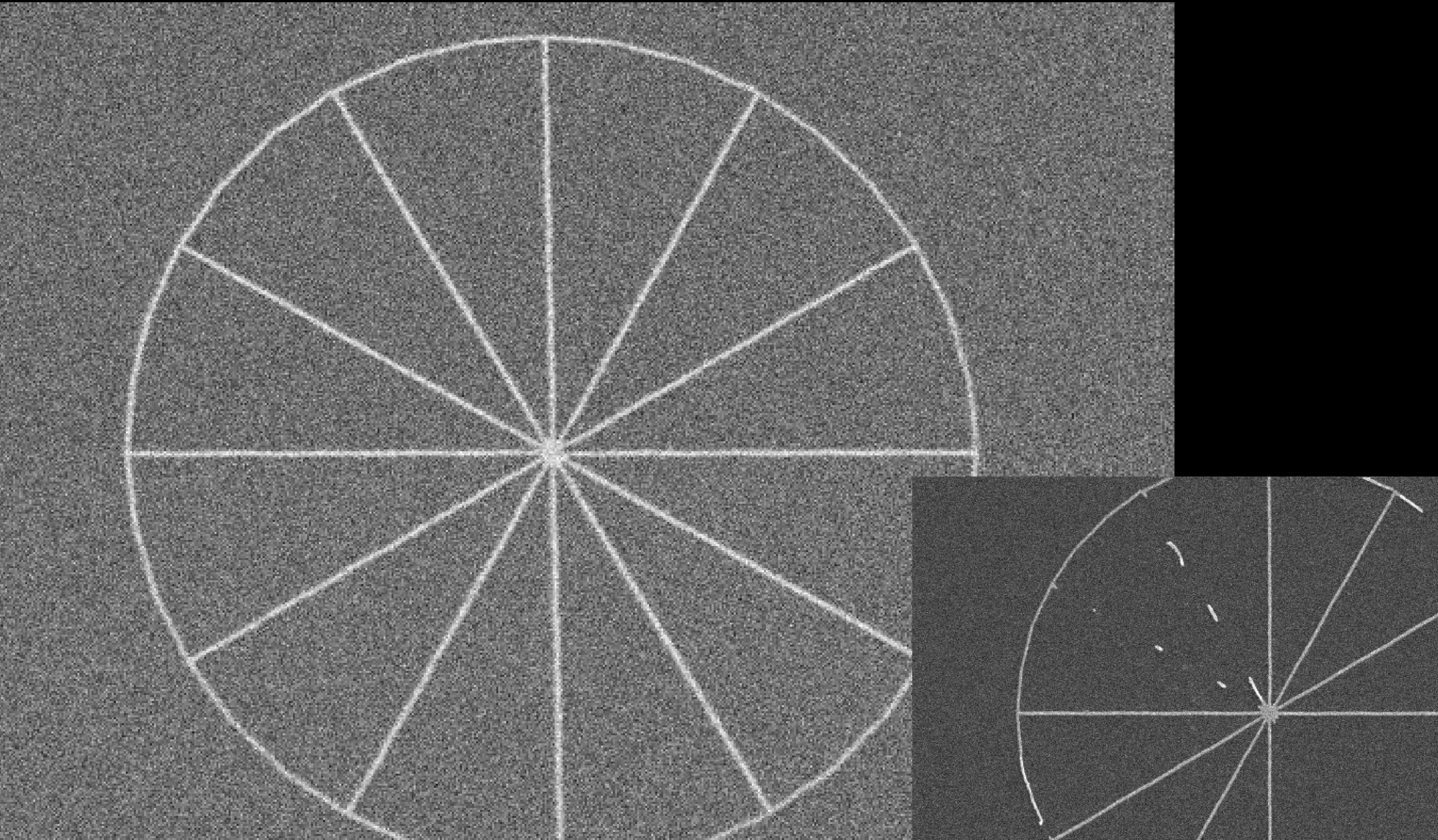
Glass





Test patterns

Wheel...

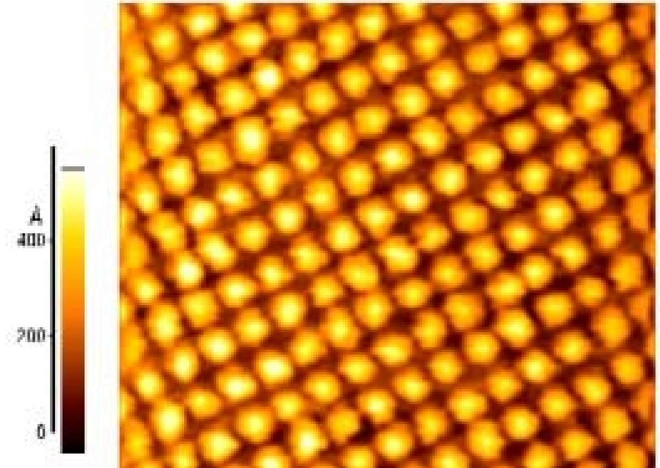


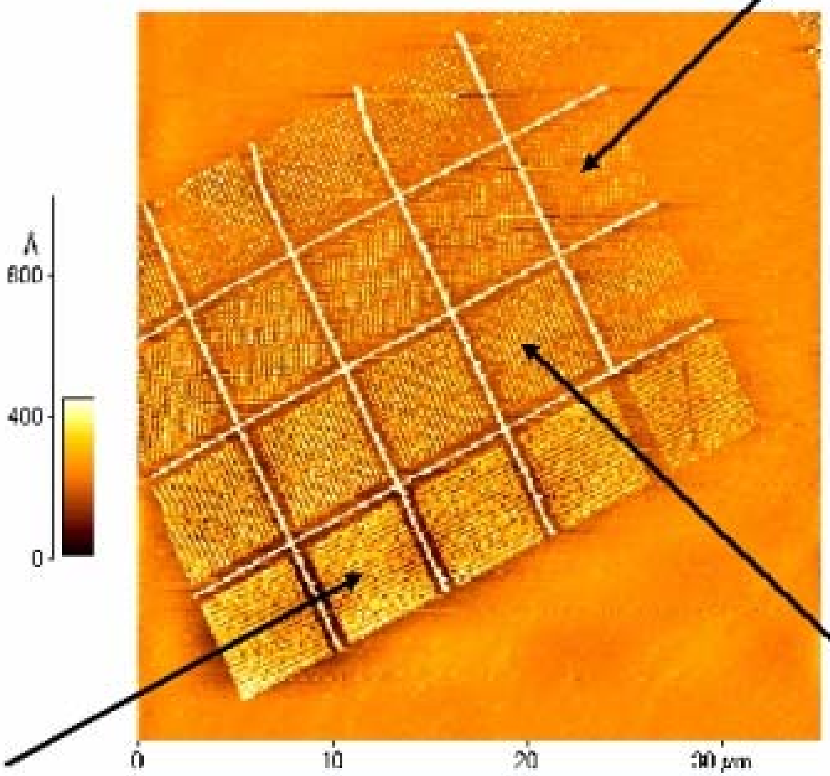
Parametric Study

- On glass

Dot spacing

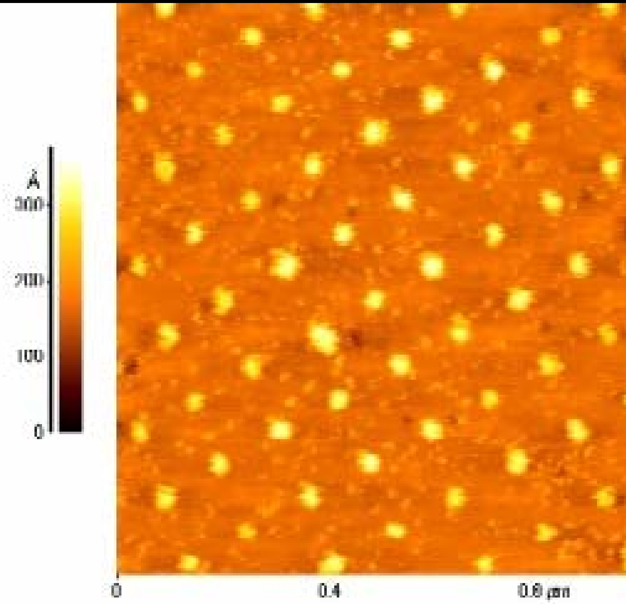
c-c 75 nm dia. 50 nm





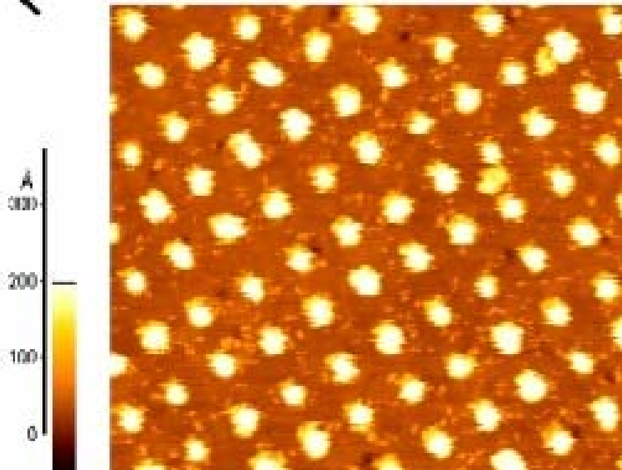
Dose

Dot height: 25nm

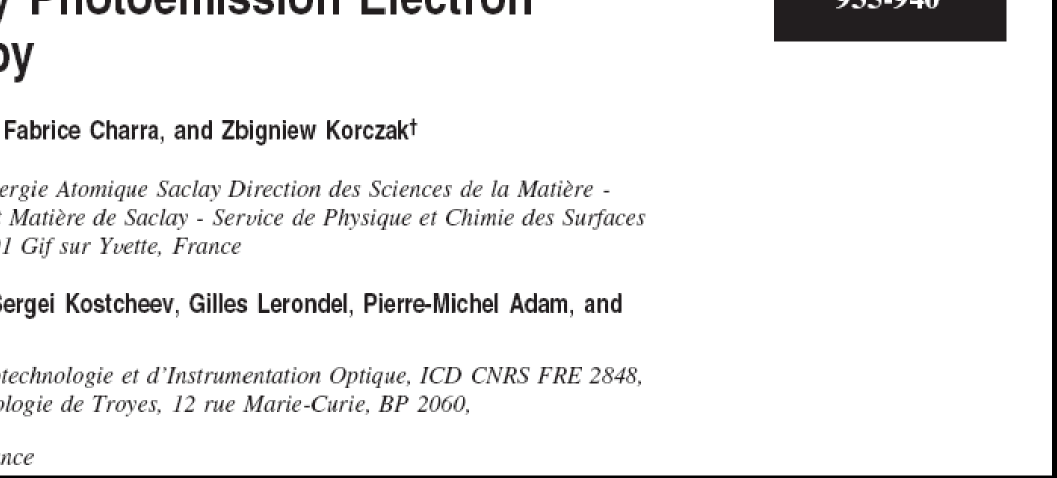


c-c 125 nm dia. 35 n

c-c 100 nm dia. 40 n



ITO substra


y Photoemission Electron
py

935-940

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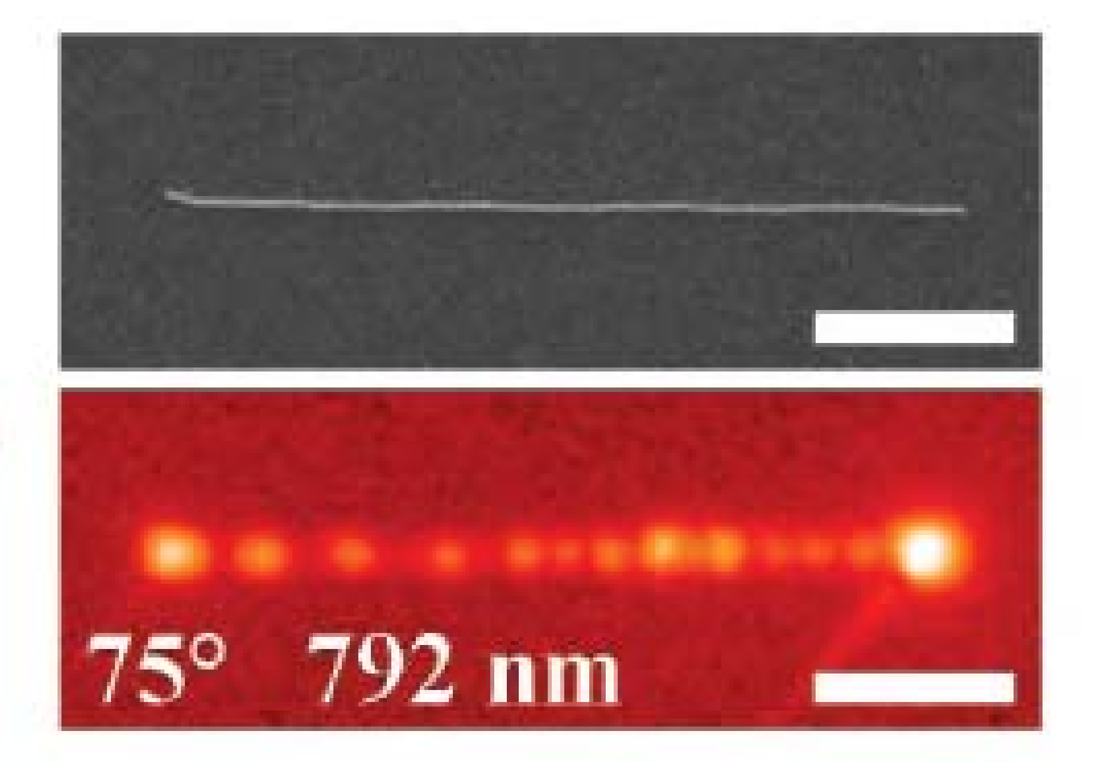


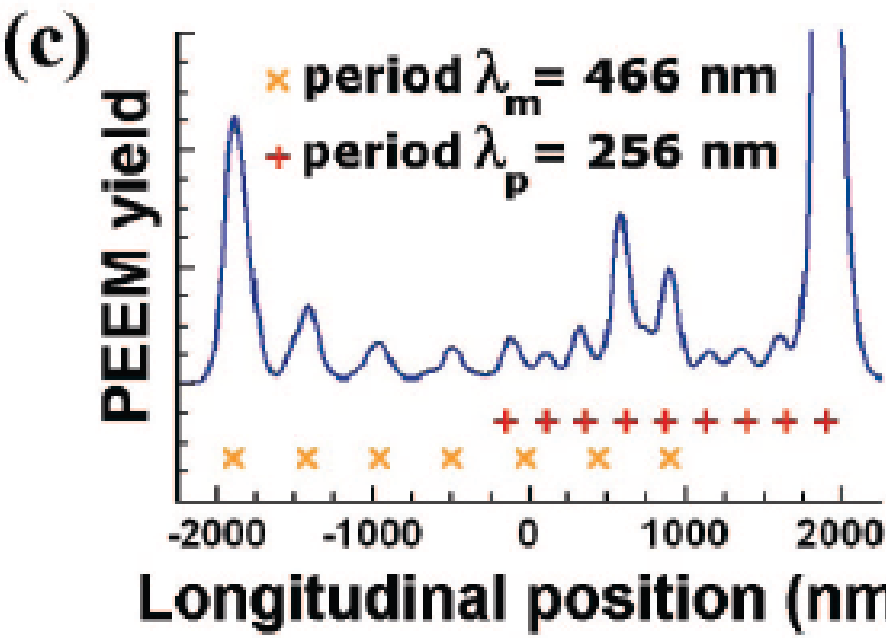
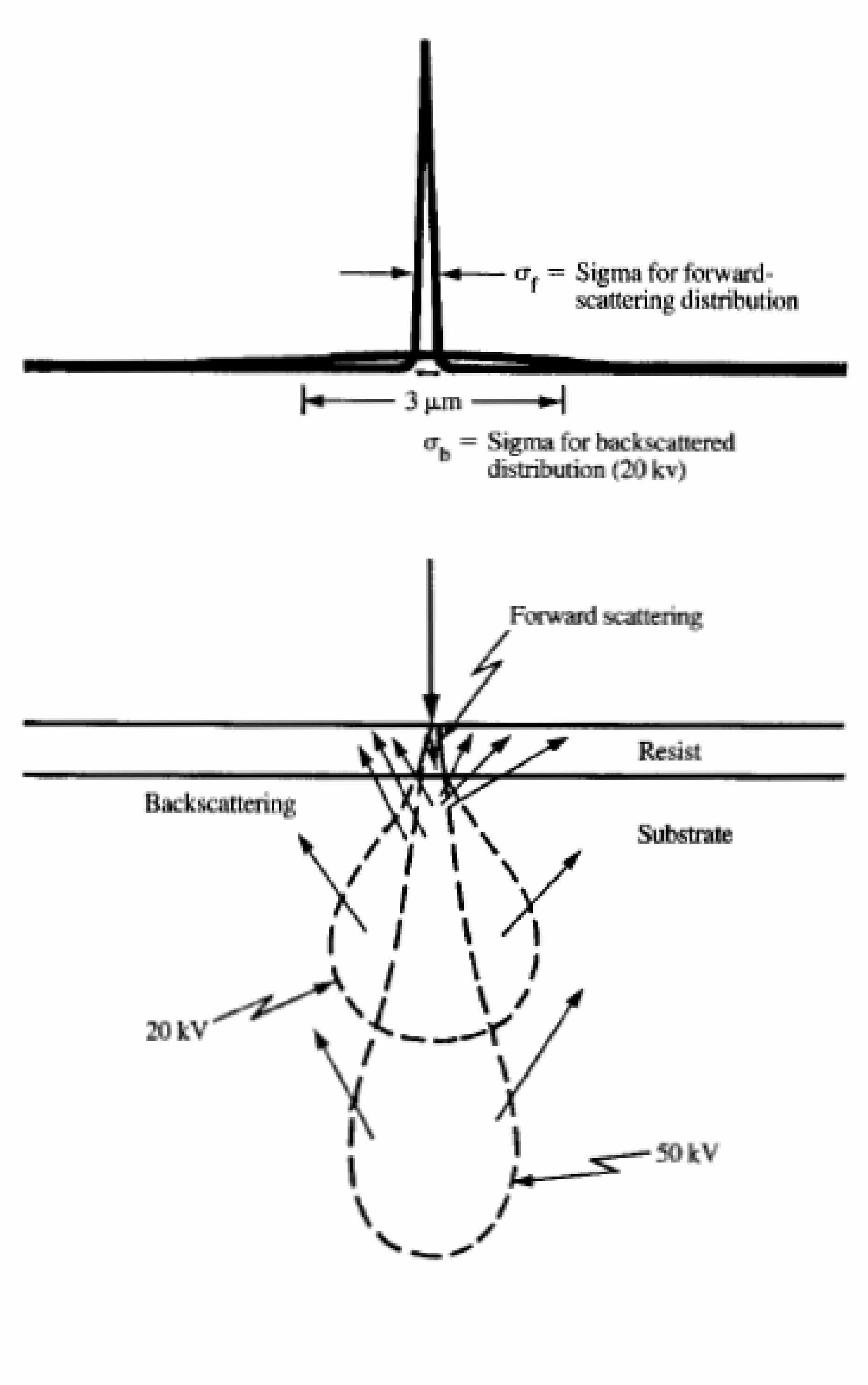


