COLLOIDAL NANOCRYSTAL BASED PHOTONIC DEVICES FABRICATION

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Outline

- Colloidal nanocrystals (NCs): active materials for high-performing photonic devices
- Processing of NCs: from close-packed to NCs in blends
- NCs in resist blends
- Building blocks for photonic devices based on colloidal NCs
- Conclusions
Colloidal nanocrystals

- Chemically synthesized Quantum Dots
- Low fabrication costs with high throughput
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- Low dimensions – strongly size-dependent optical behavior
- Thermal stability

*Epitaxial QDs*

\[ \Delta E \]

\[ d \sim 40-50 \text{ nm} \]

*Colloidal QDs*

\[ \Delta E \]

\[ d \sim 2-6 \text{ nm} \]
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- Full tunability from UV to IR
Colloidal nanocrystals

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- Thermal stability
- Full tunability from UV to IR
- Optical gain and stimulated emission
  - High volume fractions
  - Close-packed films

Close-packed films / NCs in Titania blends

- Rough films – chaotic networks of cracks
  - low optical quality – high scattering losses
  - how to process them?

NCs dispersed in titania matrix


NCs in Titania blends

- Decoupled synthesis of NCs from preparation of matrix
- Sol-gel technique under inert atmosphere
- Surface-chemistry improved to obtain high volume fractions (> 1% as required for Amplified Spontaneous Emission) with no phase separation
- Concentration of NCs exploited to tune the refractive index from 1.6 to 1.8
- Low-scattering waveguiding films
- ASE signal demonstrated at low Temperature and Room Temperature
NCs in Titania Blends

**Etching of the substrate**

H. J. Eisler, V. C. Sundar, M. G. Bawendi, M. Walsh, H. I. Smith, and V. Klimov,

**Soft-lithography**

V. C. Sundar, H. J. Eisler, T. Deng, Y. Chan, E. L. Thomas, and M. G. Bawendi,

**Glass capillaries**

M.A. Petruska, A.V. Malko, P.M. Voyles and V. Klimov,
NCs in Titania Blends

Limited freedom in the definition of the photonic device geometry

- Ridge-like geometries?
  - imprint limited by bottom residual layers
  - pre-patterning of substrates
- Need of rigid substrates
- Maximum index contrast: \(~0.3\) on glass
- Multi-wavelength devices on the same substrate: only stacked configurations
NCs dispersed in resist matrix

CdSe/ZnS nanocrystals

Gain material synthesized by means of low-cost techniques

Zn/S shell

Cd/Se core

poly(methylmethacrylate)

Sensitive to electron beam or UV radiation

SU-8 (epoxy resist)

Highly versatile active material for optical devices

- Decoupled synthesis of NCs from preparation of matrix
- Complete tunability of optical properties from UV to IR range
- Full control on the device geometry/Selective localization of emitters with nanometer scale resolution
Localization of NCs by EBL processes

- Polymer/NCs blend still behaves as a resist
- Emission properties of NCs must not be affected by electron beam exposures
SEM and AFM images of patterned blend

Stripes: width=2μm period=4μm

Pillars: diameter=0.6μm Period=2μm

The positive resist behaviour of PMMA is not perturbed by the presence of NCs

Photoluminescence maps by confocal microscope

PL signal is detected only in the unexposed regions

The emission spectrum of NCs is not affected by EBL

SU-8/NCs blend Optical Lithography

UV radiation

Cr mask

Blend

GaAs substrate

Stripes width: 2 – 100 μm

UV source: Hg i-line @ λ=365 nm
PL signal is detected only in the exposed regions
The emission spectrum of NCs is not affected by UV

NCs localization by lithographic techniques

- e-beam lithography and photolithography
- positive and negative resists
- optical properties of NCs not affected by exposure
- resolutions down to 20 nm achieved
- slight increases of exposure doses for positive resists
- for negative resists, exposure dose increase roughly proportional to the NCs concentration in the blend
NCs localization by lithographic techniques

Several advantages:

- any kind of substrate without recurring to chemical or physical treatment of the surfaces;
- not only rigid substrates but also flexible devices;
- the typical resolution is defined by the lithographic process;
- the density of emitters can be easily tuned by varying the relative molar concentration of the two components (NCs – resist);
- refractive index of the blend tunable with the NCs concentration.
Building blocks for photonic devices

- Waveguides
- Distributed Feedback structures
- Nanocavities
- Distributed Bragg reflectors
Building blocks for photonic devices

Building blocks for photonic devices

- Uniform resist/NCs layer
- Ridge waveguides
- Distributed Bragg Reflectors (DBRs)
- Distributed feedback (DFB) structures
Building blocks for photonic devices

DFB
$L_{BRAGG} = 245 \text{ nm}$
$\text{thk} = 40 \text{ nm}$

DBR
$3\lambda/4 \text{ stripes}$
$\text{thk} = 400 \text{ nm}$

And more...
Enhancement of NCs luminescence by coupling with surface plasmons

- Metallic nanopatterns defined by EBL; NCs/PMMA blends spin-coated on top
- Good control of the coupling between surface plasmons and colloidal nanocrystals
- Enhancement of the NCs emission with nanoscale control

Low index contrasts $\rightarrow$ Suspended structures

- NCs in polymeric blend increase the refractive index but:
  - maximum $\Delta n \sim 0.3$
  - maximum $n_{\text{blend}} \sim 2$
  - Substrates with low refractive indices: SiO$_2$, glasses ($n \sim 1.5$)
  - air is better ($n \sim 1$)

Low index contrasts $\rightarrow$ Suspended structures

- 1\textsuperscript{st} lithography: SU-8/red NCs (thickness: 1500 nm, grooves width: 2 – 30 $\mu$m)
- 2\textsuperscript{nd} lithography: SU-8/green NCs (thickness: 1500 nm, stripes width: 2 – 100 $\mu$m)
- single development after both exposures

-Suspended NC/resist waveguides with all-lithographic steps

- No residual NCs layers

Conclusions and further developments

• Localization of resist/NCs blends by lithographic techniques is a suitable approach for the fabrication of photonic devices with nanometer resolution

• Fabrication of the main building blocks of a photonic device: waveguides, DBRs, DFB

• Possibility to increase the NCs luminescence by coupling with surface plasmons

• All-lithographic approach for the fabrication of air-bridge structures

• Possible use of flexible substrates

• No-phase separation observed in blends with high molar concentrations of NCs

• To be checked: conditions for Amplified Spontaneous Emission in resist/NCs blends → lasers fabrication
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