

**MONA**

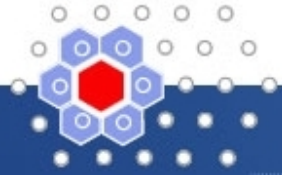
Merging Optics & Nanotechnologies

# MONA Questionnaires on Materials

## Synthesis

Roel Baets and Benoit Bataillou

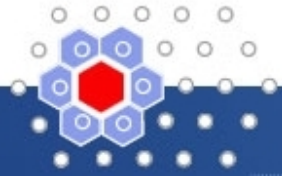
*First MONA workshop, April 7th 2006, Strasbourg. IMEC.  
R.Baets, B.Bataillou*



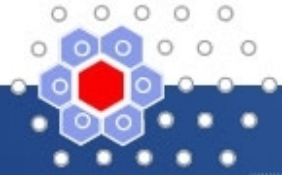
## ◆ 23 filled questionnaires received

### ➤ Subjects covered :

- Electronic confinement based structures (7):
  - Dots(4)
  - Wires(3)
- Metallic Nanostructures(7)
- Photonic crystals(2)
- Other nanostructures (4)

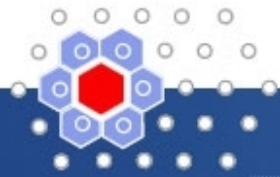


- ◆ Questionnaire Content :
  - ◆ A Material
  - ◆ An Application
    - ◆ A Tool
  - ◆ European Context

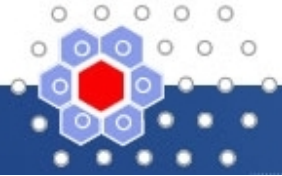


**Consider (choose) a particular nano-scale material or nano-structured material or class of such materials, with an application or potential application in photonics (material is to be understood in a broad sense here).**

- ◆ M1 Describe this material or class of materials in a few words or a few sentences.
- ◆ M2 What are, in your view, fundamental issues in the understanding of the behaviour of this material?
- ◆ M3 Can you think of key quantitative figures of merit for this material (or for its fabrication)?



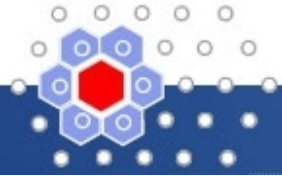
- ◆ M4 What are major (major= could be showstopper) challenges in the fabrication of this material at research (and small volume manufacturing) level?
- ◆ M5 What are major (major= could be showstopper) challenges in the fabrication of this material at high volume manufacturing level?



## Applications

***Consider (choose) a specific potentially Important application of the nano-scale material described above.***

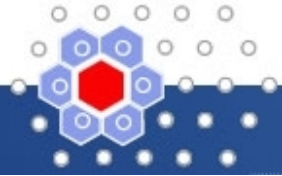
- ◆ M6 Describe this application in a few words or a few sentences.
- ◆ M7 What are, in your view, the key steps (milestones) to be taken in the development of the material for this application? If possible, specify what you expect to be a realistic timescale for those steps.



## Tools

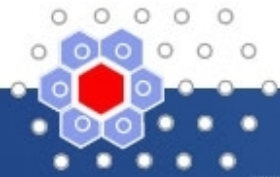
**Consider (choose) a specific tool or piece of equipment (existing or not) which is essential to manufacture a device/component based on the nano-scale material described above.**

- ◆ M8 Describe this tool in a few words or a few sentences
- ◆ M9 What are the key challenges for the development of this kind of tool? Are there major issues for using the tool in a volume manufacturing context?

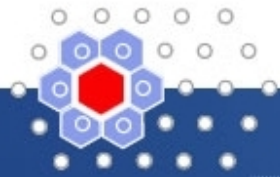


## *The European context*

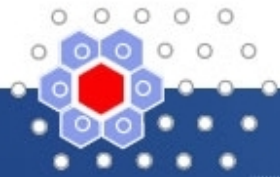
- ◆ M10 What are - for the nano-scale material and application described above - the strengths and weaknesses of Europe in terms of world-leading research and industrial deployment?



