Fabrication methods for nanophotonics

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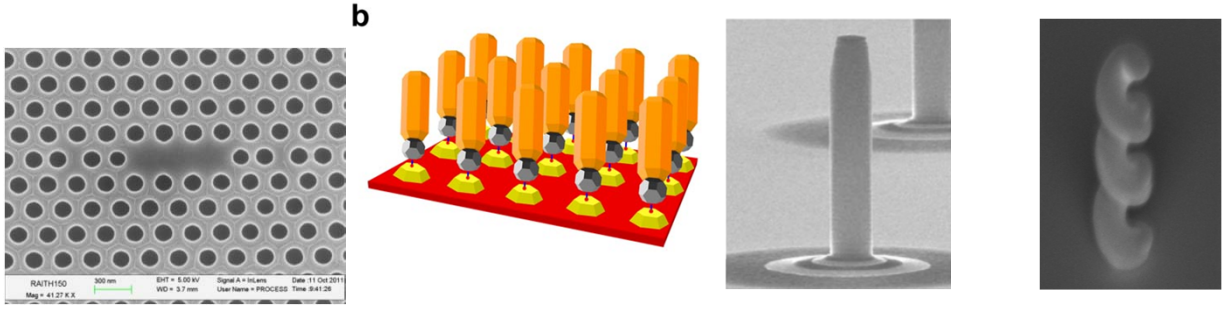
Outline

- Introduction
- Strategies for Nanofabrication
  - Self assambling method
    - Epitaxial Quantum dot
    - Nanowires
  - Strain driven 3D nanostructures
  - Ion Beam Induced Deposition (IBID) and nanostructuring

INTRODUCTION

Nanophotonics:

Is defined as the science of light-matter interactions that take place on wavelength and subwavelength scales, where natural or artificial nanostructured material controls the interaction .

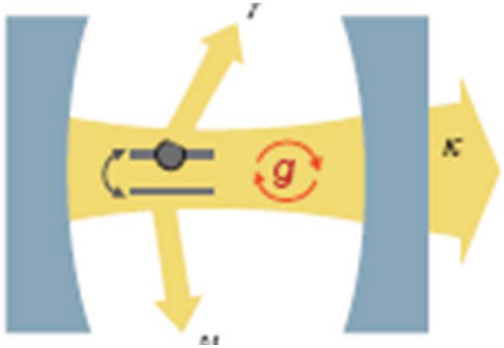


Nanophotonics is where photonics merges with nanoscience and nanotechnology, and where ***spatial confinement*** considerably modifies light propagation and light-matter interaction.

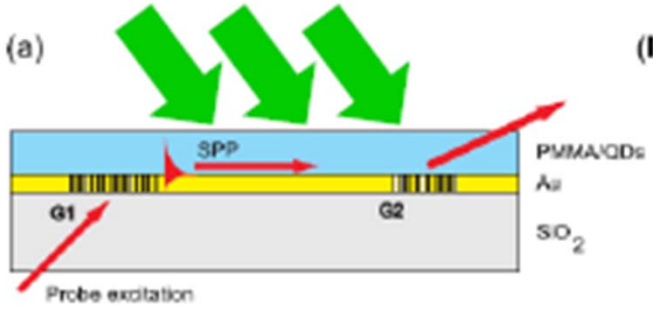
Fundamental nanophotonic systems

Nanophotonics devices

Generally they requires tight confinement and low-intensity operation down to the single-photon level. This is achieved fundamentally by two ways: resonant enhancement in dielectric structures where cavity **quantum electrodynamics** (CQED) effects can be exploited , or **plasmonic enhancement** using metals



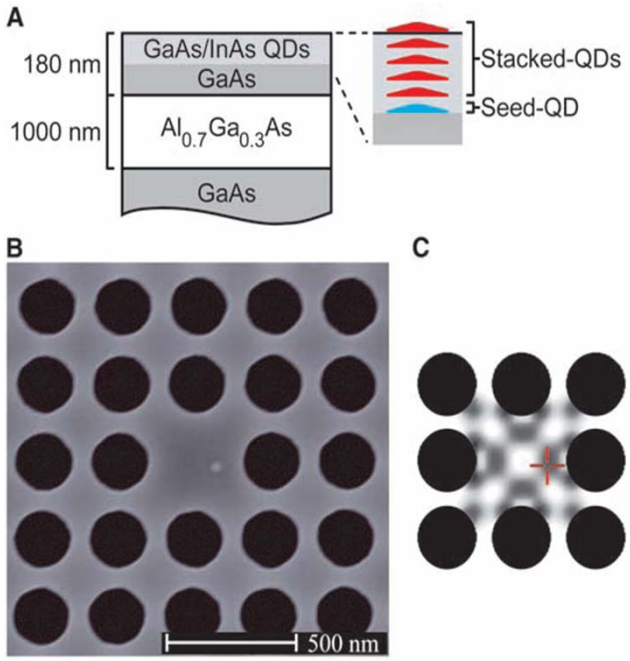
diffraction limited



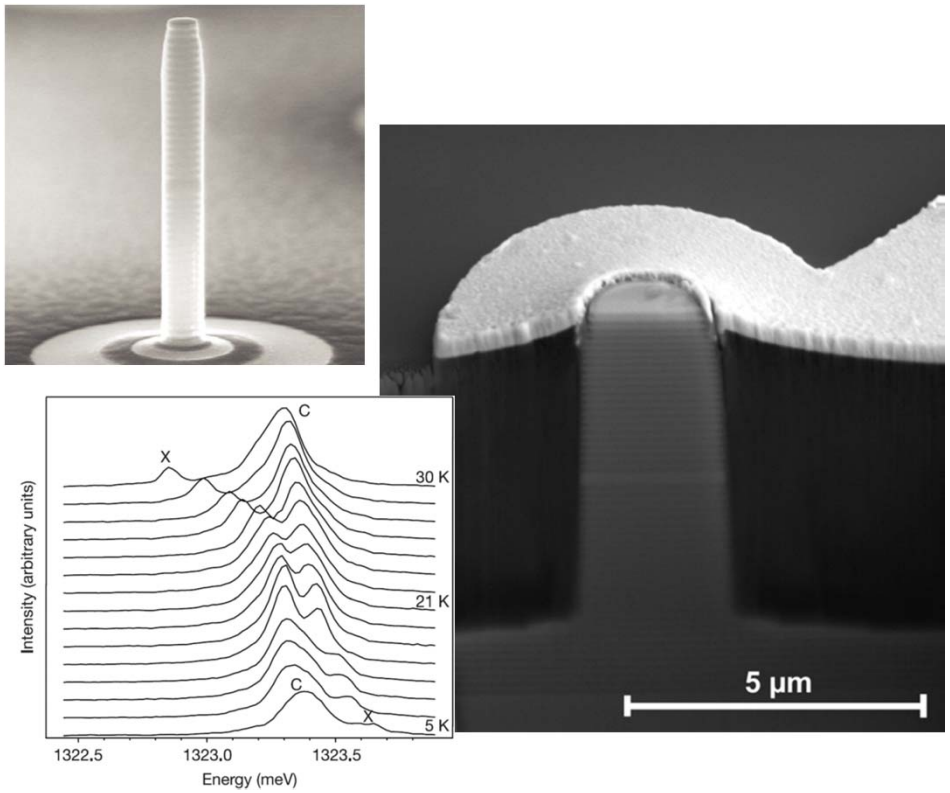
length scales far below the optical wavelength

Fundamental nanophotonic systems

Single quantum emitter strongly coupled to single cavity modes



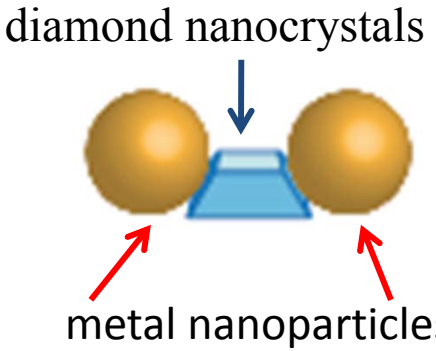
A Badolato et al. SCIENCE 2005



Fundamental nanophotonic systems

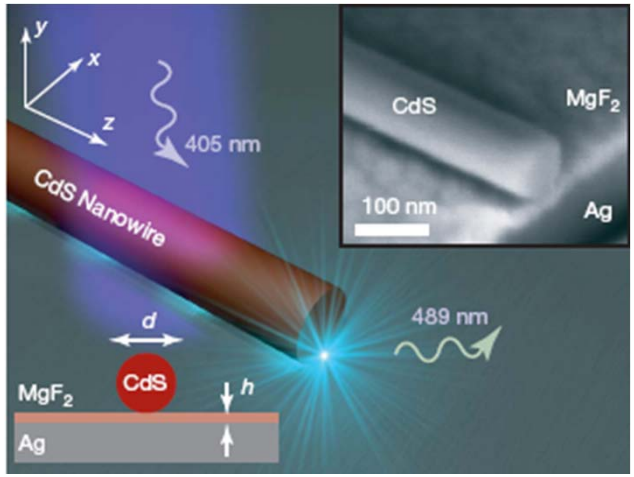
Single quantum emitter coupled to plasmon for field enhancement

Plasmonically enhanced single-photon sources



[Nano Lett. 9, 1694–1698 (2009)].

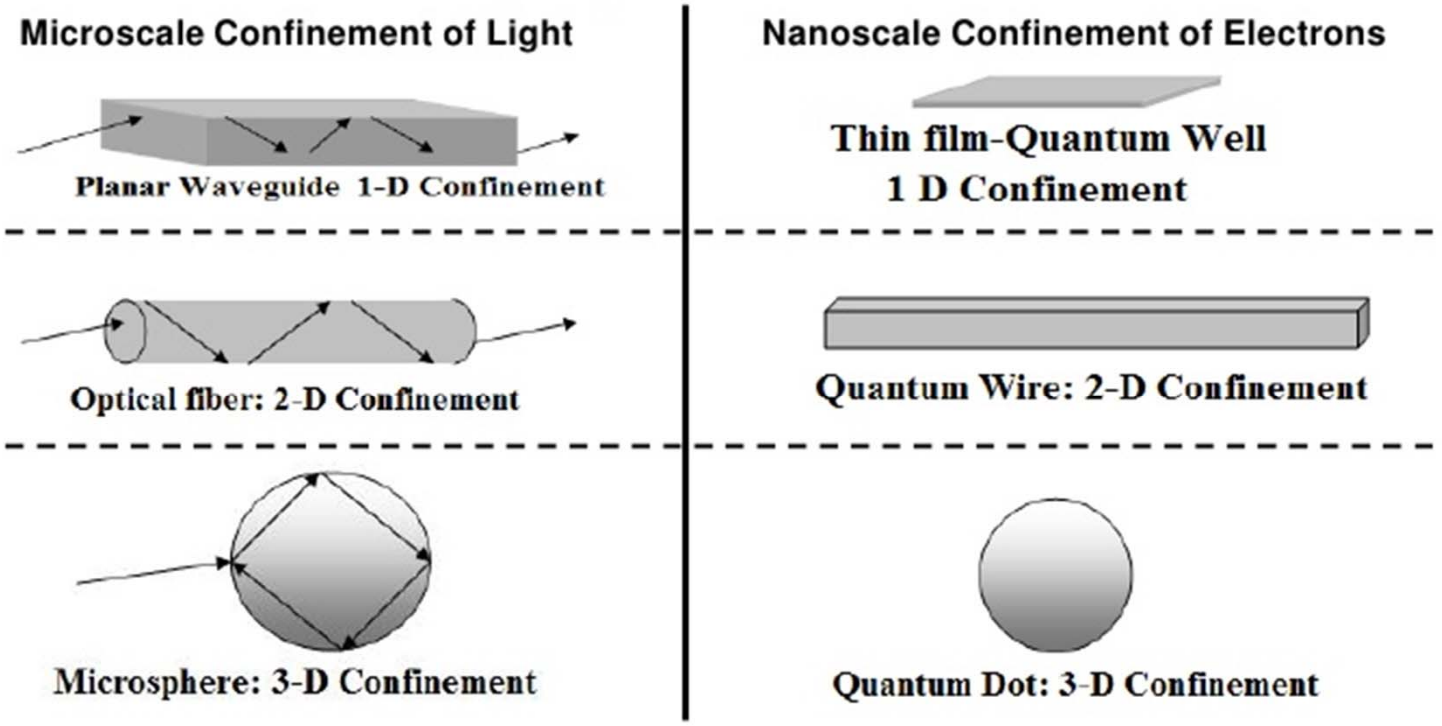
Plasmon lasers



high-gain cadmium sulphide semiconductor nanowire, separated from a silver surface by a 5-nmthick insulating gap.

[NATURE| Vol 461| 1 October 2009]

The field variations due to the confinement of light is similar to the confinement of electron in a potential well. For light, the confinement is obtained when a region of high refractive index is surrounded by a region with lower refractive index.



Quantum confinement

Size: dimensions must be smaller than the De Broglie Wavelength (λ_{DB}), due to the wave-nature of carriers

Material	Electron effective mass	Hole effective mass
Group IV		
Si (4.2K)	1.08 m_e	0.56 m_e
Ge	0.55 m_e	0.37 m_e
III-V		
GaAs	0.067 m_e	0.45 m_e
InSb	0.013 m_e	0.6 m_e
II-VI		
ZnO	0.19 m_e	1.21 m_e
ZnSe	0.17m_e	1.44 m_e

$S \approx \lambda_{DB} = h/m_e v \approx 10nm$

Key issue

Key issue: Scaling down dimensions to their ultimately form

2 different strategies :

Top down approach

Miniaturization obtained by post growth processes (Litographies, etching,…)

Bottom-up approach

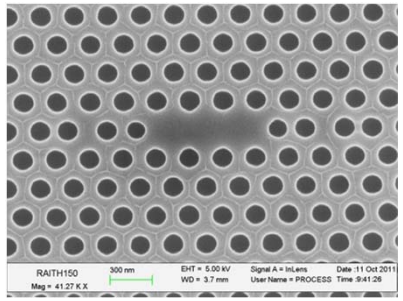
Self assembling
Self ordering

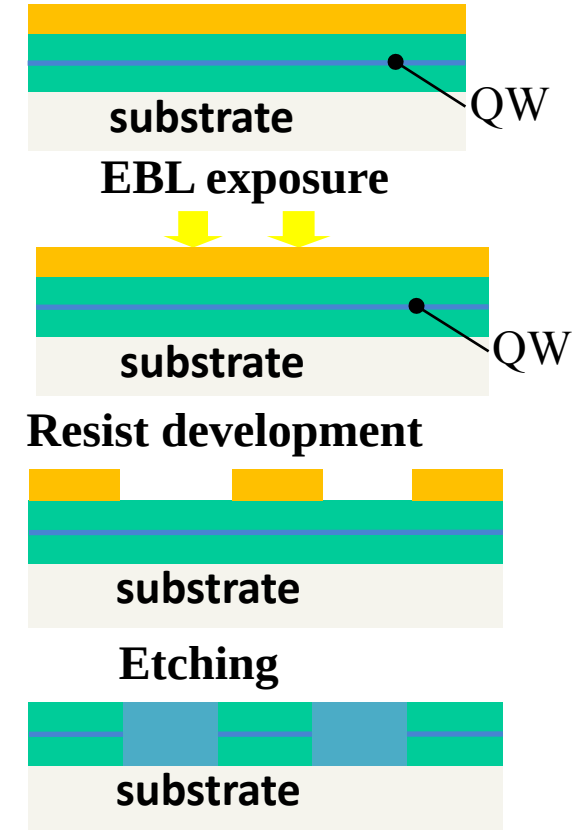
Self assembling requires interactions between the entities (submicrometre particles, large molecules, atoms) that are strong enough to overcome thermal diffusion,

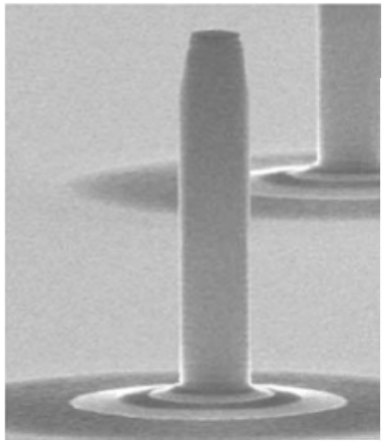
Strongly depending on material and growth technique

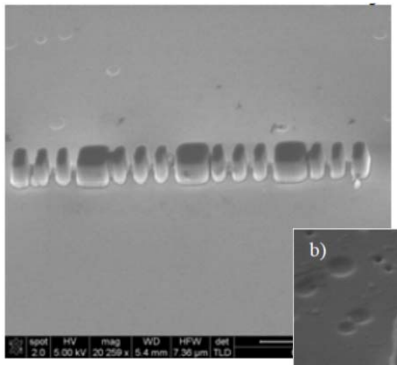
Top-down approach

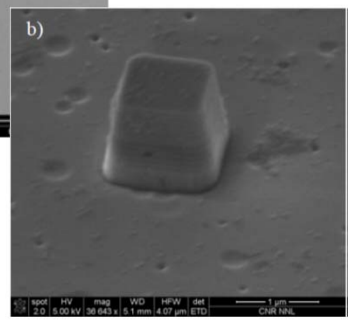
Confinement obtained by lithography process and etching on QW samples



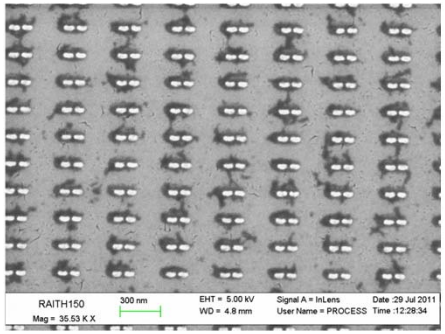








- Defect states at interfaces due to etching



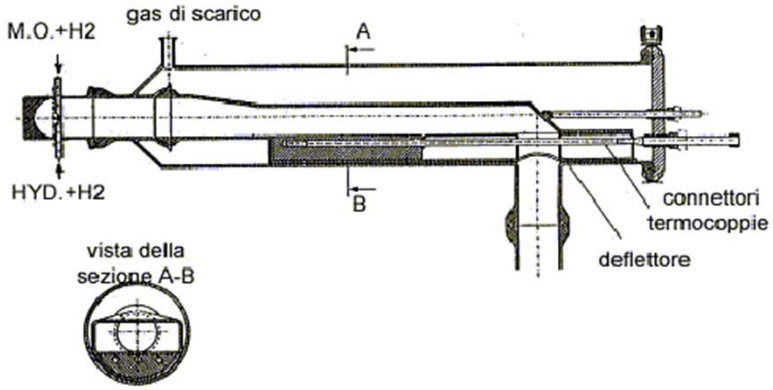
Bottom-up approach

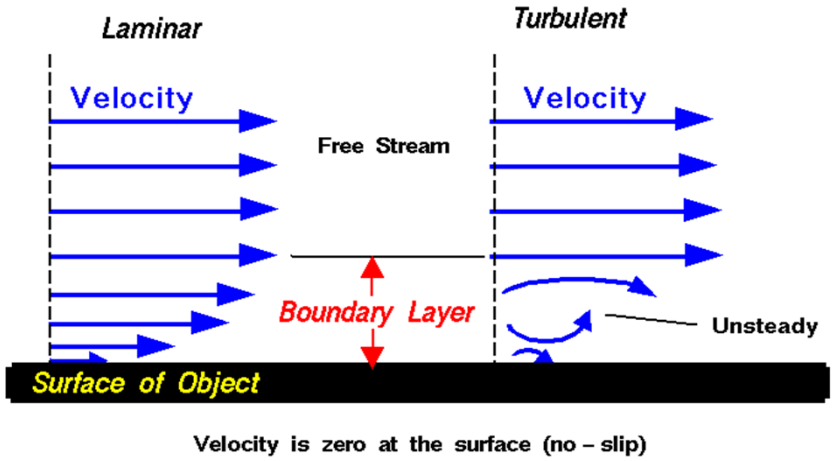
Strongly depending on material and growth technique

