NANOSCIENCE LABORATORY HIGHLIGHTS 2010

MEMBERS (2010-2011)

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SCIENTIFIC MISSION

Introduction to the Nanoscience Laboratory

The Nanoscience Laboratory (NL) is a laboratory of the Physics Department with interests in nanophotonics, silicon-based photonics and nanobiotechnologies. Its mission is to generate new knowledge and understanding from physical phenomena which occur when the matter is of nanometer size. In particular, NL is trying to apply the nanoscience paradigm to silicon or silicon compatible materials to enable new application of this key material, and to develop nanosystems compatible with the main driving silicon technologies. However silicon is not the only material studied. New projects concern the use of polymers to tailor the properties of nanostructure atom-by-atom or metals to investigate new properties which rise from plasmonics. A particular emphasis is placed on photonics and its apBenjamin Dierre (left 1.2011) Kamil Fedus (from 2.2011)

Doctoral students

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plications. Research projects span from fundamental research work on the interaction between biomolecules and silicon nanostructures or on the control of photons by dynamically structuring the dielectric environment, to more applied research work on the development of integrated optical circuits, optical switches, light emitting devices and amplifiers, novel MIR and THz sources, third generation photovoltaic and biosensors. NL is composed by more than 20 people with interdisciplinary scientific background. Researchers from physics, bio-chemistry, materials science and electrical engineering interact to form a group of interdisciplinary nature. They came from all around the world and the language spoken in the laboratory is English. Of particular mention is the collaboration that NL has with the Center of Materials and Microsystems, in particular with the Advance Photonics and Photovoltaic and the Biofunctional Surfaces and Interfaces units, of the Fondazione Bruno Kessler (FBK). The collaboration spans over the last twenty years and covers fabrication, testing and application of biomaterials and silicon based devices. Many common projects exist among which a project on the development of a multispectral protein chip for application in diagnostics (NAOMI, supported by Provincia Autonoma di Trento (PAT)).

NL covers also outreach activities: the Professional Second Level Master NanoMicro is being co-organized with FBK financed by the European Social Founding and in collaboration with many local companies. Moreover, NL, with the help of the local institutes of CNR and FBK, organizes each two years a winter school on optoelectronics and photonics: the next edition, the 6th Photonics and Optoelectronics Winter School: Physics and Application of T-Rays, will be held at the end of February 2011. Members of NL participate in the committee or organize several international conferences or workshop.

Research of NL is mainly funded by the local government (PAT), the European commission within the research frameworks, the MIUR and by companies. During the period covered by these Highlights, NL has been and is involved in several EC projects: LANCER (FP6-IST-033574), WADIMOS (FP7-ICT-216405), HELIOS (FP7-ICT-224312), LIMA (FP7-ICT-248909), POSITIVE (FP7-ICT-257401), El-Dorado (FP7-PEOPLE-235860), APPCOPTOR (FP7-PEOPLE-275150). The overall budget in these years accounted for more than 3 M€.

Silicon Nanophotonics

Silicon photonics is the technology where photonic devices are produced by standard microelectronic processes using the same paradigm of electronics: integration of a large number of devices to yield a high circuit complexity which allows for high performances and low costs. Here, the real truth is to develop photonic devices that can be easily integrated to improve the single device performance and to allow high volume production.

We are involved in researching new optical scheme for implementing optical network on a chip by using concepts of nanophotonics. Transport phenomena of charge carriers in solids have several analogies with the propagation of light waves in dielectric materials. Electronic crystals have an analogue in the form of photonic crystals which are artificial materials, where a periodic variation of dielectric constant leads to the formation of bands where the propagation of photons is allowed or forbidden. In the past years we have developed one dimensional complex dielectric systems based on porous silicon multilayers with the aim of studying in depth the photon propagations in these complex systems. Nowadays, we use the concept of whispering gallery modes which develops in microdisks or micro-rings to further tune the photon mode density. These disks or rings are coupled directly with narrow mode SOI (Silicon-on-Insulator) waveguides. High quality factor cavities allow to study fundamental quantum optics concept such as Purcell effects or optical forces. Series of coupled micro-rings are studied to implement novel scheme of phase controlled optical

networks where EIT (electromagnetic induced transparency) is manifested and exploited to route optical signals.

To develop silicon photonics, one further add-on is making silicon do something which it is not able to do in its standard (bulk) form. Low dimensional silicon, where small silicon nanocrystals or nanoclusters (Sinc) are developed, is one way to compel silicon to act as an active optical material. The key ingredient that makes Si-nc appealing for photonics are: quantum size effects which makes new phenomena appear in silicon, such as room temperature visible photoluminescence, optical gain, coulomb blockade and multiexciton generation. Our research interests are to exploit quantum confinement and reduced dimensionality to produce effective light sources, lasers, optical amplifiers. In addition, we use quantum confinement to increase the nonlinear optical properties of silicon and to achieve optical switching. Finally, two new activities which are being developed concern the use of strain to tune the non-linear optical properties of silicon waveguides and the fabrication of polymer devices on silicon to implement what we call polymer-on-silicon photonics.

Metamaterials

The ability of structuring materials well below the wavelength of interesting portions of the spectrum of electromagnetic radiation has recently generated a great deal of attention. The interest in this area of research stems from the fact that many macroscopic optical properties - for example, the refractive index - which have been traditionally bound to material properties, such as the chemical composition or the natural crystalline structure, can be controlled to a fine degree by the artificial control of structural properties. Since the resulting overall optical response goes beyond what is naturally available, these structured systems have been dubbed metamaterials (from the Greek prefix "meta-", "beyond"). Examples of useful effects are the independent engineering of optical and magnetic resonances, which can lead to simultaneous negative effective dielectric permittivity and magnetic permeability, leading in turn to negative refraction. Another notable application is the focusing and the resolution beyond the diffraction limits (the superlens effect).