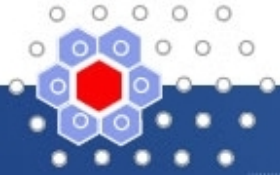
- ◆ Synthesis of responses
- ◆ Identify and discuss the major material's challenges/issues
- ◆ Try to distinguish between:
  - Challenges where we see evolutionary paths to the solution
  - Challenges where we have no clue what the solution could be



- ◆ Semiconductor Quantum Dots (by epitaxy)
- ◆ Semiconductor NanoWires (by epitaxy)
- ◆ Plasmonics/Metallic Nanostructures
- ◆ Photonic Crystals
- ◆ Colloidal nanoparticles
- ◆ Porous Silicon



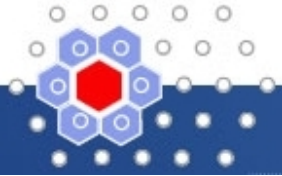
# Quantum Dots



## ◆ M1 Description

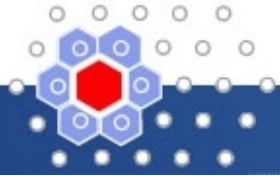
Semiconductor QDs formed by epitaxial growth techniques either in

- ◆ Top-down mode (lithographic definition)
- ◆ Bottom-up mode (self-assembly)

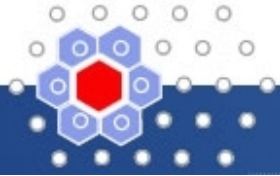


◆ *M2 : fundamental Issues*

- 1 – Size dispersion
- 2 – Position dispersion (lack of site control)
- 3 – Composition dispersion
- 2 – Modelling



- ◆ *M3 : key quantitative figures of merit for this material*
- Gain efficiency
- symmetry in gain curve
- Inhomogeneous broadening of the PL spectrum
- Areal density of site-controlled islands
- Radiative efficiency of site-controlled islands at room temperature
- Tuning the emission wavelength
- **Individual QDs**: Optical oscillator strength, nonlinear coefficients, wavelength control and homogeneous line width.



◆ *M4 : major challenges at low volume manufacturing level ?*

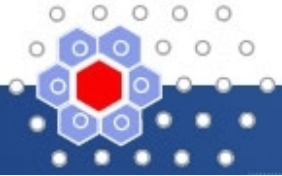
1 - Control of size dispersion

2 – Control of site of the dots

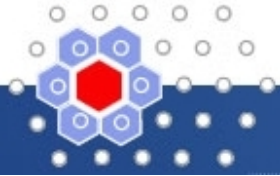
e-beam litho

optical litho

3 – Scalable fabrication schemes



- ◆ *M5 : major challenges at high volume manufacturing level ?*
- Reproducibility issues

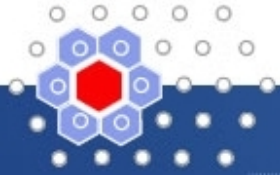


◆ *M6 : Describe an application*

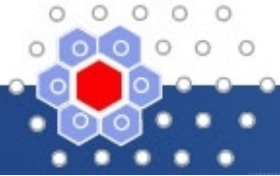
Emitting devices (edge-emitting lasers and VCSELs) for low-cost access applications,

QD lasers and amplifiers for optical tele/data communication could be developed on a GaAs basis (low threshold, low chirp, high modulation band width, temperature stability, wavelength control, high gain band width, etc.)

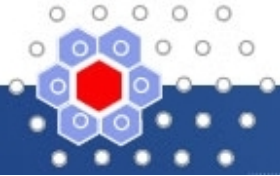
QD lasers could become key devices for low-cost un-cooled applications (FTTH).



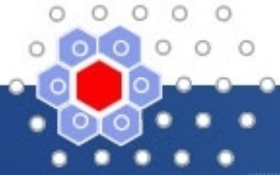
- ◆ *M7 : Timescale and challenges*
- Growth techniques control : 2 to 5 years
- Development of diode lasers based on site-controlled QDs (3-5 years)



- ◆ *M8 : Consider a specific tool or piece of equipment*
  - MBE or MOVPE with very good temperature control (over 2-3") and highly skilled grower
  - Electron-beam lithography.
  - DUV-EUV optical lithography.