Large choice of growth techniques are available

- Epitaxial techniques (MOCVD, MBE, ALD)
- Sputtering
- PECVD
- Evaporation (thermal or electronic)
- Chemical synthesis
- Self ordering of nanoparticles

MOCVD

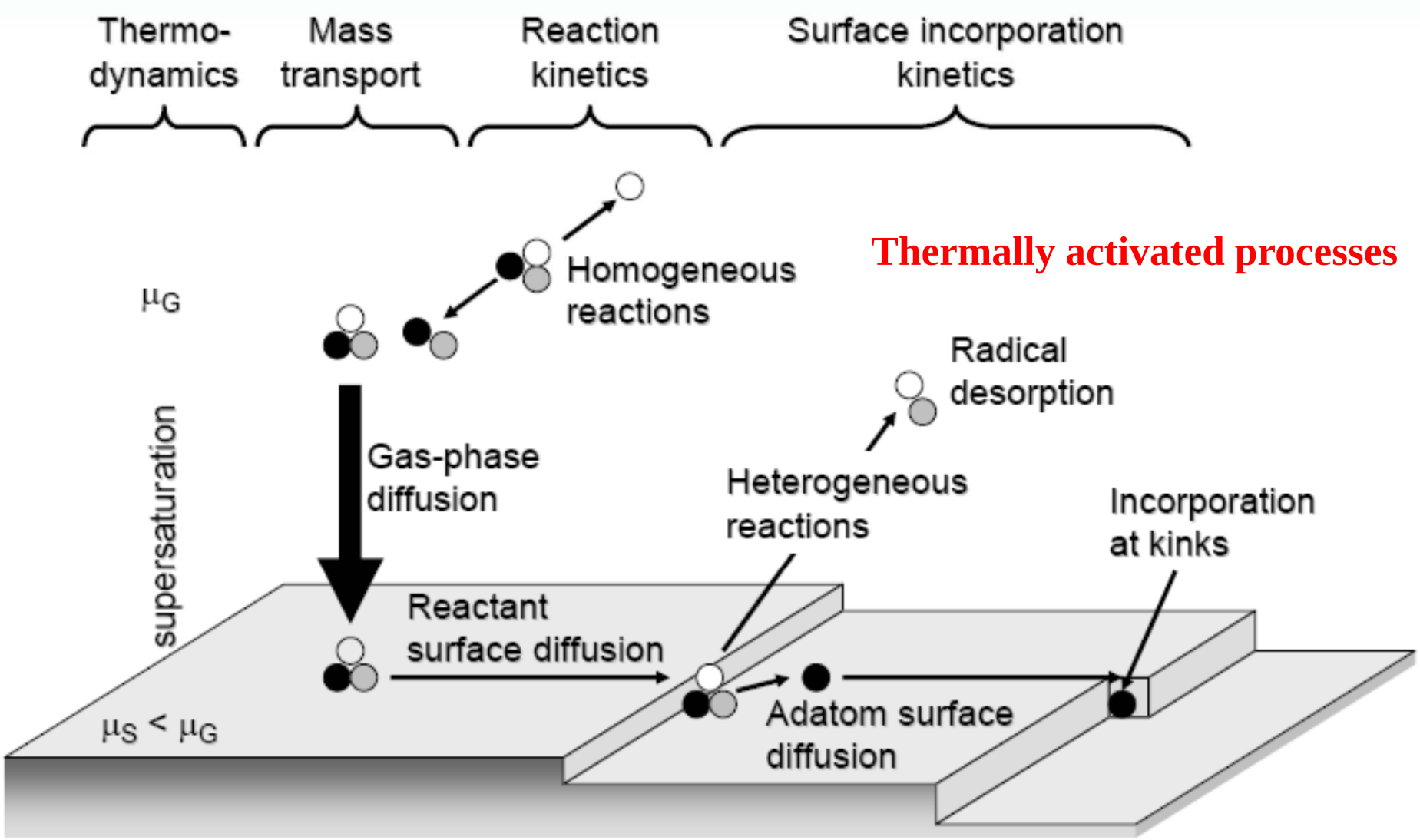




- MO vapor transported by carrier gas
- Hydride group V source gas (toxis)
- Growth controlled by mass transport and surface processes

Low vacuum and chemical reactions

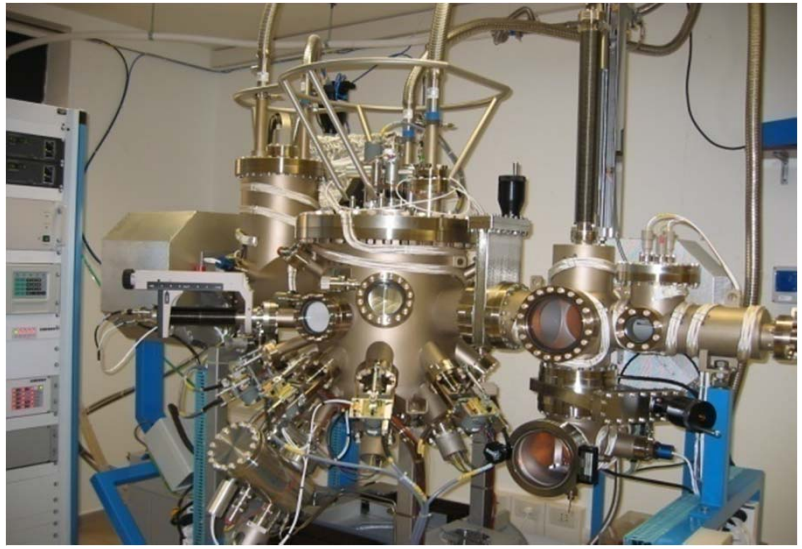
Growth step

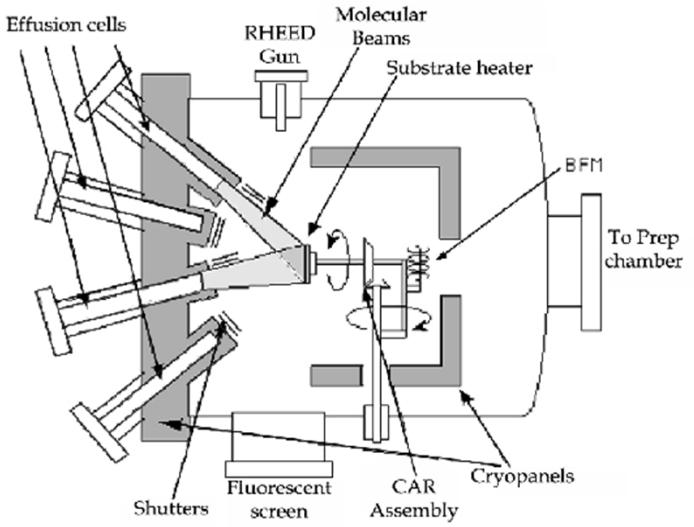


Thermally activated processes

MBE

High controlled evaporation process

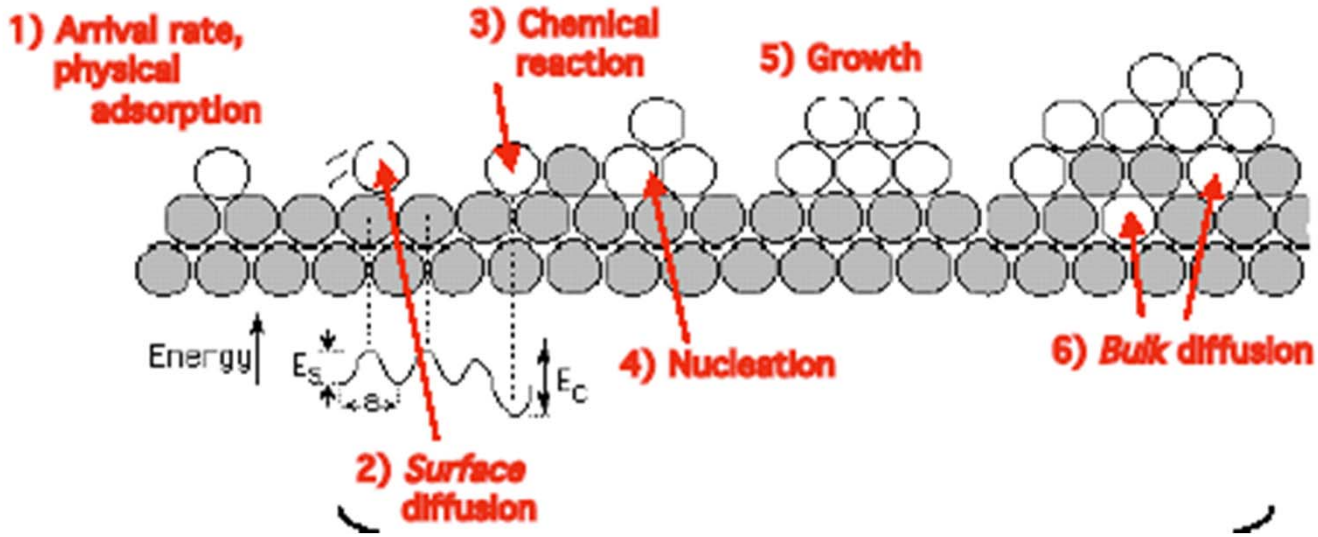




- UHV and in situ analysis
- Elemental source material
- No chemical byproducts
- Growth controlled mainly by surface kinetic

P= 10^{-10} torr

Growth kinetic

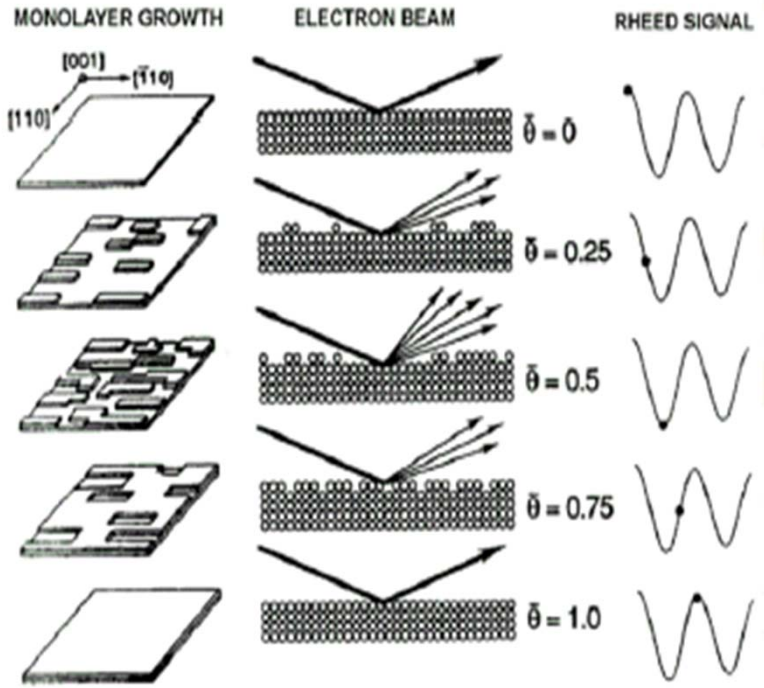


Growth steps:

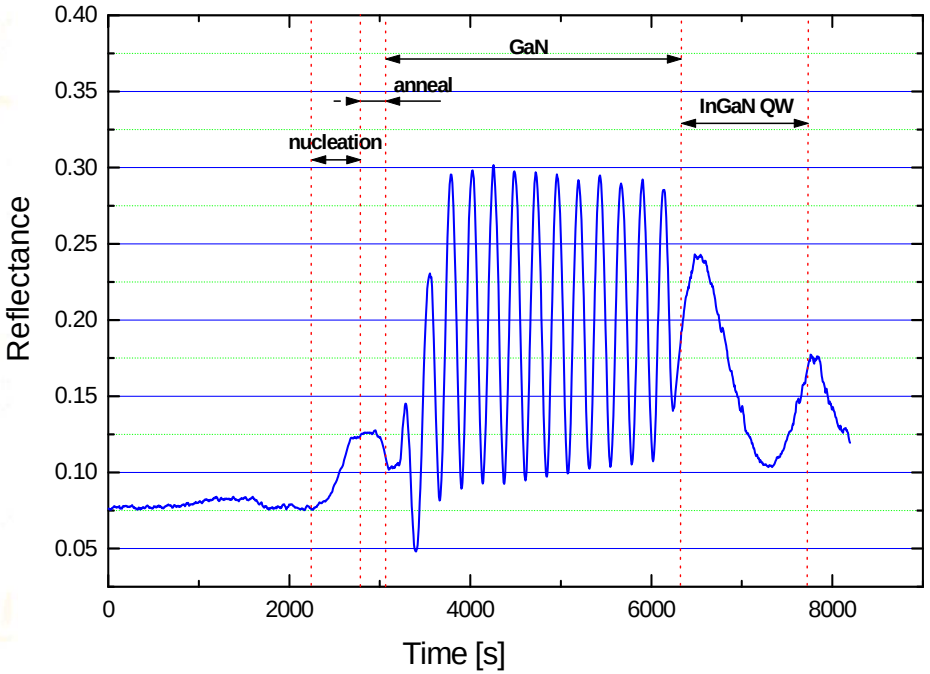
- Adsorbtion, diffusion and dissociation
- Incorporation on growth site

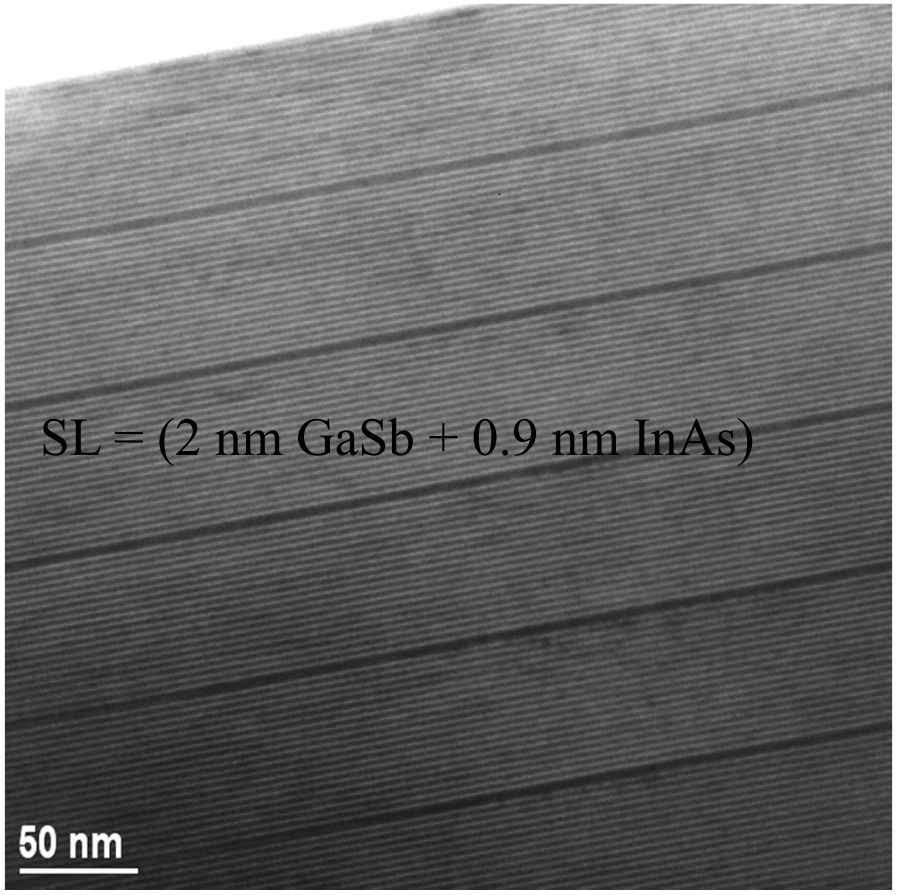
Thermally activated process $E=A \exp(E_a/KT)$

RHEED Measurement (MBE)

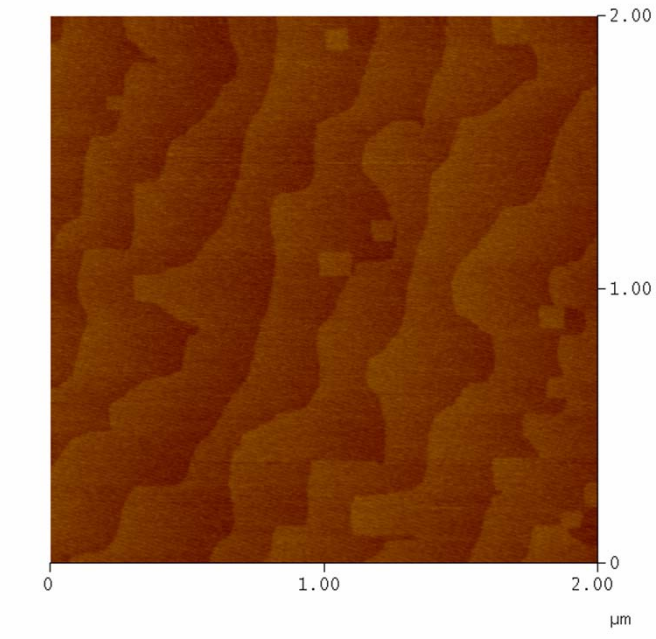


Reflectance Measurement (MOCVD)