Figure 1. Off-resonant single Au nanowire investigation
picture of a 4 μm long nanowire. (b) PEEM near field
(grazing incidence $\alpha = 75°$, p polarization, excitation w
$\lambda_0 = 792$ nm, incident power $P = 110$ MW/cm^2). Lo
resolution is 41 nm;[19] color scale is logarithmic. (c) Pro

aphy

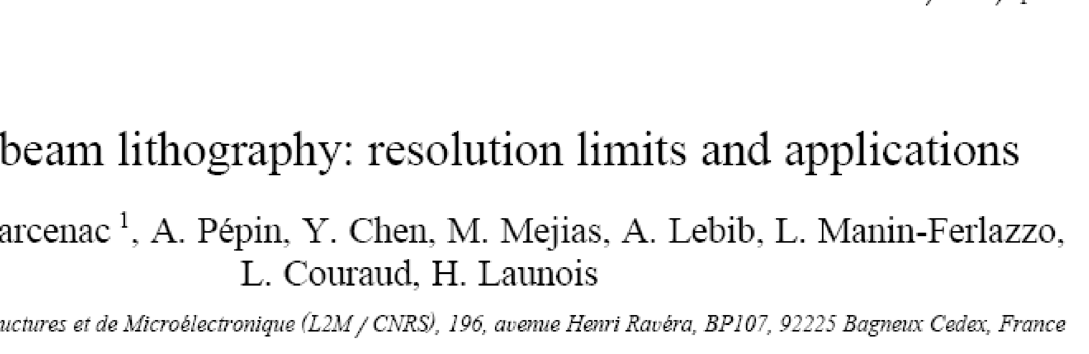


Beam size < 1nm

(Acceleration Voltage)

Resist thickness

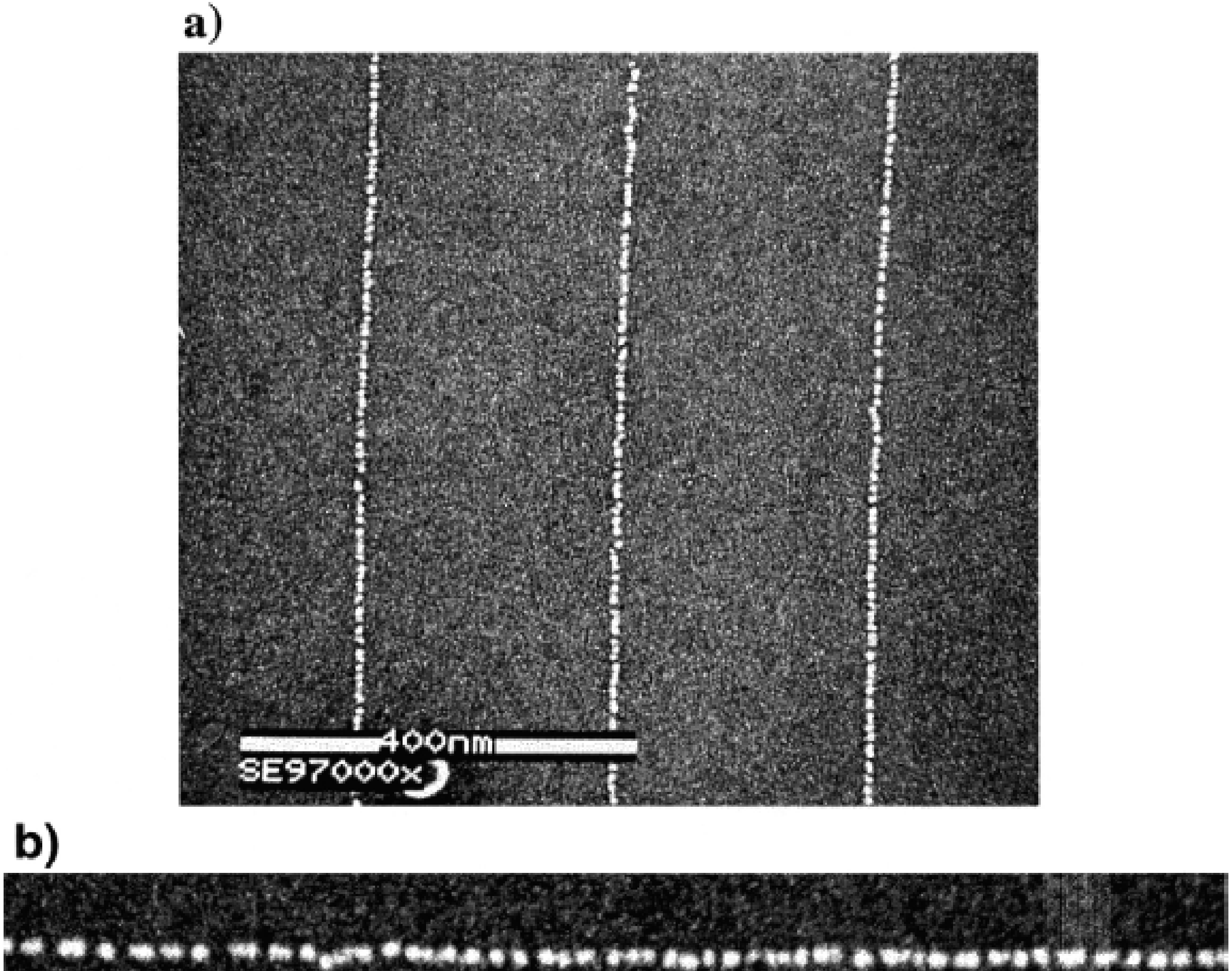
EBL resoluti

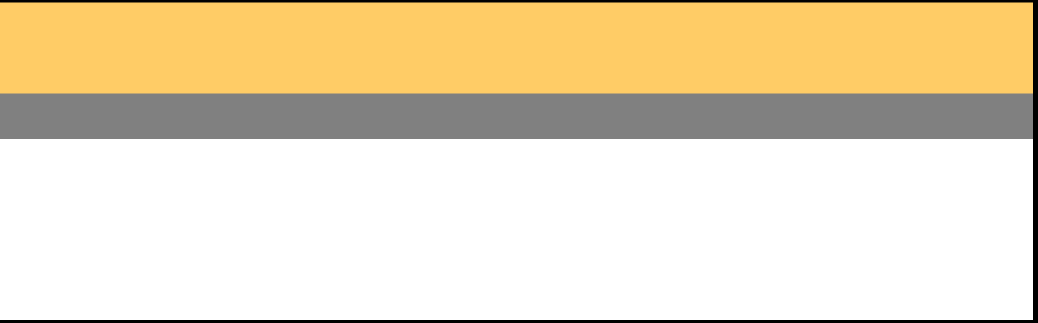


beam lithography: resolution limits and applications

arcenac [1], A. Pépin, Y. Chen, M. Mejias, A. Lebib, L. Manin-Ferlazzo,
L. Couraud, H. Launois

uctures et de Microélectronique (L2M / CNRS), 196, avenue Henri Ravéra, BP107, 92225 Bagneux Cedex, France





Cr $\longrightarrow$ TiO_2 or Cr_2O_3

ss

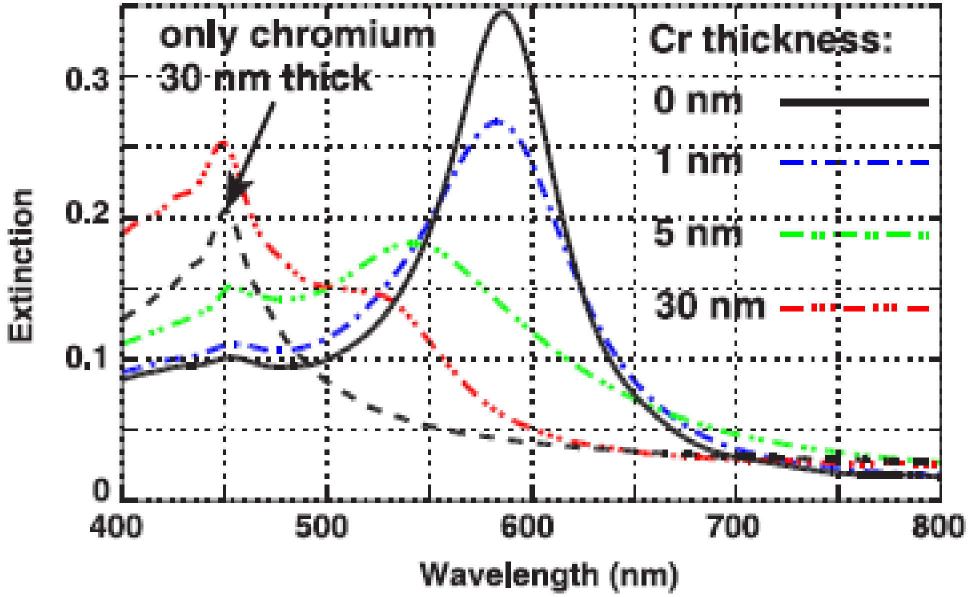


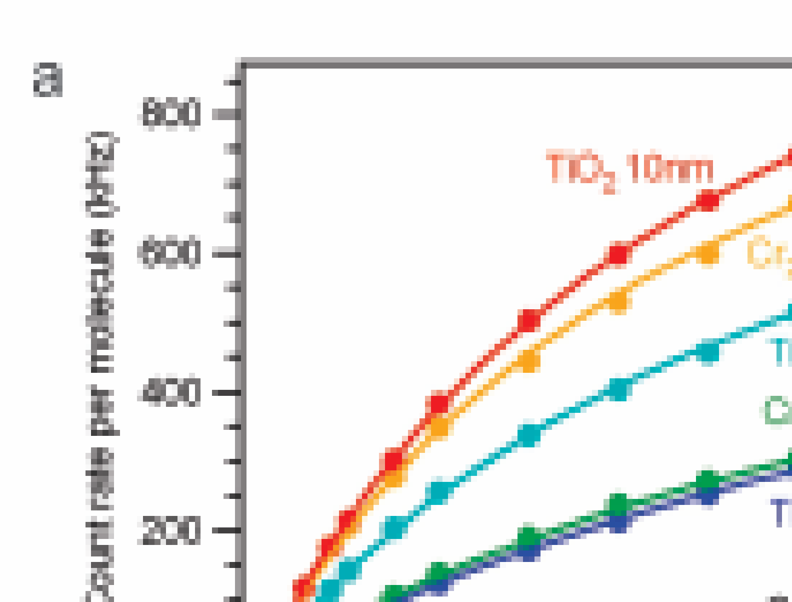
Figure 7. Extinction spectra for a gold cylinder (diameter 100 nm, height 50 nm) calculated for different chromium intermediate layer thicknesses: 0 nm, 1 nm, 5 nm and 30 nm, respectively. The extinction spectrum for a 30 nm high chromium cylinder is also presented.

f dispersion properties of
ans of the critical points

Crucial Role of the Adhesion La
the Plasmonic Fluorescence
Enhancement

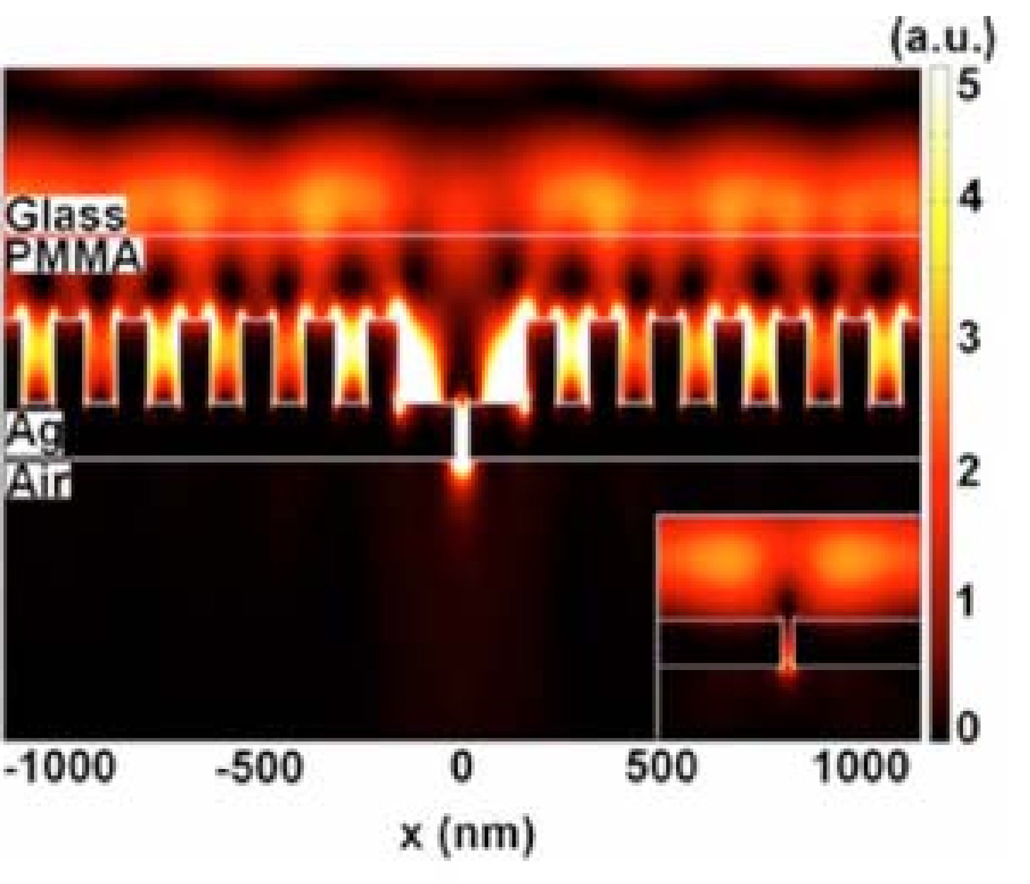
Haykel Aouani,[†] Jérôme Wenger,[†,*] Davy Gérard,[†,‖] Hervé Rigneault,[†] Eloïse Devaux
Farhad Mahdavi,[§] Tingjun Xu,[§] and Steve Blair[§]

[†]Institut Fresnel, Aix-Marseille Université, CNRS, Ecole Centrale Marseille, Campus de St. Jérôme, 13397 Marseille, France, [‡]Institut
Supramoléculaires, Université Louis Pasteur, CNRS, 8 allée G. Monge, 67000 Strasbourg, France, and [§]Electrical and Computer Engi
Utah, 50 South Central Campus Drive, Rm. 3280, Salt Lake City, Utah 84112. [‖]Current address: LNIO, Institut Charles Delaunay, Uni
France.



EH, MINATEC, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France
toire de Nanotechnologie et d'Instrumentation Optique, Institut Charles Delaunay, CNRS FRE
Iniversité de Technologie de Troyes, 12 rue Marie Curie, BP 2060, 10010 Troyes Cedex, France

PMM
templated lithograp



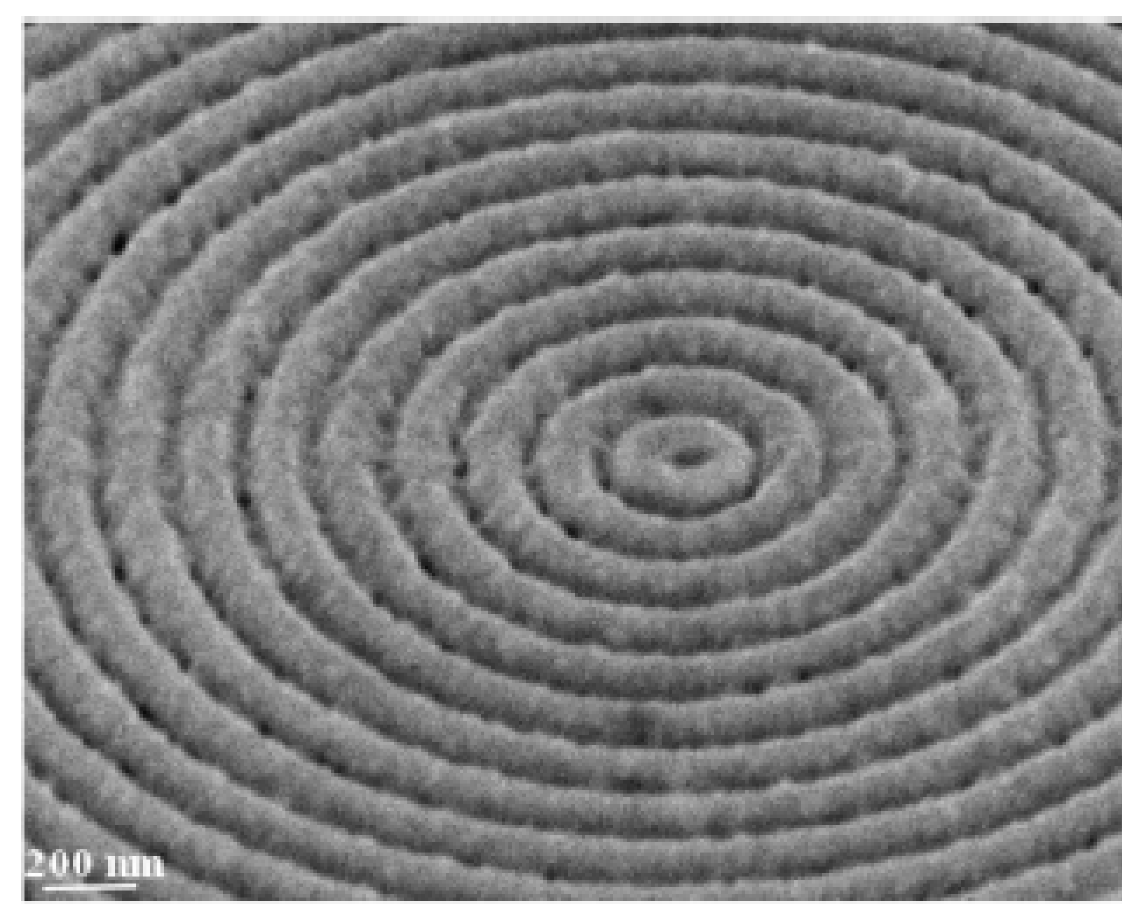


FIG. 3. Top view (scanning electron microscopy image) of th
structure. The dimensions of the Bragg gratings are $a=165$

on meta

PMMA structuring

or

Lift-off of dielectric strutures (SiO_2)

on

metallic films

A. Hohenau et al. Optics Letters 30 (8) 2005

Focused Ion Bea

Important technique for the realization of « test » samples

Principle: id. SEM but with heavy charged particles (ions) …

…Direct writing (physical process)