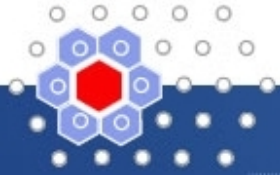


- ◆ *M9 : issues for this tool in high volume*
- Same challenges as the IC industry: nanopatterning
- Currently available reactors are able to do the job (MOVPE)
- Key challenge : recipes for highly controlled QD growth scheme



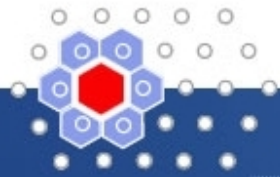
◆ *M10 : European context*

- More research efforts should be put on manufacturing sciences
- very strong (leading) research efforts on QDs and QD-based devices.
- Investments in III-V epitaxial growth (MBE and MOVPE) apparatus will be needed
- strong in epitaxial growth and photonics research
- weak in industrial fabrication of lasers and amplifiers (Japan, US)

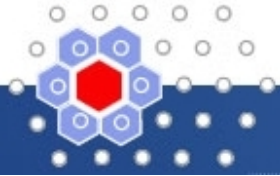


## CONCLUSION?

- ◆ Challenges with evolutionary roadmap
  
  
  
  
  
  
  
  
  
  
- ◆ Challenges with no-clue roadmap



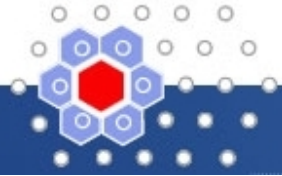
# Nano Wires



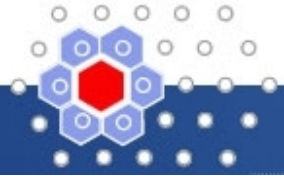
- ◆ M1 Description
- GaAlInN NWs
- NWs grown on Silicon

Interest stems from:

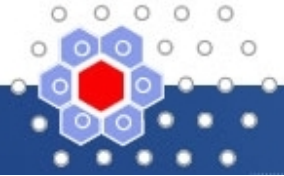
- dislocation-free material
- Growth on mismatched substrates
- Increased light extraction (no bulk with high index)
- High growth rate



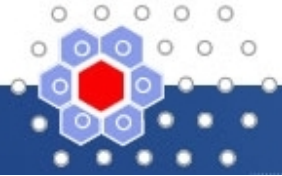
- ◆ *M2 - fundamental issues in the understanding of the behaviour of this material?*
- Need study of 1D electronic properties (levels, excitons), confinement, guiding.
- Optical properties.
- Effects resulting from dimensions / crystal structure itself (hexagonal symmetry for GaAs) ?



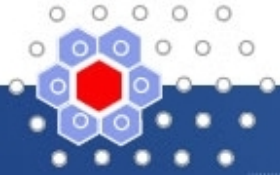
- ◆ *M3 : key quantitative figures of merit for this material (or for its fabrication)?*
  
- No dislocations in heterostructures :
- increase the light extraction due to the geometry
- growth time is probably lower than ½ hour
- capability to handle single photon or electron



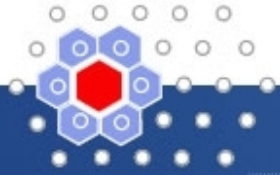
- ◆ *M4 : major challenges in the fabrication of this material at low volume manufacturing level ?*
- Growth and “handling” is difficult
- Control of heterostructures (longitudinal and radial)
- Size of the NWs
- Doping



- ◆ *M5 : What are major (major= could be showstopper) challenges in the fabrication of this material at high volume manufacturing level ?*
- Need for a dedicated MOCVD



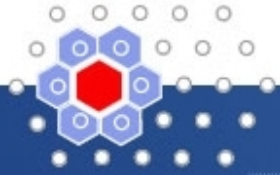
- ◆ *M6 : Describe an application*
  - Lighting application
  - Solve the UV challenge (to overcome the doping problem of planar substrates)
  - Could lead to breakthroughs in single electron transistors or single photon emitters, ex : quantum cryptography.



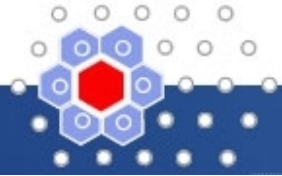
◆ ***M7 : Timescale and challenges***

- **Physics** of such structures and to ascertain the real application fields.
- **Optical engineering: (1 year)**  
definition of the best structures
- **Growth control: (3 years)**  
(seed location, optimization of growth parameters, doping control)
- **Improve performance (3 years)**
- **Integration: (2 years)**  
planarization metallic contact
- **Device development: (2 years)**

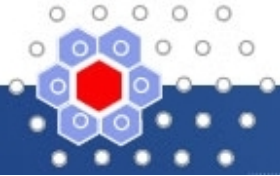
Most of these steps can be performed in parallel. total **4-5 years**.