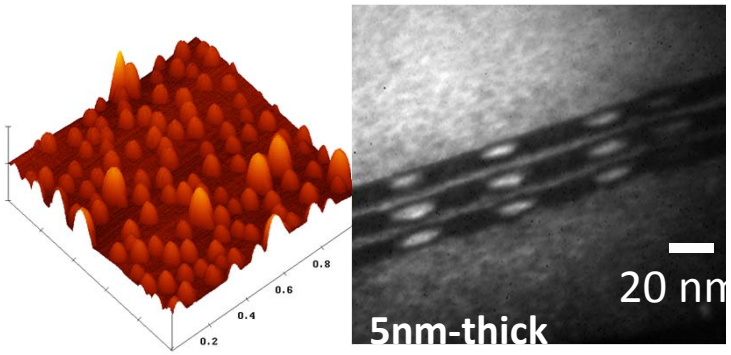
Monolayer control



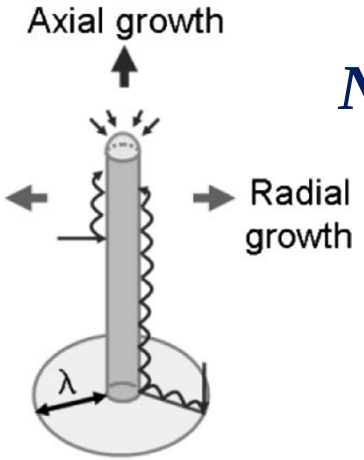
Step-flow growth mode

Self assembled structures by epitaxy

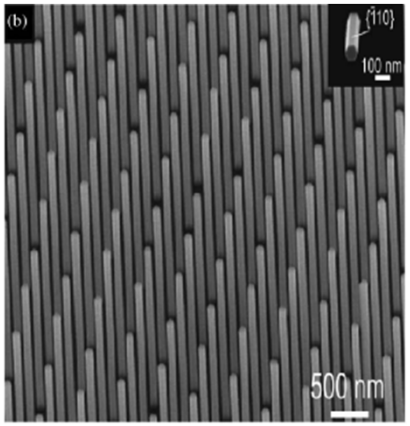
Examples

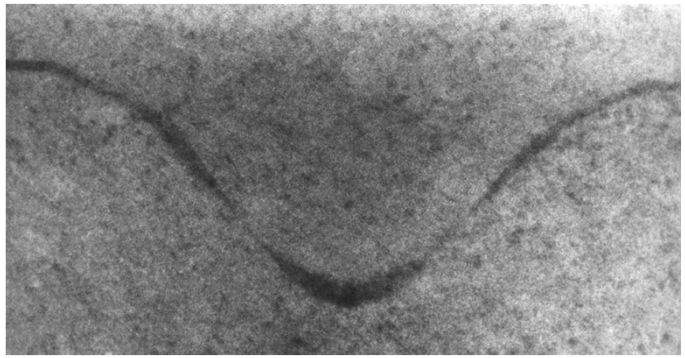


Epitaxial Quantum Dots



Nanowire





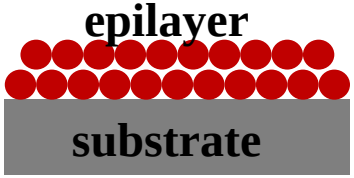
V growed quantum-wire

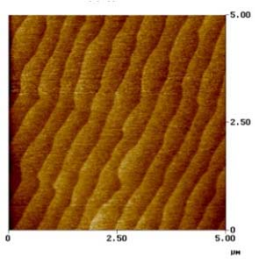
Growth mode

epitaxial growth (Bottom-up approach)

Growth mode

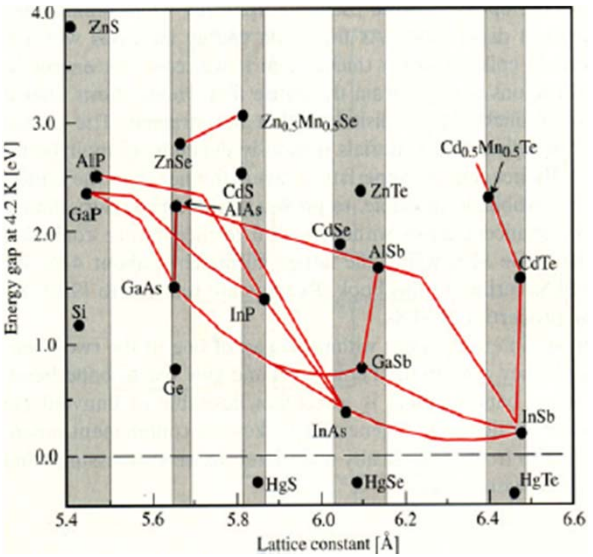
Frank-van der Merwe
(layer by layer)

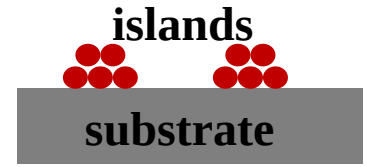




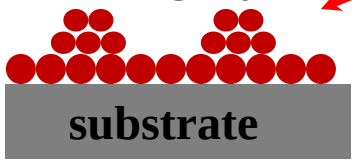
Key parameters:

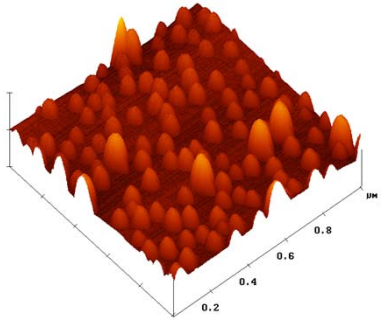
- Strain energy
- Surface energy





Stranski-Krastanov
(strain-driven)





Different material combinations
InAs/GaAs, InAs/InP,
GaSb/GaAs

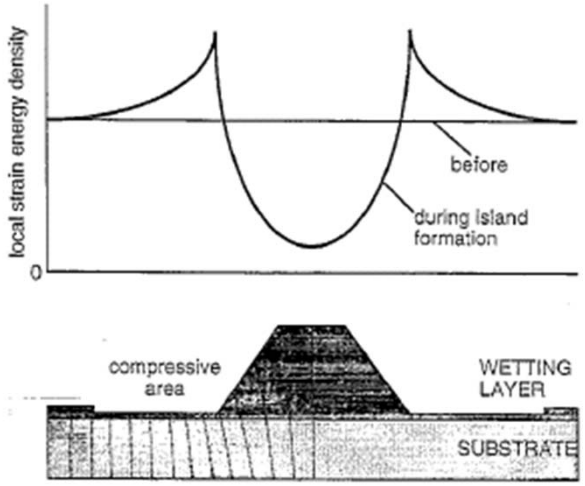
Stranski-Krastanov growth

a_{GaAs}= 5.65325
a_{InGaAs} = 5,8558 → f = 4%

$$\Delta\sigma = \sigma_E + \sigma_I - \sigma_S < 0$$

I° step - Strained 2d Wetting layer $E_{el} = Cf^2At$

2° step – Nucleation: After a critical thickness strain is relaxed by island formation (reducing deformation energy and increasing surface energy)

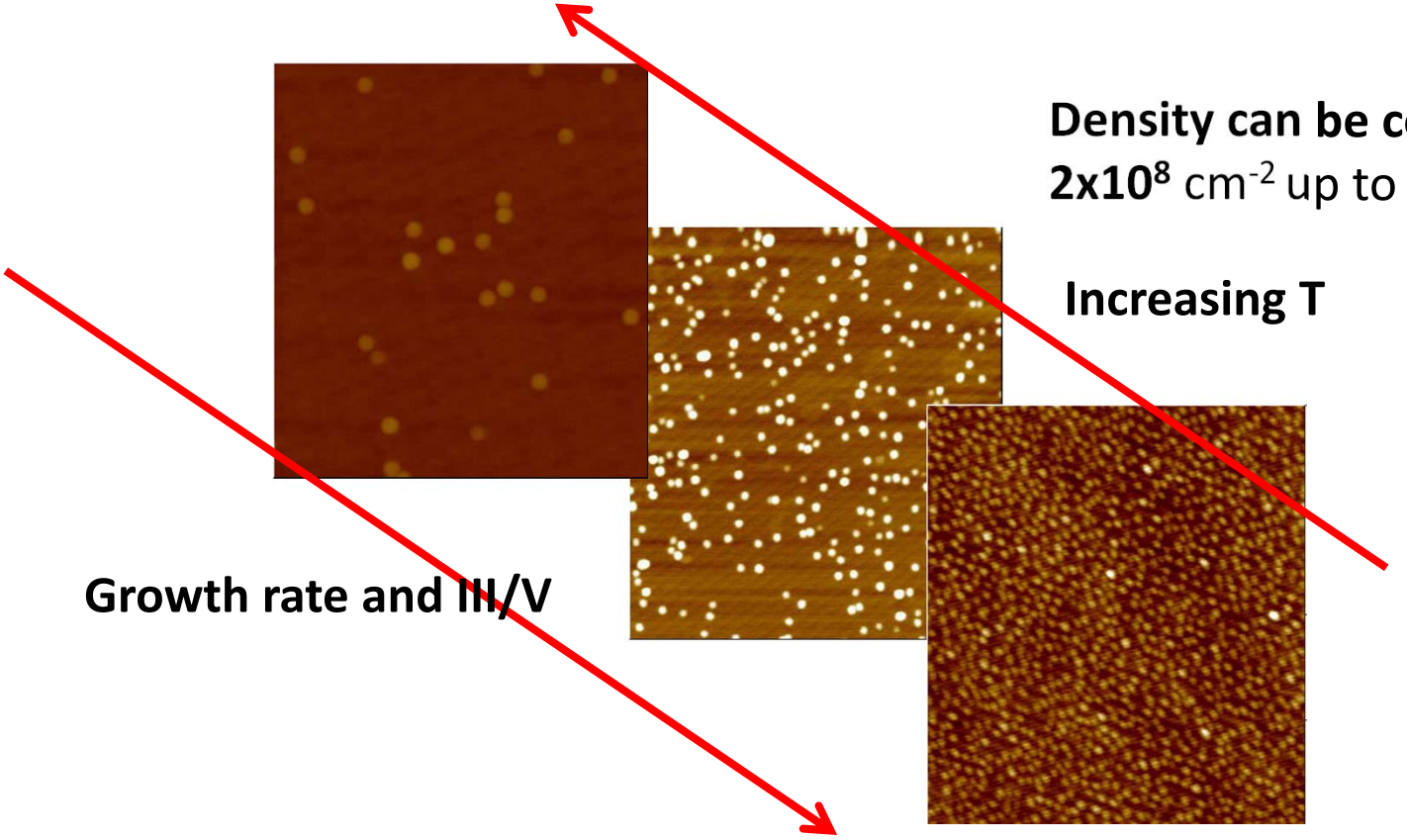


Key Issue

- Control of wavelength emission (composition, shape, dimension)
- Uniformity: lateral < 10% and vertical < 5%
- Compositional homogeneity
- Density (10^{10}-10^{11}dot/cm^2)
- Polarization properties

Density control

Strain is the main driving force for the QD formation, but surface kinetics is crucial to control the QD structural and optical properties.



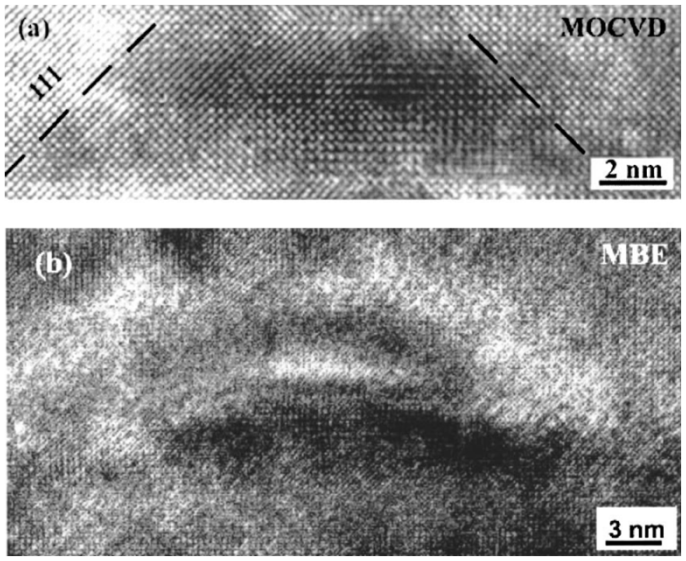
[A.Passaseo et al., J. Appl. Phys. 89, 4341 (2001)]

Wavelength control

$$E_n = E_g + \frac{\hbar^2 \pi^2}{2 m_r L^2}$$

growth dynamics (i.e. growth condition) could controls:

- Size
- Shape
- composition



Principal factor controlling size → Strain

Low growth rate, low III/V and temperature can modulate size and aspect ratio

Different shape due to growth technique:

- ✓Truncated pyramid by MOCVD
- ✓Lens shape by MBE

[A.Passaseo et al., Appl. Phys. Lett. 82, 3632 (2003)]

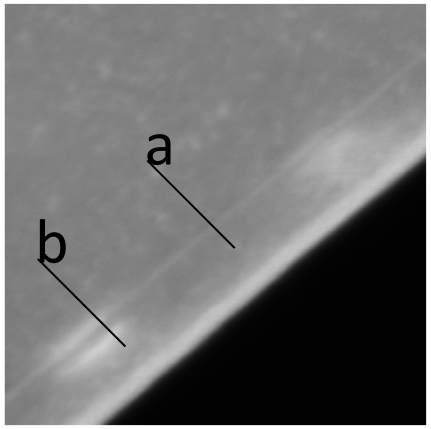
Material composition

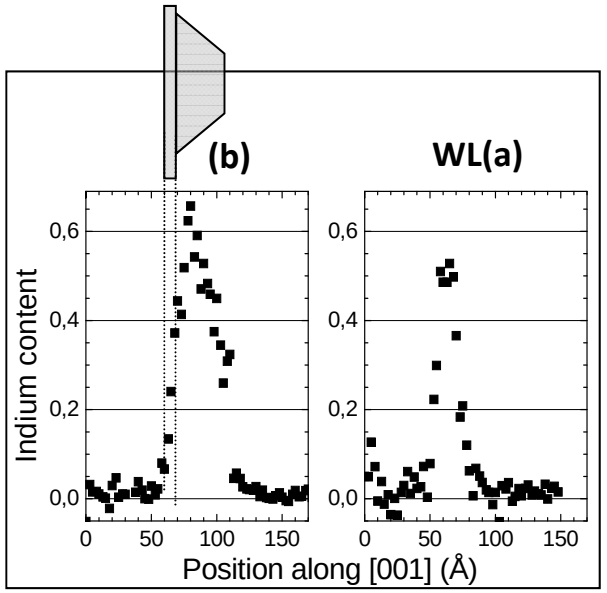
Large variation can be found as a function of the growth method and condition (interdiffusion, segregation)

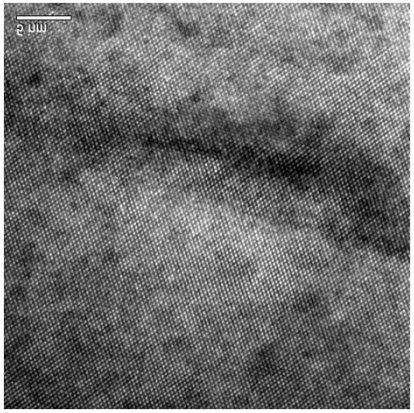
InGaAs QD (50%) MOCVD

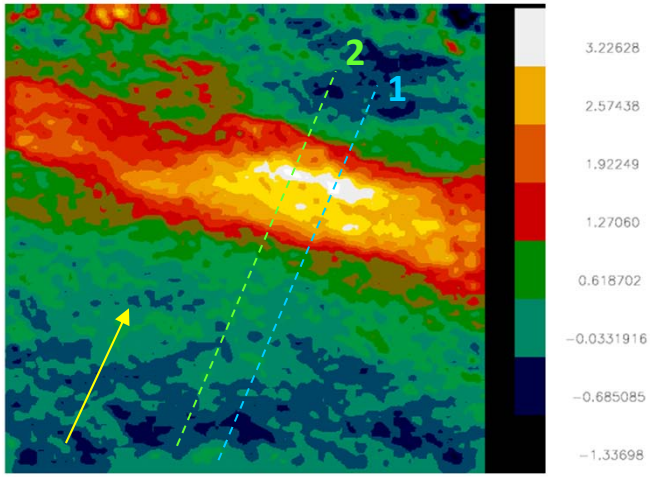
In content enhancement (60 %) at the center of the dots

Weak interdiffusion (about 2-3 MLs)









Lattice Distortion Analisys (LADIA)

MBE InAs QD

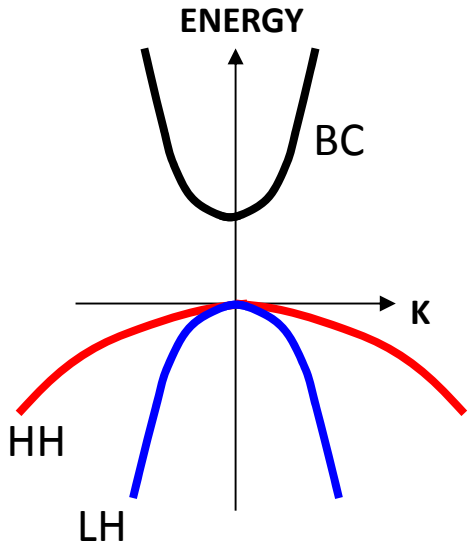
Maximum In content 80% localized in the upper dot surface

Weak interdiffusion (about 2-3 MLs)

Polarization properties

Standard SK QDs do emit dominantly in transverse-electric (TE)-mode, due to their flat shape and quasi-biaxial compressive strain.

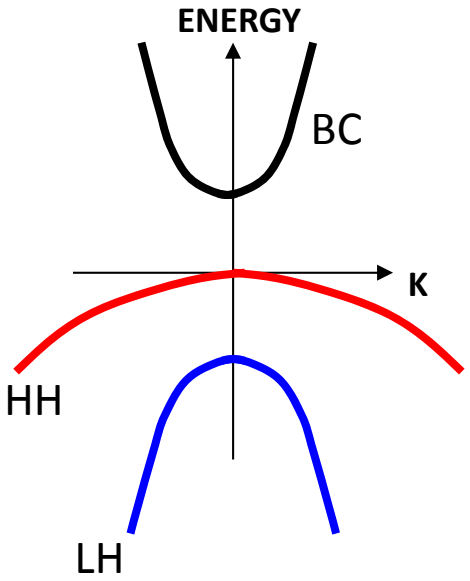
Bulk material



HH and LH degenerate in the valence band

polarization insensitive material gain

Quantum Dot



different quantization levels for HH and LH bands

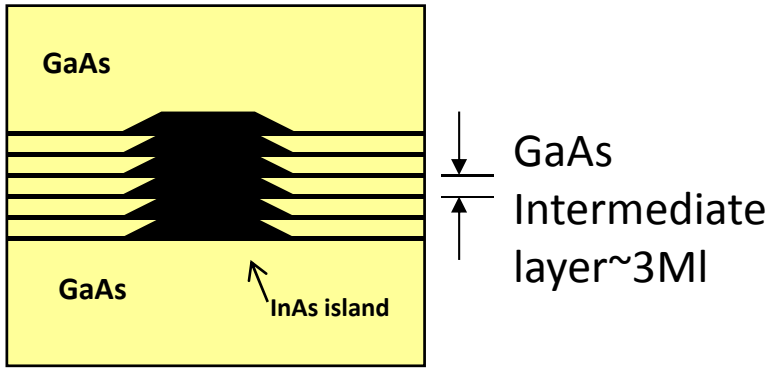
Emission of QD is polarized TE

QDs as an active medium offer potential advantages with regards to polarization because their electronic wavefunctions can be changed by growth.