Dynamic photonic crystal are time-dependent structures that can enable interesting phenomena, potentially attractive for applications (for example, to by-pass fundamental trade-offs such as the time-bandwidth constrain of optical response) as well as for fundamental research, where they can be experimental frameworks for electromagnetic frequency shifts based on Doppler effect, all the way to advanced investigation tools for effects predicted in presence of large gravitational fields or accelerations. In this research, we aim at achieving fast and large tunability of permittivity in real time. This will let us generate dielectric refracting and reflecting dynamic interfaces. The difference from the known phenomenon of reflection and refraction is that these interfaces are moved, and - importantly with no true mechanical motions of media. Absence of mechanical motions allows for potentially very high speed "movements", making this an enabling technique to observe intriguing phenomena, such as photonic energy lifters, strong Doppler shifts, wavelength converters, and, potentially, event horizons and emission of Unruh radiation

Nanobiotechnologies, antioxidants and human health

All the aspects related to the nano-bio interfaces (which are the structures where the co-existence of physical principles and biological molecules is clearly evident) are a challenging field of research. Though the leading research concerns the design, synthesis and dynamic behavior of nano-structured bio-interfaces, more specifically we are working on three research topics: silicon-based sensing systems, single molecule detection, and antioxidant behavior in micelle systems.

To develop silicon based bio-sensors, we are currently focused on silicon based hybrid nanostructures. In particular silicon or silicon nitride flat or porous films are the starting inorganic support into which bio active layers are designed. Biological recognition elements are introduced on this hybrid layer. Molecular surface density, active layer thickness and integration of the bio-active interface with photonic devices will be the future challenges to develop the sensor system. In addition, we are developing nanostructured hybrid interfaces to capture bio-analytes and enhance their Raman signals. Gold and silver nanoparticles are used as enhancers. We are optimizing the enhancement by assembling the bio-active interface into a nanomechanic system.

Beyond traditional sensor applications, silicon nanostructures can be used as "nanosensors", which monitor the intracellular events without introducing irreversible perturbations. To this regard light emitting silicon quantum dots appear very promising. We are studying the nanoparticle coating to increase optical stability and decrease toxicity, moreover conjugation to biological molecules and strategies to increase cell uptake and control intracellular localization are future steps of this research.

Antioxidant compounds are able to control reactive and damaging forms of oxygen, referred to as free radicals. Though antioxidants have been largely studied, much remains unknown about the human body adsorption and use of these compounds. We are investigating the synergistic effect of plasma antioxidants at the interface of micelle systems. Beyond the basic biophysical investigation, the crucial point is the development of devices and methodologies to monitor the antioxidant action. Being these processes free-radical mediated, a very high detection sensitivity is required. Moreover, to have physiological significance, the experiments should be performed in heterogeneous systems mimicking an unperturbated biological environment. Thus we are proposing a new theoretically based methodology to compute antioxidant capacity and efficiency starting from oxygen concentration measurement, as well as, we are designing a nanostructured

electrode to monitor molecular oxygen in real time.

Experimental facilities

The NL facilities allow for detailed experimental studies in nanoscience, photonics and biotechnologies. Since the effective collaboration with FBK most material processing and device productions are performed within their premises.

For photonics, we have facilities to cover the light spectrum from the THz to UV ranges with whatever time resolution is needed. Laser sources comprehends: Ti-sapphire fs-ps laser (1 W average over 1000-700 nm, 2 ps or 70 fs pulses, 82 MHz repetition rate) interfaced with a second harmonic generator and pulse picker; Nd-Yag laser interfaced with an optical parametric oscillator which allows scanning the 400-3000 nm wavelength region (pulse 50 mJ, 10 ns, 10 Hz); TOPAS pumped with an amplified Ti:Sa laser which covers the 1-2 µm range with 30 fs, 10 kHz, 3 mJ; one CW Ar lasers; two tunable CW lasers (1200 - 1700 nm and 1500 - 1600nm) fiber pig-tailed; several pig-tailed diode lasers, ASE source at 1550 nm and a broad band SLD at 800 nm. Three high-power true-CW DPSS single-line laser operating at 532, 473 and 355 nm. Detectors comprehend: visible and infrared photomultipliers and CCDs, a streak camera with ps resolution, 4K cooled bolometers which cover THz region, avalanche photodiodes for vis and IR ranges. To perform spectral analysis several set-ups are available: FTIR and dispersive spectrophotometers, a micro-Raman setup, a micro-FTIR and a UV-vis-IR spectrophotometer (shared with other laboratories), UV-Vis and fluorescence spectrophotometer dedicated to biochemical experiments. Five dedicated apparata for WG characterization equipped with nanopositioning systems and polarization controllers are available, each one specified on a given functions: visible, infrared, pump-probe, grating coupling and non-linear measurements. Other apparata are: - visible and infrared photoconductivity setup; - a solar simulator for cell sizes up to 5 inches; two nanoprobe stations (AFM and SNOM) coupled with a femto-jet system for local infiltration of the samples and biological experiments; - two semiconductor probe stations (4 and 8 inches) and many different electrical characterization set-ups (I-V, Z-w, EL-I, etc.). Two VIS to NIR optical spectrum analyzers are available to NL-Lab. A probe station is fiber-bunch interfaced with a spectrometer interfaced with IR and visible liquid nitrogen cooled CCD. For sample production and treatment and high sensitivity analytical detection, an electrochemical laboratory equipped with several chemical hots, spinners, galvanostates and voltammeters is available. An electron beam lithography set-up (SEM attachment) is also owned. For optical, electrical molecular dynamic simulations, the laboratory uses free and commercial software, a dedicated cluster with 16 nodes and work-stations. Two laboratories one dedicated to chemical synthesis and the second to biological sample preparation are also available.