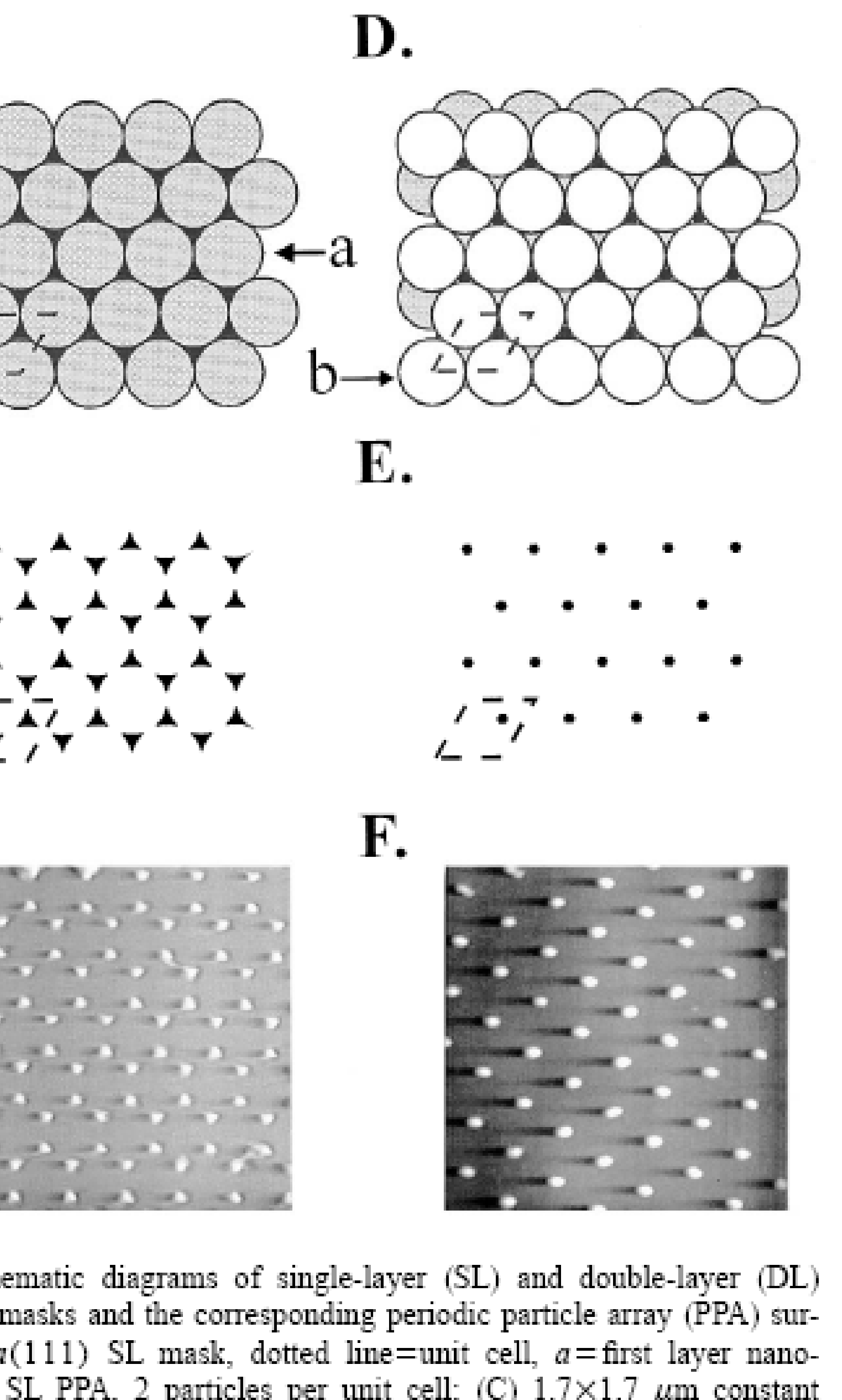
Drawback: possible contamination and redeposition

Examples of structure : See T. Ebbesen presentation

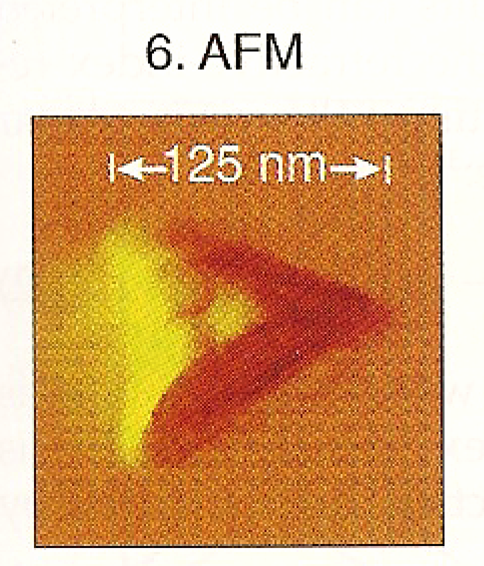
Alternative methods

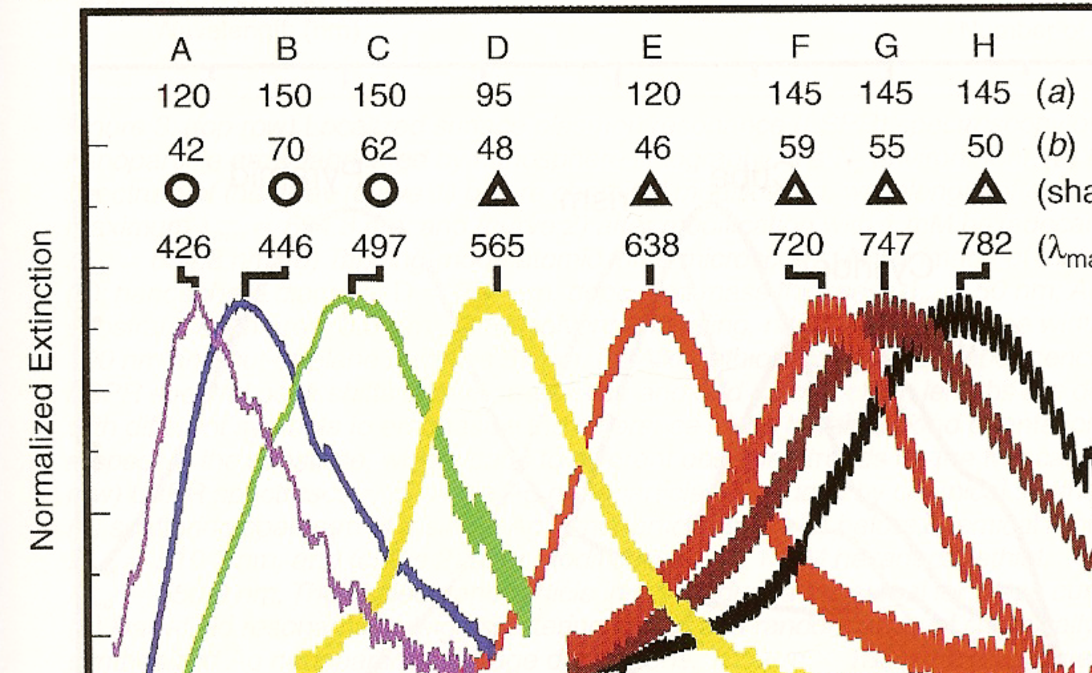
Surface chemistry

Lithograp



ematic diagrams of single-layer (SL) and double-layer (DL) masks and the corresponding periodic particle array (PPA) sur- (111) SL mask, dotted line=unit cell, a=first layer nano- SL PPA, 2 particles per unit cell; (C) 1.7×1.7 μm constant





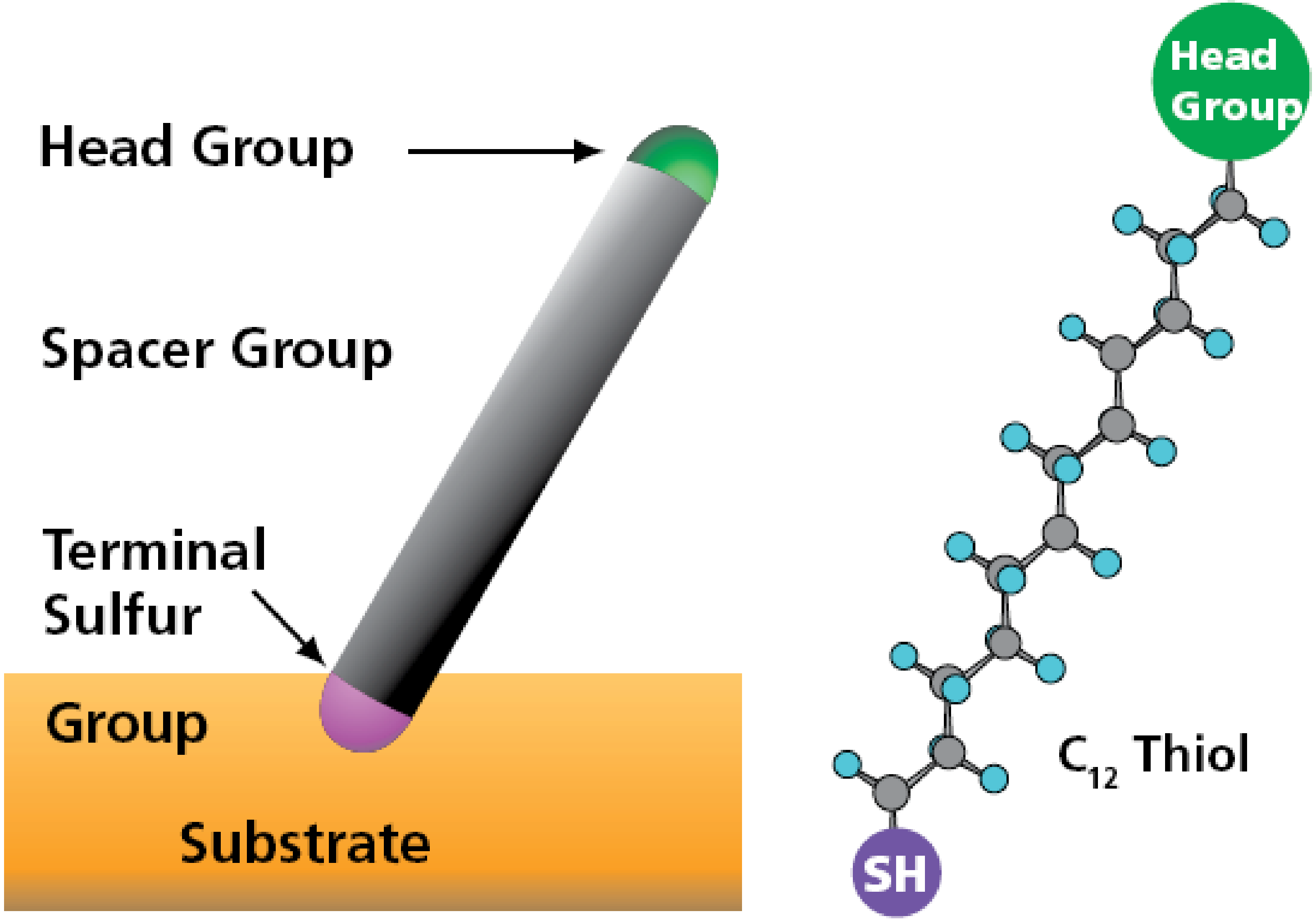


Figure 1. Schematic diagram of a thiol molecule.
The sulfur group links the molecule to the gold surface. The head group can be designed to provide virtually any surface chemistry, binding capacity, or property.

Au-thiolate (Au_0-S)

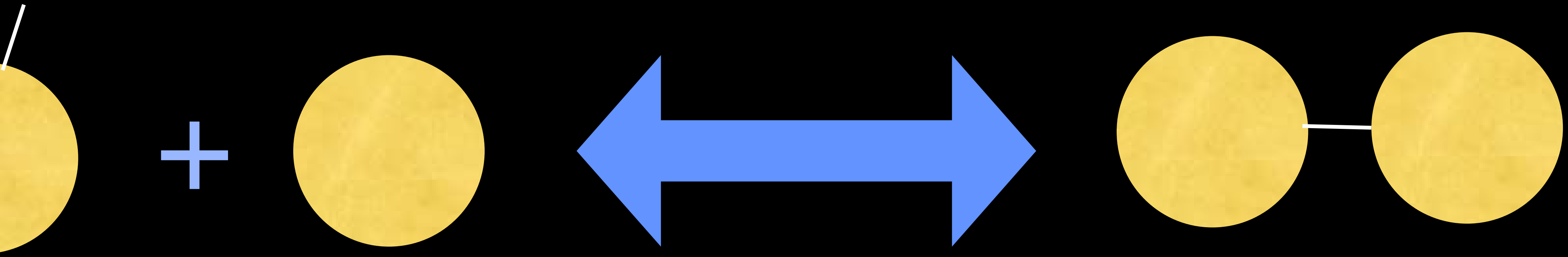
Binding energy of (Au_0-S)

electrostatic interaction < (Au_0-S) < covalent bond

le 3: Some head group examples useful for the applications

pplication	Common Head Group
on-fouling surfaces	PEG_n, Mannose
pecific binding receptors	Biotin, NTA, Peptide, Carbohydrates
ell supports	Peptide
olecular electronics	CH_3, SH
icroarrays	DNA, Peptide, PEG_n
eparations	NTA
urface reactions	Azide, COOH, NH_2, OH, SH

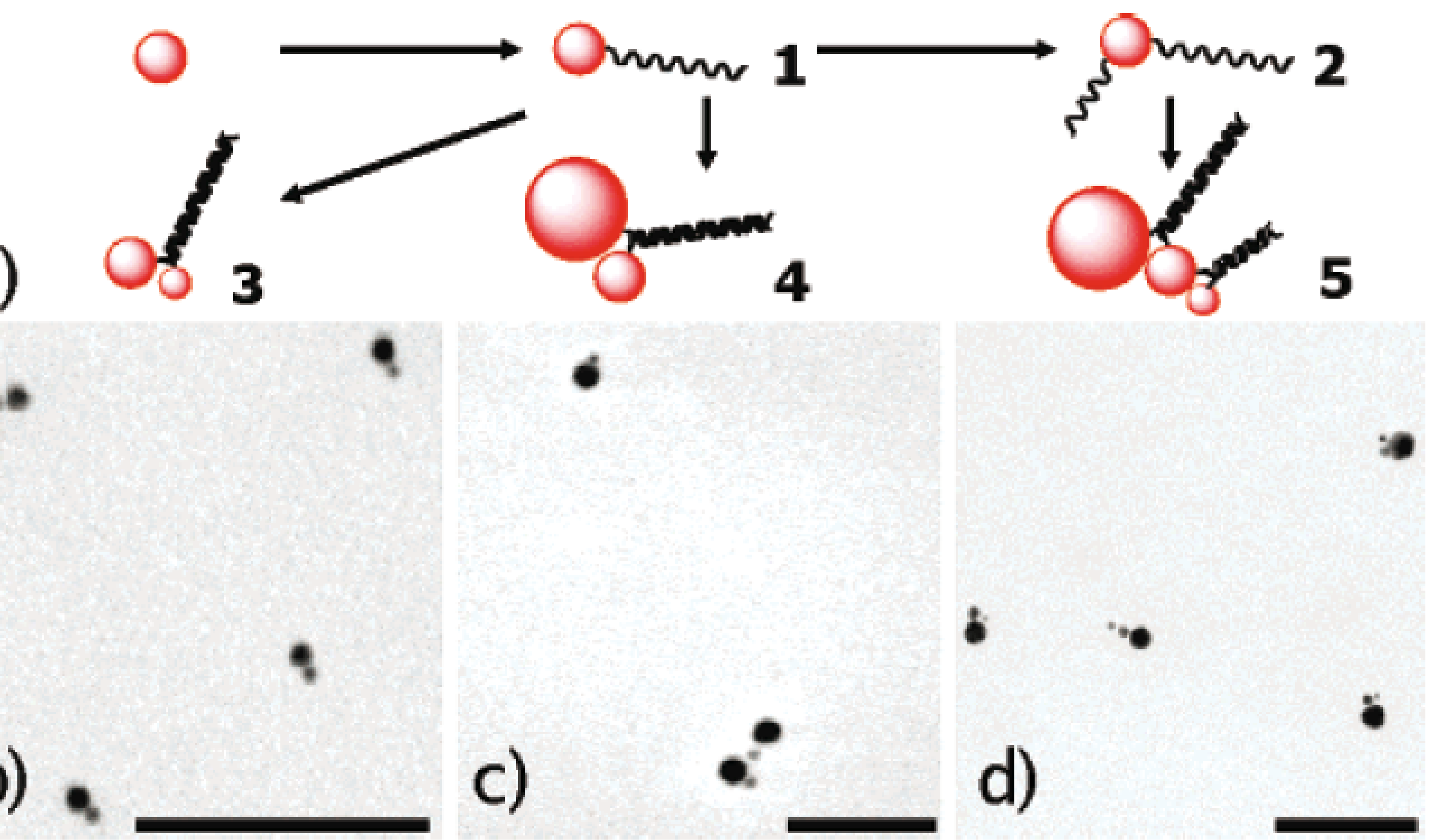
From colloids to complex architectures



architectures

ien Bidault,*,† F. Javier García de Abajo,‡ and Albert Polman†

thiolated



gure 1. (a) Nanoparticle assembly scheme. 8 nm diameter Au particles e attached to one 5′ thiolated 100b ss-DNA molecule to produce building ocks **1**. **1** is sequentially functionalized with a 5′ thiolated 50b ss-DNA olecule to yield **2**. Hybridization of **1** with 5 and 18 nm diameter Au rticles monofunctionalized with the 3′ thiolated complementary strand elds structures **3** and **4**. **5** is obtained by hybridizing **3** with 5 and 18 nm