- ◆ M8 : Consider a specific tool or piece of equipment (existing or not) which is essential(etc)
- High quality MOCVD setup

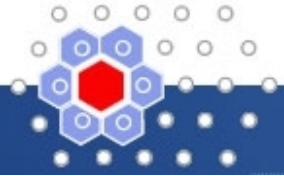


- ◆ M9 : issues for this tool in high volume
- Validate the NW growth with high volume equipment



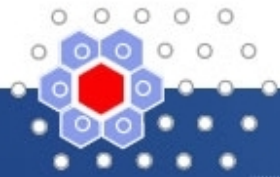
## ◆ M10 : European context

- NW efforts have been mainly focused in Europe on nanoelectronics properties (transistors, diodes...) but not on optical properties
- World-leading research is presently conducted in the States, Korea and China seem to be catching up

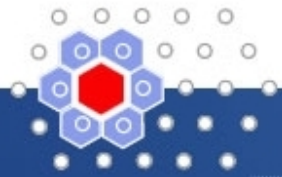


## CONCLUSION?

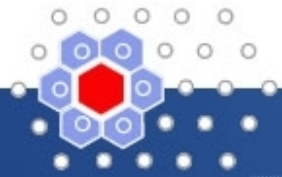
- ◆ Challenges with evolutionary roadmap
  
  
  
  
  
  
  
  
  
  
- ◆ Challenges with no-clue roadmap



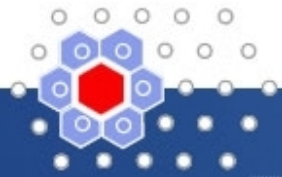
# Plasmonics/Metallic Nanostructures



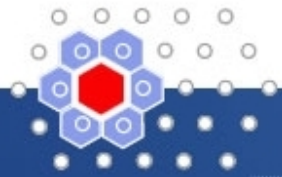
- ◆ M1 Description
  - Metallic nanostructures patterned by lithography
  - Chemically synthesized metallic nanoparticles
  - Metallic nanowire arrays
  - Thin metallic film + heating
  - Ordered nanoscale metallic metamaterials



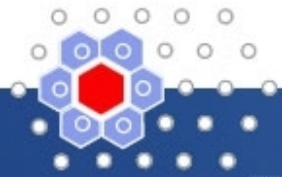
- ◆ *M2 : Fundamental issues in the understanding of the behaviour of this material?*
- Understand the mechanism of the interaction of these materials with an optical field (which geometry for which optical property?)
- Modelling metal structures at the nanoscale (very hard to predict)
- Highest field enhancement achievable in the nanostructures?
- Understand the technology of formation of metallic nanoclusters in glassy media
- Interaction of light emitters (molecules, QDs) with these materials (local field enhancement vs. quenching)
- Slow light in metallic nanostructures: unexplored
- Non-linear optics in metallic nanostructures: unexplored
- Quantum effects?



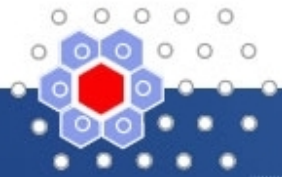
- ◆ *M3 : key quantitative figures of merit for this material (or for its fabrication)?*
- *Depends strongly on application*
- *Losses*
- *Losses*
- *Losses*



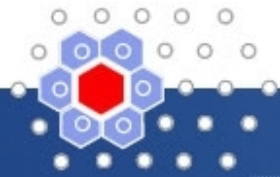
- ◆ *M4 : What are major challenges at low volume manufacturing level ?*
  
- Manufacture very small structures or patterns (feature size between 10 and 20 nm)
- Fabricate a homogeneous photonic material with limited optical losses.
- Introduce metal nanoclusters inside a glassy matrix
- Homogeneity in size
- Reproducibility is low due to strong dependence on geometry
- Availability of good metals is low
  - Ag: not so stable (O, S)
  - Au: more loss but more stable
  - Other??