Selected 2010 publications

- "Purcell factor and superradiance in Si-patterned waveguides", A. Pitanti, P. Bettotti, D. Sarchi, L. Pavesi, Opt. Letters, 35, 3384 (2010).
- "Positronium Cooling and Emission in Vacuum from Nanochannels at Cryogenic Temperature", S. Mariazzi, P. Bettotti, R. S. Brusa, Phys. Rev. Lett., 104, 243401 (2010).
- "Ultrafast all-optical switching in a siliconnanocrystal based silicon slot waveguide at telecom wavelengths" A. Martínez, R. Spano, J. Blasco, P. Sanchis, J. V. Galán, J. García, E. Jordana, P. Gautier, Y. Lebour, S. Hernández, R. Guider, N. Daldosso, B. Garrido, J. M. Fedeli, L. Pavesi, and J. Martí, Nano Letters 10, 1506-1511 (2010).
- "Energy transfer mechanism and Auger effect in Er³⁺ coupled silicon nanoparticle samples" A. Pitanti, D. Navarro-Urrios, N. Prtljaga, N. Daldosso, F. Gourbilleau, R. Rizk, B. Garrido, and L. Pavesi, Journal of Applied Physics, 108, 053518 (2010).
- "Probing the Spontaneous Emission Dynamics in Si-Nanocrystals-Based Microdisk Resonators" A. Pitanti, M. Ghulinyan, D. Navarro-Urrios, G. Pucker, and L. Pavesi, Physical Review Letters, 104, 103901 (2010).
- Silicon Nanocrystals; Fundamentals, Synthesis and Applications edited by L. Pavesi and R. Turan (Wiley-VCH Verlag GmbH, Berlin 2010) ISBN: 978-3-527-32160-5, March 2010

2010 RESEARCH HIGHLIGHTS

1 Silicon nanocrystals for photovoltaics (Philip Ingenhoven)

Silicon Nanocrystals (Si-nc) are a promising material for photovoltaic devices. Due to the quantum confinement, they show a wide range of band gaps which are larger than that of bulk Si. We are testing two ways to use these properties, as optical down shifter and as an active material within the depletion zone of the solar cell.



Fig. 1: Cross section and image of the SiNC cell on a quartz substrate. Process by FBK-APP

For silicon solar cells, the efficiency is mostly limited by the thermalization of hot carriers. Here we aim to explore whether tandem cells based on silicon nanocrystals are an effective way to avoid this thermalization loss. Therefore, the photovoltaic effect was investigated in devices with a metal-insulator-semiconductor (MIS) structure (see fig. 1), where the insulator is a silicon rich oxinitride matrix containing Si-nc. Still the efficiency of the cell is low, mostly due to the poor transport properties of Si-nc in the oxide. Work supported by FP7-LIMA

2. Silicon nanocrystals based down-shifter for enhanced silicon solar cell (Fabrizio Sgrignuoli)

One of the methods to improve the solar cell efficiency is the spectrum modification of the incidence sunlight by the down-shift (DS) effect. The DS effect reduces the low wavelength losses by shifting photons into an energy range where the solar cell has a high external quantum efficiency (EQE) (Fig. 2).



Fig. 2: (a) Solar spectrum and external quantum efficiency of a silicon cell (b) Measured absorption and emission spectra of Si-nc: Si-nc absorb high energy photons and re-emit low energy photons due to photoluminescence with a measured efficiency of 20%.

We investigate this innovative effect using silicon nanoparticles (Si-nc) dispersed in a silicon dioxide matrix (SRO) as active material. A 14% relative increase of the photoconductivity in the UV region of the spectrum of was measured. On the contrary, we found, from simulations, an absolute increase of 0.5 % in efficiency due to the DS when we put on top of a c-Si solar cell 70nm of SRO and 50nm of SiO2 as anti-reflection-coating.

Work supported by FP7-LIMA

References

1. Yoan Jestin, Goerg Pucker, Mher Ghulinyan, Lorenza Ferrario, Pierluigi Bellutti, Antonio Picciotto, Amos Collini, Alessandro Marconi, Aleksei Anopchenko, Zhizhong Yuan, Lorenzo Pavesi," Silicon solar cells with nano-crystalline silicon down shifter: experiment and modeling" Proceeding of SPIE Vol. 7772: Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion, Loucas Tsakalakos, Editors, 77720B (2010)

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3. Silicon nanocrystals based devices for optical interconnects (Alessandro Marconi)

Silicon nanocrystals emit light with high efficiencies (>20%). However, since they are formed in a dielectrics (SiO₂), it is difficult to stimulate electroluminescence. We developed LEDs with world record power efficiency (>0.2%) which are based on direct tunneling of electron and holes into Si-nc by engineering the active material. The idea is to perform injection barrier engineering by thinning the tunneling barrier (SiO₂) down to less than 2 nm and to grade the Si-nc band-gap (Fig. 3). In this way, a concurrent electron and hole direct tunneling into 2 nm wide Si-nc occurs. Indeed the LED operates efficiently and at low voltages (1.5 V). Though the good results, the obtained efficiencies are still low and further optimization of the device is needed.



Fig.3: Schematic cross-section of the multilayer LED. The inset shows a TEM image of the active layer and an optical photograph of the device geometry. Process by FBK-APP

We further demonstrated that it is possible to use this device both in forward bias as an emitter and in reverse bias as a detector. In this way we realized an all silicon based optical interconnect link between two different part of the chip (Fig. 4). A TTL signal was used to drive the LED and was detected by the detector up to a driving frequency of hundred of KHz.