ien Bidault,*,† F. Javier García de Abajo,‡ and Albert Polman†

architectures

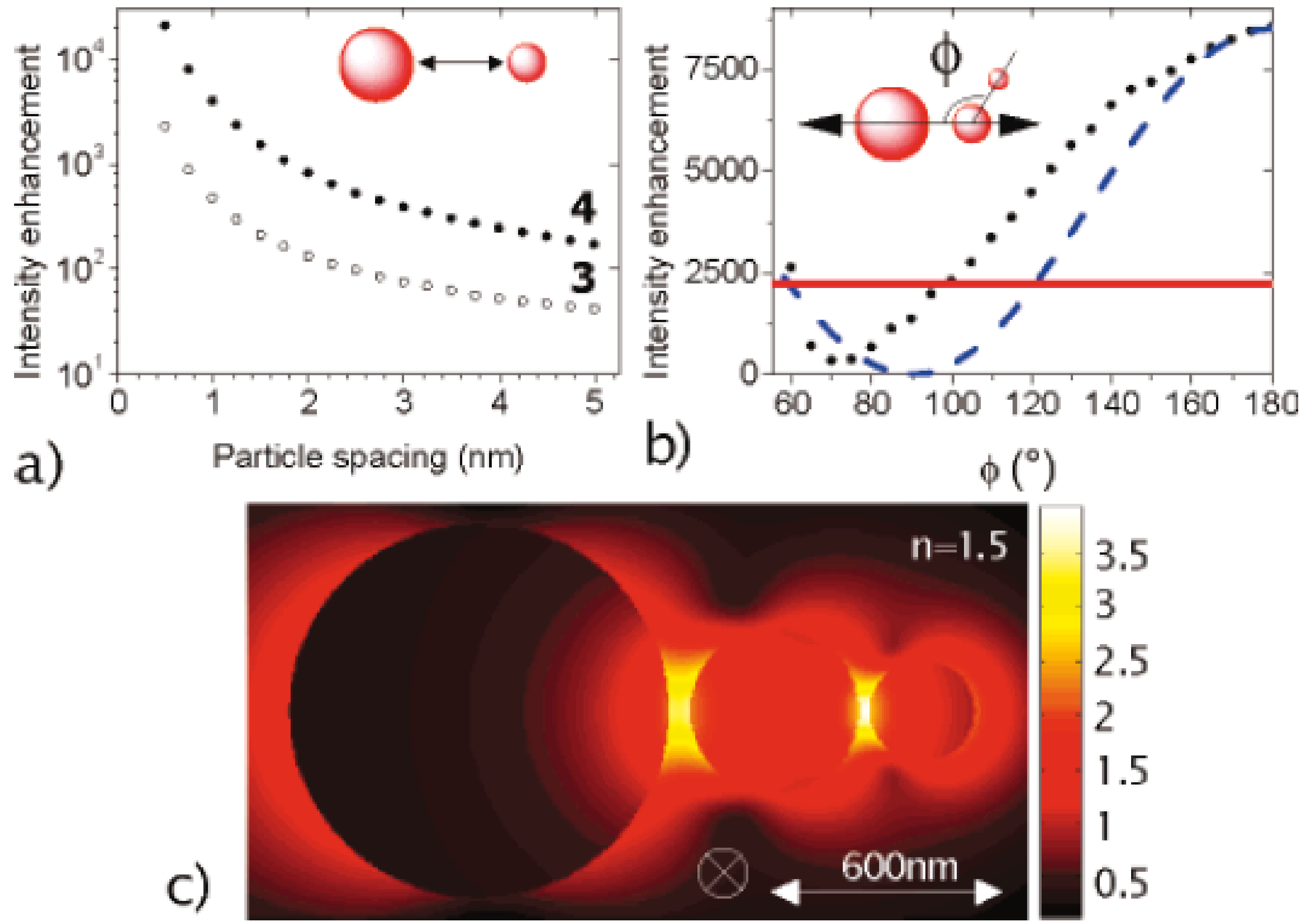
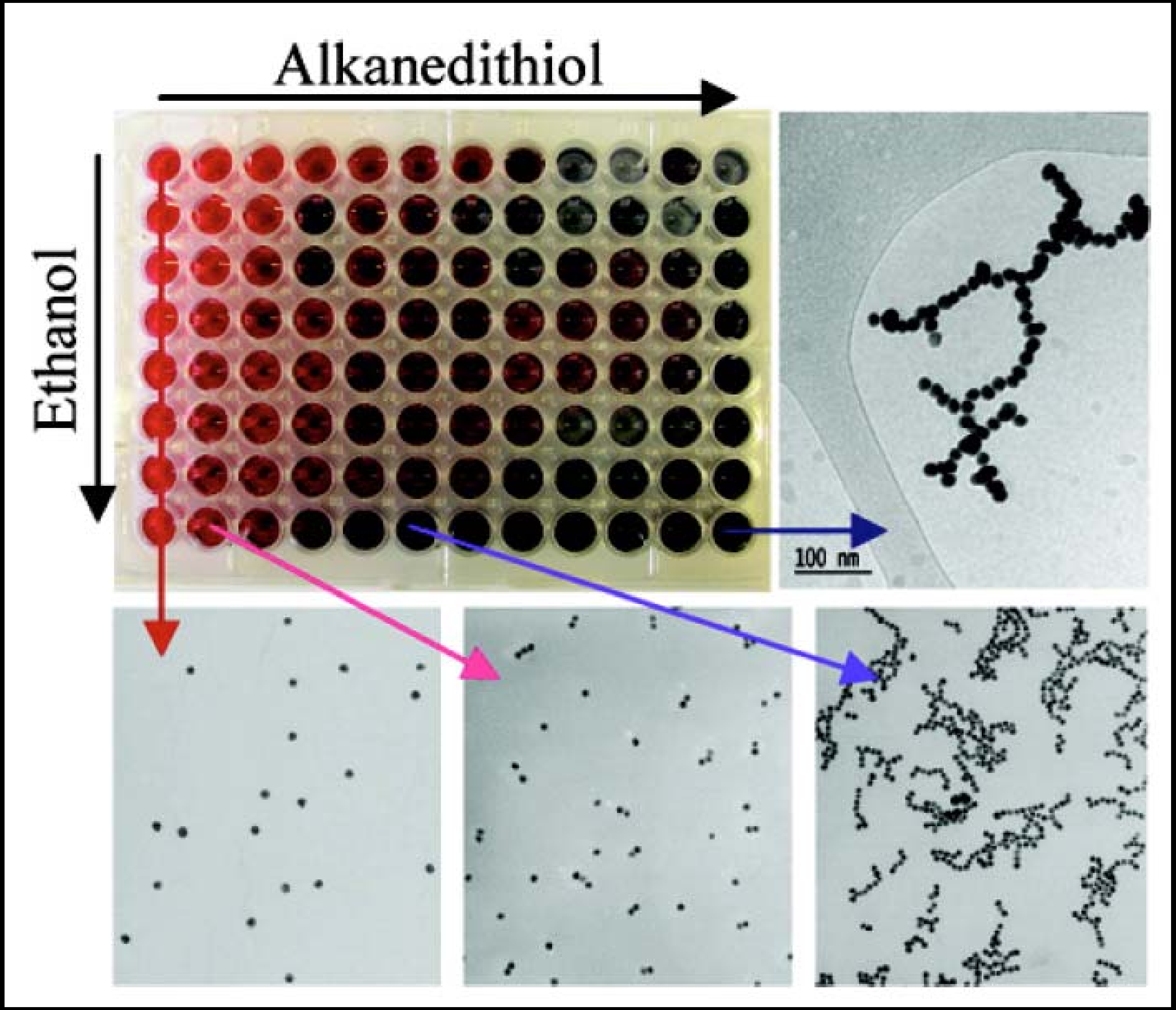


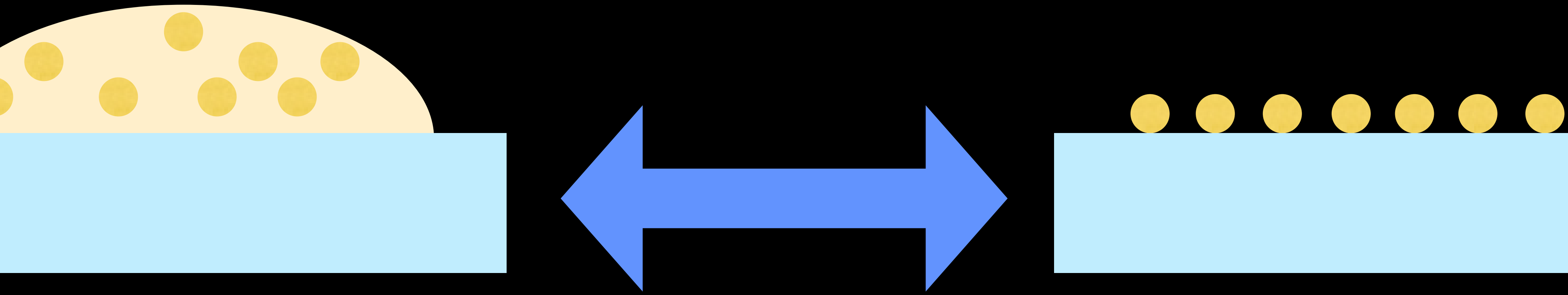
Figure 2. (a) Calculated maximum intensity enhancement (I^{enh}) in the gap of groupings **3** (○) and **4** (●) for particle spacings ranging from 0.5 to 5 nm ($n = 1.5$ dielectric environment). (b) Evolution of I^{enh} on the surface of the 5 nm particle in groupings **5** (1 and 0.5 nm spacings), for ϕ ranging from 60° to 180° and incoming polarization along the 8−18 nm particles axis. The red line corresponds to I^{enh} in grouping **3** for 0.5 nm spacing, and the dashed blue line is a $\cos^2(\phi)$ evolution. (c) I^{enh} (logarithmic scale) in aligned 18, 8, and 5 nm spheres with 1 and 0.5 nm spacings, respectively.

Langmuir, **Article ASAP** • DOI: 10.1021/la804207y

complex architectures



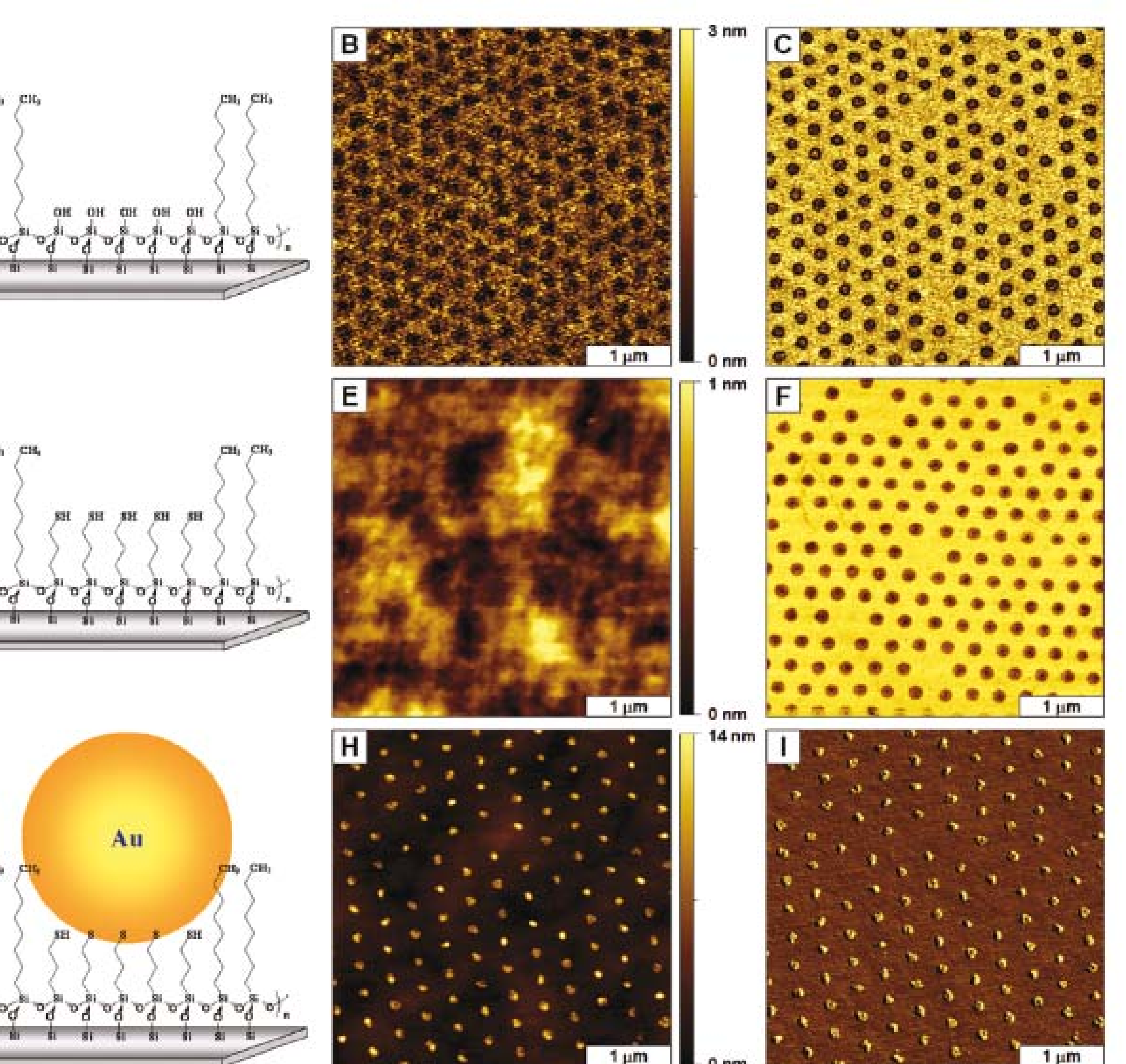
rom colloids to complex architectures: 1D to 2



