MECHANICAL ENGINEERING / PHYSICS / PRESERVATION OF THE ARCHITECTURAL HERITAGE / STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING / URBAN PLANNING, DESIGN AND POLICY / AEROSPACE ENGINEERING / ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING / ARCHITECTURAL URBAN INTERIOR DESIGN / BIOENGINEERING /DATA ANALYTICS AND DECISION SCIENCES / DESIGN / ELECTRICAL ENGINEERING / ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY / ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING / INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING / INFORMATION TECHNOLOGY / MANAGEMENT ENGINEERING / MATERIALS ENGINEERING / MATHEMATICAL MODELS AND METHODS IN ENGINEERING

DOCTORAL PROGRAM IN PHYSICS

Chair:
Prof. Marco Finazzi

The Doctoral Program in Physics at Politecnico di Milano aims at attracting bright students with good scientific background and clear interest towards development and applications of new ideas and technologies. It offers a wide range of opportunities in the fields of advanced applied physics, such as photonics and optoelectronics (lasers, ultrafast optics), biomedical optics (optical tomography), vacuum technologies (thin film depositions), material technologies (microelectronics and nanotechnologies, micromechanical processing), and advanced instrumentation (electronic and atomic microscopy, nuclear magnetic resonance).
Scientific education and training to develop general research abilities in all areas of applied physics is increasingly needed by advanced technological companies. Through a general education in the basic areas of applied physics and a specific knowledge in condensed matter physics, as well as optics and lasers, the PhD Program aims at the development of an experimental approach to problem solving techniques and at the attainment of a high level of professional qualification.

The Doctoral Program has strongly experimental character. The contents are strictly related to the research activities carried out in the laboratories at the Department of Physics. They can be divided into two main areas:
Condensed Matter Physics, including photoemission; spin-resolved electronic spectroscopy; magneto-optics; X ray diffraction; magnetic nanostructures for spintronics; synchrotron radiation spectroscopy, positron spectroscopy, semiconductor nanostructures.
Photonics and Quantum Electronics, including ultrashort light pulse generation and applications; UV and X optical harmonics generation; biomedical applications of lasers; diagnostics for works of art; laser applications in optical communications; time domain optical spectroscopy and diagnostic techniques. All research activities rely on advanced experimental laboratories located at Politecnico di Milano (Milano-Leonardo Campus and Como Campus) and are performed in collaboration with several international Institutions. Consistent effort is devoted to experimental research, development of innovative approaches and techniques, and design of novel instrumentation.

The educational program can be divided into three parts: 1) Courses specifically designed for the PhD program as well transdisciplinary courses; 2) Activities pertaining to more specific disciplines which will lay the foundation for the research work to be carried out during the Doctoral Thesis; 3) Doctoral Thesis. The thesis work is the major activity of the Program. It has a marked experimental character and will be carried out in one or more laboratories at the Department of Physics.
The students are also encouraged to perform part of their thesis work in laboratories of other national or foreign Institutions. Collaborations that may involve the PhD students are presently active with several national and international research and academic Institutions, such as: ETH-Zürich, EPL-Lausanne, Lund Institute of Technology, University of Paris-Sud, Ecole Polytechnique-Paris, University of Berkeley, University of Cambridge, University College London, Massachusetts Institute of Technology, Harvard University, European Space Agency, ENEA, Elettra-Ts, PSI-Villigen, Agenzia Spaziale Italiana, European Synchrotron Radiation Facility (ESRF-Grenoble), IFN-CNR, IIT–Istituto Italiano di Tecnologia.

At present, the number of students in the three-year course is eighty-eight, and eighty-six of them have a fellowship.

The PhD Program Faculty, who takes care of organizing and supervising teaching and research activities, consists of members (listed here below), who are all highly qualified and active researchers covering a wide spectrum of research fields. This ensures a continuous updating of the PhD Program and guarantees that the students are involved in innovative research work.

FAMILY NAME	FIRST NAME	POSITION*
BERTACCO	RICCARDO	FP
BISCARI	PAOLO	FP
BRAMBILLA	ALBERTO	AP
CERULLO	GIULIO	FP
CICCACCI	FRANCO	FP
CUBEDDU	RINALDO	FP
DALLERA	CLAUDIA	AP
D'ANDREA	COSIMO	AP
DELLA VALLE	GIUSEPPE	AP
DE SILVESTRI	SANDRO	FP
DUÒ	LAMBERTO	FP
FINAZZI	MARCO	FP
GHIRINGHELLI	GIACOMO	FP
ISELLA	GIOVANNI	AP
LANZANI	GUGLIELMO	FP
LAPORTA	PAOLO	FP
MARANGONI	MARCO	AP
NISOLI	MAURO	FP
RAMPONI	ROBERTA	FP
STAGIRA	SALVATORE	FP
TARONI	PAOLA	FP
TORRICELLI	ALESSANDRO	FP

*Position: FP = Full Professor; AP = Associate Professor.

The Doctoral Program relies also on the advice of a Steering Committee, formed by distinguished experts (see table below) coming from R&D industries or research laboratories, who take care that the goals of the PhD Program are in line with the needs of non-academic world.