Staked samples

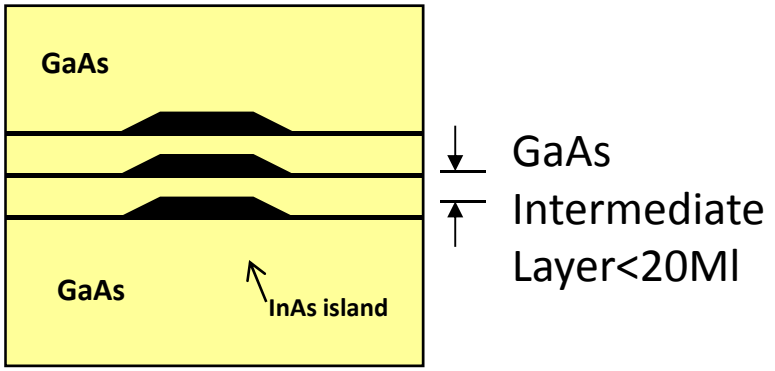
Ratio between Hydrostatic and Biaxial Strain
can be tailored by staking

columnar QDs structures



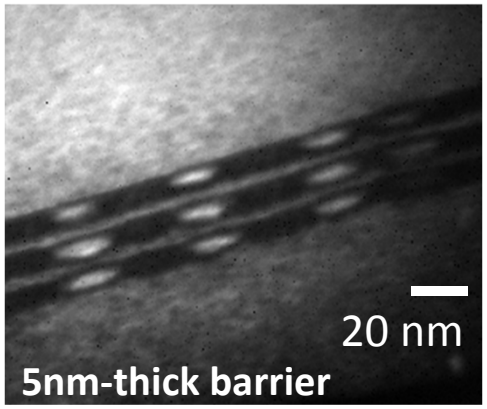
Kita et al. APPLIED PHYSICS LETTERS **88, 211106 (2006)**; Kawaguchi et al. Jpn. J. Appl. Phys. **45, L1244–L1246 (2006)**

multilayers of closely-spaced QDs

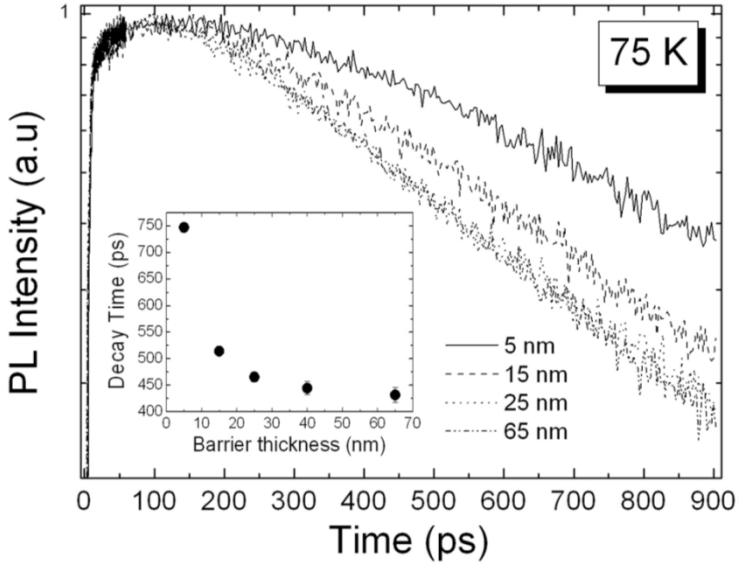


Yu et al. Phys. Rev. B **60, 16680–16685 (1999)** ; Anantathanasarn et al. Appl. Phys. Lett. **88, 063105 (2006)**

Electronic coupling of QDs

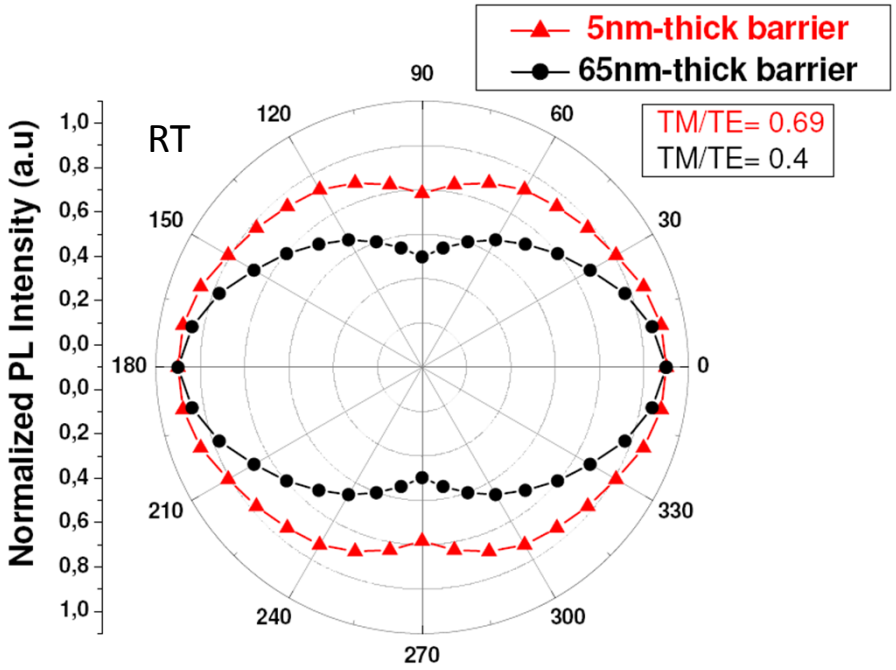


Time resolved measurements



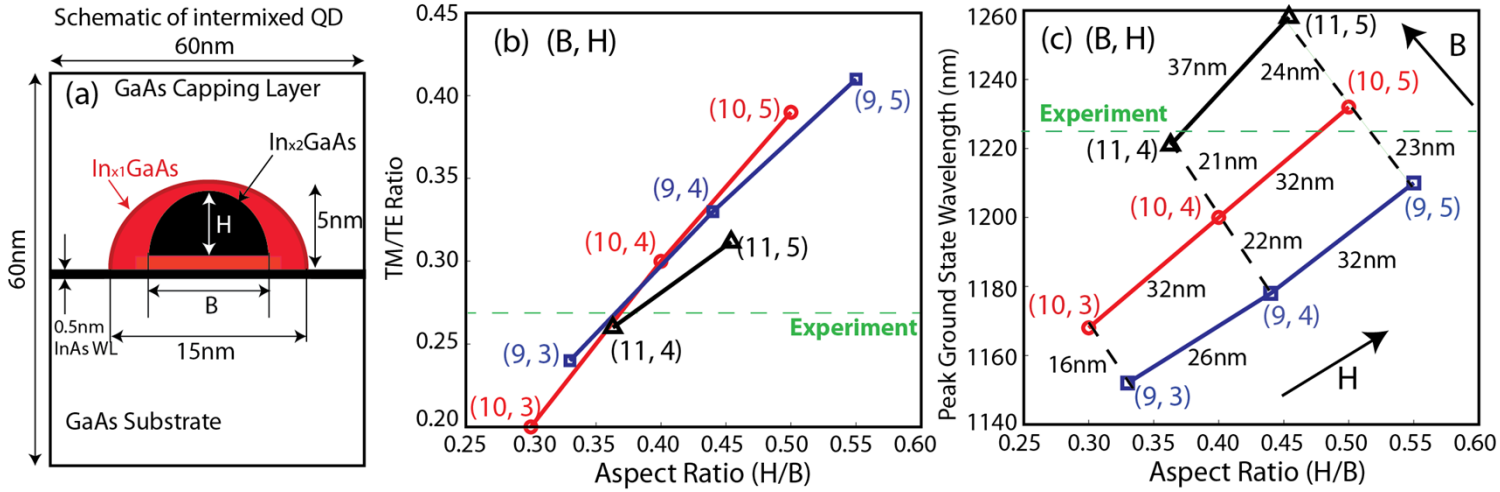
Radiative decay time increase

Polarized PL spectra



TM/TE ratio reaches a value of 0.69 for a sample with 3 QD layers separated by 5nm thick-GaAs spacer

Atomistic simulations

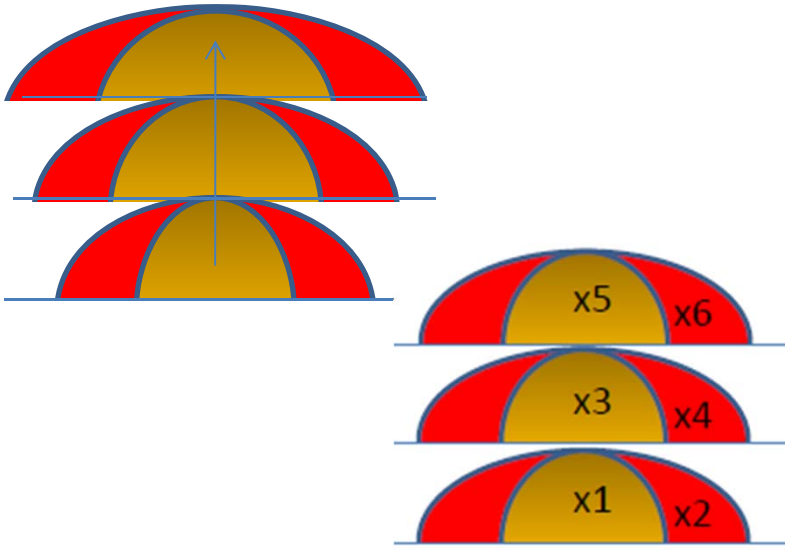


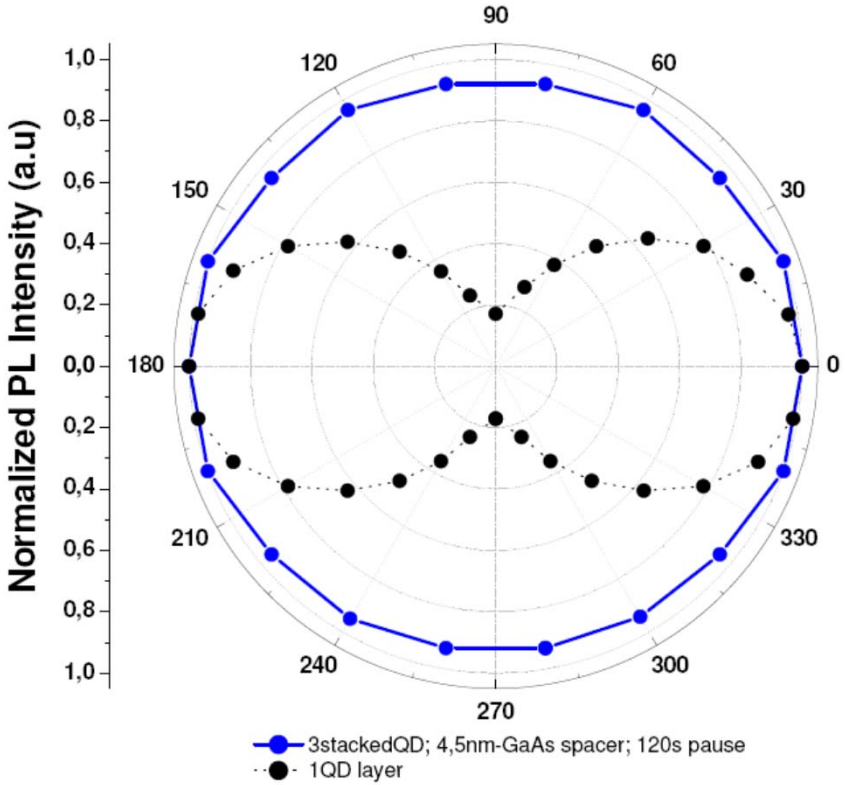
QD Model	ϵ_H	ϵ_B	δE_c meV	δE_{HH} meV	δE_{LH} meV	δE_{HH-LH} meV
(a)	-0.0842	-0.1536	427.7	54	-222.4	278.4
(b)	-0.06	-0.148	304.8	73.2	-193.2	266.4
(c)	-0.0818	-0.1449	415.5	48.6	-212.2	260.8

[M.Usman, Nanotechnology 2012]

Final result

Nearly unpolarized active materials obtained only by playing with surface reconstruction during growth

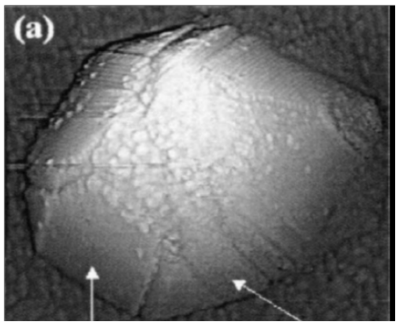


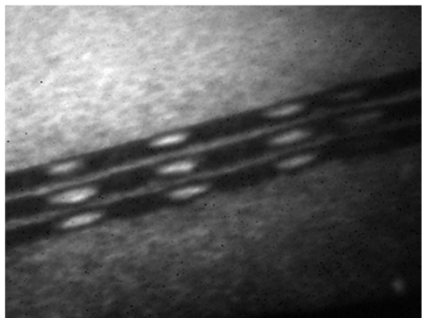


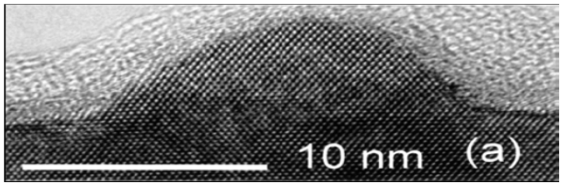
A nearly total polarization independence (TM/TE=0.92) with only 3 closely QD layers

Epitaxial Quantum Dots

Principal application: optoelectronic devices





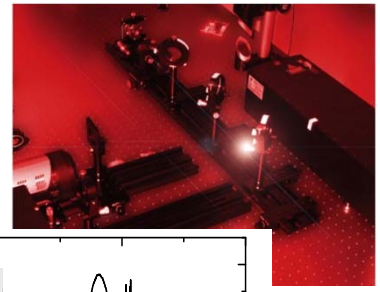


Devices for optical data transmission:

✓Laser sources

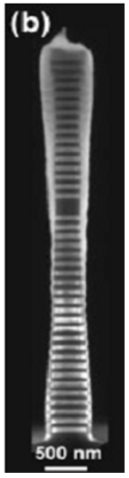
✓Semiconductor optical amplifiers (SOAs)

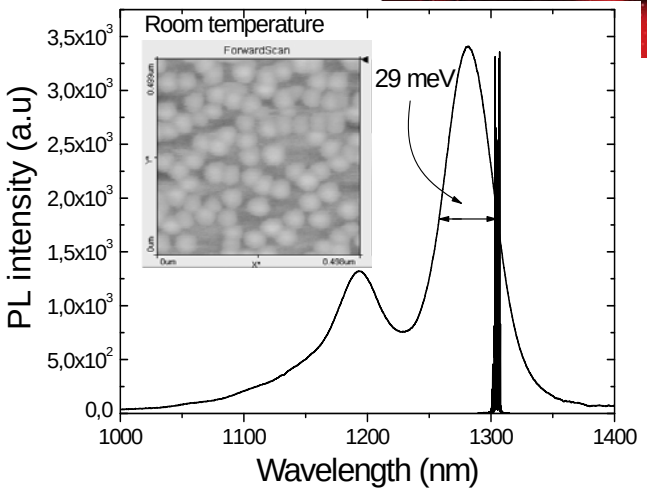
✓Infrared detectors



QD solar cells
(extended absorbtion)

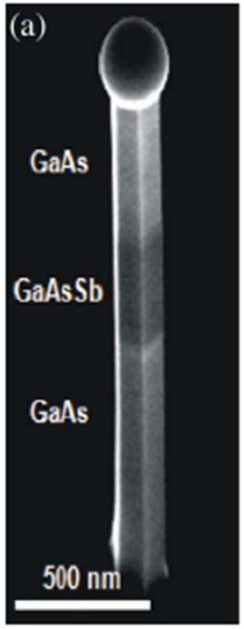
Single PHOTON SOURCES for
Quantum Computing/cryptography
(coherent states of charge)





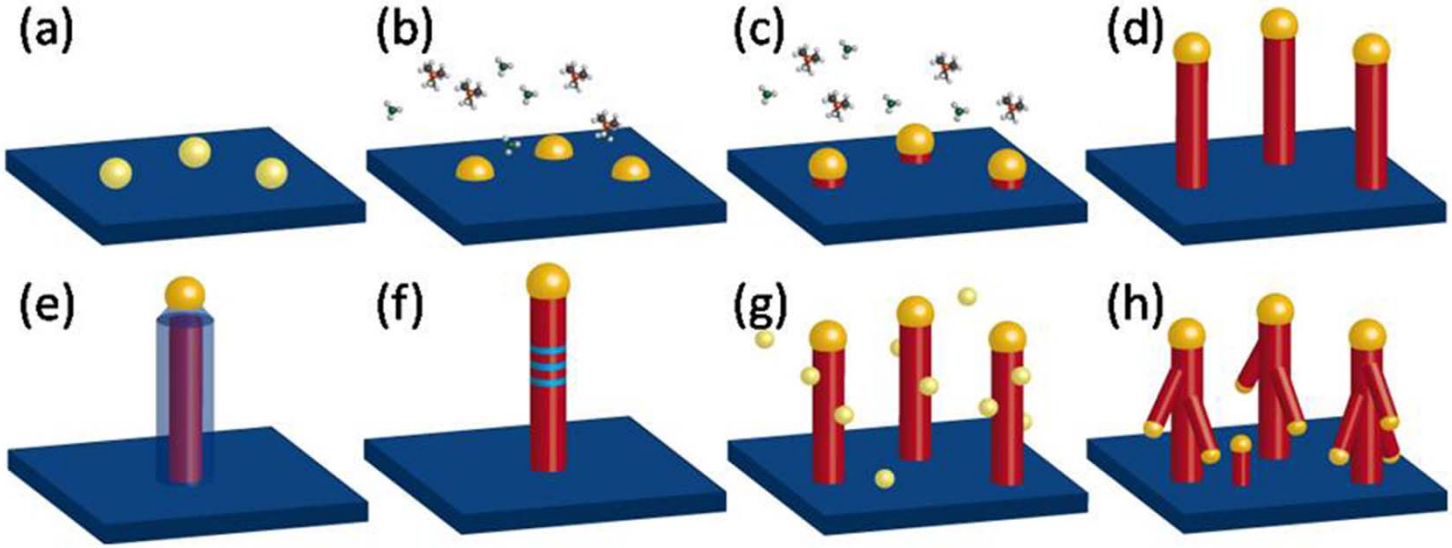
Nanowires

Semiconductor nanowires are filamentary crystals with the diameter being of the order of few nanometers.