on of Organosilanes

sker,† Jing-Jiang Yu,‡ and Jayne C. Garno†,*

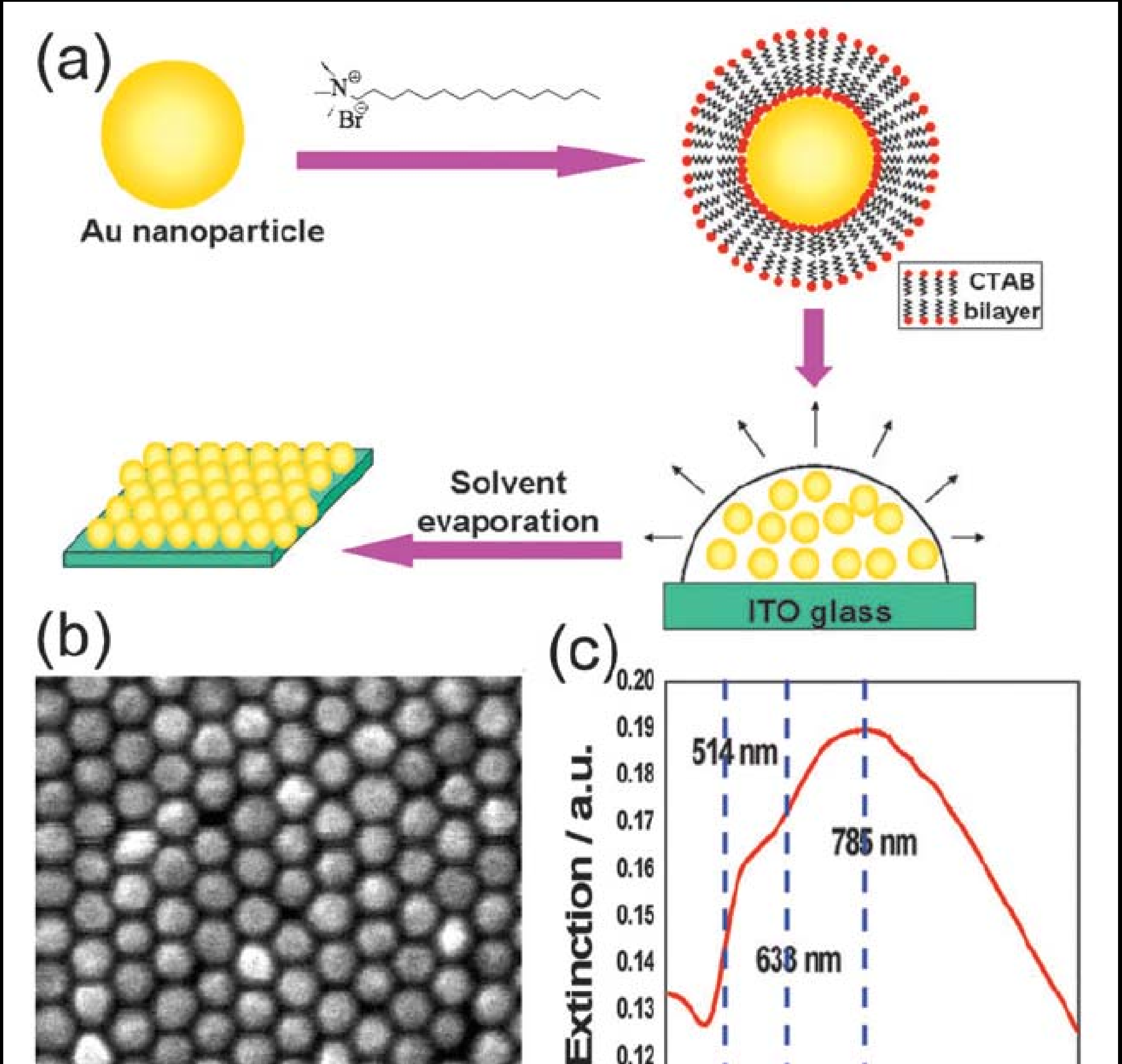
architectures: 1D to 2



Chemical nanopatternin

Pallandre et al. NanoLett 2
Plain et al. small 2006

architectures: 1D to 2



architectures: 1D to

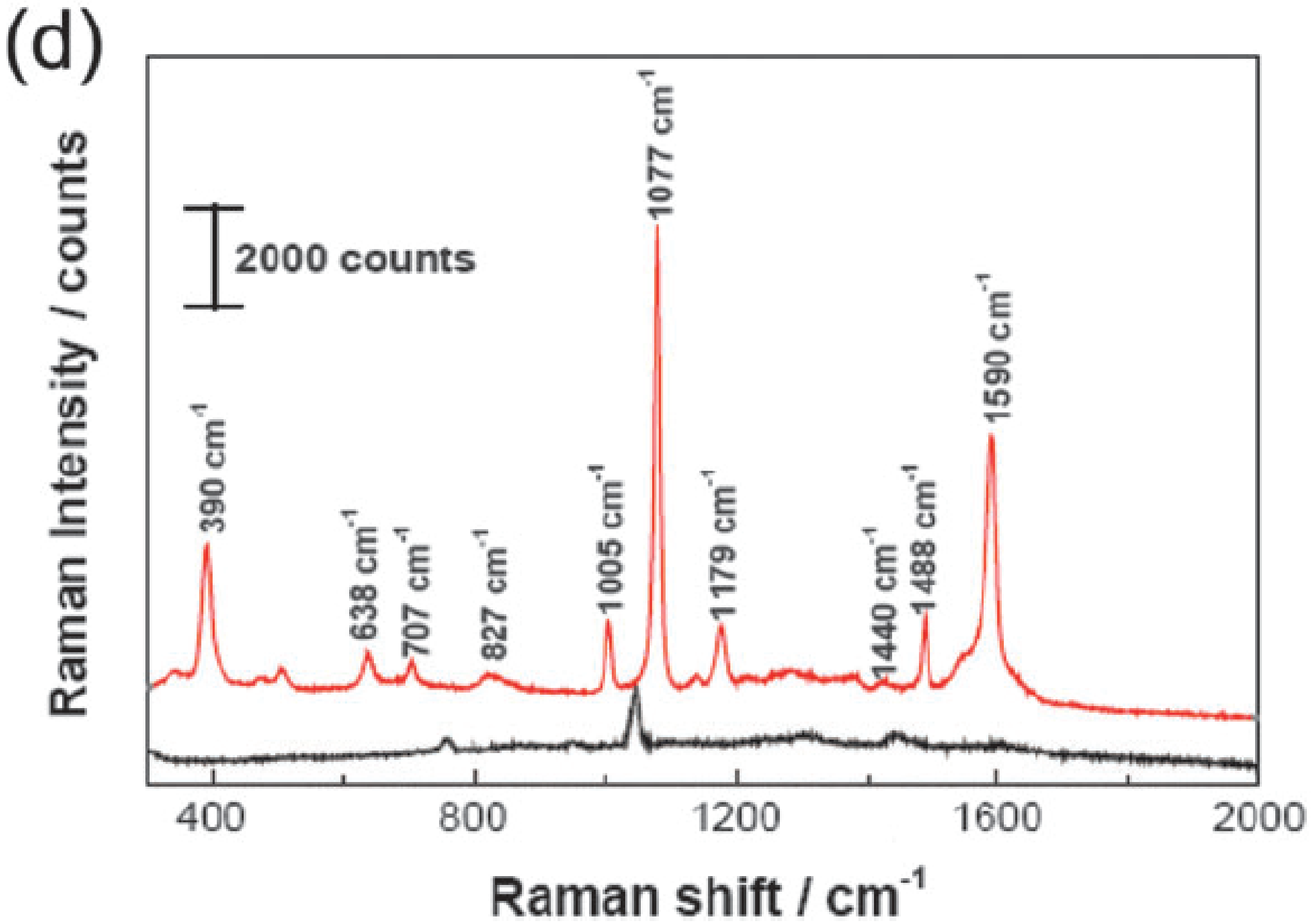


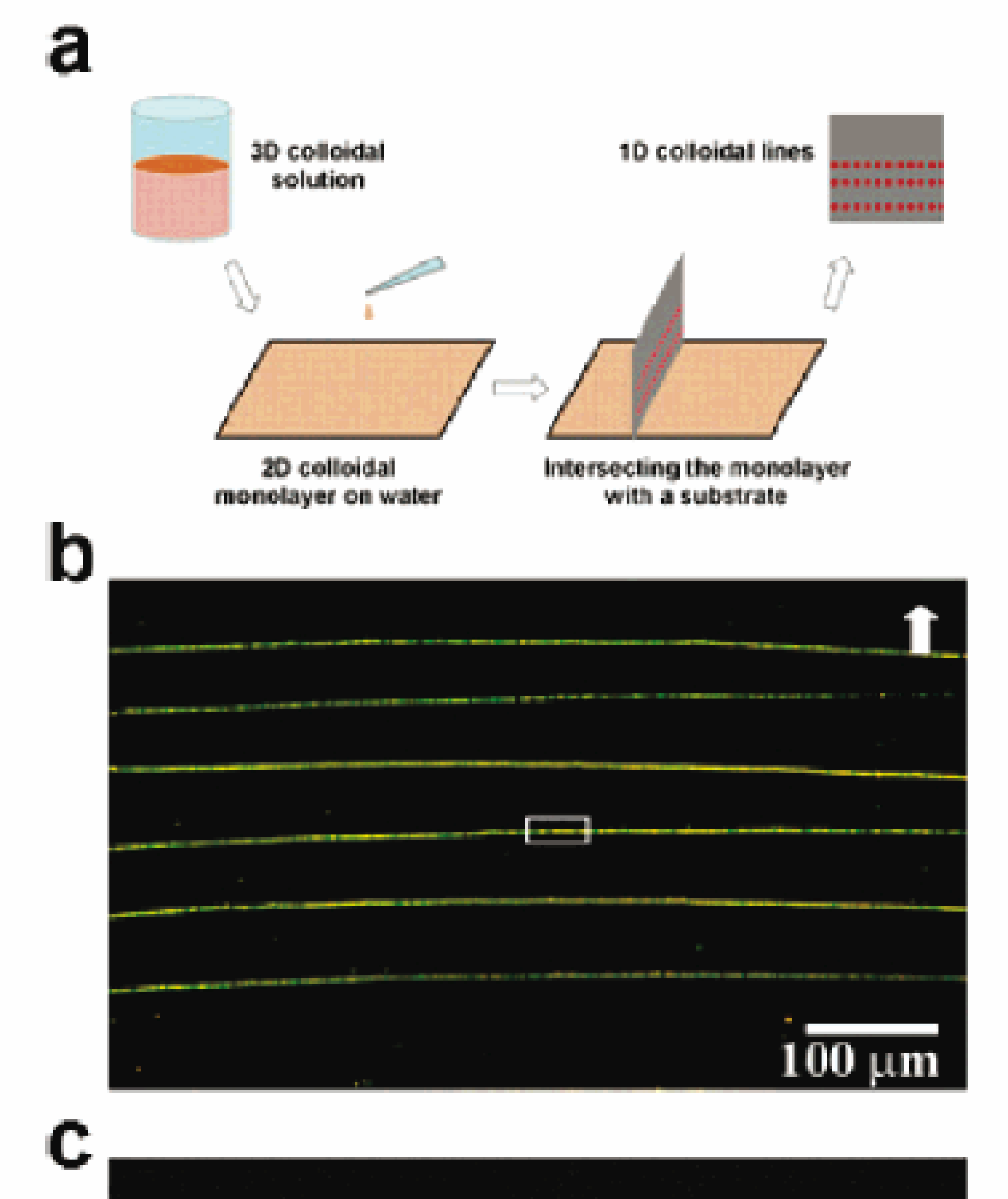
Fig. 9 (a) Schematic illustration of the fabrication of sub-10 nm gap Au NP arrays. (b) SEM image of a Au NP array on ITO glass. (c) Vis-NIR extinction spectrum of the NPs arrays (solid curve). (d) SERS spectra of *p*MA adsorbed on the Au nanosphere arrays. The red curve is a SERS spectra of *p*MA and the black curve is the spectra of Au

architectures: 1D to 2

Colloidal Particle Lines

Vol. 6, No. 3
524–529

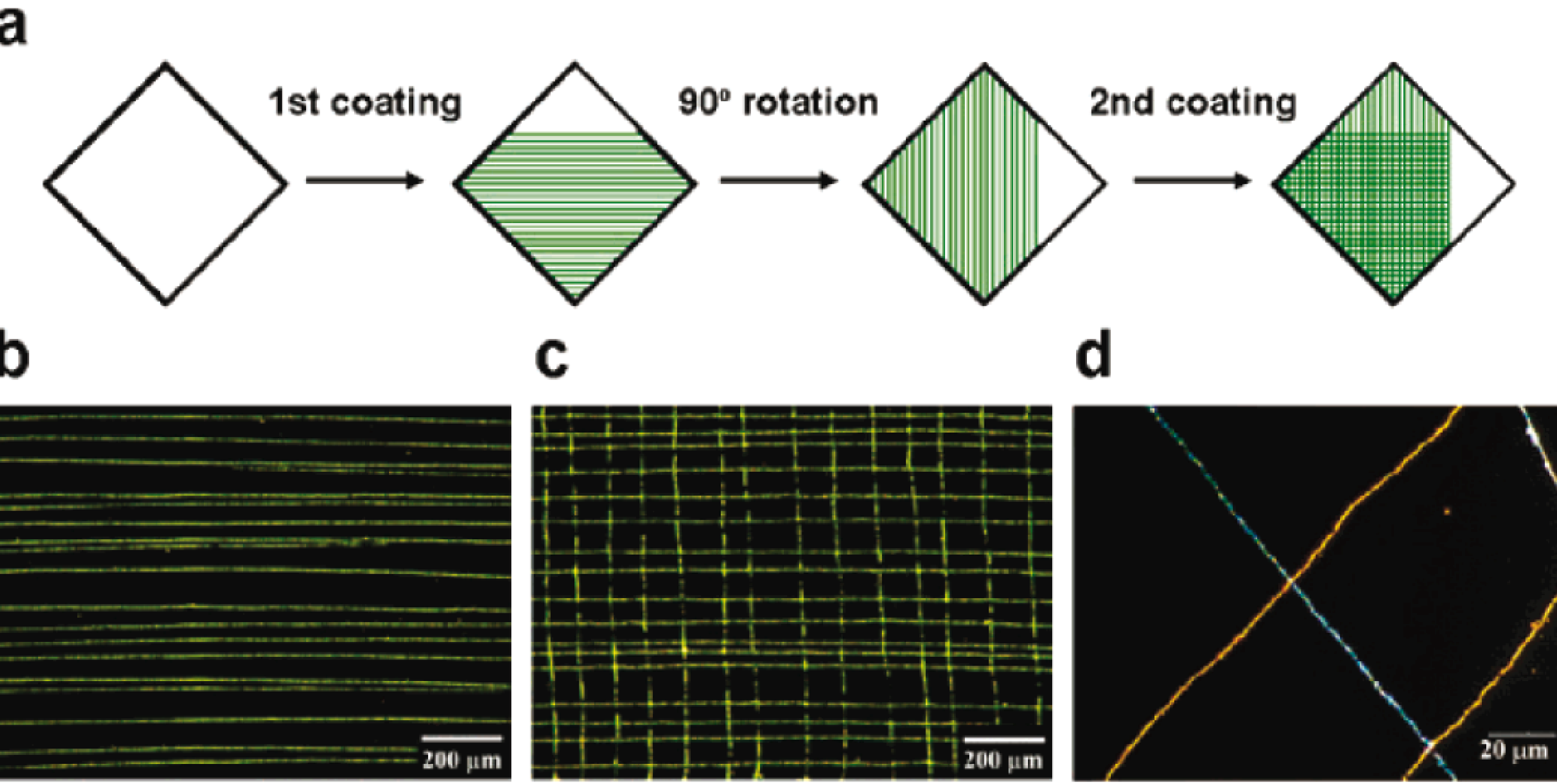
Andrea R. Tao, Stephen Connor, Rongrui He, and Peidong Yang*



lloidal Particle Lines

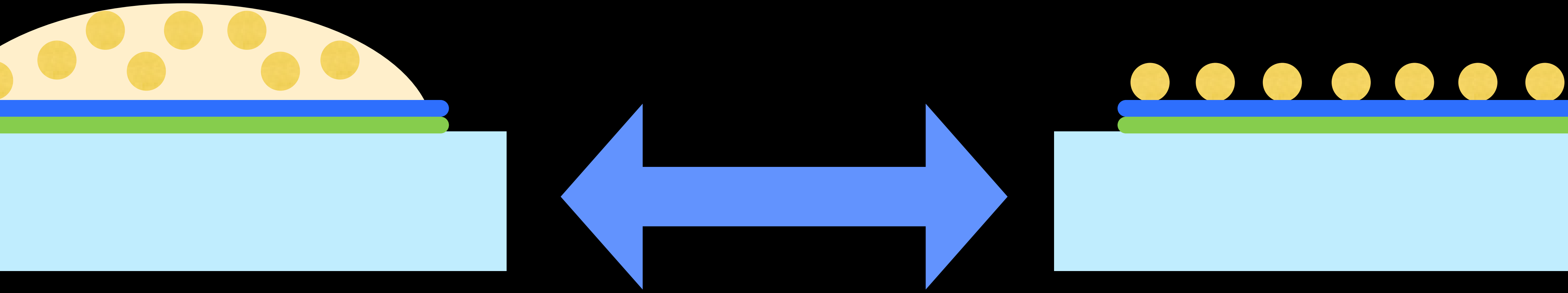
drea R. Tao, Stephen Connor, Rongrui He, and Peidong Yang*

architectures: 1D to 2



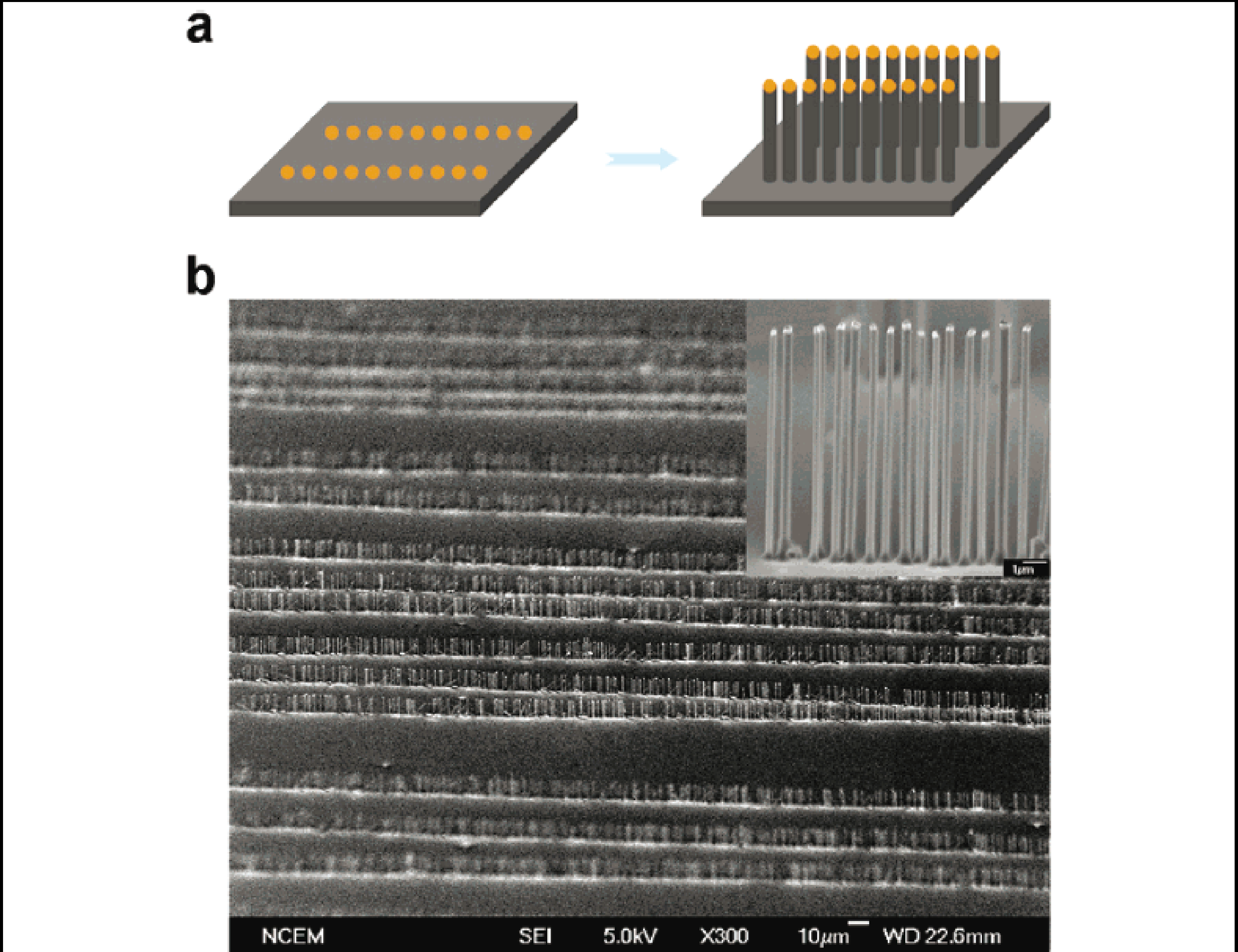
re 3. (a) Schematic diagrams illustrating the grid patterns obtained by two sequential crossed dip-coatings. Optical microscopy i ing (b) the Au single particle line pattern obtained by the first coating, (c) the grid pattern obtained by coating a second line p ndicular to the first one, and (d) hybrid Au−Ag grid pattern by two dip coating steps of Au and Ag nanoparticles, respectiv