FAMILY NAME	FIRST NAME	INSTITUTION
PIROVANO	AGOSTINO	Micron Semiconductor Italia s.r.l.
DONATI	FABIO	EPFL – Lausanne, CH
HECHT	BERT	Università di Würzburg, D
LURIDIANA	SEBASTIANO	Tecno Vacuum s.r.l.
BLANDINO	DAVIDE	Optec s.p.a.
MAJORANA	SALVATORE	IIT – Technology Transfer Office

SMART ORGANIC INTERFACES FOR REMOTE OPTICAL CONTROL OF LIVING CELLS PHYSIOLOGY

Ilaria Abdel Aziz - Supervisor: Maria Rosa Antognazza

Cell intracellular signalling is a cascade of biochemical events that regulate basic physiological processes as cell division, growth and proliferation. In the past years, relevant studies demonstrated the involvement of signalling disfunctions in many pathological events, assisting the changeover from the focus of biology niche to the target of modern therapeutic methodologies. By and large, both exogenous and endogenous cues have been extensively employed as active modulators, in order to overcome the limitations of pharmaceutical approach, as invasiveness and selectivity. Two main strategies have been studied so far, namely relying on direct stimulation of cells with external stimuli and on actuators for the signal transduction. Among all, the exploitation of light for cell physiology modulation is one of the most promising approaches: coupling low invasiveness and high resolution helped out the transition from passive diagnostic element to active modulator. Both direct stimulation of cells by means of light stimuli and administration of phototransducers are currently under investigation in many research groups. Approaches relying on endogenous absorbers exhibit low selectivity and scarce dose-effect reproducibility. To overcome the lack of natural absorbers, effort has been directed towards manipulation of

cell genetic set, to let them express light sensitive proteins. Though, the need of viral transfection for gene deliver limits the applicability to *in vitro* models. In this framework, the exploitation of exogenous absorbers emerged as a reliable alternative. Organic based compounds, and in particular polythiophene-based materials, have been successfully employed for rat visual acuity restoration, enhancement of endothelial progenitor propagation and growth, light sensitization of small animals (*i.e.* the Hydra Vulgaris), among others, proving to be reliable and biocompatible platforms for physiology modulation. Upon photoexcitation, light triggers the synergic cascade of photoelectrochemical, photothermal and photocapacitive processes, that act as primary, exogenous signals, codified by the cells. The latter activate an intracellular response, namely the secondary signalling, that modulates the physiological activities. Though, the precise description of the phototransduction mechanism is still under investigation, that is the research question this thesis is willing to address.
Recently, nanoparticles entirely made of poly-3-hexyl-thiophene (P3HT) were fabricated and administered to a cell line model. After internalization and diffusion through the cytosol, they can be easily stimulated by means of a visible light source. The

interaction between the photoexcited nanoparticles and cells has been studied in terms of intracellular messaging. We reported an active role of the photoexcited nanoparticles, being able to modulate the Calcium (Ca^{2+}) response mediated by Reactive Oxygen Species (ROS) modulation. Interestingly, the generation of ROS resulted in a non-toxic, functional interaction, corroborating the hypothesis of the involvement of this intracellular messenger into important physiological activities. The possibility of interacting with intracellular signalling paves the way for the employment of this class of semiconducting polymers to be an active photo-transducer for metabolism modulation. It is worth noting that the main reaction chain of cell metabolism takes place across a specific organelle, namely the mitochondrion, whose external membrane hosts the transmembrane proteins responsible for the electron transfer reactions leading to ATP production. Many diseases have been ascribed to mitochondrial disfunctions, typically depending on protein defects and consequent inability to carry the electrons from one site to the other. Therefore, the development of a tool able to generate and transfer electrons with intracellular moieties is mandatory. In this scenario, the P3HT is still a valuable tool: the HOMO and LUMO energetic levels are well aligned with

the reduction potential of oxygen towards superoxide radical anion, this reaction being the origin of the photocatalytic current recorded in aqueous conditions. Remarkably, the energetic levels of P3HT are also well aligned with the reduction potential of Cytochrome C, a transmembrane protein located across the mitochondrial membrane responsible transferring a single electron in the last steps of ATP production. On the wake of the on-going research, we have first characterized the interaction between a thin film of P3HT and oxidized Cytochrome C, in an extracellular environment, by means of spectroelectrochemistry and scanning electrochemical microscopy. The protein redox state con be easily assessed through optical measurements, therefore we have monitored Cytochrome C absorption spectrum in the visible range during photostimulation of P3HT. Interestingly, we observed an increasing amount of reduced protein, both dependent on applied voltage and illumination time. The good alignment between protein and superoxide energetic levels suggests an oxygen-mediated transfer. Nevertheless, a direct electron transfer activity takes place, as demonstrated by measurements carried out in controlled, nitrogen atmosphere. On-going studies are focused on demonstrating the efficacy of the transfer also in intracellular