The most common method to fabricate nanowires is the vapor–liquid–solid (VLS), in which a metal nanodroplet preferentially gathers and decomposes the growth precursors, allowing the growth of nanowires. The metal most commonly employed for the nucleation and growth is gold

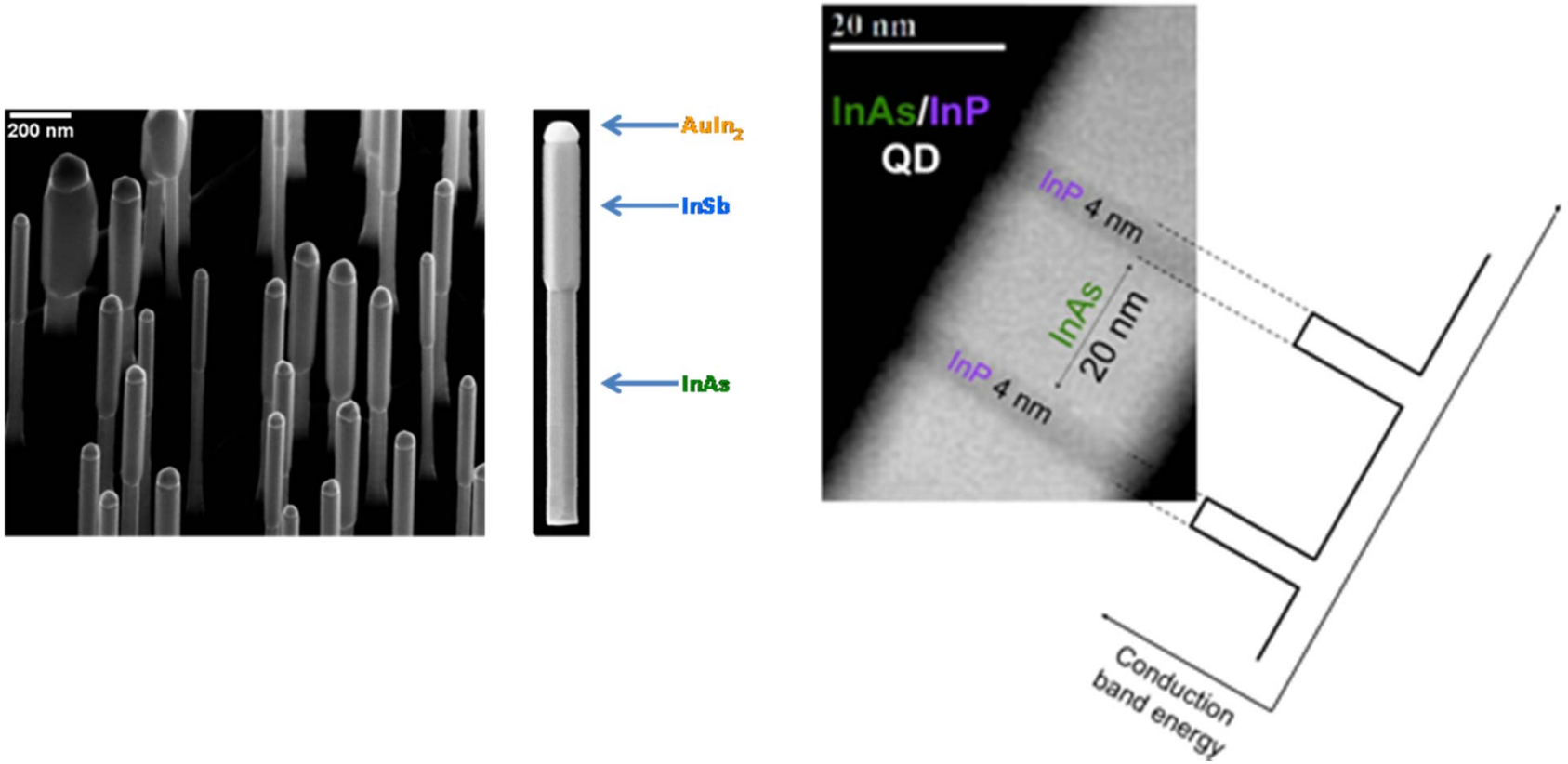
Au assisted growth of GaAs NWs



(a) The seed particles are deposited on the substrate and (b) by heating the substrate to a desired temperature and introducing growth materials an alloy is formed. (c) When a supersaturation of the alloy particle with growth material is achieved, nucleation occurs at the particle-substrate interface. (d) Nanowire growth occurs at the particle-wire interface as long as growth material is provided. (e) By switching to growth conditions favoring planar growth, radial heterostructures, can be grown. (f) Nanowires containing axial heterostructures can be formed by switching between different growth materials. (g) If a second generation of gold particles is deposited onto the as-grown nanowires and (h) the growth process is repeated, branched nanowires for formation of nanowire networks can be grown.

Au assisted growth

InAs-InSb heterostructured nanowires grown by Au-assisted chemical beam epitaxy



L. Lugani et al., J. Cryst. Growth, Vol. 323, Issue 1, 15 (2011), pp. 304-306

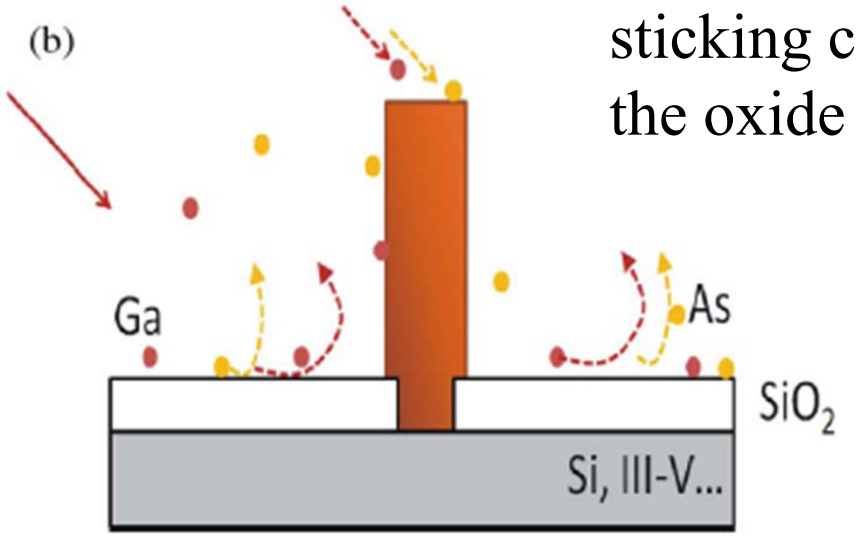
Au free nanowire growth

When gold atoms are incorporated in semiconductors, often they form deep level traps and scattering centers

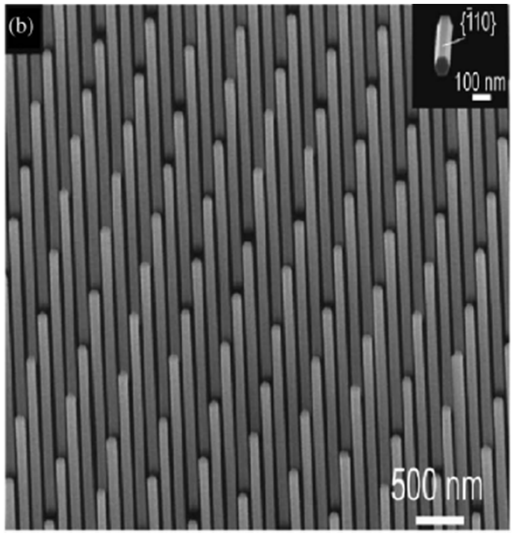
Several strategies have been used to avoid the use of gold for the synthesis of semiconductor nanowires, like **group-III-assisted growth** or **Selective Area Epitaxy (SAE)** on patterned substrate

Selective Area Epitaxy

The growth conditions are chosen so that the sticking coefficient of the adatoms is zero on the oxide and nonzero in the apertures



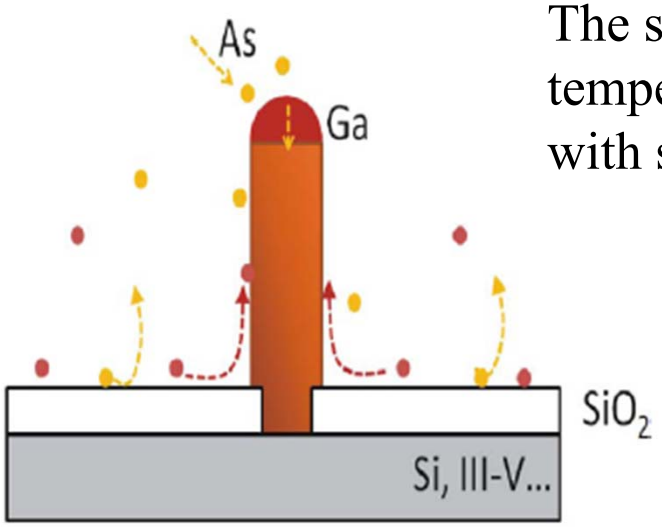
any substrate orientation can be used.



In epitaxy, different facets are formed as a result of the different growth rates between them.
The conditions leading to nanowires correspond to a high growth rate in the [1 1 1]B direction and slow in the <1 1 0> directions. Nnanowires are formed only under high substrate temperatures and low arsine partial pressure (typically 750 ◦C and 5.0 × 10−4 atm,).

the flow of arsenic limits the growth rate.

Ga assisted growth



The substrate temperature must be close to the congruent temperature (gallium liquid droplet can exist in equilibrium with solid)

gallium should not wet the surface

Catalyst-free MBE growth of GaAs NWs under Ga-rich conditions

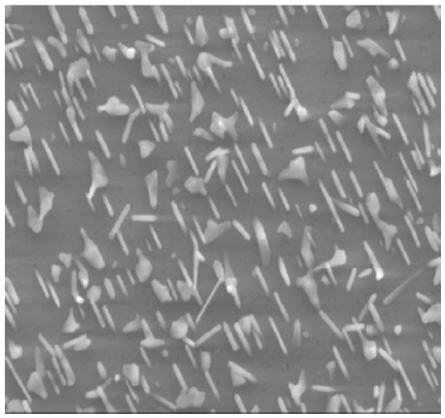
1) As-adatoms impinging on the substrate are immediately desorbed and do not contribute to the growth;

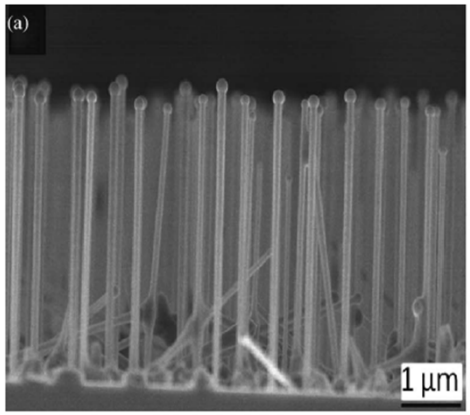
2) Ga-adatoms impinging on the substrate diffuse and form droplets, where the NWs nucleate;

3) once the NW is formed, Ga-adatoms continue to diffuse through the substrate surface and along the NW facets to continuously refill the Ga droplets;

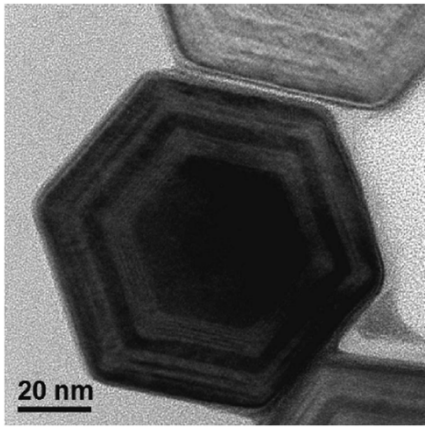
4) As-adatoms impinging on Ga-droplets determine the NW growth rate.

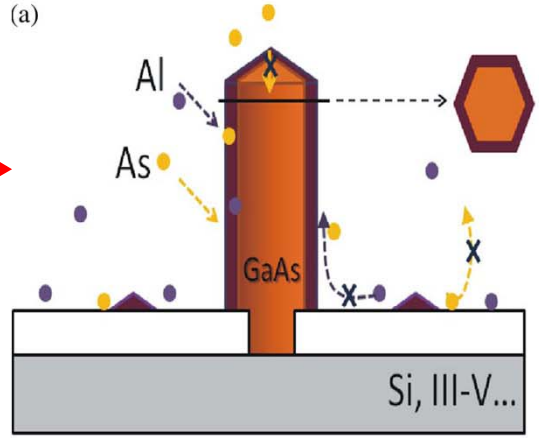
Ga assisted growth



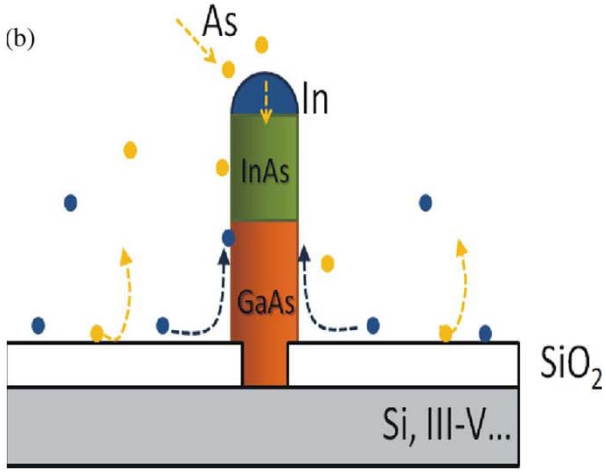


By switching to growth conditions favoring planar growth radial or axial heterostructures can be grown





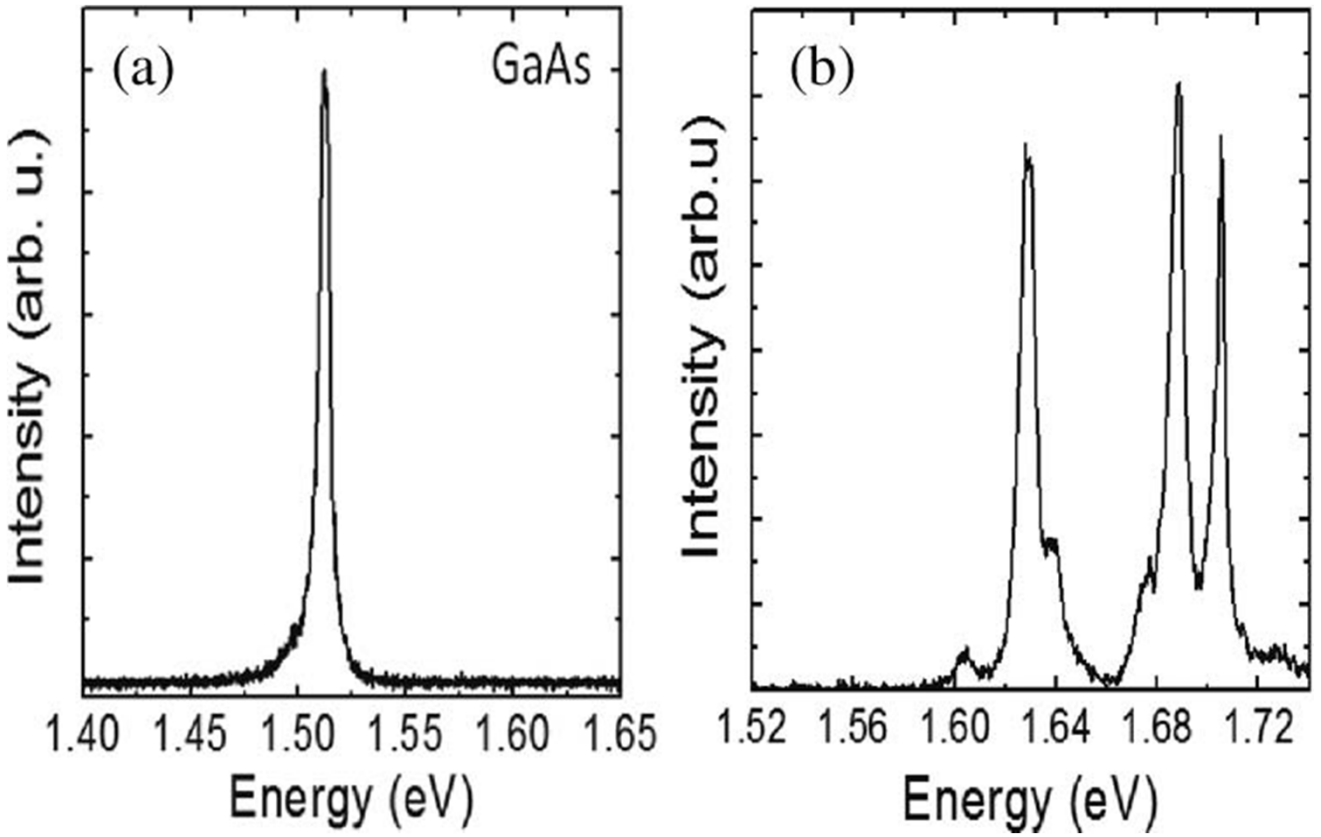
Radial heterostructure



Axial heterostructure

IEEE J. SELECT. TOPICS IN QUANTUM ELECTRONICS, VOL. 17, NO. 4, 2011

Materials



(a) PL spectrum of a single GaAs nanowire. (b) PL spectrum of a nanowire containing three prismatic QWs of thicknesses 0.6, 1.4, and 5.8 nm.

*[A. Fontcuberta i Morral, IEEE J. Of Selected Topics in Quantum Electronics, **17**, 2011]*

GaN nanowires

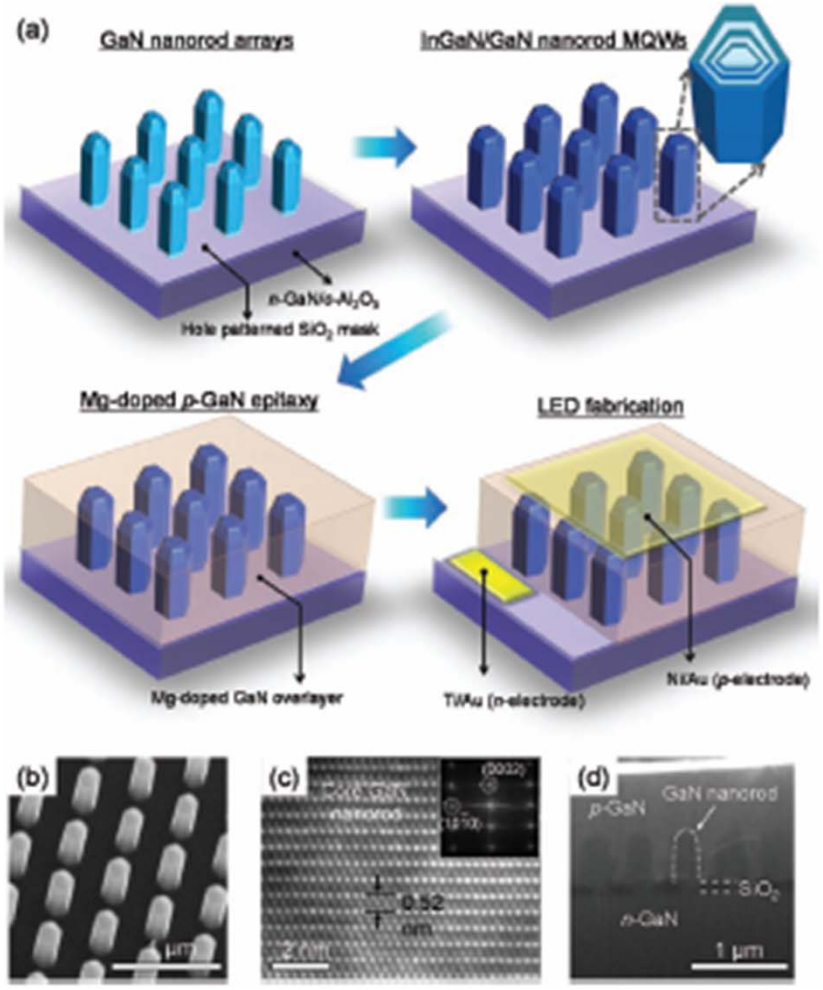


Figure 1. Fabrication of nanorod-embedded LEDs and electron microscopic images. a) Selective MOVPE growth of GaN nanorod arrays on n^+-GaN/Al_2O_3(0001) substrates (left upper panel), followed by heteroepitaxial coating of 3D $In_xGa_{1-x}N$/GaN MQWs (right upper panel). Subsequently, Mg-doped p-GaN was coated on the nanorod MQW arrays to form a continuous overlayer (left bottom panel). The LEDs were fabricated by making ohmic contacts on both the topmost p-GaN surface and n-GaN layer beneath the nanorods (right bottom panel). b) Bird's-eye view SEM image of GaN nanorod arrays. c) HR-TEM image of single-crystalline core n-GaN nanorods. The inset shows the diffraction pattern of the GaN nanorods. d) Cross-sectional SEM image of a Mg-doped GaN overlayer and $In_xGa_{1-x}N$/GaN MQWs on GaN nanorod arrays.