rom colloids to complex architectures: 1D to 3



ea R. Tao, Stephen Connor, Rongrui He, and Peidong Yang*

architectures: 1D to 3



From colloids to hybrid architectures

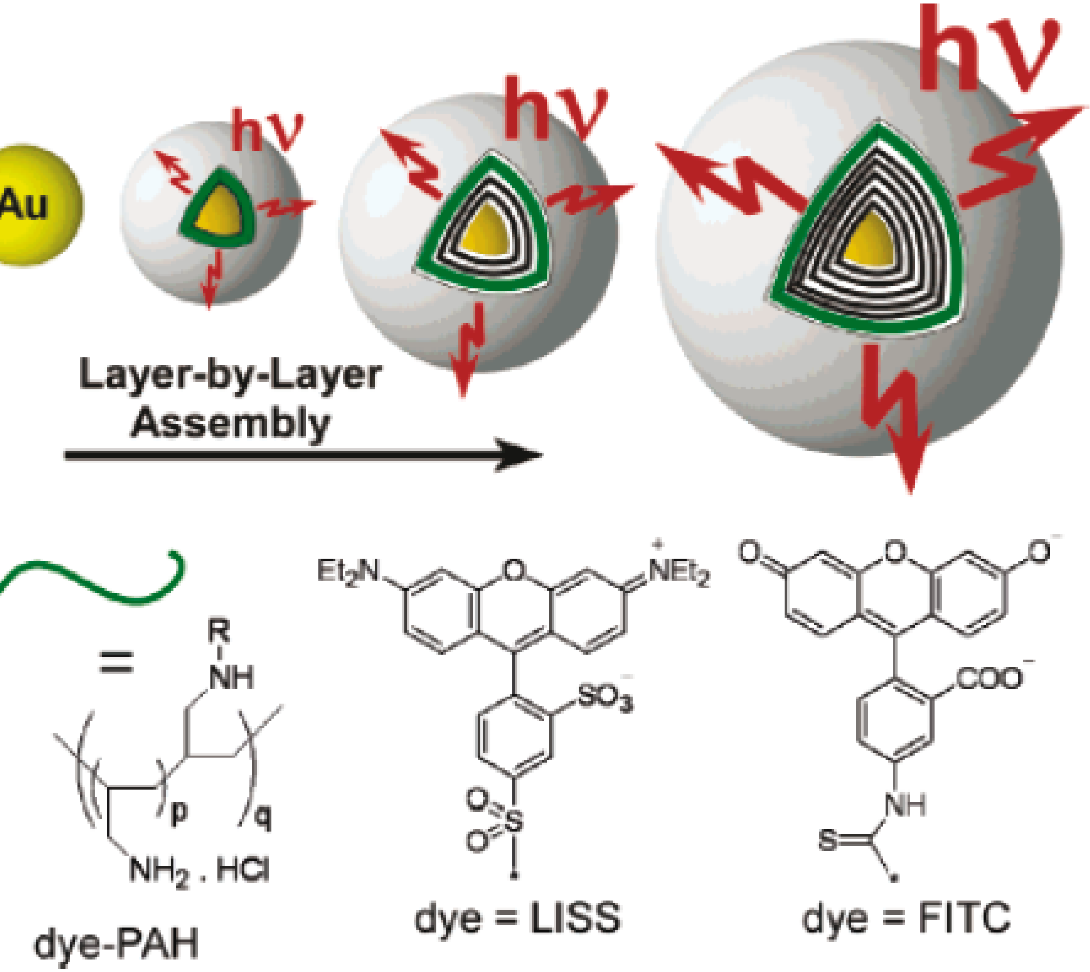
architectures

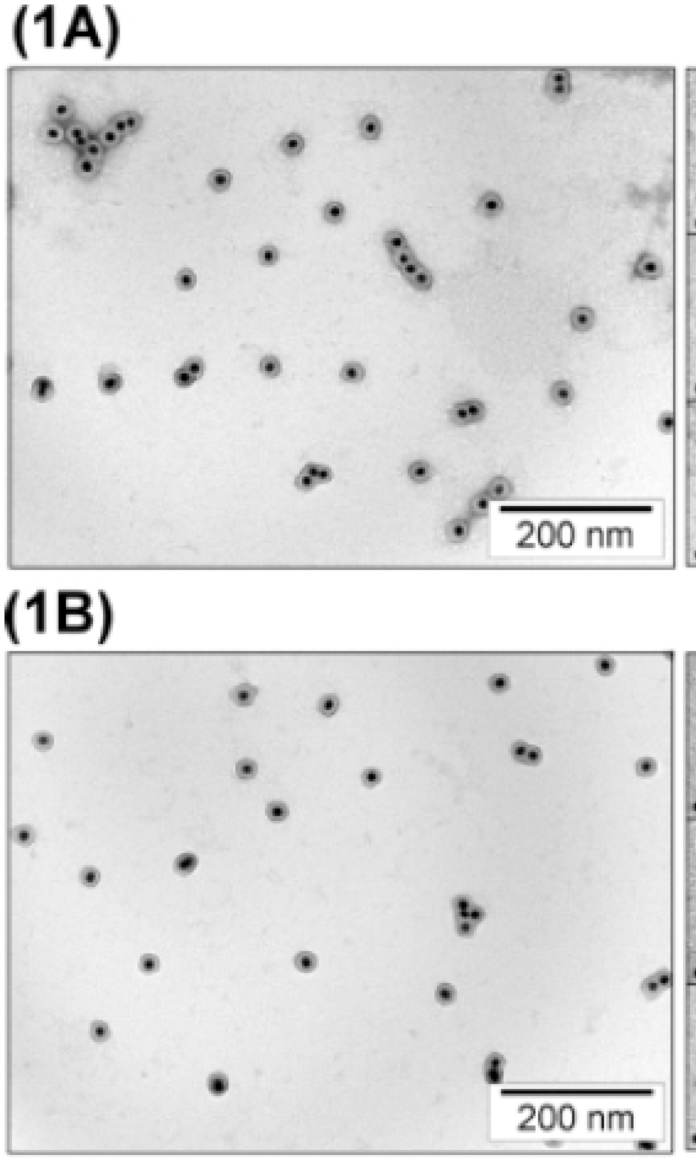
ng on Gold Nanoparticles
hed with Layer-by-Layer
led Polyelectrolytes

ler and Gero Decher*

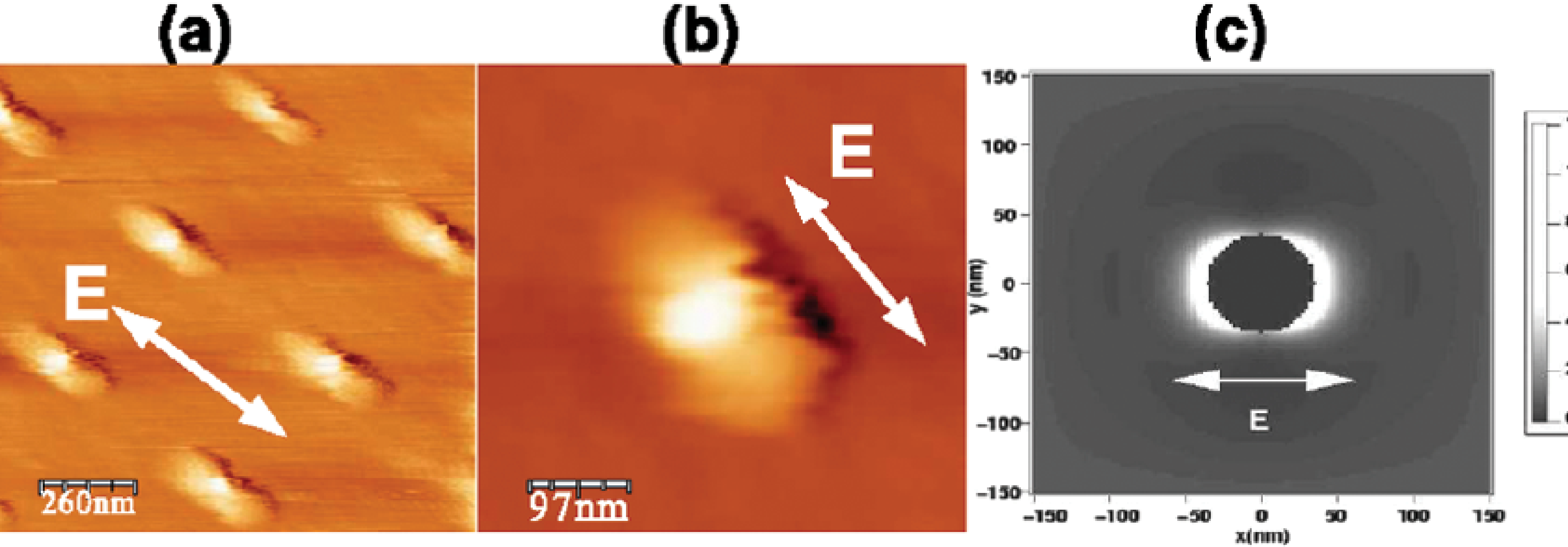
530–536

ne 1. Layer-by-Layer Assembly for the Construction of re–Shell Nanoparticles Containing Fluorescent Corona Layers[a]





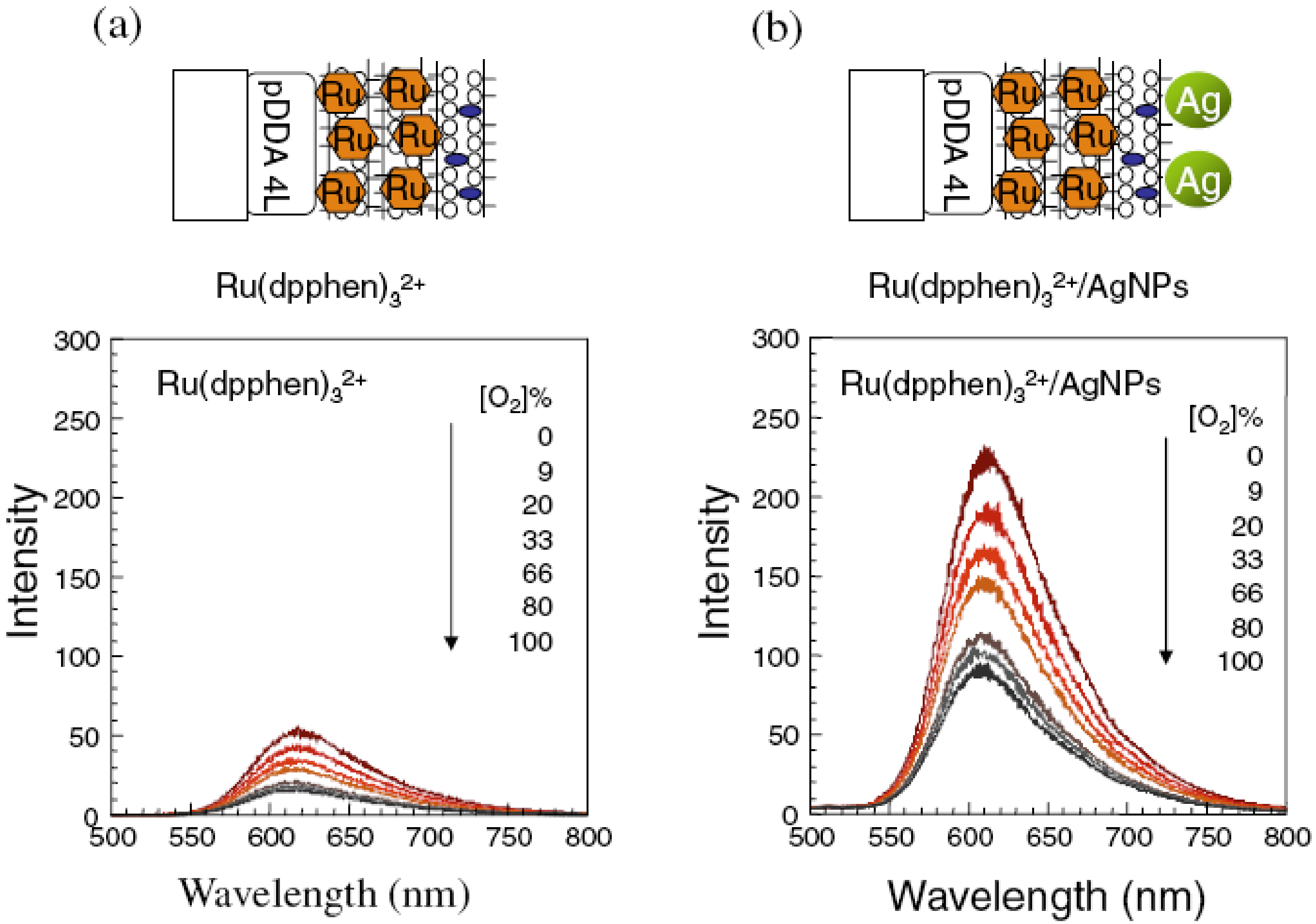
architectures



IG. 2 (color). (a) and (b) AFM images recorded after irradia ion and developing of the silver nanoparticles arrays covere ith the photopolymerizable formulation. (c) Intensity distribu ion in the vicinity of an Ag particle embedded in the formulatio s calculated by FDTD method ($\lambda = 514$ nm). The white arro

MITSUISHI,[†] Miki ISHIFUJI, Hiroshi ENDO, Hiroyuki TANAKA, and Tokuji MIYASHITA

architectu

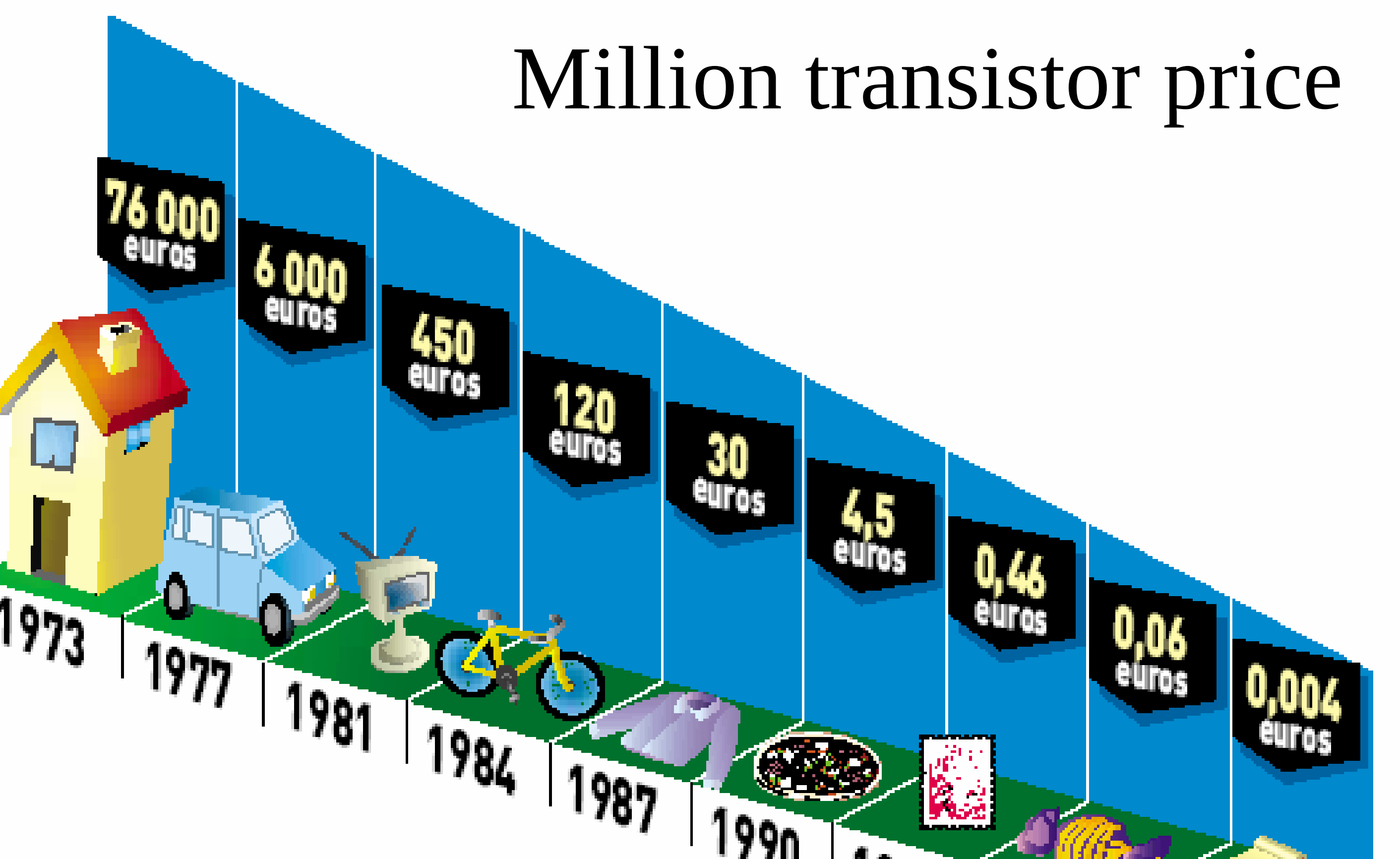


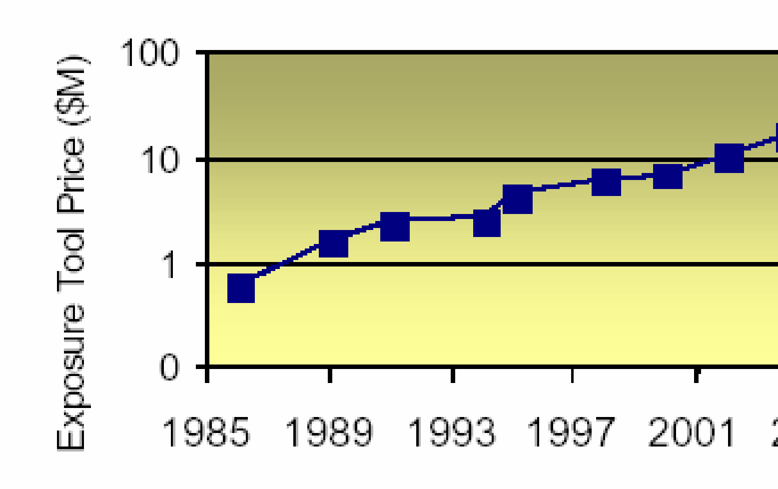
9. Luminescence spectra of (a) four-layer p(DDA/Ru) nanosheets and (b) four-layer p(DDA/Ru) nanosheets + Ag
ey were assembled on quartz slides.