environment.
Recent developments in the biology of Stem Cells (SC) highlighted their pivotal role in the field of regenerative medicine, for their ability of potential differentiation towards neurons, muscles cells, osteoblasts, *inter alia*. The developments in the SC studies unravelled the involvement of intracellular messengers, as the Ca^{2+} ions, in the commitment towards differentiation, thus the development of tools able to modulate the intracellular signalling is currently under intensive investigation. Though, the use of exogenous materials is still at its embryonal stage. We focused our attention on Adipose SC (ASC), multipotent SC which are retrieved from the fat tissue and do not involve ethical issues, in order to assess whether the P3HT could act as a modulator of the cell differentiation pattern. We recorded the modulation of the membrane potential (V_m) of ASC plated on P3HT thin films. The V_m changes are associated to opening and closing of membrane channels, responsible for the cell correct homeostasis and intra-extracellular balance. Importantly, these changes were associated with enhanced intracellular Ca^{2+} dynamics, modulated by the illumination of P3HT. The potential modulation of P3HT on differentiation pathways is still under investigation, relying on the ability of the polymer to regulate important intracellular messengers, as the Ca^{2+}

ions.
Overall, this doctoral thesis demonstrates that the P3HT is a good phototransducer, either by establishing a modulation of secondary signalling moieties, as the ROS and the Ca^{2+} fluxes, or by modulating membrane potential channels, in different cell lines. Future works are being directed towards the implementation of different 2D and 3D structures, posing as unique limit the human imagination for further development of these devices.

THE ROLE OF MATERIALS AND DEVICE ENGINEERING IN PHOTOELECTROCHEMICAL HYDROGEN PRODUCTION FROM HYBRID ORGANIC SYSTEMS

Antonio Alfano – Supervisor: Fabio Di Fonzo

The dramatic impact of fossil fuels exploitation lead to an ever more evident environmental damage, which consequences could become irreversible if actions are not taken in due time. The increased awareness of this situation prompted the design and adoption of specific plans at national, international and global scale. In this scenario, promoting the penetration of renewable sources in the energetic market plays a fundamental role. Solar energy holds the potential to replace high carbon-emitting sources due to its high abundance and widespread distribution. A promising approach aims at storing its energy in the form of the chemical bonds of a molecule or compound, allowing then for an easy storage, dispatch and utilization according to the grid needs. This defines the concept of solar fuels, in which hydrogen is a prominent example.

Photoelectrochemical hydrogen production gained momentum through the years, as it allows to directly produce H_2 when photons with sufficient energy are absorbed by a semiconducting material immersed in an electrochemical solution. Lowering the final cost of produced hydrogen required to rethink the design of the devices realized for this purpose. This prompted the use of organic semiconductors in place of their inorganic counterparts. These materials benefit of a lower cost, convenient fabrication techniques and ease of tuning their optoelectronic properties. In order to fully exploit their potential, specifically designed architectures need to be realized in which charge selective contacts are employed to extract photogenerated charges from the photoactive layer. In this Ph.D. thesis a rational, step-by-step approach is presented which addresses the maturity of Hybrid Organic Photoelectrochemical (HOPEC) devices for water splitting (WS) with specific focus on the performance of Hybrid Photocathodes (HPC). Eventually, the guidelines retrieved will serve as a useful tool to extend this analysis to the akin field of photovoltaic solar cells. These topics are discussed in the three main sections of the thesis, offering a comprehensive view on solar conversion technologies.

The first section will address the realization of a fully organic-based tandem cell for solar powered water splitting. Here, a specifically optimized, high performing HPC will be coupled with a Perovskite solar cell (PSC) and an oxygen evolution catalyst. This three-element system achieves the very first demonstration of substantial water splitting from hybrid-organic devices. Through dedicate modelling this system will be accurately described, allowing to envisage its optimization to reach 10% and 20% solar-to-hydrogen efficiency (STH) in a short- and long-term perspective, respectively. This will highlight the HPC related parameters on which attention must be focussed to increase its performances. At the current state, they are mainly limited by the high voltage losses and series resistance of the device, which causes the tandem stack working point to fall in a potential region where charge accumulation leads to an accelerated degradation of the photoactive layer. This prompted a reasoned optimization of a novel HPC which will combine high electrochemical stability and good performances. This is achieved introducing a Transition Metal Dichalcogenide (TMD) based hole selective layer (HSL). Starting from an amorphous thin film deposited *via* Physical Vapour Deposition (PVD), a controlled post deposition treatment will grant selective access to its crystalline phases. This will allow to tune the work function, absorptance and charge transport properties of the material, enabling a reasoned integration in a HPC architecture. A detailed investigation of its properties will be discussed, and an in-depth understanding of the charge transport properties will be obtained through impedance spectroscopy techniques. When coupled with a novel photoactive layer, a TiO_2 electron selective layer and a hydrogen evolution reaction catalyst, the HPC stability and performances were significantly improved. During operation, as shown by the picture of the HPC in Figure 1, H_2 bubbles can be clearly seen on the surface.

The relevance of HSL engineering opened up to the investigation of novel solutions to increase the performances and stability of solar conversion devices. In the final section, two intriguing approaches will be presented. The first addressed the realization of a HSL in which a poly(3-hexylthiophene-2,5-diyl) (P3HT) matrix has been functionalized with copper thiocyanate (CuSCN) water splitting active species. This composite material imparted moisture resistance to a PSC, preventing environmental humidity to degrade the photoactive layer. The effect has been ascribed to the catalytic activity of the composite HSL, which dissociates water into its constitutive components and favours a p-doping effect on the P3HT matrix. As a result, the PSC retained its performances in a high RH (>80%) environment for

Fig. 1 - Picture of an HPC in the electrochemical cell. On its surface, H_2 bubbles can be observed.