- ◆ *M5 : major challenges at high volume manufacturing level ?*
- Manufacture very small structures or patterns (between 10 and 20 nm)
- Most research structures are fabricated with a FIB
- Self-assembly techniques only rarely produce structures that are good over large areas.
- Soft-lithography of thick (thicker than a couple of monolayers) metal structures is still in its infancy.

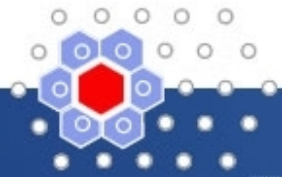


- ◆ *M6 : Describe an application*
- ◆ Electronic and optoelectronic devices, catalysts, and chemical and biochemical sensors
- ◆ Patterned polarisers with arbitrary microstructures.
- ◆ Biological sensors(3/5)
- ◆ Surface Plasmon Lithography - resolution : 10 to 20 nm.
- ◆ High density photonic integrated circuits
- ◆ Nanometer size waveguides
- ◆ Negative refractive index: perfect lens
- ◆ Plasmonic crystals in general
- ◆ Surface plasmon resonance (SPR) devices
- ◆ Surface plasmon guides
- ◆ Near-field optical microscopy and high density data storage
- ◆ All-optical dynamic and active nanodevices
- ◆ optical transistor and modulator and nanolaser.

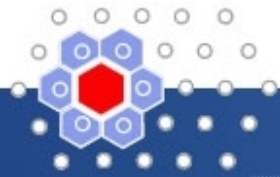


## ◆ *M7 : Timescale and challenges*

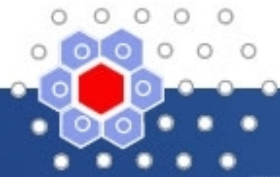
- Optimisation of the nanostructure parameters for achieving the strong electromagnetic field enhancements (3-5 years)
- Hybridising metallic nanostructures with active materials (nonlinear polymer, dye molecules, quantum dots)—(3-8 years)
- Design and testing integratable nanocomponents (5-10 years).
- “I think the next 5 years will see major steps forward”



- ◆ *M8 : Consider a specific tool or piece of equipment (existing or not) which is essential(etc)*
- X-ray/FIB litho
- High throughput litho
- Adaptation of existing top-down fabrication for CMOS to metals or microcontact printing or imprint lithography.



- ◆ *M9 : issues for this tool in high volume*
  - Focused ion beam: too slow
  - Bottom-up techniques : more target on metals needed
  - Near-field microscopy needs to be made more robust so that it can be used by people without needing to be trained for at least a year



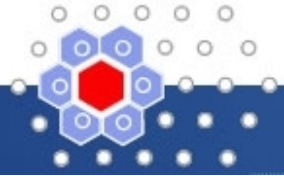
## ◆ *M10 : European context*

New nano-optic and optoelectronic excellence centres

Surface plasmon lithography(w mask): no research work in Europe – only a few studies in USA and Japan

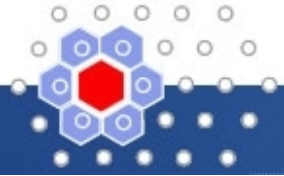
At least 2 Networks of Excellence are dedicated for a large fraction to metallic metamaterials, EU seems to be ahead

High risk, high gain type material. Industry does not seem interested

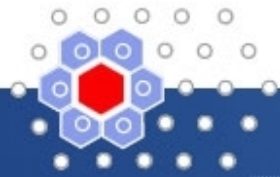


## CONCLUSION?

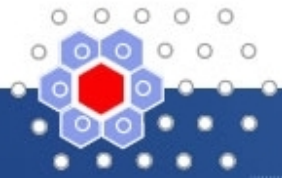
- ◆ Challenges with evolutionary roadmap
  
  
  
  
  
  
  
  
  
  
- ◆ Challenges with no-clue roadmap



## Photonic crystals / high-index waveguides



- ◆ M1 Description
  - High-index-contrast nanophotonic waveguides and cavities in semiconductor membranes (suspended or solid) embedded in dielectrics: enormous progress in last couple of years especially in Silicon (usage of CMOS technology)
  - 3D photonic crystals: little progress in last couple of years



- ◆ M2 Fundamental issues in the understanding of the behaviour of this material?