Fig. 4: Two Si-nc based devices are optically coupled. The light emitted from the transmitter is collected by an optical fiber and sent to the detector. Process by FBK-APP

References:

1. A. Marconi, A. Anopchenko, G. Pucker, L. Pavesi "Power Efficiency Estimation of Silicon Nanocrystal Based Light Emitting Devices in Alternate Current Regime" Applied Physics Letters (in press 2011)

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4. Er doped luminescence and electroluminescence in CMOS fabricated devices (Aleksiy Anopchenko)

Er-doped silicon nanoclusters (Si-nc:Er) is one of the key gain media in the silicon photonics research of efficient and integrable light sources. The effect of a number of deposition parameters on the electrical transport properties and electroluminescence of Si-NCs embedded in SiO₂ matrix, and of Er ions coupled to Si-NCs, has been studied in detail and the external quantum efficiency values are correlated to the different transport mechanisms.



Fig. 5: EL intensity at 1.54 μ m (left axis, blue symbols) at a fixed injected current of 1 μ A as a function of average content of silicon excess for a series of multilayer LEDs (squares) and single-layer LEDs (stars) and corresponding driving voltages (right axis, red symbols).



Fig. 6: EL intensity at 1.54 μ m of a Si-NC:Er LED as a function of driving voltage under pulsed electrical excitation for low (black squares) and moderate excitation frequency (red circles). Inset shows a moderate-to-high voltage range. The low panel shows EL spectra at the moderate frequency and driving voltages in ascending order indicated by arrows.

Mechanisms of electrical excitation of Er-ions in a series of Si-nc:Er LEDs are elucidated by applying both direct electrical current and pulsed current excitation schemes (Fig. 5).

We found that electroluminescence is dominated by energy transfer between Er-ions and Si-nanoclusters below a certain voltage threshold (Fig. 6). Above this voltage threshold electroluminescence originates from impact ionization of Er ions. Sequential injection of electrons and holes into silicon Si-NCs under the pulsed excitation leads to an extended voltage range over which the energy transfer dominates impact excitation of Er ions.

Work supported by FP7-HELIOS

References:

1. Nikola Prtljaga, Daniel Navarro-Urrios, Alessandro Marconi, Aleksiy Anopchenko, Jean Philippe Colonna, Frederic Milesi, Nicola Daldosso, Olivier Jambois, Blas Garrido, Jean Marc Fedeli, Lorenzo Pavesi "Erbium implanted silicon rich oxide thin films suitable for slot waveguides applications" Optical Materials (in press 2011)

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3. A. Tengattini, A. Anopchenko, A. Marconi, N. Prtljaga, N. Daldosso, J. M. Ramírez, O. Jambois, Y. Berencén, D. Navarro-Urrios, B. Garrido, F. Milesi, J.-P. Colonna and J.-M. Fedeli, and L. Pavesi, "Electrical Excitation of Erbium and Energy Transfer in Efficient Silicon Nanocomposite LEDs," submitted to the 13th Italian National Conference of Photonic Technologies, Fotonica 2011.

4. A. Anopchenko, A. Tengattini, A. Marconi, N. Prtljaga, J. M. Ramírez, O. Jambois, Y. Berencén, D. Navarro-Urrios, B. Garrido, F. Milesi, J.-P. Colonna and J.-M. Fedeli, and L. Pavesi, "Alternating Current Excitation of Erbium in Efficient Silicon Nanocluster LEDs," in preparation.

5. Efficient functionalization of silicon surfaces for bioapplications (Elena Froner)

For a silicon based device intended to work within a biological environment or in contact with bio-derived specimens, surface plays a very important role. In a biosensor the inorganic silicon surface must be treated in order to let organic target molecules interact with it in a strong and selective way and/or to make biological molecules detectable. We can achieve these two goals by applying to silicon, porous silicon (p-Si) or silicon nitride (SiN) different wet chemical procedures.

Based on the immobilization of metal nanoparticles on p-Si samples, we can produce efficient support for biomolecules detection exploiting surface enhanced Raman scattering (SERS): Ag or Au nanoparticles bind to amino groups introduced on p-Si by reacting oxidized p-Si surfaces with an aminosilane (Fig. 7). P-Si rough surface helps metal nanoparticles to cluster in configurations favorable for the enhancement of Raman signal of molecules deposited onto this surface. SERS spectrum of Rhodamine 6G deposited on Ag particles-covered macroporous Si is clearly detectable even when we are exciting less than 40000 molecules.



Fig. 7: Steps leading from fresh porous silicon to an efficient SERS support. Step 1: preparation and oxidation of p-Si (macroporous Si with pore size of 1 micron, mesoporous Si with pore size of 60-70 nm); Step 2: silanization of p-Si, which introduces aminogroups on pores surface; Step 3: preparation of colloidal metal nanoparticles (Ag and Au particles of about 60 nm and 20 nm, respectively); Step 4: immobilization of metal nanoparticles on silanized p-Si surfaces.

Other reactive groups can be grafted onto Si or SiN surfaces. A sensor for proteomics is currently being developed where SiN-covered microreactors (engraved on optical waveguides providing exciting light) are functionalized with carboxylic groups. These -COOH groups are needed to immobilize specific DNA fragments (aptamers) on the surface. Aptamers, in their turn, can selectively recognize and bind a specific protein (thrombin) if present in a body fluid. Thrombin molecules stuck on the wells surface can be detected by marking them with other specific fluorescent aptamers. Work supported by FUPAT-NAOMI

6. Biosensing based on whispering gallery mode resonator (Eveline Rigo)

Microdisk resonators offer several advantages for use as biosensing platforms. They provide label-free, sensitive, quantitative, and real-time detection capabilities. Owing to their small footprint, arrays of microdisk resonators can be fabricated on a small chip, enabling multiplexing capabilities. In addition, microdisk resonators can be ultimately mass-produced at low cost, as they are fabricated using standard CMOS technology.