28 days. Following this approach, a new class of composite materials has been investigated in which a matrix has been functionalized with finely dispersed species to tune its final properties. Several composites will be discussed, elucidating how the dispersed phase determines the transparency, crystallinity and electronic structure of the final material. This allows to engineer the selective contact to match the photoactive layer, ultimately enhancing the efficiency of the whole device.

In conclusion, in this thesis the role of HOPEC-WS toward matching the need of sustainable H_2 production has been discussed at the current, short- and long-term scenario. The relevance of a reasoned device optimization to reach the short- and long-term goal has been corroborated through the realization of an efficient and stable HPC. Selective contact engineering has been further extended to the akin field of PSC, realizing a P3HT@CuSCN HSL which allowed to retain the performances of a PSC in high RH% environment. Similarly, novel composites materials have been introduced, which benefit of a superior tuneability which would allow a seamless integration in solar conversion devices.

SINGLE PHOTON DETECTION IN SELF-ASSEMBLED GE-ON-SI MICROCRYSTALS

Andrea Barzaghi - Supervisor: Giovanni Isella

In recent years, single photon detection has generated a lot of interest due to its possible applications in the field of quantum technology, such as quantum photonics, quantum communications and quantum information processing. Single photon detectors also outperform conventional detectors such as p-i-n and linear avalanche photodetectors (APDs) in many application including light detection and ranging (LiDAR), facial recognition and rangefinding.

The standard devices for single-photon detection are silicon Single-Photon Avalanche Diodes (SPADs), which can be fabricated using established CMOS processes and high-quality material, resulting in very good performance at room temperature. However, due to the absorption properties of Si, the cut-off wavelength of such SPADs is limited to ~1 µm.

Many applications, such as LiDAR, would however benefit greatly from the ability to operate at near-infrared (NIR) wavelengths (up to 1550nm). At such wavelengths the power of the light source can be increased by an order of magnitude while being eye-safe, and the negative environmental effects due to the solar background and highly scattering medias (e.g. water, snow, fog, smoke) are reduced. Commercially available NIR single-photon detectors are superconducting nanowire detectors and InGaAs

SPADs, which are expensive compared to Si-based devices. A new approach to cost effective NIR single-photon detectors is to integrate semiconductors with a lower energy gap on standard Si wafer. Of particular interest is germanium, which is easier to integrate on Si than other materials and is compatible with existing CMOS processes. However, single-photon detection requires high quality epitaxial films, since a large density of defects (e.g. threading dislocations) will reduce the SPDE, increase the noise and lower the response time of the devices.

Ge has a lattice parameter 4% larger than that of Si, resulting in the nucleation of threading dislocations and in cracking of the epitaxial film due to thermal strain during Ge-on-Si heteroepitaxy. A novel approach to the deposition of high-quality Ge on Si has been demonstrated, exploiting deeply patterned Si substrates. These substrates have been etched to obtain high-aspect ratio Si pillars with a lateral size of a few micrometers. The growth of Ge on this kind of substrates results in the self-assembly of arrays of fully faceted Ge microcrystals, which are separated from each other by a distance as small as a few tens of nanometers (Fig. 1). Ge microcrystals have been demonstrated to be fully relaxed and with a very good crystal quality, thanks to the expulsion of threading dislocations and the absence of

cracks even after the deposition of a large amount of material. Moreover, the finite lateral dimension of the microcrystals results in the confinement of light and therefore an increased optical path compared to a flat epitaxial film, thus improving light absorption.

The focus of my PhD work is to exploit the self-assembly of microcrystals as a starting point for the fabrication of Ge-on-Si SPADs. In addition to all the advantages resulting from the high quality of this material, having arrays of microcrystals, each one acting as an individual microSPAD, would result in high-fill factor, high efficiency detectors with photon counting capabilities.

There are many optimization steps required to obtain a working Ge-on-Si uSPAD. The electric field in the p-n junction region must be large enough for a single electron-hole pair, generated by a photon absorption, to trigger an avalanche. Such a large field however can only be sustained by a semiconductor with a larger energy gap than germanium, such as silicon. Moreover, a fine control of the doping profile at the p-n junction is required to reach the desired electric field intensity.

We optimized both the structure of the substrates (i.e. the size of the pillars and their arrangement) and the deposition parameters (i.e. deposition rate and temperature) to obtain separated, self-assembled silicon

microcrystals. The doping profile at the junction has been carefully designed to account for the 3D geometry of the microcrystal, avoiding possible side effects such as localized breakdowns outside of the active part of the device. The correct electrical behaviour of the microSPADs has been verified by I-V measurements performed inside a scanning electron microscope with a nanomanipulator (Fig. 2), to individually probe the microcrystals.