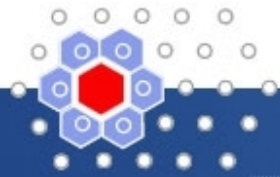
*Required geometrical accuracy:  $O(1 \text{ nm})$*

*Active characteristics due to incorporation of dopants, nanocrystals, nanoparticles*

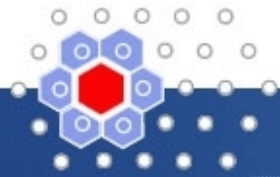
*Photonic band dispersion simulation*

*Resonant behaviour, field distribution*

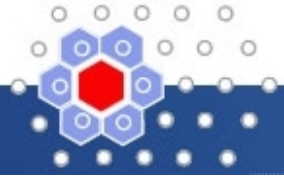
*Photonic mode propagation (simulation and measurement).*



- ◆ M3 Key quantitative figures of merit for this material (or for its fabrication)?
  - *Losses*
  - *polarization birefringence control*
  - *anomalous dispersion relations at the bandgap edges*
  - *Thermal properties for power applications.*
  - *Exceptionally high third order nonlinear susceptibility*

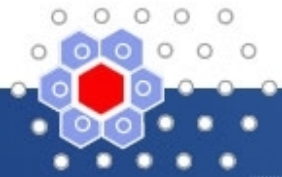


- ◆ M4 What are major challenges in the fabrication of this material at research level
  - Control and reproducibility of  $O(1\text{nm})$  accuracy*
  - Homogeneity of the material and its refractive index during deposition.*
  - Stability of the deposited films (peeling off and cracking).*
  - Etching quality: selectivity to mask (aspect ratio) and sidewalls roughness*

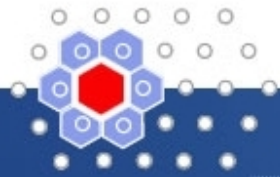


- ◆ *M5 What are major (major= could be showstopper) challenges in the fabrication of this material at high volume*

High accuracy lithography down to nano-feature size for mass production (deep UV litho, extreme UV litho, nanoimprint).



- ◆ *M6 Applications*
  - High density photonic integrated circuits
  - Possible applications in biophotonics.
  - Frequency conversion in photonic circuitry via third harmonic generation
  - Four-wave mixing techniques for optical switching
  - High-Q photonic crystal nanocavities for all-optical switches.



## ◆ **M7 Key steps (milestones) to be taken in the development of the material**

Development of low sidewall roughness etching with high aspect ratio – 5years.

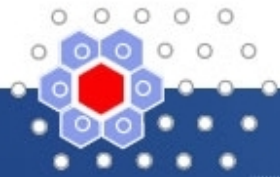
Development of multi-layer deposition of stable films with different thermal coefficients – 5 years.

Development of large scale nano-litho – 10 years.

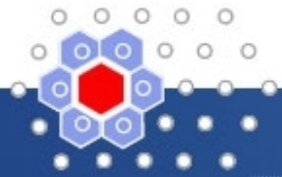
Improve design by including optical, electrical and thermal properties.

## **Second timeline (2nd expert)**

1. quantitative characterization of the effect in a guided wave configuration (2-3 yrs)
2. refinement of simulations techniques for system design (2-3 yrs)
3. system integration in a planar wave geometry with integrated input and output channels
4. experimental demonstration of the functionalities (5-7 yrs total)



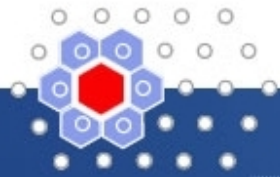
- ◆ M8 Describe this tool in a few words or a few sentences.
  - High throughput litho for nano-components.
  - Bonding methods for semiconductor membranes (molecular bonding, BCB-bonding, etc)
  - Deposition methods for low loss amorphous semiconductor membranes (eg a-Si)



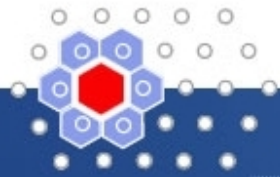
- ◆ M9 What are the key challenges for the development of this kind of tool? Are there major issues

*Light sources for extreme UV litho – for volume manufacturing (for research e-beam is OK)*

*Improvements in nanoimprint and soft lithographies (pattern quality and replication via solid stamps)*

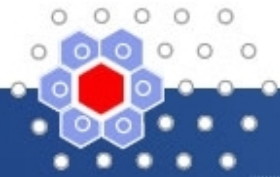


- ◆ *M10 strengths and weaknesses of Europe*
  - More research efforts should be put on manufacturing sciences: often limited to a minor task large EU projects
  - World-leading level of theoretical and experimental investigations on SOI structures.
  - Scarce collaborative effort in manufacturing equipments and in device prototyping and development, that should meet large-scale interests.