Emerging methods
and
Fourth coming issues

Applicatio

How fast, how small and how large?
Solution : being able to write fast and small on a large surface, VLSI





architecture

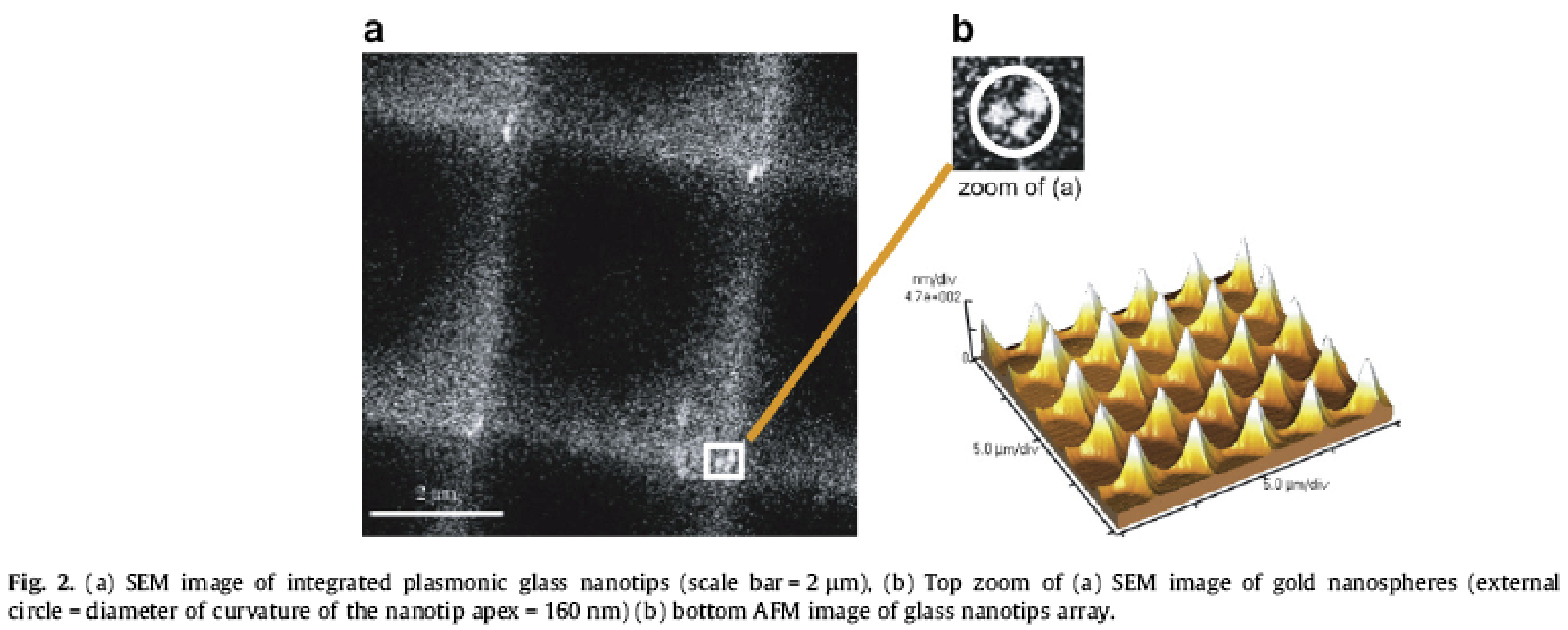
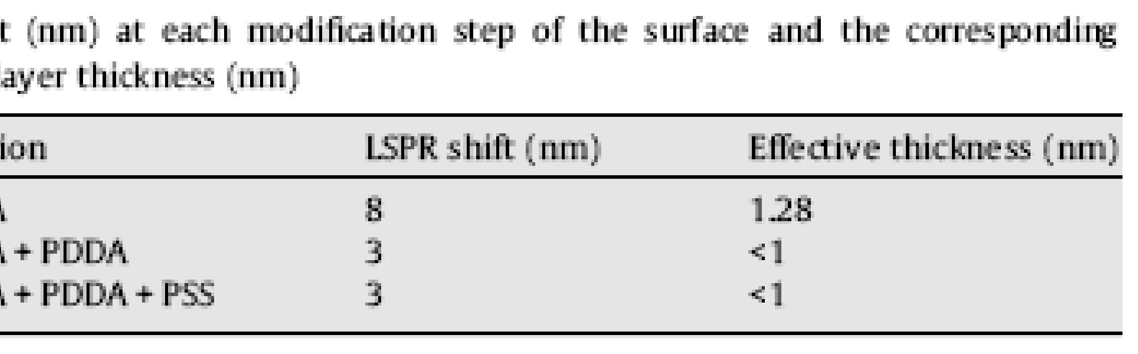


Fig. 2. (a) SEM image of integrated plasmonic glass nanotips (scale bar = 2 µm). (b) Top zoom of (a) SEM image of gold nanospheres (external circle = diameter of curvature of the nanotip apex = 160 nm) (b) bottom AFM image of glass nanotips array.



t (nm) at each modification step of the surface and the corresponding ayer thickness (nm)

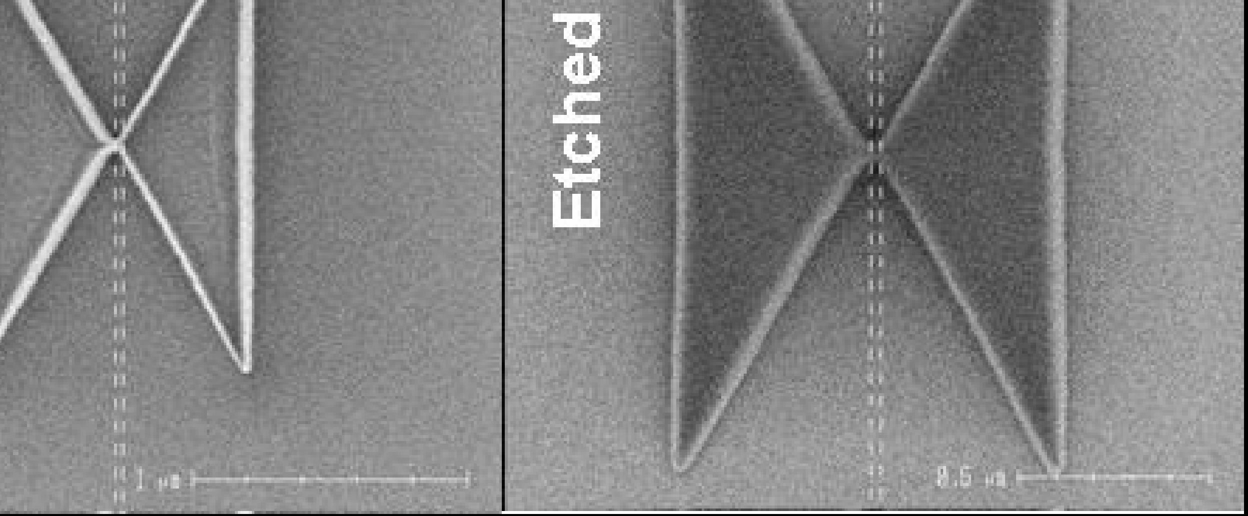
ion	LSPR shift (nm)	Effective thickness (nm)
A	8	1.28
A + PDDA	3	<1
A + PDDA + PSS	3	<1

1. Surface functionalization

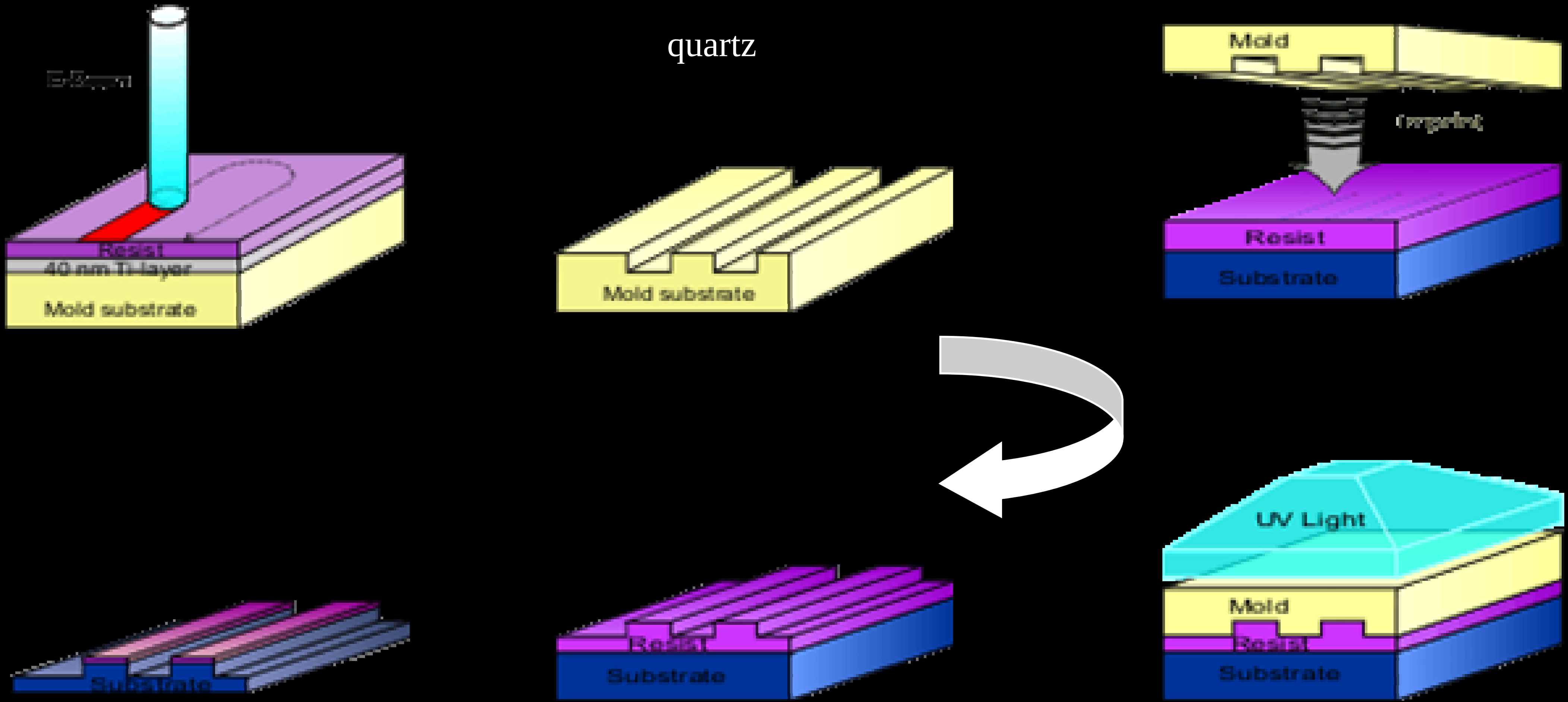
(40 nm gold particle grafting)

2. Holographic patterning

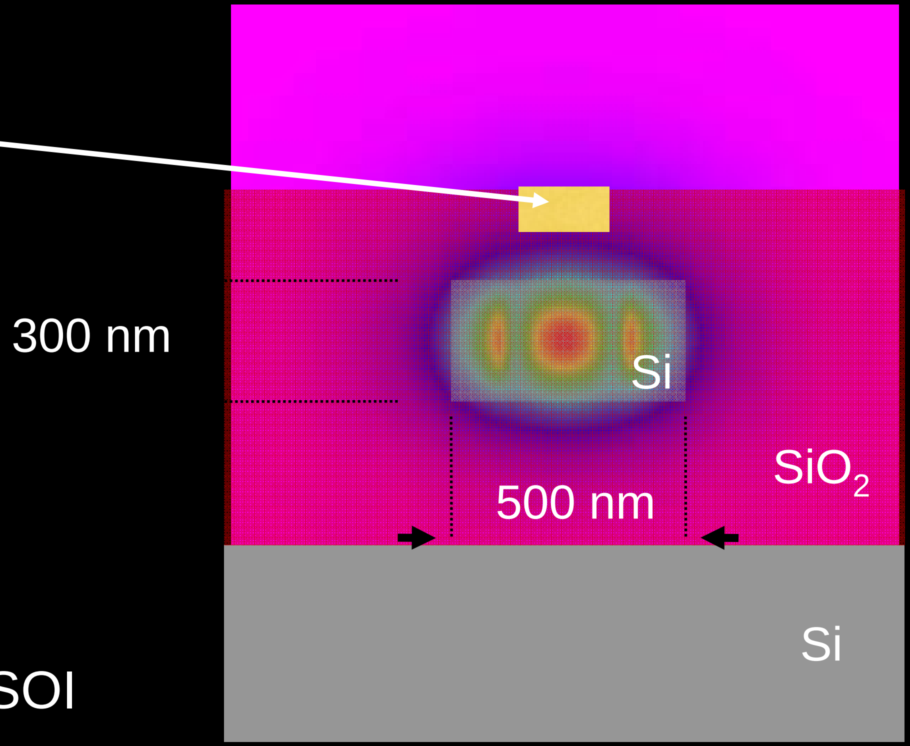
3. Glass wet etching



Courtesy of S. Landis CEA/LETI



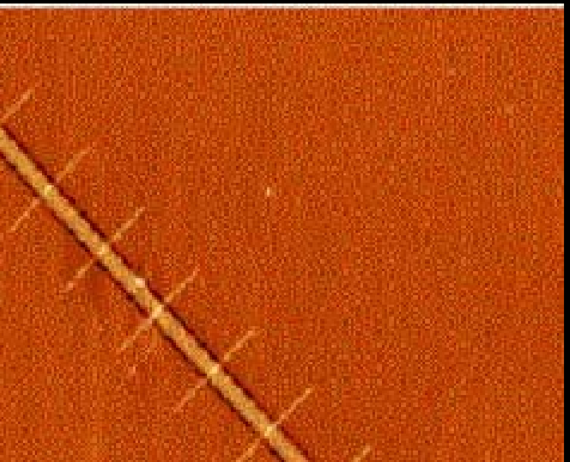
Ultimate refractive silicon photonics



$$\Delta n > 2$$
$$E_{surface} < 1\% \, E_{guided}$$

SWIFTS

ne of the first metallic
structures realized on SOI
vaveguiding structure



PLACIDO ANR proje

See Poster session today M. Février p5

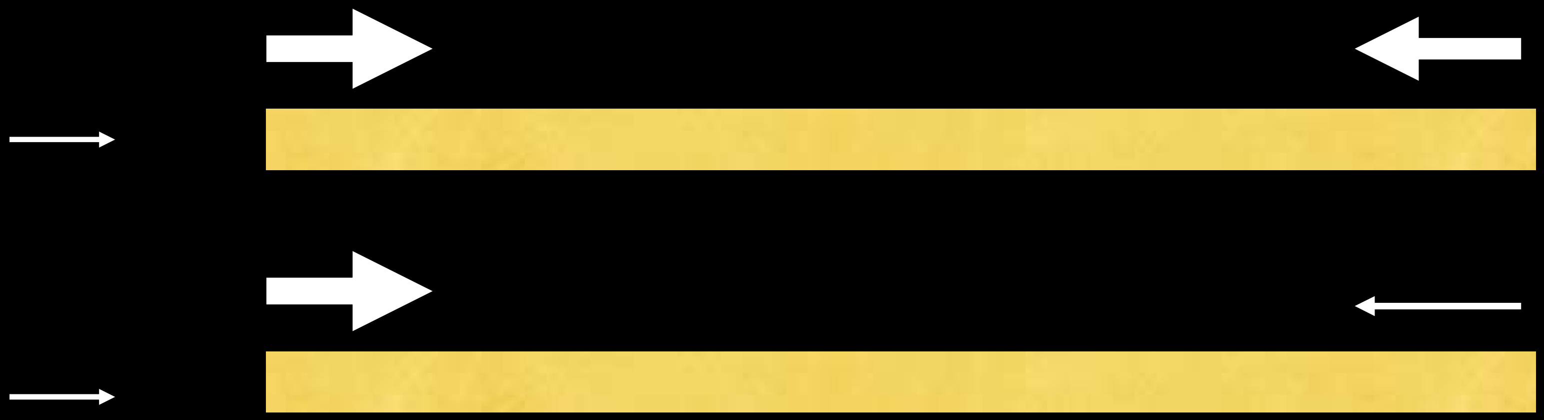
related issu

Gold ⇒ Cupper

Alloy

Crystal quality

Diltbacher et al. PRL 95, 257403 (2



emically
ynthized

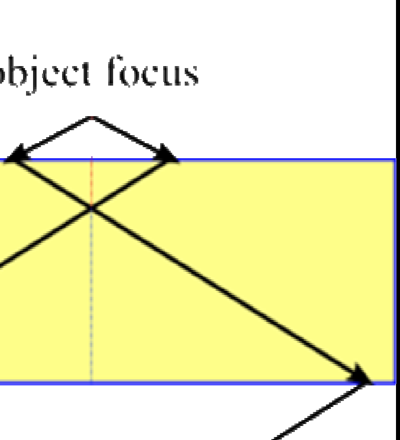
m fabricated

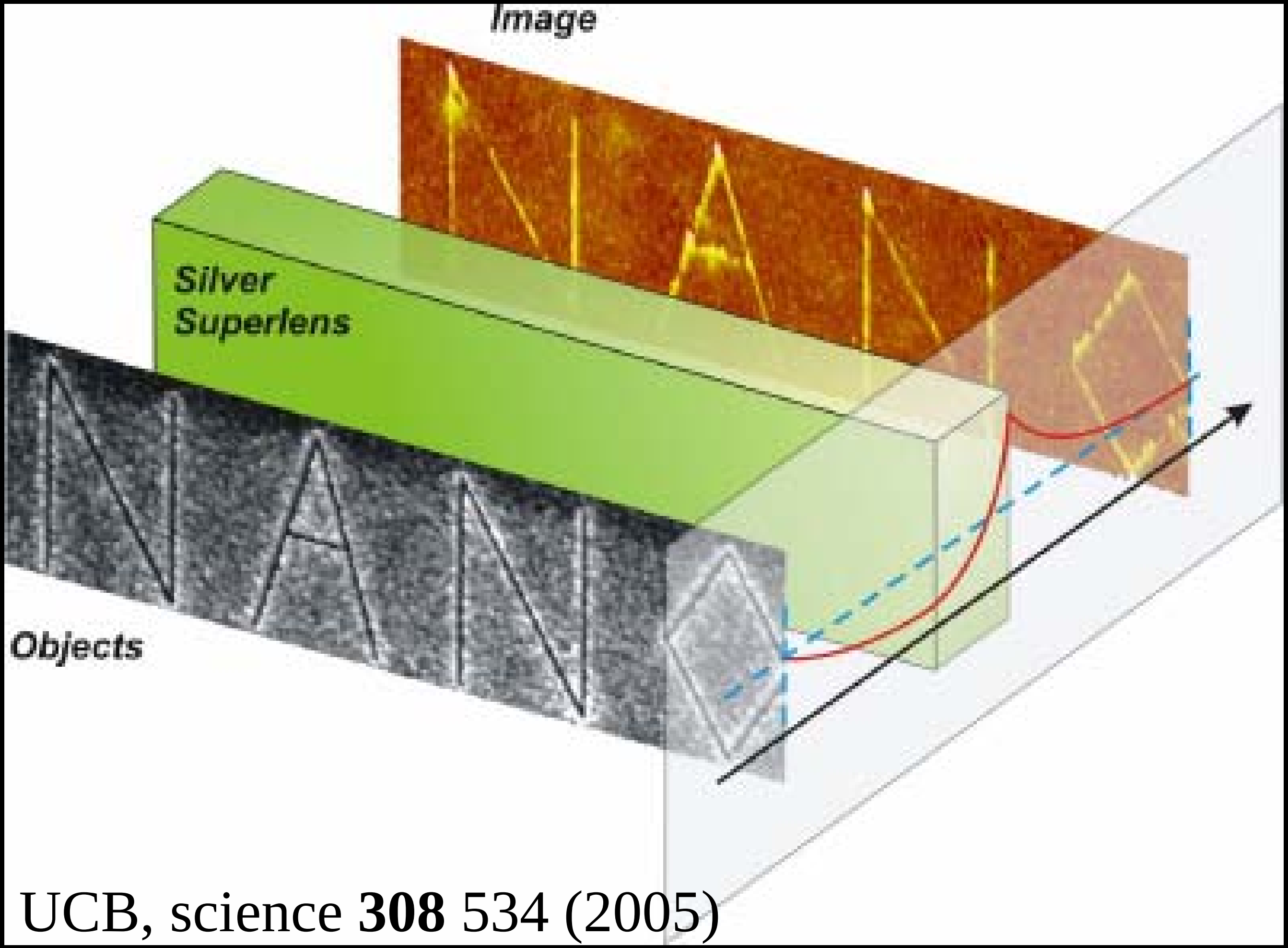
Plasmonics for nanofabrication

SP assisted lithograph

Superlens

PRL **85** (2000)