Once the Si microSPADs have been optimized, we moved on to the integration of Ge on Si. This is done by depositing a nominally intrinsic germanium layer on top of the microSPADs, to act as an absorbing layer and extend the operation to the NIR wavelength range. Since this was the first attempt at depositing Ge on fully faceted Si microcrystals, we studied the defect density in this kind of samples by means of defect etching and TEM cross-sections, and we found the dislocation density to be lower than that of Ge deposited

on Si pillars with a flat top surface. The Ge-on-Si microSPADs have then been electrically characterized by I-V measurements, which showed the breakdown behaviour required for SPAD operation (Fig. 2b).
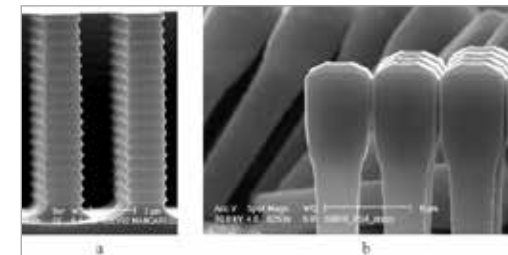

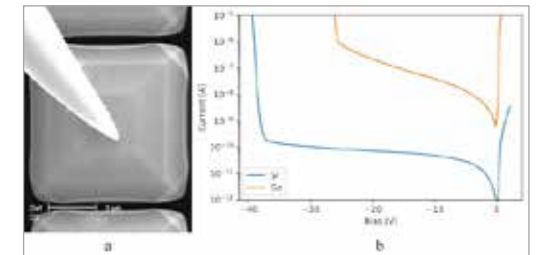Fig. 1 - Side view of a) etched Si pillars and b) 5µm of Ge deposited on Si pillars.

Fig. 2 - a) Nanoprobe landed on a microSPAD. B) I-V curves of a Si and Ge-on-Si microSPAD.

IMPROVING THE LEARNING EXPERIENCE IN STEM PROGRAMMES: PEER LEARNING AS A KEY FACTOR OF AN INTEGRATED APPROACH IN LARGE SIZE CLASSES

Matteo Bozzi - Supervisor: Maurizio Zani

Since the early 2000s the process of globalisation has shown that countries can be competitive and play a paramount role on the international stage only if their citizens are given the opportunity to build a significant background in science, technology, engineering and mathematics (STEM). Although the labour market has recently been seeking specialists in these fields, the percentage of STEM graduates in post-secondary education remains unquestionably low in the developed countries. A critical issue in this regard is that STEM programmes experience a considerable dropout rate in the first years of higher education. With specific reference to academic Physics courses, it has been argued that an inadequate preparation and a substandard performance in high school are significant individual factors which may lead undergraduates to attrition, particularly in the case of freshmen in STEM programmes. Another significant element which could adversely affect undergraduates' Physics learning is the fact that students may have some misconceptions in Physics. Furthermore, most academic Physics courses are characterised by a pedagogy centred on traditional lectures. As a classic lecture does not seem to perfectly combine with diversified learning modes and backgrounds, this could be the alleged cause of students' failure to achieve satisfactory learning in university

Physics courses. Conversely, many studies demonstrate that learning improves if students are actively engaged during their lessons. Furthermore, it has been pointed out that a student-centred pedagogy increases class attendance, learners' acquisition of expert attitudes towards the discipline as well as student engagement.
Considering these critical issues, two different courses of action characterised my research.
Firstly, I analysed some possible misconceptions in Physics among the students enrolled in some STEM faculties of different countries to identify their level of knowledge in Physics at the beginning of their academic career. Secondly, I investigated the effectiveness of an introductory Physics course which was characterised by an untraditional design and the synergistic use of traditional lectures, peer learning and technology in the context of large size classes.
To achieve the first objective, I carried out a case study, which was developed in the academic year 2018-2019. The possible incorrect conceptions investigated were partly novel, for instance those related to static friction, while others were to a certain degree well known, like those regarding displacement and distance travelled. All these misconceptions pertained to issues studied at high school and covered

in the introductory Physics courses at university. I did not select any items from existing concept inventories, but I created an authentic ad hoc multiple-choice questionnaire which was administered to 1,271 learners at the beginning of each Physics course involved in the research. The outcomes demonstrate that the students conceptual understanding of these specific Physics topics was adversely influenced by misconceptions that are widely spread among learners, regardless of the learner country, educational path, experience and socio-cultural background, and the Physics macro-area to which the topics belong. Moreover, I analysed whether to attend a STEM faculty for some months diminishes students' misconceptions in Physics and whether this potential impact is connected up with progress in either learners' study method, their knowledge or both. Data analysis showed that to cover some Physics topics in an academic course, thus improving the student knowledge of them, generated some degree of effectiveness in decreasing the spread of misconceptions and bringing about students learning. It should be emphasised that this result was not something obvious or self-evident, as the misconceptions persistence as well as the ineffectiveness of traditional academic courses are amply documented in the scientific literature. A second step consisted in considering students at the beginning of different

terms and comparing their findings in those items of the questionnaire which focused on topics already covered at high school, but not yet studied in any academic course. Although to study at university for six months or one year probably plays a part in developing students' general and integral process of maturation, this attendance did not appear to influence appreciably the evolution of their study method. Not unlike the freshmen at the beginning of their academic career, the learners who attended classes for longer did not actually seem to be able to critically review some Physics concepts and topics already studied at high school. As regards the second course of action included in this research project, I conducted a quasi-experiment to investigate the impact of an innovative teaching practice in the context of a