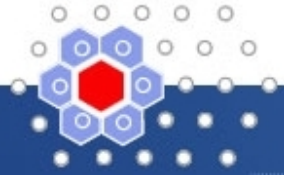


## CONCLUSION?

- ◆ Challenges with evolutionary roadmap
  
  
  
  
  
  
  
  
  
  
- ◆ Challenges with no-clue roadmap

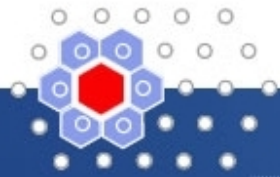


# Colloidal nanostructures



## ◆ *M1 description*

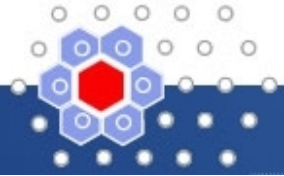
- Nanometer-sized (1-50 nm) crystalline metal, semiconductor or insulator particles that are synthesized by means of colloid chemistry techniques



- ◆ *M2 Fundamental issues in the understanding of the behaviour of this material?*

Non-linear optical properties have been investigated far less, although a few reports indicate enhanced nonlinear refraction.

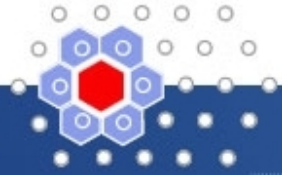
Integration of colloidal particles with the Si platform has not been explored yet.



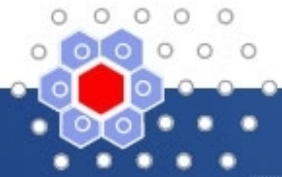
◆ *M3 key quantitative figures of merit for this material?*

*Can be metal or semiconductors colloids*

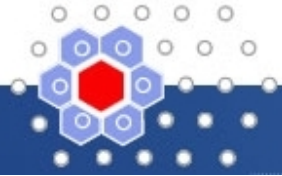
- quantum confinement leads to a discrete set of energy levels and a size-dependent bandgap transition
- surface states can be passivated effectively leading to photoluminescence efficiency approaching unity
- size, shape and dielectric properties of the surroundings determine the position and the spectral width of the plasmon resonance.



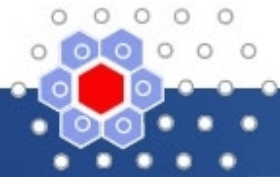
- ◆ *M4 major challenges in the fabrication of this material at research level?*
- At research level, state-of-the-art colloidal synthesis has reached a high degree of perfection
- Challenges : integration of these particles with existing technologies.



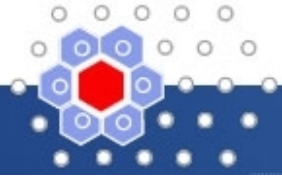
- ◆ *M5 Major challenges at high volume manufacturing level?*
- Need to use hazardous chemicals in an inert atmosphere



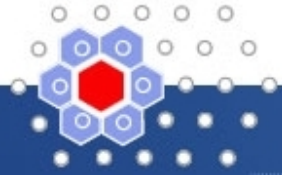
- ◆ M6 Describe an application
  - *use as a coating or overlay material for semiconductor waveguides (sensing or transfer of non-linear properties).*



- ◆ *M7 the key steps (milestones) to be taken in the development of the material for this application?*
- **Convincing people of the benefits of a hybrid technology that combines lithographic structures with colloidal nanocrystals**
- Development of reliable, easy-to-implement techniques to deposit colloidal nanocrystals on semiconductor structures with high spatial resolution.