Fig.8: Resonance wavelength shift of a 40 μ m diameter disk due to protein deposition on the disk surface.

Whispering gallery mode resonators have been demonstrated as quantitative biosensors for label-free detection of biomolecules (Fig. 8). The great interest in this kind of biosensor is due to the high sensitivity they can achieve. In this work we investigated SiN_x microdisks as proteins biosensor. Coupling between the microdisk and the waveguides can either be vertically or laterally. The microdisk resonators used in this work are vertically coupled to input/output waveguides. The sensing mechanism is based on a shift in the resonant wavelengths induced by the presence of analytes on the disk surface which is functionalized with receptor sites that can selectively bind specific molecules. The molecules attached on the surface of the resonator change the effective refractive index of the guided modes, which cause a shift in the resonant wavelengths. Work supported by FUPAT-NAOMI

7. Waveguide based optical bioreactor for on-chip diagnostic (Silvia Larcheri)

For most biological and medical applications, compact biosensors with high sensitivity, fast response and potential for mass production are needed. These requirements can be achieved with optical sensors since optics technology allows the integration of passive and active optical components on the same substrate, endowing the flexible development of miniaturized devices with multiple sensors on the same chip. In particular, integrated photonic biosensors based on silicon technology show great capability as diagnostic tools, thanks to their high sensitivity, specificity and reliability.

Our research activity is focused on the design, fabrication and testing of a silicon waveguide-based optical sensor for proteomics. Thanks to the presence of multiple bioreactors on the same chip (Fig. 9a), multianalyte detection of proteins in biological samples is possible. The measurement approach is based on the fluorescence technique, by labeling proteins with a fluorescent marker. Fluorescence is excited through the evanescent field of the waveguide bioreactor (yellow arrow in Fig. 9b) and detection is performed in transmission through the output waveguide (red arrow in Fig. 9b). The proper functionalization of the waveguide top surface allows the selective detection of specific proteins in complex biological mixtures. The presented photonic chip has been engineered to be integrated with microfluidics and a silicon SPAD detector matrix, obtaining a modular-stack lab-on-chip microsystem, with top detection of the fluorescence signal (Fig. 9c).



Fig. 9: (a) Silicon photonic chip with multiple sensor sites. (b) Transmission detection geometry using the fluorescence approach. (c) Modular stack architecture of the lab-on-chip device. Process by FBK

This work paves the way for the development of a novel, portable analytical tool for in situ and real-time diagnostic sensing.

Work supported by FUPAT-NAOMI

References:

1. E. Rigo, R. Guider, S. Larcheri, M.R. Vanacharla, B. Han, G. Pucker, and L. Pavesi "A Silicon photonic chip for sensing application: optical characterization and FDTD simulations", in submission to Optics Express

8. Optical properties of silicon nanocrystals chromophore (Nikola Prtljaga)

Although silicon in its bulk form is emitting light poorly, porous silicon (PS) shows that nanocrystalline silicon could act as an efficient visible-NIR light emitter.

The most common Si-nc's preparation methods produce solid state samples where Si-nc are embedded within suitable matrix (typically SiO_2) and whose surface properties are largely unknown. For fundamental studies more appropriate system are the colloidal dispersions of individual Si-nc where surface properties could be controlled to a great extent (Fig. 10).

By using the suitable functionalization scheme, the surface impact on the light emitting properties can be minimized, producing samples where the quantum confinement effects become dominant. Moreover, additional coating acts as a potential barrier which prevents the exciton inter-dot hopping even in agglomerated sample. This simplifies greatly the study of complex phenomena such as electrostatic (Stark-like) absorption/emission modification due to ionic surface charging. An additional control of surface properties allows an efficient elimination of surface quenching centers, resulting in high quantum yield (~30 %) nanoparticles. The size is easily tailored through the usage of chemical methods (by slow, controlled oxidation) and interfacing with biological systems for bioimaging and drug delivery purposes becomes quite straightforward.



Fig. 10: a, c) – Photoluminescence of Si-nc of different sizes under UV illumination. b) Stretched exponential fit parameters (squares, circles) obtained from the fit of decay curves of functionalized Si-nc-COOH in ethanol. A PL spectrum (line) is also reported.

This fairly simple system allows, as well, detailed study of some classical phenomena such as Mie scattering of small particles. The big advantage of this approach is that measured scattering properties are easily comparable with computer simulation allowing for extraction of some values needed in classical approximations, such as effective refractive index of Si-nc's ensemble. Moreover, an impact of the interparticle distance and density on the light emitting capabilities of such ensemble is easily established.

References:

1. Nikola Prtljaga, Elvira D'Amato, Alessandro Pitanti, Romain Guider, Elena Froner, Silvia Larcheri, Marina Scarpa and Lorenzo Pavesi "Photoluminescence of hydrophilic silicon nanocrystals in aqueous Solutions" submitted to Nanotechnology.

9. Silicon nanocrystals as fluorescent probes in biology (Elvira Damato)

Luminescent silicon nanocrystals have several unique optical and chemical features. These features make them desirable fluorescent tags for cell and developmental biological applications that require long-term, multi-target and highly sensitive imaging. For silicon quantum dots to be used in biomedical applications it is essential that they have substantial photoluminescence quantum yield in the visible region and are water soluble and hydrophilic to prevent aggregation and precipitation in a biological environment (Fig. 11).



Fig. 11: Process of surface functionalization of silicon nanocrystals

Water- dispersible Si-nc are produced by modifying the

nanocrystals surface with carboxylic acids.