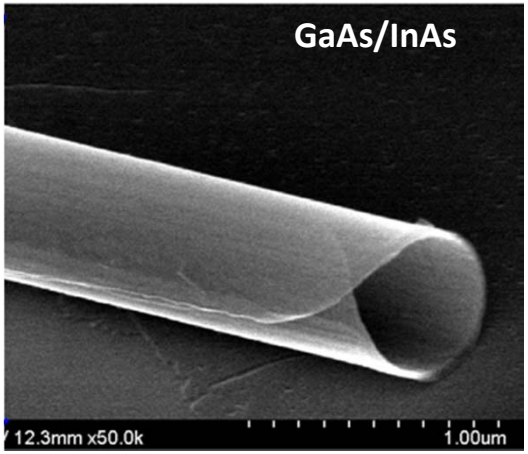
Advanced MaterialsVolume 23, Issue 29, 2011

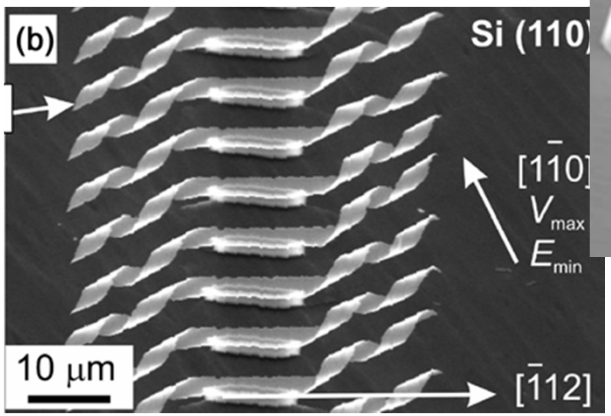
Outline

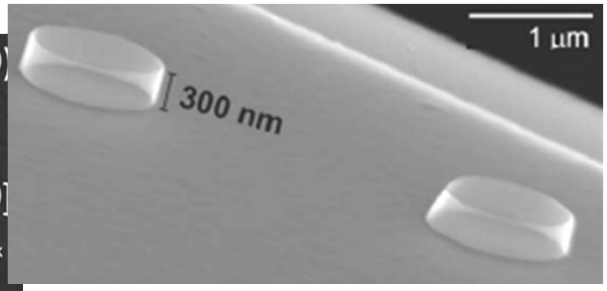
- Introduction
- Strategies for Nanofabrication
  - Self assambling method
    - Epitaxial Quantum dot
    - Nanowires
  - Strain driven 3D nanostructures
  - Ion Beam Induced Deposition (IBID) and nanostructuring

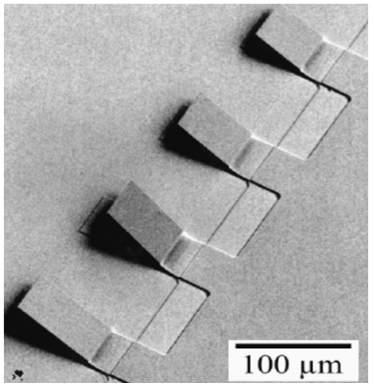
Strain driven 3D nanostructures

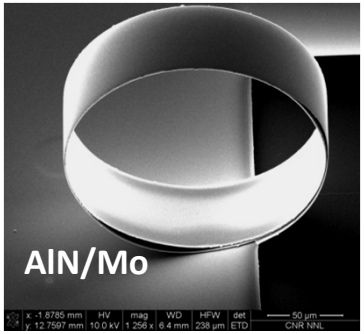
3D objects, obtained by strain release, by using a combination of bottom–up and top–down approach

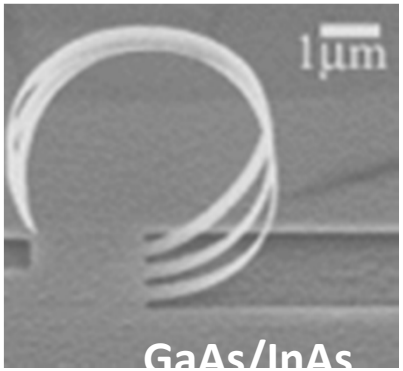


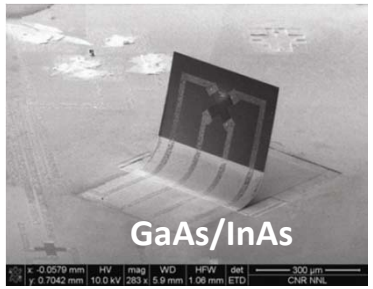






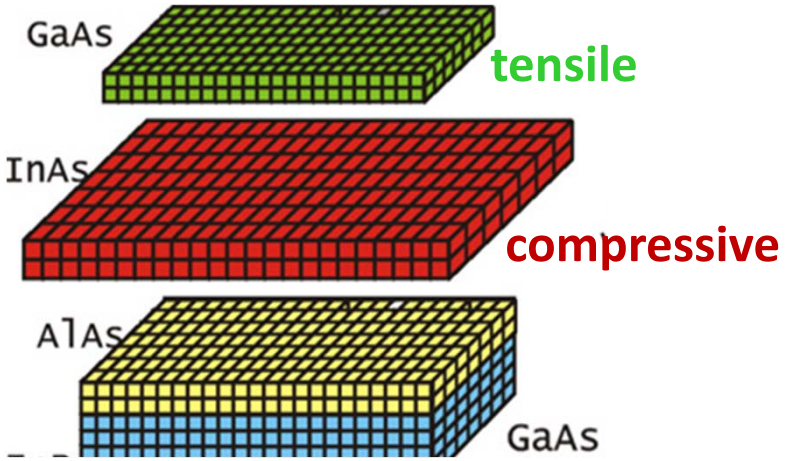


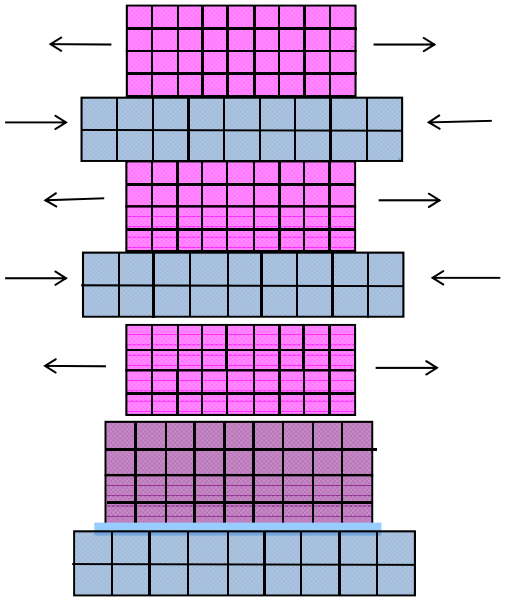




Formation process

bottom–up process: ***self-rolling*** induced by strain release

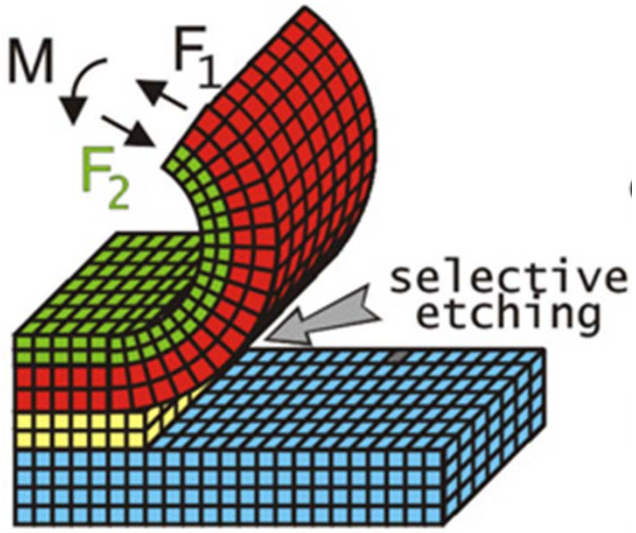




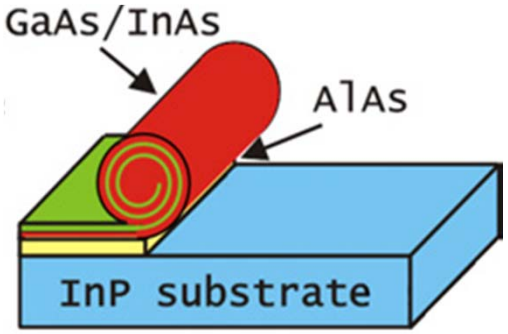
Basic structure: bilayer with opposite strain on sacrificial layer

Each layer undergoes opposite elastic forces due to strain

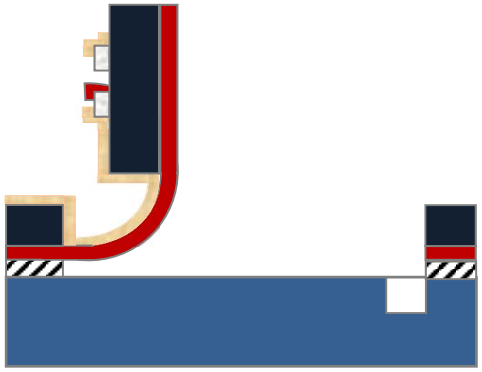
Formation process



By removing the sacrificial layer the bilayer release the strain energy by bending the structure (a momentum M due to the opposite forces F_1 e F_2 is established in the structure)

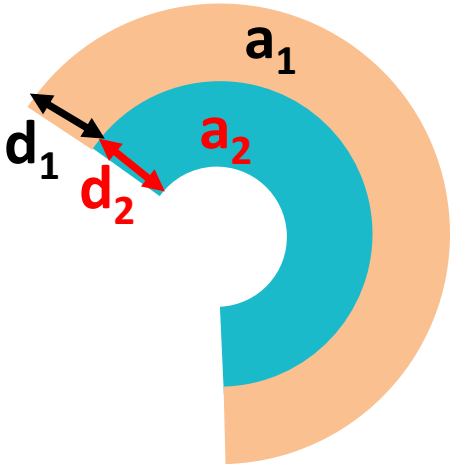


Final shape depend on total stain and etching geometry.



Curvature radius

Depend on built-in strain and bilayer total thicness

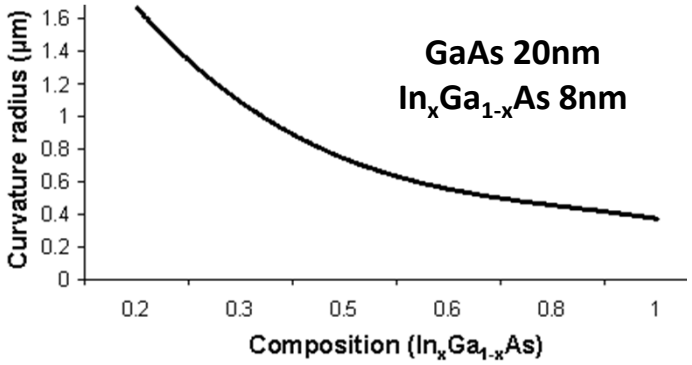


strain $\varepsilon=[(a_2 - a_1)/a_1]$

Curvature radius (macroscopic model)

$$R = \frac{d\{3(1+m)^2 + (1+m*n)[m^2 + (m*n)-1]\}}{6\varepsilon(1+m)^2}$$

d=d_1+d_2 total thickness of the bilayer
m=d_1/d_2 ratio of the two thicknesses
n=Y_1/Y_2 ratio of the Young's modules



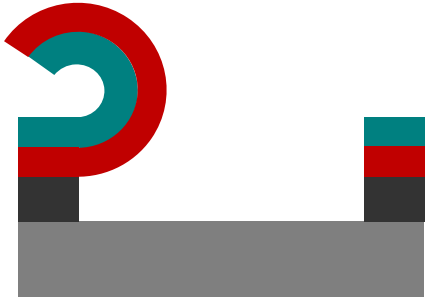
Fabbrication

top-down process : ***Lithography***
controls dimension and position down to nanometer scale

bilayer

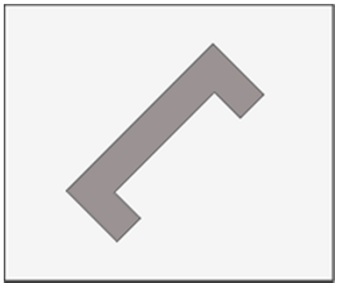
planar epitaxial growth

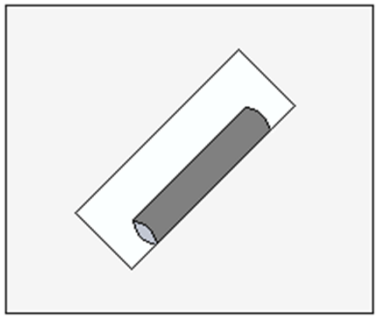
Photolithografy and
etching (wet or dry)



Etching of sacrificial
layer and structure
bending

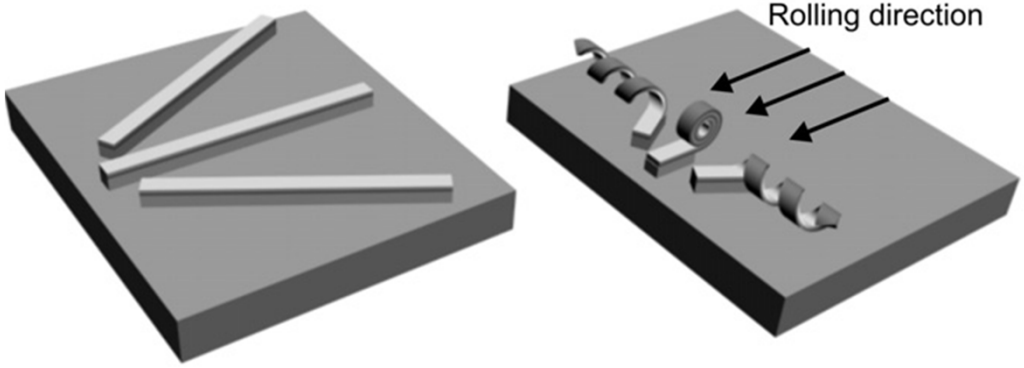
Top wiew



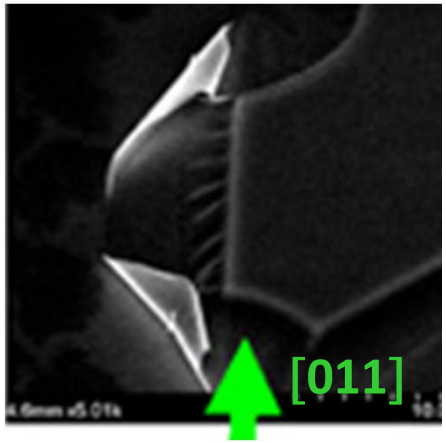


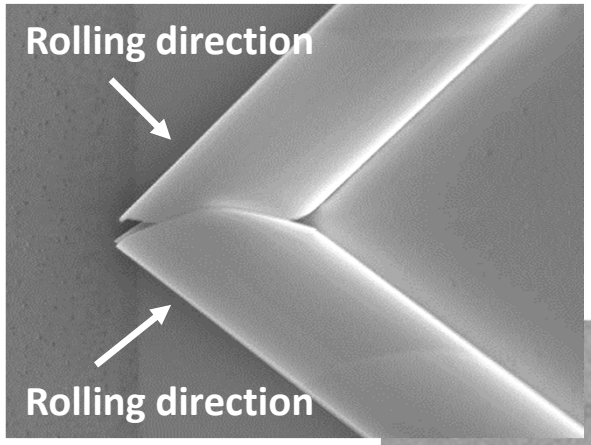
Versatile and simple technique.