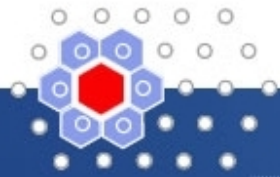


- ◆ **M10 European context**
- Europe has expertise in synthesis of colloidal nanocrystals
- A weakness, as compared with US institutions for instance, is the lack of integration between different players in the field
- lack of integrated multidisciplinary team (example of IBM Watson research center)

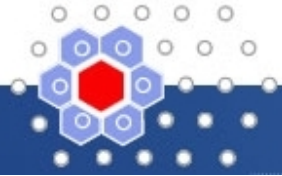


## CONCLUSION?

- ◆ Challenges with evolutionary roadmap
  
  
  
  
  
  
  
  
  
  
- ◆ Challenges with no-clue roadmap

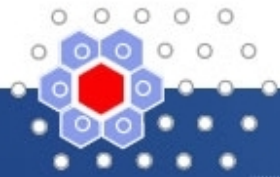


# Porous Silicon

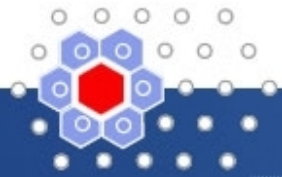


## ◆ M1 Description

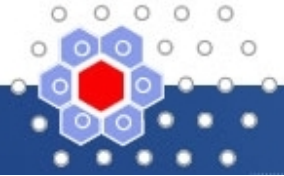
Nanostructured Porous Silicon – random or ordered arrangement in volume of low-dimensional (1D, 0D) or fractal interconnected Si nano-particles and air nano-pores.



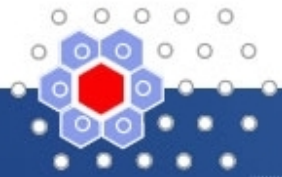
- ◆ *M2 fundamental issues in the understanding of the behaviour of this material?*
- Control of the porous structure formation at nano-scale level
- Roles of surface states, dimensions and crystalline morphology of the porous Si nanoparticles on their electronic properties.



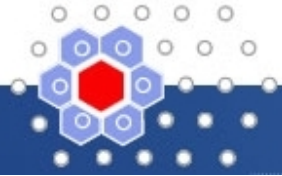
- ◆ *M3 key quantitative figures of merit for this material*
- Refractive index of porous silicon can be varied over a wide range. porosity dependent refractive index varying from 2.8 down to 1.2
- Operation on pores allow to realize different photonic devices, such as: photonic crystals, Bragg mirrors and optical filters.



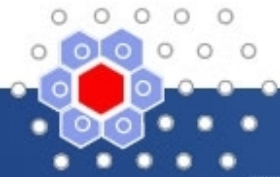
- ◆ *M4 Major challenges in the fabrication at research level?*
  - Control of interface quality
  - In-depth homogeneity of the layer porosity and thickness
  - Chemical coverage of the Si nano-particle surface.



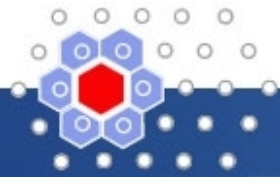
- ◆ *M5 What are major challenges at high volume manufacturing level?*
  - Aging
  - Homogeneity of the porous structure at large surface (wafers of 300 mm).



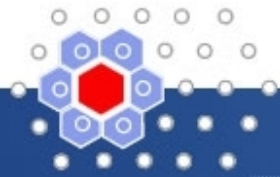
- ◆ *M6 Describe an application*
- Application of the photonic devices based on porous Si nanostructures as sensing elements in bio-medical or (bio)-chemical field



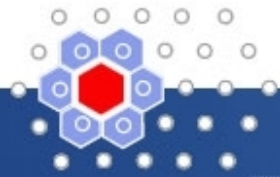
- ◆ *M7 key steps (milestones) to be taken in the development of the material for this application?*
- Study of interaction of the porous Si nanostructures with liquids and gases (wetting, permeability, aging)
- Bio-chemical functionalization of the porous Si specific surface.



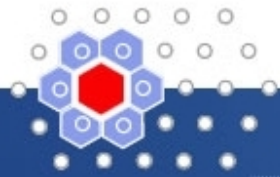
- ◆ Describe a tool
  - High power pulsed current generator



- ◆ *What are the key challenges for the development of this kind of tool?*
- Realization of high power pulsed current generators capable to treat in parallel a large number of Si wafers (especially of low resistivity).



- ◆ *M10 the strengths and weaknesses of Europe*
- Strength – existence of high level scientific teams specialized in porous silicon and in porous silicon based photonic devices.



## CONCLUSION?

- ◆ Challenges with evolutionary roadmap
  
- ◆ Challenges with no-clue roadmap