Si-nc themselves, are produced by sonication of just etched porous silicon. Since the procedure is performed under argon, the Si-nc surface is predominantly hydrogen terminated. The tailoring of the surface is achieved by coating with an alkylic chain bearing a carboxylic tail. This step is performed to: 1) realize a chemically active surface (thanks to the carboxylic group) in the event of a further functionalization; 2) introduce an organic component into the inorganic Si to make easier hydrophobic interactions (by alkyl chain) or electrostatic interactions (by the carboxylic group).

Although being hydrophobic, these Si-nc exhibit poor colloidal stability in buffer and cell culture media. This problem may be easily avoided by using surfactants. Stabilization by physisorption of organic molecules improves significantly colloidal stability of this system in biological environment. Natural detergents belonging to the bile acid class are known to form efficient carrier structures aimed to deliver and protect insoluble fatty molecules. In particular sodium deoxycholate (DCA) was used for in vitro cell-studies. First images of the intake of the Si-nc by cellule are shown in Fig. 12. Moreover, natural biodegradability of these QDs in aqueous environments is maintained through the slow, controlled oxidation.



Fig. 12: Fluorescent microscopic image of SKOV-3 cells treated with coated DCA Si QDS.

References:

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10. Porous silicon-based lab-on-a-chip for monitoring of food allergies (Paolo Bettotti)

Food allergies are common in 1-2% of adults and up to 8% of children, corresponding to a serious public health problem that affects over 15 million people in Europe from infants to the elderly and its prevalence is increasing. They are more frequent in young children but to date routine GP allergy testing of children under two consists of repeated and uncomfortable skin tests that are difficult to administer. Thus there is a need for a point of care diagnostic platform that can quickly and safely monitor for specific IgE to common food allergens. Porous silicon is an almost ideal material as a signal transducer for label free optical biological sensing. The control achieved in PS fabrication enables the realization of high optical quality PS biosensor compatible with present-day on-chip microelectronics and nanophotonics productions . Two different types of biosensing optical elements are proposed within POSITIVE project, each one with predetermined porous layer morphology: one based on photonic bandgap multilayer structures (interferometric transducer) and another based on birefringent monolayer structures (polarimetric transducer).

The extremely large internal surface ($\sim 500 \text{ m}^2/\text{cm}^3$) can in principle be leveraged to enhance device sensitivity many orders of magnitude over a planar device of comparable transducer diameter . Our evaluations show a detection limit in the order of 0.1 pg/mm^2 . The high sensitivity of the proposed biosensor is achieved via the dramatically enhanced interaction area of the PS combined with high sensitivity measurements via the analysis of interference signals. Work supported by FP7-Positive

11. Modelling of microresonators based optical network (Marco Masi)

Novel routing concepts based on side coupled integrated spaced sequences of resonators (SCISSOR) and coupled resonator optical waveguide (CROW) to achieve large bandwidth by multiple cascading and/or multiple coupling (low group velocity) periodicity effects were investigated.

With increasing integration densities, resonators have smaller bent radiuses and small coupling gaps. This implies that one cannot neglect in the modelling effects such as coupling losses, effective index differences and modal mismatches between the straight and bend waveguides. For a radius of curvature smaller than R<5 um in a SOI system, the traditional algorithms furnish very rough estimates of the optical response of microresonators, especially for some high-order filtering applications. Moreover, the situation gets worse for devices based on sequences of microresonator like in SCISSOR or CROW devices. Therefore, we described accurately small microresonator or multiple cascaded microresonators in order to enhance design methods of complex optical systems which can tackle, at least partially, fabrication tolerances, narrowing the gap between models and real devices.

By means of coupled mode theory (CMT) a full description of the single racetrack was performed. The dispersion law of the straight waveguide, the characterization of curved waveguides and the influence of the bending on the effective index was examined. Also the determination of bending and coupling losses, the calculation of the coupling coefficients and length, and a comparison between the obtained parameters with experimental results have been done. These data were used for a detailed transfer matrix formalism in order to model SCISSOR and CROW structures. Later on, novel SCISSOR based geometries were presented which have the capability of routing spectral bands, i.e. coarse WDM in contrast to dense WDM channel routing, and of a switching behaviour based on phase

modulation.



Fig.13: Optical microscope pictures of the silicon circuits. Magnifications: MMI splitters and crossings. Inset: the 20 inch wafer. Process by LETI.

First attempts were made to build some device prototypes and test them experimentally after the fabrication on SOI wafers (see snapshot in Fig. 13). SCISSOR band routing systems and a two bus SCISSOR router based on phase modulation was modelled and realized. Other phase modulating routing and switching devices were explored further in more detail at a theoretical level applying it to few SCISSOR configurations. Work supported by FP7-Wadimos

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12. Observation of CRIT in SCISSOR (Manga Rao Vanacarla)

SCISSOR structures are composed of integrated sequence of microring resonator coupled to two bus waveguides. These structures have potential application for building compact devices like routing, filtering, and switching for on-chip optical communication. The design principle for building devices with such structures is based on engineering of two kind of resonances: microresonator resonances and Bragg resonance (determined by distances between the resonators). A simultaneous satisfaction of these two resonances leads to interesting phenomena, e. g. coupled resonator induced transparency (CRIT), which occurs due to coherent coupling between any of the two resonators in the sequence with slight varying resonance frequencies (Fig. 14).



Fig. 14: Optical images of the scattering of light in a SCISSOR structure for various signal wavelengths. The top and central panel refer to wavelengths in resonance with CRIT while the bottom panel to a wavelength out of resonance.