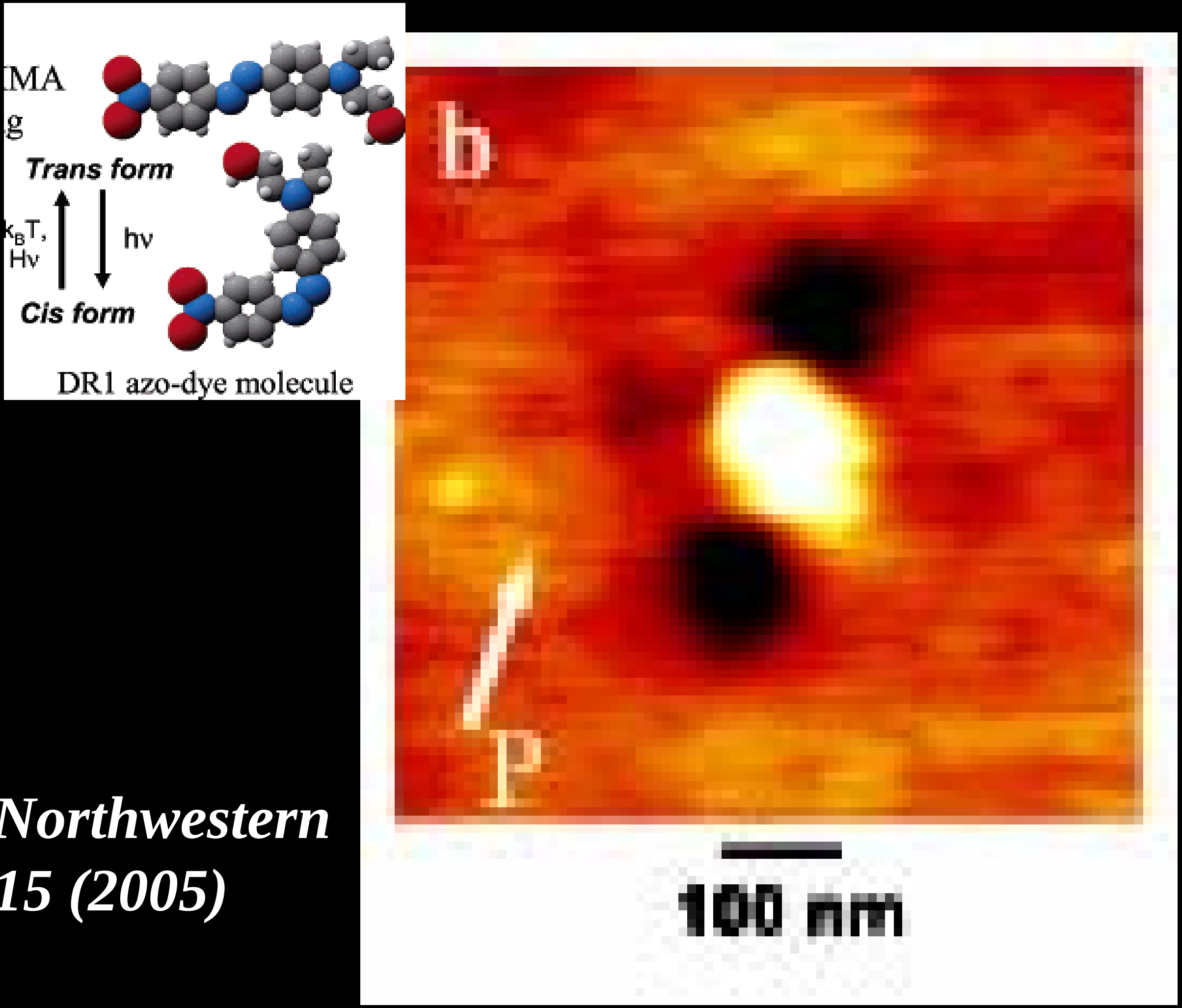




UCB, science **308** 534 (2005)

lithograph

Localized plasmons assisted « lithography »



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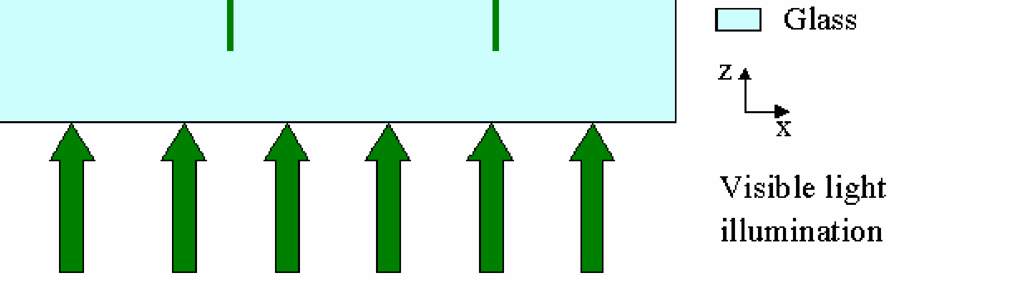
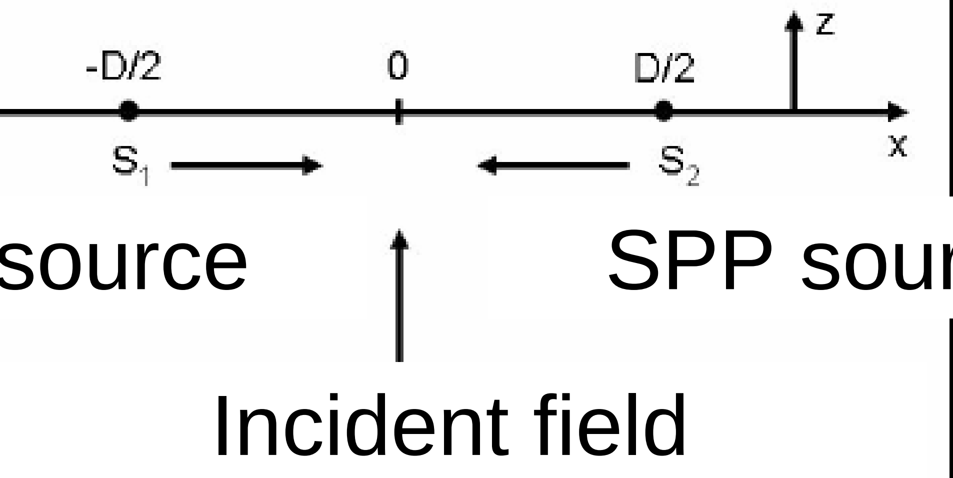


lithograph

nons interferences printing

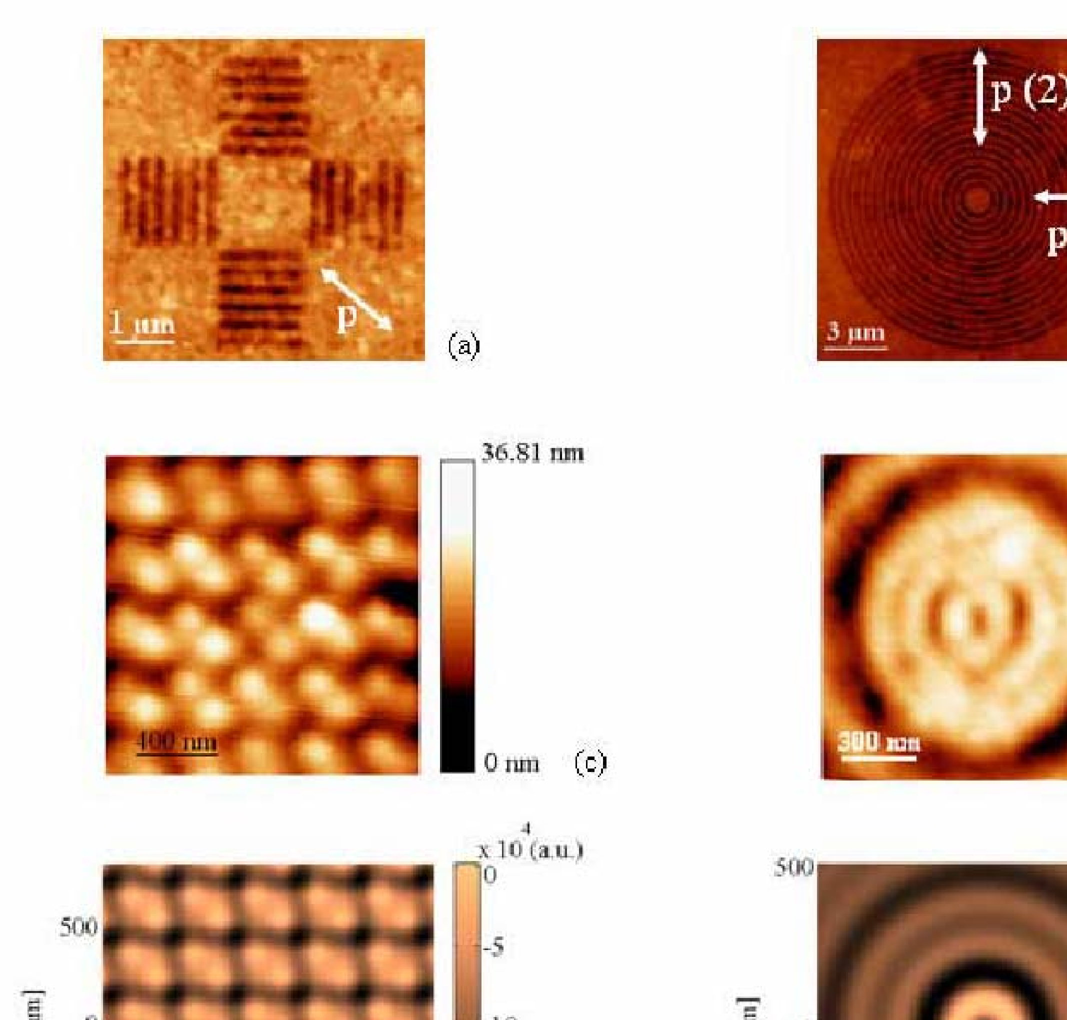
$\lambda_{sp} = \lambda / \mathrm{Re}(n_{eff})$



source

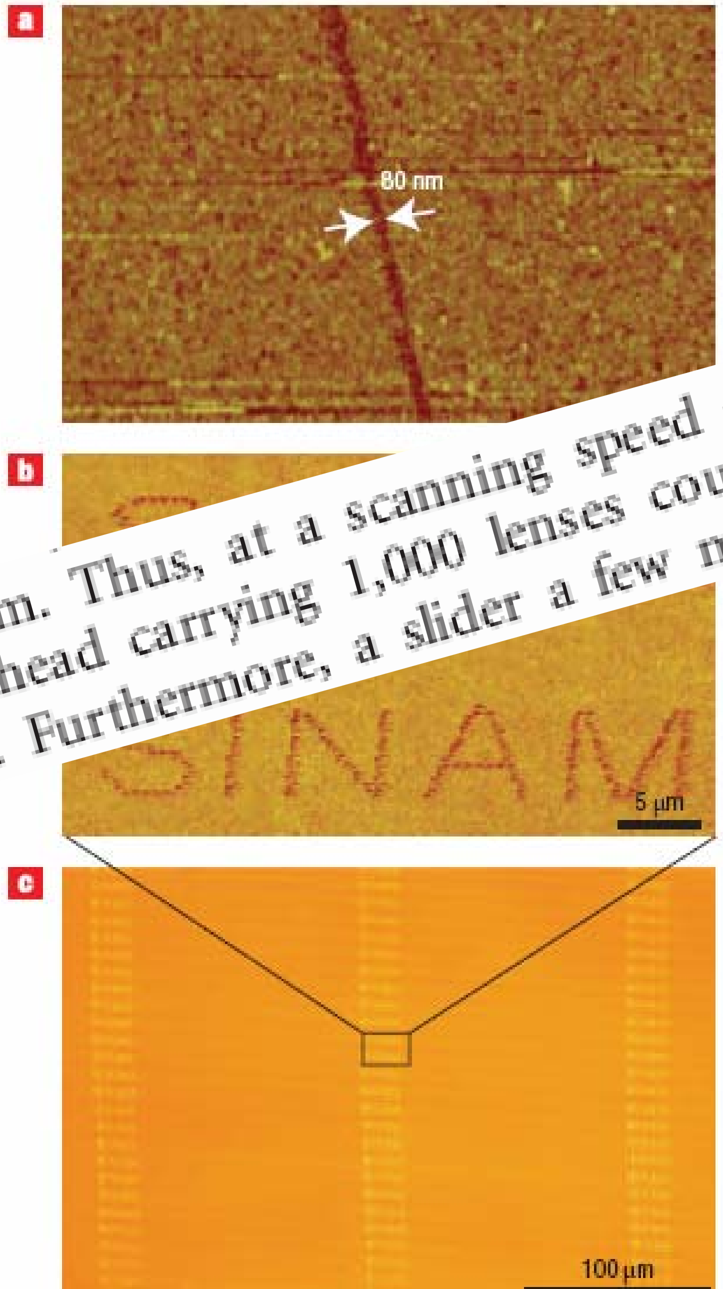
SPP source

Incident field

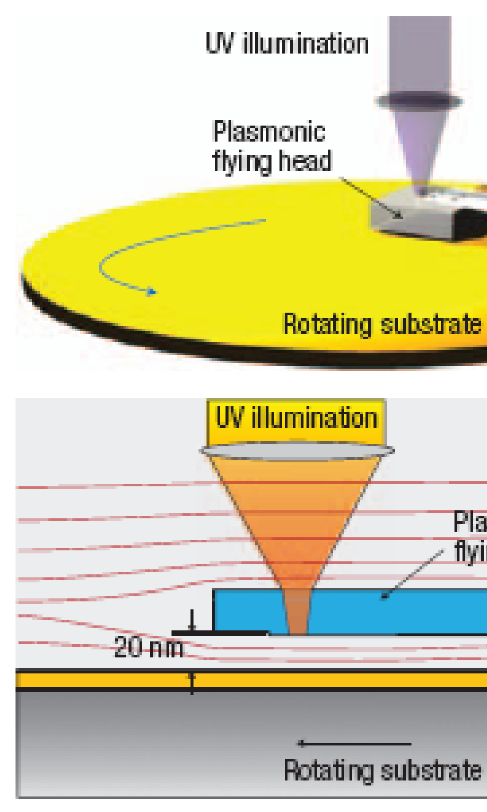


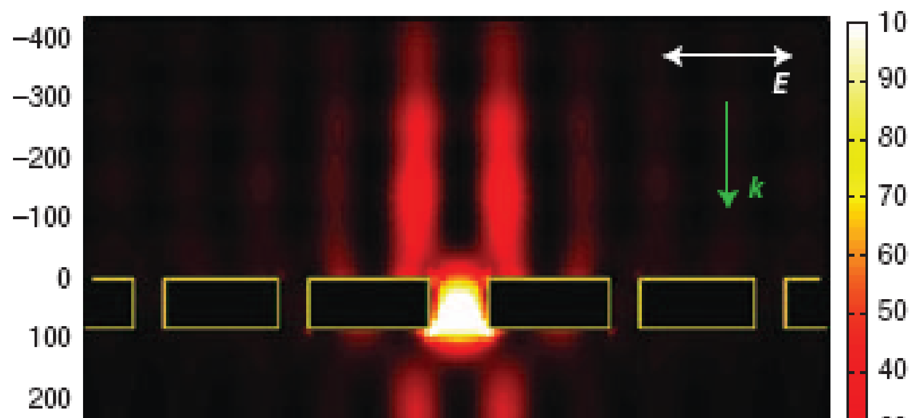
VANICH†, LIANG PAN†, YUAN WANG†, CHENG SUN, DAVID B. BOGY
*
ngineering, University of California, Berkeley, California 94720-1740, USA
qually to this work.

Plasmo lithograp



nm. Thus, at a scanning speed of 10 m s^{-1}, a plasmonic
g head carrying 1,000 lenses could write a 12 in. wafer in
n. Furthermore, a slider a few millimetres in size may take





Concluding remarks

Nanofrabrication ⇔ plasmonics

Combination of techniques is required

including soft chemistry routes

and 3D nanoobjects assembly

Coming issues:

Silicon photonic integration

Elaboration of (hybrid) functional Materials

Thank you