Physics course that was addressed to a large size classroom. The effectiveness of this intervention, that was implemented in the academic years 2017-2018 and 2018-2019, was compared to an equivalent Physics course which adopted a classical teaching design.
Descriptive and inferential statistics were used to analyse the data collected over the course of the two consecutive academic years. Analysis of the results confirmed that the integrated teaching strategy used with the experimental group was effective in facilitating Physics learning in a large size format. This pedagogical practice proved to be all the more successful in enhancing student performance than the traditional teaching approach based on academic lectures. Although this methodology seemed to be fruitful

in teaching Physics topics of different levels of difficulty, the size of the effect tended to be considerably different. In case of easy topics, the size of the effect tended to be huge, whereas it was small in case of more complex topics. Moreover, in addition to the possible correlation that may be drawn between this innovative teaching strategy and the improvements in the learners' level of knowledge in Physics, also the role of the instructors and their contribution to students' learning may deserve further investigation.
This study also identifies a threshold at which learner exposure to peer learning is likely to be effective in large size classes. Although the level of exposure to peer learning seems to be dependent on the complexity of the Physics topics covered in class, it seems to correspond to a small percentage of the total hours of the Physics course analysed (e.g., 2% - 2.5%). Therefore, the transition of the traditional pedagogic approach towards this innovative methodology would require only a slight adjustment by the instructors who would not need, all in all, to revolutionise their course design and their teaching approach. This may be a strong point in favour of the implementation of the integrated teaching approach described in this dissertation.
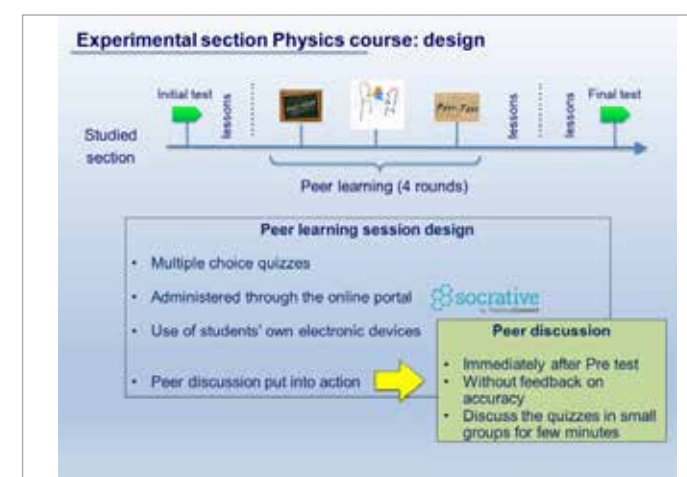

Fig. 1 - Design of an innovative teaching practice in the context of a Physics course.

COMPRESSIVE SENSING IN LIGHT SHEET FLUORESCENCE MICROSCOPY

Gianmaria Calisesi - Supervisor: Andrea Bassi

Light Sheet Fluorescence Microscopy (LSFM) also known as Selective Plane Illumination Microscopy (SPIM), is a fluorescence microscopy technique which, from its first publication in 2004, has been increasingly used in biological applications, from developmental biology to mounted tissues analysis. The basic idea behind LSFM is to focus the incoming excitation beam, which is collimated, to a single plane (referred to as light sheet), and thus to acquire the resulting fluorescence signal with a common widefield detection path, which is orthogonal to the light sheet axis. Said focusing can be obtained in a variety of ways, the easiest of which is using a cylindrical lens. The obtained narrow light confinement confers an intrinsic optical sectioning capability to the microscope. One of the main advantages of LSFM is its high-speed volumetric acquisition with respect to point scanning imaging approaches, in which light is focused on a diffraction limited spot. To this extent, LSFM also minimizes the light damage induced to the biological sample: its design in fact is such that every illuminated portion of the specimen is consequently acquired, whilst point scanning techniques deliver photon over an entire cone, to image a single point. Altogether, these reasons make LSFM an ideal tool for rapid 3D and 4D *in vivo* imaging. As an alternative to LSFM, Selective Volume Illumination (SVI) microscopy

has been recently developed with the goal of further increasing the acquisition rate. As for LSFM, SVI uses a perpendicular illumination and detection paths. In this technique, rather than illuminating the sample in a single plane, the incoming excitation beam is modulated across a confined volume In SVI, the illumination volume is chosen to cover the part of the sample which is of interest, rejecting the background generated by fluorescent or diffusive regions outside said part. On top of this, Light emitting Diodes (LED) are usually not considered a good light source for LSFM because the lack of spatial coherence makes it difficult to tightly focus light along one direction. However, using LED in fluorescence microscopy brings advantages such as color availability, low cost, and reduced presence of speckle patterns. Moreover, in a configuration in which illumination and detection path are mutually