Recently, we have observed CRIT effects in a SCISSOR structure consisting of eight micro-rings fabricated using SOI technology. The main highlights of our observation on CRIT are: a) Multiple CRIT is formed due to possible combination of coherent coupling among micro-rings in the SCISSORs. These resonances occur in the stop band region of through port manifesting into transparency states. 2) CRIT states can be tuned in their spectral positions or can be suppressed by using thermo-optical effects or free carrier dispersion. The above mentioned phenomena were successfully demonstrated in our fabricated samples. In addition to the spectral characterization, imaging of out-of-plane scattered light from the SCISSOR provides useful information to determine rings that are coherently coupled to each other (see Fig. 14). Especially, the slow modes $(v_g < c)$ show a pronounced scattering of light which is true for band-edge modes and CRIT states occurring in a sequence of coupled resonators. Work supported by FP7-Wadimos

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1. M. Masi, M. Mancinelli, A. Battarelli, R. Guider, M. R. Vanacharla, P. Bettotti, J-M. Fedeli, and L. Pavesi "A silicon photonic phase router device based on SCISSOR concept", submitted to Optical Express (2011).

13. New concept for UDWDM based on CRIT phenomena (Mattia Mancinelli)

Optical networks on chip (ONoC) envisage core to core photonic interconnects with large bandwidth, fast switching, low power consumption and support of optical wavelength-division multiplexing (WDM) methods. SOI photonic structures offer compatible fabrication processes with CMOS technology.

Photonic devices based on coupled optical resonators presents many novel effects. In particular, coupled resonators induced transparency (CRIT) effects can occur in coupled optical resonators due to classical interference. This effect was recently demonstrated in side coupled integrated spaced sequence of resonators (SCISSOR) where CRIT effect occurs when round-trip phase between 2 or many rings is a integer multiple of 2π . If this resonant condition is satisfied, the resulting transmission spectrum exhibits very narrow transparency peak inside the resonance band of the structure.



Fig. 15: (a) Schema of the new SCISSOR with its through response: (black) flat box like response of the resonance state, (red arrow) CRIT state. (b) Schema representing a 4X1(1X4) multiplexer (demultiplexer) based on this design in which the colored circles identifies the pair that does CRIT and the corresponding 12GHz channel. Simulated spectral response of the 4 channels in which the colors are linked to the schema of the structure.

We study the presence of CRIT effect in a novel design of SCISSOR based on resonators of different radius (Fig. 15). This effect can be exploited to realize high performance add/drop filters, multiplexers and routers. These new types of structures are able to reach very narrow bandwidths, low crosstalk and insertion losses while keeping reasonable requirements on fabrication tolerance and design complexity. In particular, they show properties that makes them preferable to single ring resonator based scheme for Ultra Dense WDM.

Work supported by FP7-Wadimos

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14. Sensing in low refractive index contrast photonic structures (Paolo Bettotti)

Integrated optical sensor is a powerful technology joining the flexibility given by physical sensing methods with the benefits of an integrated design.

Recently the so called slot-waveguide geometry was proposed which is particularly suited for sensing applications. In this configuration, the optical field is concentrated inside the low refractive index region and enables an optimum overlap with the environment to be analyzed. Despite the large effort on silicon based material, no works focused on the realization of slot waveguide sensors in low index materials (eg. polymers). Polymers have a number of advantages if compared to semiconducting or oxide materials. They are cheaper and easier to structure down to the nanoscale level, they can be surface functionalized and impregnated with active nanoparticles using a plethora of chemical receipts.



Fig. 16: a) AFM topographical image of a double slot waveguide. The two narrow trenches (roughly 100 nm wide) are the regions where the transverse field component concentrate more effectively. The yellow line describes the field profile of the fundamental quasi-TE mode. Note the different scales on xy-plane and z-axis. b) Simulations that report a figure of merit proportional the sensitivity (confinement factor) for low index (LI) and high index (HI) systems. It is clear that LI material can rival in absolute terms with HI, and are even more performing for certain geometries.

Our work aims at demonstrate that low index material can be used to fabricate sensors with high performances. Since a sensor has to have a strong interaction between the guided field and the environment, the light confinement properties of high index dielectrics are of marginal utility in this applications. Fig. 16a reports a typical section of a slot WG together with the field profile of the fundamental quasi-TE mode. Fig. 16b reports a graph that compares the sensitivity of low and high index materials, it is observed that similar sensitivity can be achieved in low index material. Work supported by PAT-Gopsi

References:

1. P. Bettotti, A. Pitanti, E. Rigo, F. De Leonardis, V. M. N. Passaro, L. Pavesi, "Modeling of slot waveguide sensors realized in polymeric materials", submitted to Sensor.

15. Spatially resolved Raman mapping of strainfield in stressed silicon waveguides (Federica Bianco)

We characterized the strain-field inside of a strained

silicon waveguide by high resolution spatially resolved Raman back-scattering performed on the waveguide facet. Fig. 17 reports a summary of the experimental results where we measure the strain-field induced by different kind of stressing layers. The stressing overlayer is obtained by depositing a film of silicon nitride within different process conditions.



Fig. 17: On the top left side the crystalline symmetry of silicon is related to the waveguide structure. The two top panels show the zz and xx strain tensor elements. More interestingly the three bottom panels show the yy strain-tensor elements related to the silicon waveguide crystalline deformation.

With this work we show that spatially-resolved Raman back-scattering characterization is a powerful tool to measure the microscopic and macroscopic crystalline deformation of waveguides.

Work supported by FUPAT NAOMI and CARIPLO

16. $\chi^{(2)}$ -induction in silicon waveguides: bulk second harmonic generation (Massimo Cazzanelli)

Nonlinear silicon photonics is a novel research field which is enables the realization of novel photonic devices. Most of the reported results have exploited the well known third-order nonlinear susceptibility of silicon. A much more efficient way to convert light in silicon devices would rely on second-order effects (i.e $\chi^{(2)}$), but the crystalline centro-simmetry of silicon prohibits these possibilities. Our idea is to inhomogeneously break the crystalline symmetry of silicon via mechanical strain. Therefore, we strained silicon waveguides by using a stressing overlayer. In this way we broke the silicon symmetry and hoped to induce a second order nonlinearity. The first results are very encouraging and demonstrate for the first time the possibility to generate second harmonic inside the silicon waveguides with a clear fingerprint that this light conversion "happens" in the bulk of silicon itself. Fig. 18 show the typical experimental results which witness the appearance of second harmonic generation in silicon waveguides.