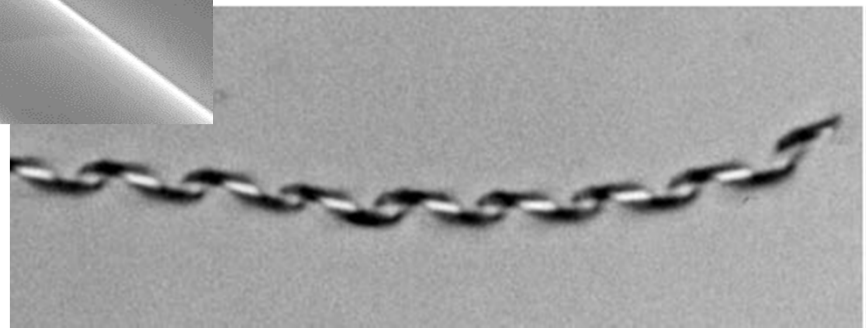
Strain anisotropy



In GaAs Young modul for the [100] direction is 85.3 Gpa and 121.3 GPa for [110]

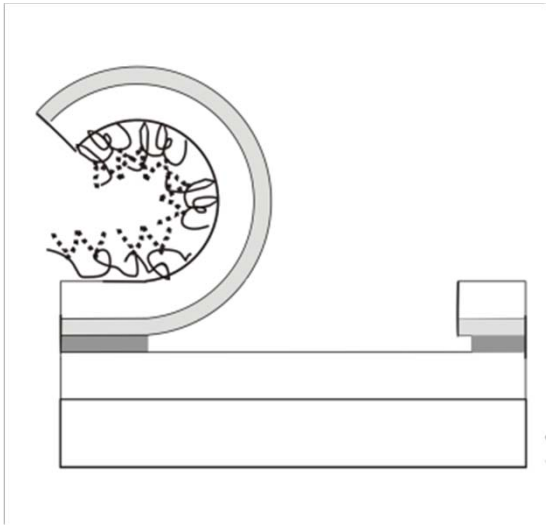


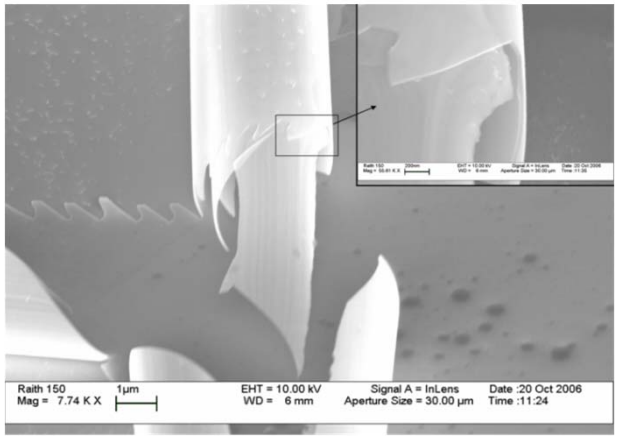




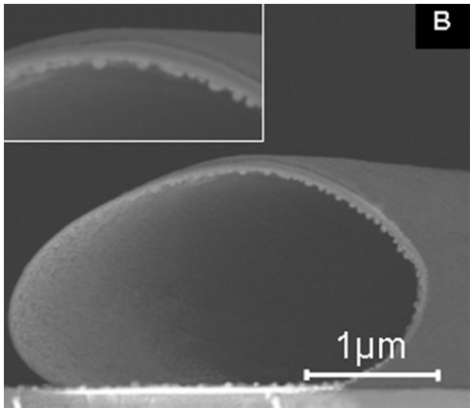
Elaborated shapes are allowed by strain anisotropy

Hybrid microtube





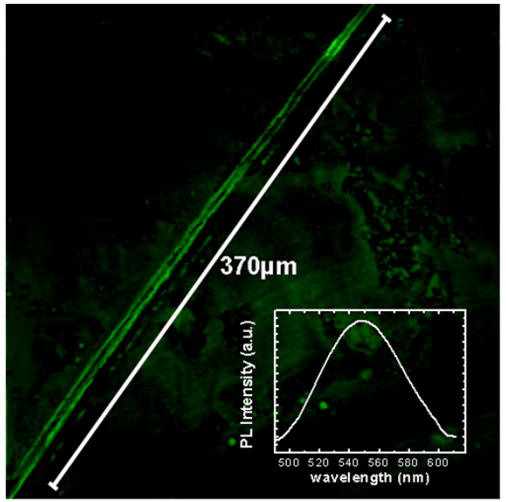
SEM analysis of a broken hybrid microtube



The GaAs template can be completely removed

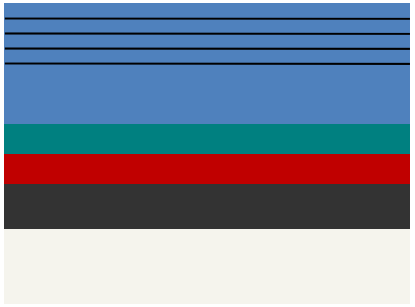
[M T Todaro et al. 2010]

The polimeric template can be infriltrate with policristals or dye molecules



Fluorescence images of funtionalized microtubes

Integrated 3D magnetic sensor

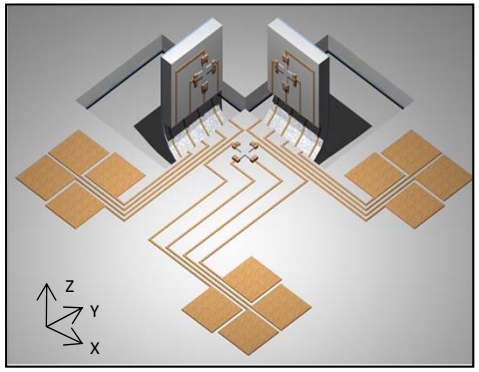


} p-HEMT structur

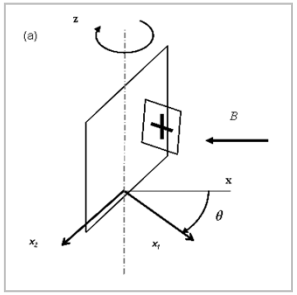
} bilayer

2DEG μ ≈8000 $cm^2/V{\cdot}s$

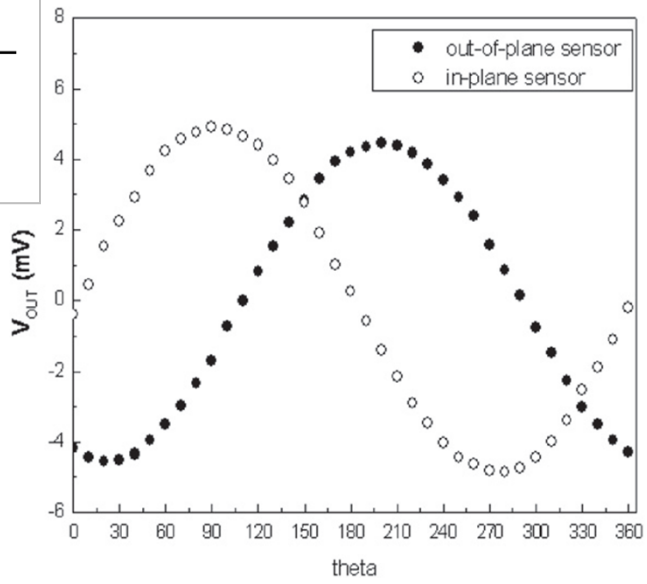
$n= 6.75{\cdot}10^{11}\ cm^{-2}$

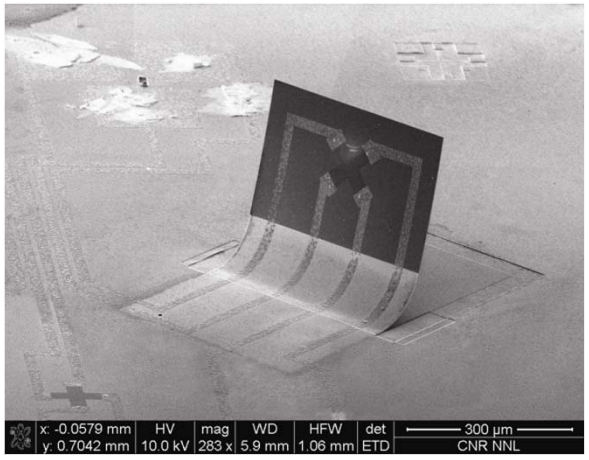


Patent "Integrated Triaxial magnetic sensor"
No: P03246 EP



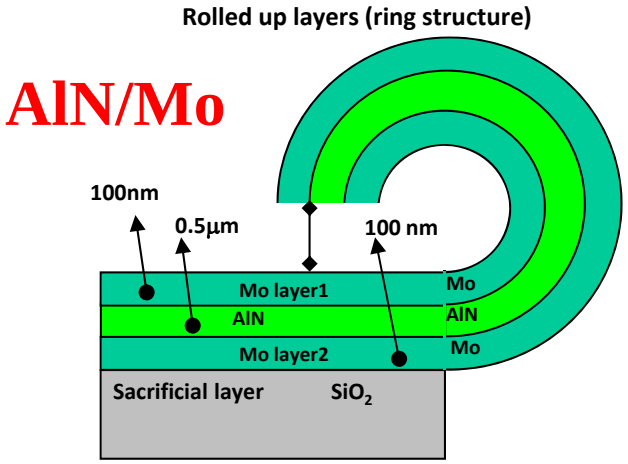
Sensitivity:
1007 V/AT

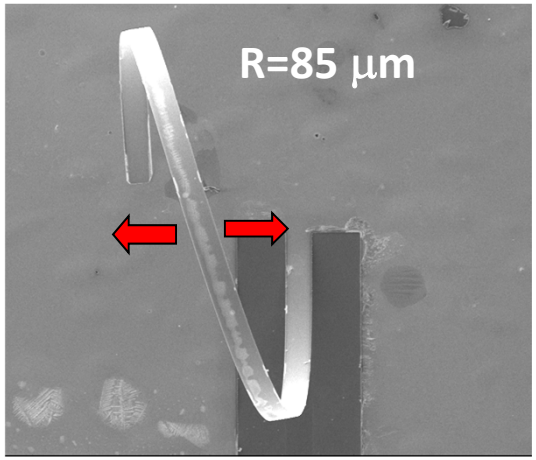




Hall voltages versus the mechanical angle

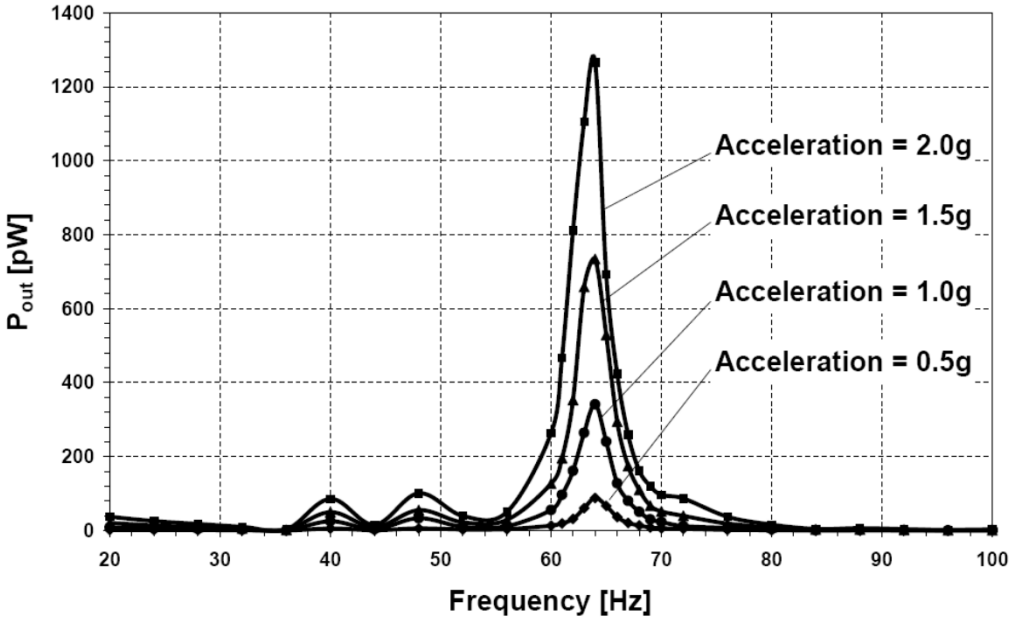
Piezoelectric rings for energy harvesting





Power density
30.2 µW/mm³

Resonant frequency
64 Hz

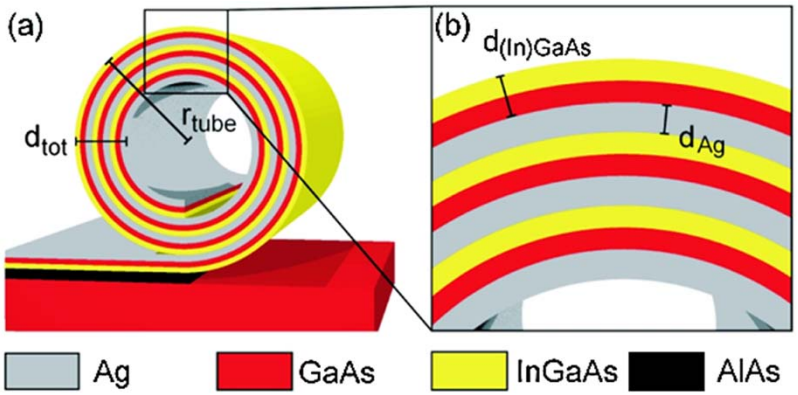


microscale dimensions and compatible with CMOS technology

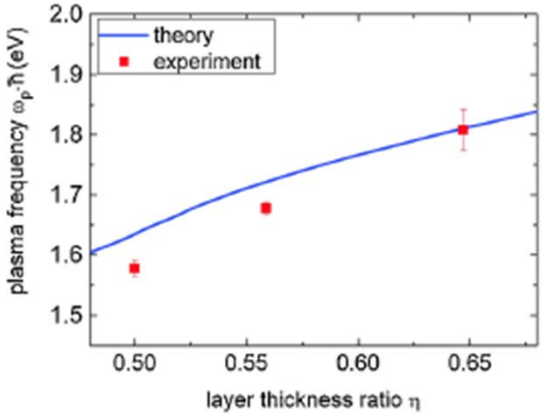
[A. Massaro et al. 2011]

3D structure for metamaterial

Rolled-Up Three-Dimensional Metamaterials with a Tunable Plasma Frequency



The wall of the tube represents a RSL that consists of alternating layers of metal and semiconductor.



Accurately tunable unit cells and lattice constants

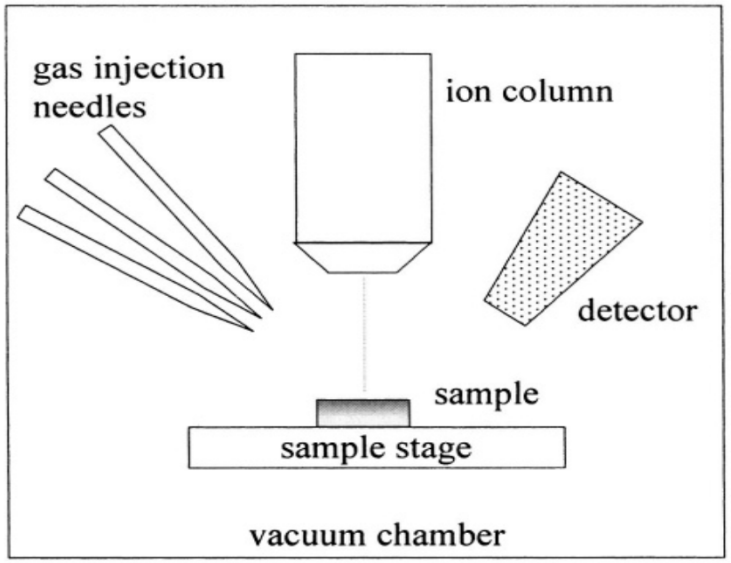
tunable plasma frequency in the visible range

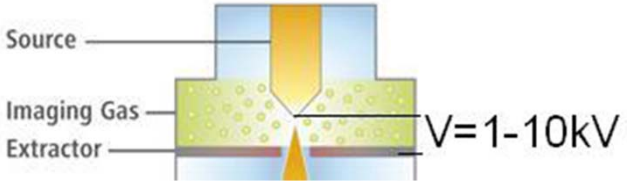
S. Schwaiger et al, PRL 102, 163903 (2009)

Outline

- Introduction
- Strategies for Nanofabrication
  - Self assambling method
    - Epitaxial Quantum dot
    - Nanowires
  - Strain driven 3D nanostructures
  - Ion Beam Induced Deposition (IBID) and nanostructuring

Focused Ion Beam

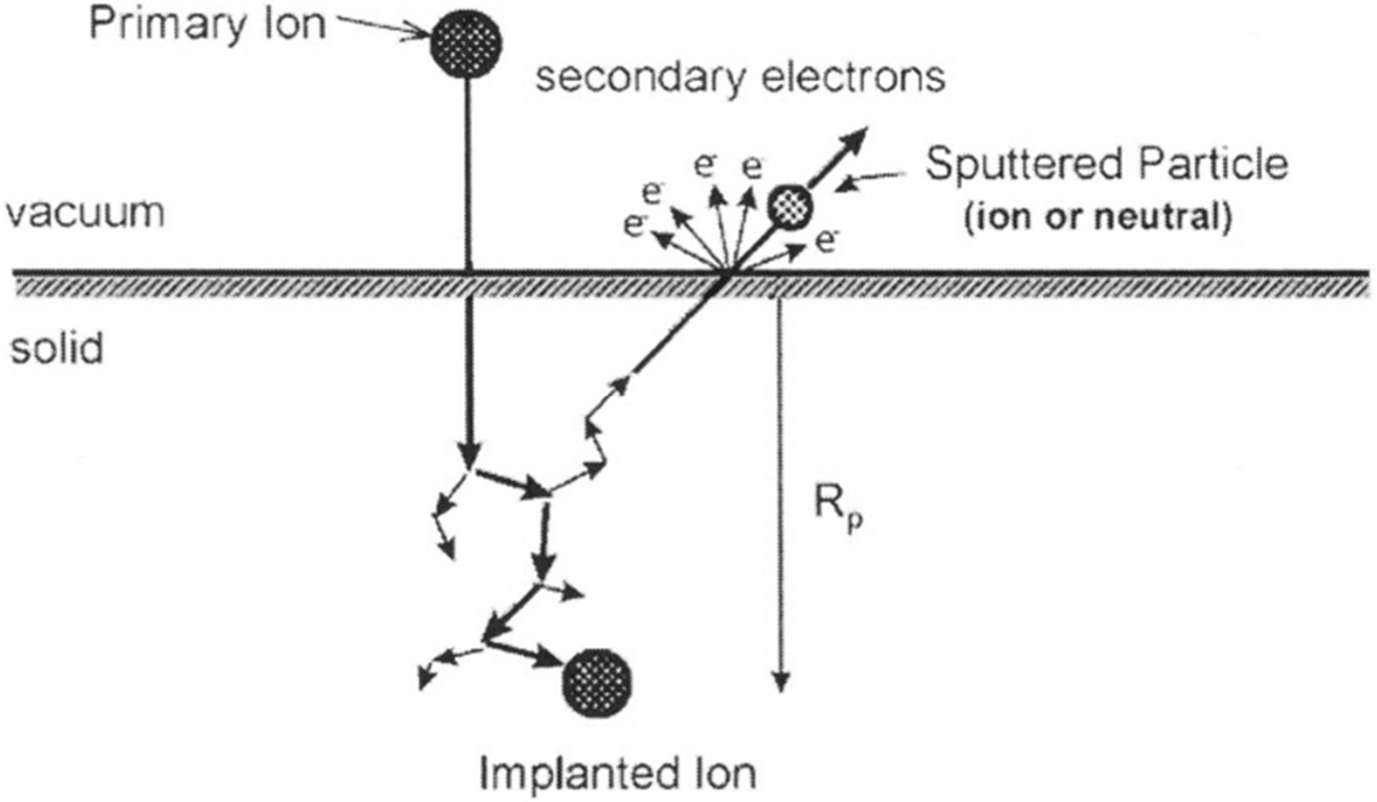




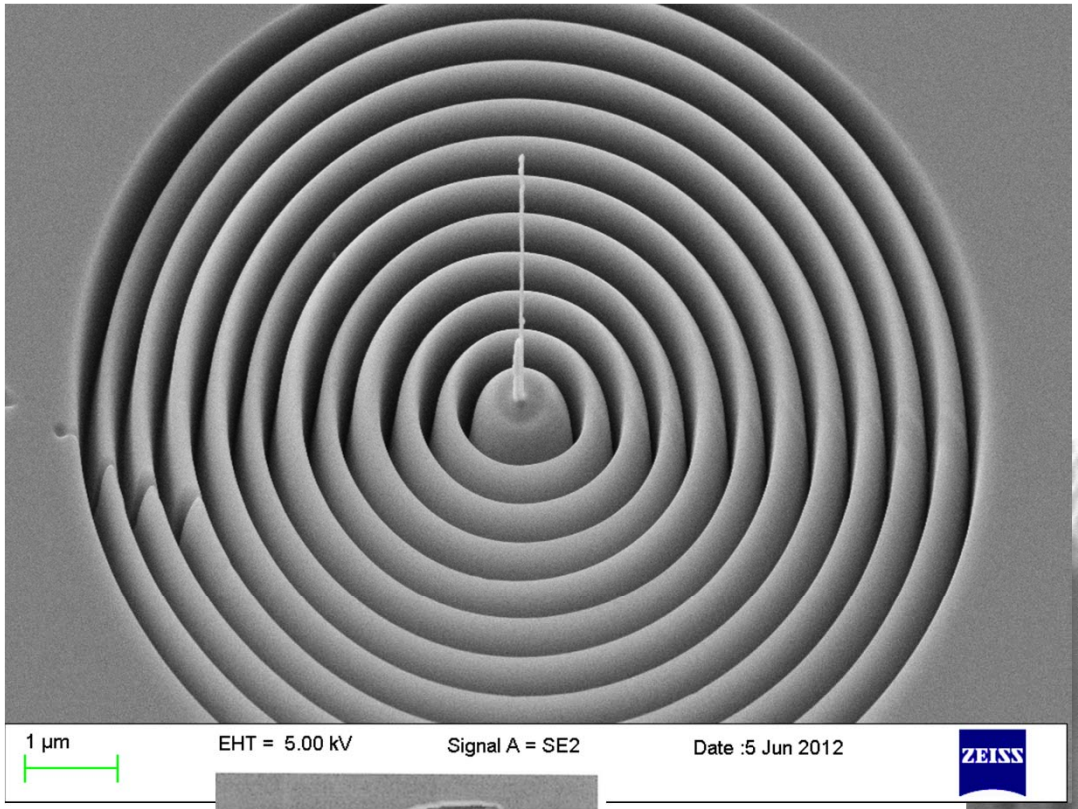
The capabilities of the FIB for small probe sputtering are made possible by the liquid metal ion source (LMIS). The LMIS has the ability to provide a source of ions of ~ 5 nm in diameter.