orthogonal, this can avoid the typical shadowing artifacts of LSFM. In my PhD I demonstrated that, upon selectively illuminating a volume of the sample with LEDs, it is possible to volumetrically reconstruct it. The volumetric light modulation is possible thanks to a spatial light modulator, which is coupled to an illumination orthogonal to the detection axis, as shown in Fig.1 a). In this configuration, said modulation happens within the depth of field of the detection objective. After the acquisition of N patterns, an inversion problem is solved, resulting in the sample volumetric reconstruction. This modulation approach would only reconstruct a thin volume of the sample, according to the illumination optics depth of focus. Furthermore, I illustrated how the use of patterned acquisition is compatible with Compressive Sensing, a signal analysis technique that reduces the number of modulation patterns
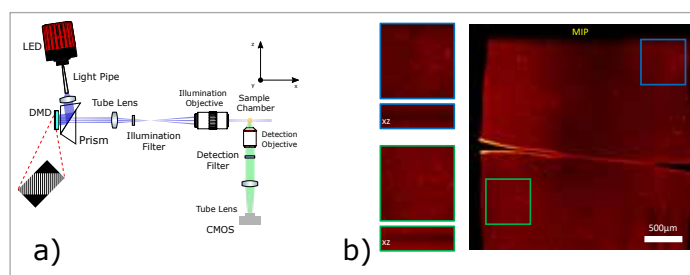
Fig. 1 - a) Experimental setup presented in the thesis. Illumination and detection are kept mutually orthogonal as in LSFM. 1 b) Reconstruction of a mouse brain: in the leftmost panels are shown together details and reslices, it can be distinguished the defocus effect of the detection, which results in a lower SNR.

to be acquired for a 3-dimensional reconstruction, compared to that given by the classical Nyquist-Shannon sampling criterion. This is achieved upon solving an ill-posed problem with further mathematical constraints which are related to the sample spatial features. The technique yields an accurate reconstruction of the sample anatomy even at significant compression ratios, up to compressed reconstruction in which only the 12,5% of the whole patterns set was used, hence achieving higher volumetric acquisition rate, and eventually reducing photodamage on biological samples. In my PhD, I also demonstrated that the presented technique yields the absence of shadowing artifacts which are removed thanks to the broad spatial frequency support of an incoherent light source such as an LED. To extend the reconstructed volume, I firstly implemented a scanning of the illumination patterns along the illumination axis, in Fig1 a), by means of a fast-translating stage. The synchronization of the motion with the line-wise acquisition of a CMOS camera, enables a reconstruction volume of 3 x 3 x 0.150 with isotropic resolution (2.5), by using a 4X, long working distance objective, as shown in Fig. 1 b). Nonetheless the acquired volume could be increased up to 7 x 7 x 0.2 thanks to a lower magnification objective (namely a 2X). Moreover, the

reconstructions resolution is limited by the finest degree with which is possible to spatially modulate light, ultimately the spatial modulator pixel size. Finally, once I obtained a technique in which the volume of imaging was ultimately limited by the sensor dimensions i.e., along and , a computational way to overcome the limited Depth of Field extension has been implemented. This limitation in fact hinders the possibility of having thicker samples, which are correctly imaged only in a 200 thick volume (for a 2X detection objective lens). Said computational method is an implementation of a deconvolution procedure, which aims at removing the defocused contribution of the known optical properties of the detection (in the mathematical formulation of its Point Spread Function), ideally obtaining the diffraction limited distribution of fluorophores. In practice however, due to non-ideal experimental conditions, deconvolution fails at finding a corrected solution for every point of the axial sample profile; nonetheless a Richardson-Lucy algorithm was able to increase to extension of the imaged volume. In the last part of my PhD, I extensively tested the cited strategies altogether, to assess for the overall achieved performances. I measured samples ranging from *Danio rerio*, a biological model in developmental

and ecotoxicological studies, to adult *Mus musculus*, i.e., lab mouse, from *Arabidopsis thaliana*, a well-studied plant model, to *Drosophila melanogaster*. The samples were imaged in different media, in whole organisms and explanted tissues to demonstrate how the technique can be of interest for both *in vivo* and *ex vivo* imaging application at different scales.

STUDY OF THE PHYSICAL–CHEMICAL PROPERTIES OF CADMIUM YELLOW

Marta Ghirardello - Supervisor: Daniela Comelli

During the last decades, the scientific study of cultural heritage has experienced great expansion and innovation, with the development of advanced devices and new analysis methods for the in-depth characterization of different cultural heritage artifacts. Physical and chemical analyses allow to identify the artistic materials, often present as complex mixtures of organic and inorganic compounds. Due to the intrinsic material complexity, multiple techniques are needed to overcome the limitations of the individual method and achieve a better comprehension by combining different information. The detailed knowledge of the employed materials enables the definition of proper conservation protocols, the application of suitable restoration procedures, the detection of the degradation processes, the study of the historical evolution of the material and the authentication of the artworks.