At present we are working on MIR light downconversion via $\chi^{(2)}$ induction in silicon with the aim to develop efficient all-silicon based MIR sources. Work supported by FUPAT NAOMI and CARIPLO

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Fig. 18: Panel a): spectrally resolved pump and SHG spectra with their spectral tunability (panel b). Panel c) quadratic behavior of the SHG emitted power as a function of the pump power under fs excitation, while panel d) reports the same behavior unde ns excitation. Panels e) and f): spectral behavior of the SHG when the pump wavelength is tuned.

17. Whispering gallery modes in silicon nanocrystals active microdisk (Romain Guider)

In the last years, optical devices such as switches, memories, and logic elements have been demonstrated in the field of silicon photonics. Nowadays the use of optical bistability is one of the most frequently used approaches for all-optical signal processing.

Owing to strong light confinement in ring and disk resonators, optical bistability can be observed at relatively low optical pump powers in these devices. Since Si-nc have larger third-order optical nonlinearities compared to bulk silicon, one can observe efficient nonlinear response from Si-ncs at much lower intensities of the external optical pump.

We were able to demonstrate low power optical bistability from a Si-nc-based monolithic whisperinggallery mode (WGM) resonator coupled vertically to passive integrated bus waveguides via both thermooptic, carrier-induced and ultrafast Kerr effects (Fig. 19). We observed, by pumping the resonator mode with a 68 μ W near-infrared CW-pump power, a resonance shift in the transmission spectrum of the order of 80pm. Considering these extremely low switching thresholds in a CMOS-compatible fully integrated optical device, our observations can open new prospects towards the realization of resonator devices for on-chip low-power nonlinear optics and signal processing.



Fig. 19: (a) Spectral positions of the pump laser, the lowpower mode resonance and its Lorentzian fit used in the numerical model. The dotted blue line shows the calculated mode position at the low-transmission state. The inset shows an optical image of the monolithically integrated Si-nc-based WGM resonator with the bus waveguide. (b) The measured optical bistability curve (-•-) shows a hysteresis in the transmitted power at the waveguide output. The solid line is the calculated according to the model curve.

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18. Superradiance and collective phenomena in patterned Si waveguides (Alessandro Pitanti)

Although the photonic density of states can be locally tailored in periodic dielectric structure to enhance (Purcell effect) or suppress (photonic band gap) the spontaneous emission rate of photo-active materials, its spatial localization is strongly limited by the electromagnetic field shape.

This implies that usually only single emitters can be precisely overlapped with the tightly confined, large DOS Bloch modes of standard photonic crystal structures, impeding the appearance of collective phenomena such as superradiance, also known as collective spontaneous emission.

The so-called slot waveguides offer alternative routes to this end, being able to confine the electric field within a low refractive index material. In particular, this latter could be though as air trenches filled with active quantum dots. Then, waveguide patterning can be useful to realize 1D photonic crystals in which a large number of emitters within the trenches is strongly coupled via a slow light band edge Bloch mode (Fig. 20). The Purcell factor within a trench can be easily calculated, while the feasibility to observe superradiant phenomena in such a structure is confirmed by rate comparison of the different decay channels of the embedded emitters.



Fig. 20: Spectral and spatial Purcell factor in the center of the fundamental cell of a 2D-infinite waveguide. Purcell factor isosurfaces for a 3D-infinite waveguide.

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19. Purcell enhancement in Si-nc-based microdisk resonators (Mher Ghulinyan)

Field-matter interactions can deeply modify the spontaneous emission rate (Γ_r) of Si-ncs, when these are coupled to optical cavity modes; the presence of large photonic density of states shortens the radiative lifetime, τ_r ($\sim \Gamma_r^{-1}$), of emitters due to Purcell effect. From a general point of view, Si-ncs are not ideal candidates for studying the Purcell effect, the possibility to measure emission rate enhancement, ϵ , would provide useful information on the effective average line widths through which Si-nc emitters are coupled to resonator modes.



Fig. 21: (left) Si-ncs provide isotropic emission of visible light from a WGM resonator under a laser pump. At resonant wavelengths photons emitted from close vicinity of the WGM mode (ii) can experience Purcell enhancement, while the total PL emission will include background Si-nc emission from the rest of the microdisk volume as well (i). (right) An example of measured out-of-resonance (empty circles, $\lambda = 853$ nm) and on-resonance (full squares, $\lambda = 846$ nm) PL signals from the WGM resonator. The data have been fitted using single and double stretched exponential decays, respectively.

We directly estimate the Purcell enhancement for Sincs coupled to Whispering-gallery modes (WGM) of a microdisk resonator through RT time-resolved measurements (Fig. 21). The emission lifetimes (τ) of Sincs are measured to be up to 70% shorter at wavelengths resonant with the WGMs (coupled) with respect to τ 's probed at out-of-resonance wavelengths (uncoupled). Such a difference in τ leads to fairly modest Purcell factors as expected in the bad emitter regime, when the emitter homogeneous line width $\Delta \omega_{em}$ is larger than that of the cavity ($\Delta \omega_{cav}$). We show that such estimated line widths imply upper limits for cavity quality factors, Q, that could be utilized for efficient Purcell enhancement in Si-ncs. Moreover, we predict that larger Purcell factors can be still probed using resonators with ultra-small cavity mode volumes. Finally, the used method can be easily applied to other systems where fundamental line widths are unknown or which are in the bad-coupling regime.

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For more info

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