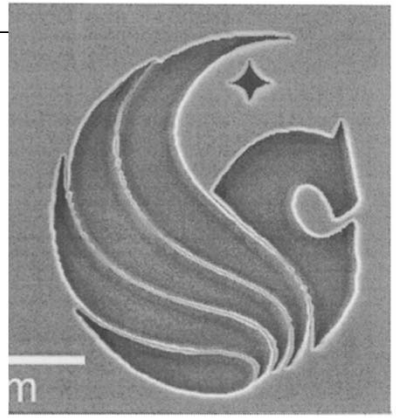
Ion Milling

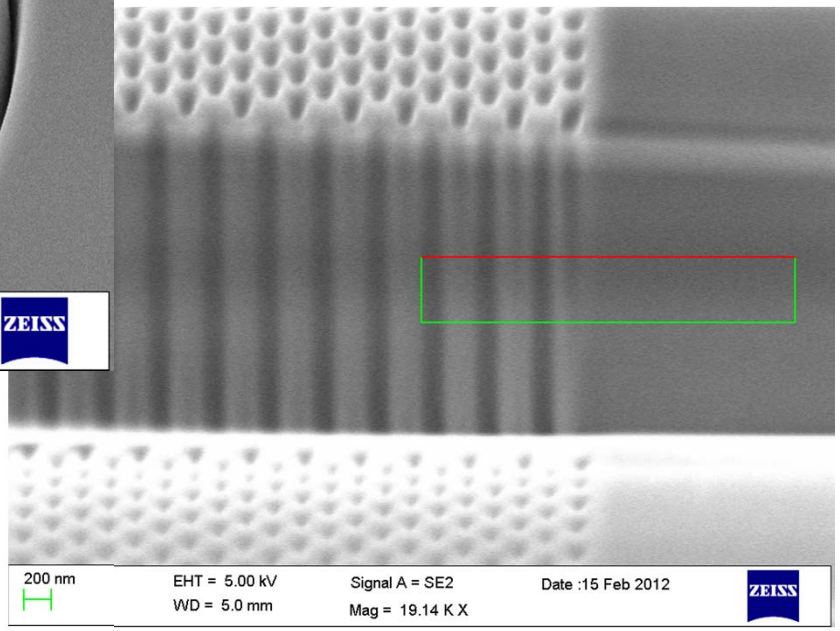
Sputtering occurs as the result of a series of elastic collisions where momentum is transferred from the incident ions to the target atoms within a collision cascade region. The kinetic energy must be sufficient to overcome the surface binding energy (SBE) of the target material



Ion Milling

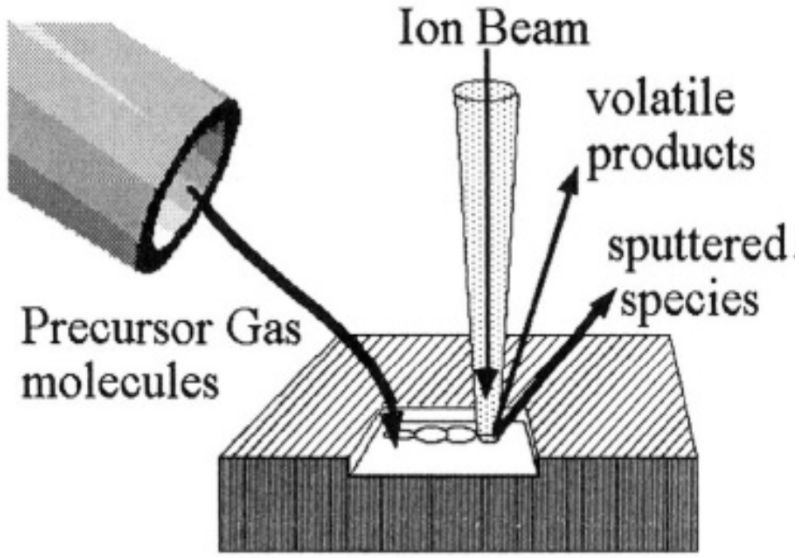

1 µm
EHT = 5.00 kV
Signal A = SE2
Date :5 Jun 2012
ZEISS




200 nm
EHT = 5.00 kV
WD = 5.0 mm
Signal A = SE2
Mag = 19.14 K X
Date :15 Feb 2012
ZEISS

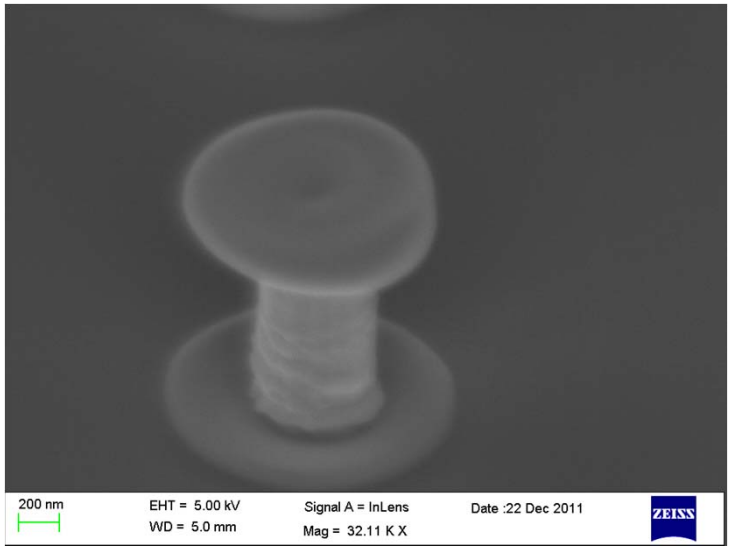
Ion Beam Induced Deposition

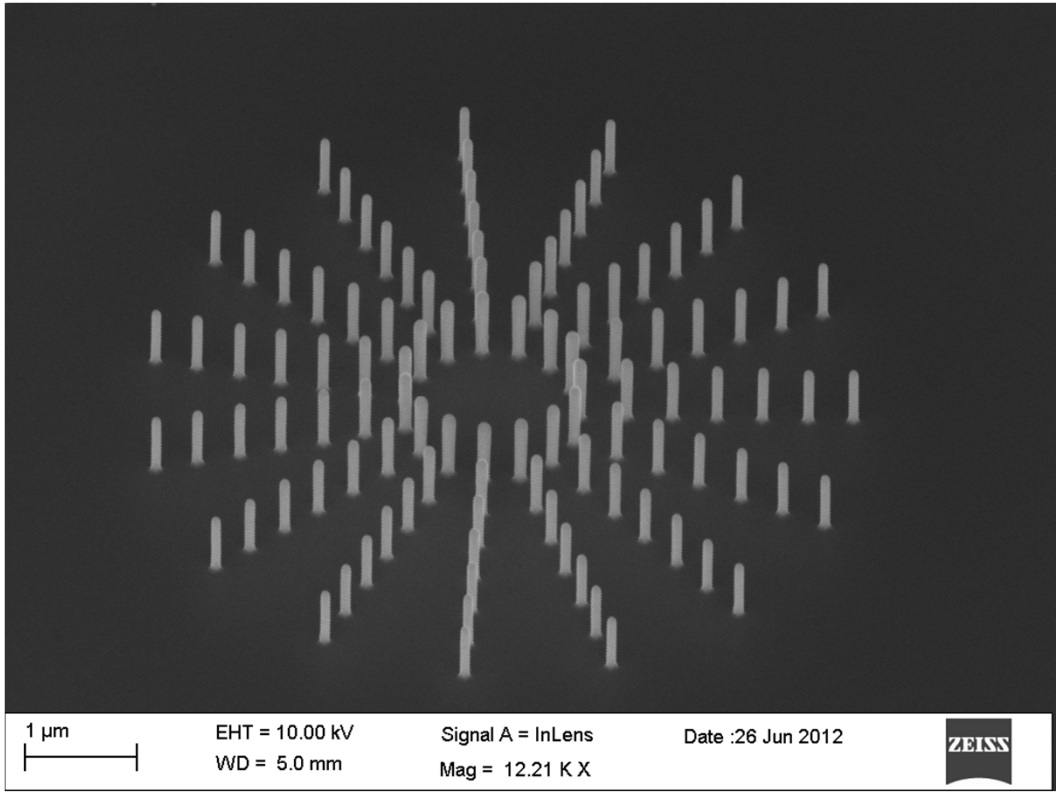
Gas delivery systems can be used in conjunction with the ion beam to produce site specific deposition of metals or insulators on almost any solid surface with very high (nanometer) spatial precision



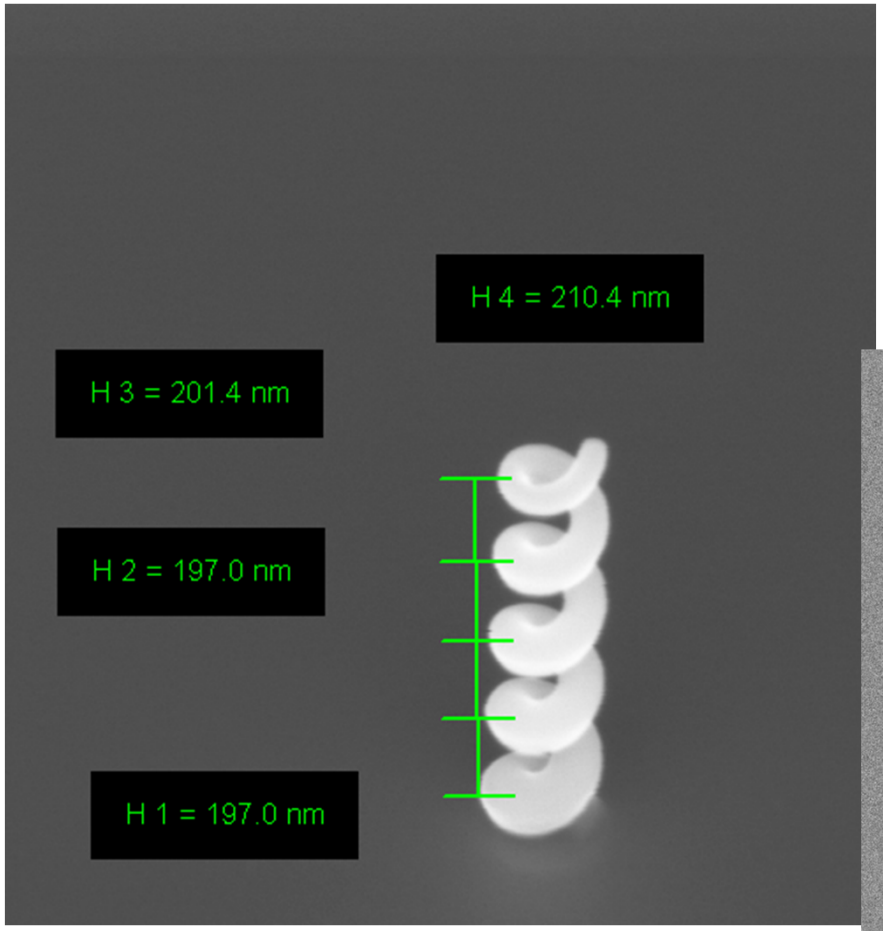
The gas molecules are adsorbed on the surface near the gas inlet, but decompose only where the ion beam strikes

Ion Beam Induced Deposition

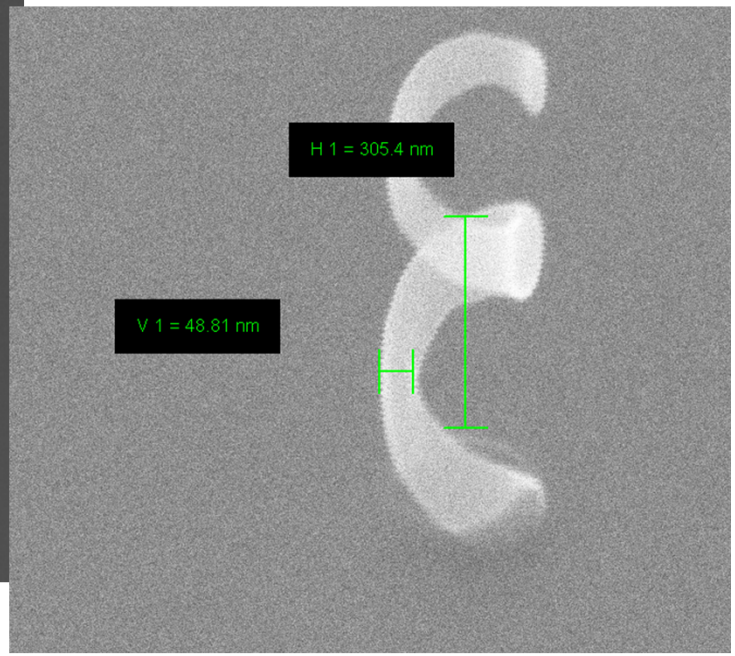




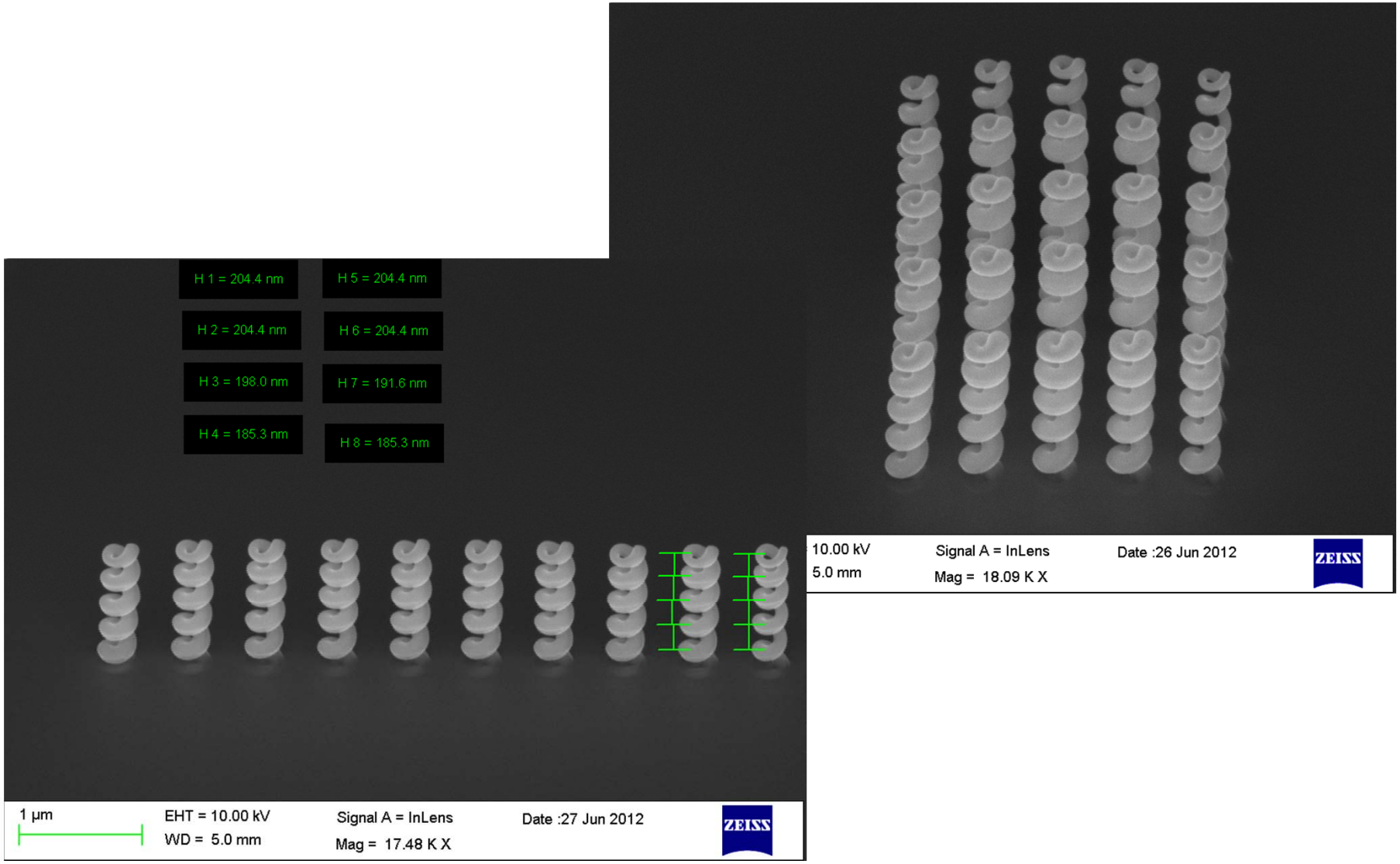
Ion Beam Induced Deposition



Smaller feature with Ion Beam is around 100÷80 nm
With E-Beam can be lowered to around 30 ÷ 40 nm



Ion Beam Induced Deposition



THANK FOR YOUR ATTENTION