When dealing with such precious objects as artworks, non-invasive and non-destructive methods are highly required for both in-situ (museums or art galleries) and laboratory analysis. The application of optical techniques has demonstrated to be particularly suitable for non-invasive study, also thanks to their simplicity and ease of use. Many research studies have demonstrated that photoluminescence techniques are a beneficial strategy for the

analysis of cultural heritage, with applications ranging from detecting material heterogeneities to identifying previous restoration treatments and monitoring cleaning procedures. The research presented in this thesis concerns the application of physical and chemical analyses to the study of Cadmium Yellow pigments and paints. Cadmium Yellows are a class of inorganic pigments based on the semiconductor cadmium sulfide (CdS), introduced during the middle of the 19th c. and widely employed by modern artists such as Vincent Van Gogh, Pablo Picasso and Henri Matisse. Recent studies have reported the degradation of Cadmium Yellow paint in masterpieces of the late 19th to the early 20th c., such as *The Scream* by Edward Munch, raising questions about the triggering factors of degradation. In this work,

using photoluminescence analysis combined with other microscopy and spectroscopy analytical techniques, we have investigated the properties of Cadmium Yellow from raw pigments to model and real paints, to gain further insight on pigments characteristic and their role in the degradation process. It has been hypothesized that the reactivity of Cadmium Yellow paint is linked to the use of imperfect production methods of the pigment. To characterize the pigment properties in relation to the synthesis method and to evaluate how the synthesis can affect the paint stability, we have first reproduced the historical manufacturing processes of Cadmium Yellow pigments following the Winsor and Newton 19th c. archive database. The database is a primary source of information of the manufacturing processes employed by one of the
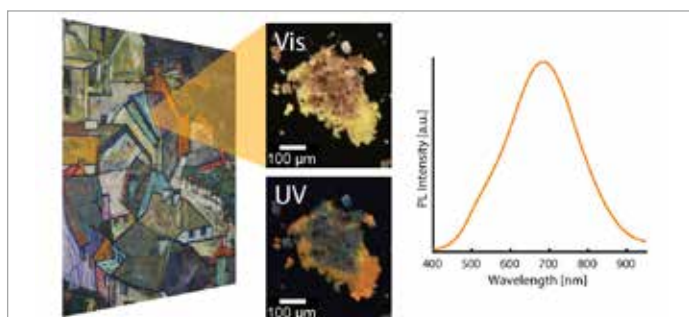

Fig. 1 - Detail of Egon Schiele painting *Stadtende/Häuserbogen III* (1918, Photo © Universalmuseum Joanneum, Graz) and of the micro-fragment analysed through hyperspectral photoluminescence micro-imaging. The degraded Cadmium Yellow paint presents an intense pink-orange emission under UV light, peaked at 680 nm, different from the typical emission spectra of intact CdS (emission peak 720-750 nm).

leading colour company of the 19th c. and its study has allowed the selection of historical preparation methods of Cadmium Yellow and their replication in laboratory. The synthetized pigments, characterised by complementary analytical techniques, have small particle size, mixed crystal structure and reduced luminescent emission with respect to commercially available and modern synthetized pigments. All these factors could influence the reactivity of the pigment when employed in paints.

To effectively study the degradation mechanism of Cadmium Yellow paints, the historically reconstructed pigments have been transformed in model paints, which then have been artificially aged. By this study we were able to observe that the degradation is strongly affected by the synthesis method of the pigment. In particular, we have demonstrated that nanocrystalline CdS pigments are more prone to develop degradation compounds, due to their higher reactivity.

Beside the development of degradation compounds, in some of the aged paints we detected a peculiar pink-orange photoluminescence emission, observed also in real degraded paints from Pablo Picasso painting *Femme* and Egon Schiele *Stadtende/Häuserbogen III* (Fig.1). Part of the work has been hence

dedicated to study in details this emission and understand its origin. We demonstrated that the photoluminescence emission has a microsecond lifetime and suffer of saturation phenomena when the excitation intensity is sufficiently increased, all properties that recall a trap state emission induced by defects in crystalline compounds. Further, the study of the chemical speciation in different samples has allowed us to infer that this emission can be associated to a high density of surface defects in nanocrystalline CdS, rather than to other fluorescent paint components. The positive correlation between the tendency to degrade of nanocrystalline CdS pigment and the occurrence of a peculiar PL emission allowed us to conclude that photoluminescence measurements can be employed for effectively probing the presence of degraded Cadmium Yellow paints. A part of the work has been dedicated to the development of novel techniques for the non-invasive study of the photoluminescence emission from artworks. The potentiality and limitations of two different investigation methods, based on photoluminescence excited at variable fluence and hyperspectral time-gated imaging, are illustrated and discussed. Beside the technological advantages (as compactness, flexibility of the setup for micro and remote analysis and high spectral

resolution) we demonstrated how the employed methodologies are highly informative of the nature of different recombination paths in crystalline pigments and paints and allow a deep characterization of the emission from luminescent materials.

ULTRAFAST PROCESSES IN DOPED SEMICONDUCTOR

Michele Guizzardi - Supervisor: Francesco Scotognella

The radiation emitted from the Sun is our biggest source of energy. However, the 45% of the solar radiation is in the near infrared (NIR) and, thus, is not absorbed by the most common photovoltaic materials. To convert the NIR solar radiation into electricity, we are using unconventional plasmonic materials and study the plasmon assisted hot carrier extraction in heterojunctions that include such materials. Instead of metals that work mostly in the visible, we used a doped semiconductor nanocrystals. In particular, we studied Indium Tin Oxyde (ITO), that has a tunable absorption between 1300 nm to 4000 nm, due to a localized plasmon resonance. To extract electrons we coupled ITO with a semiconductor (TiO2), that act as electron acceptor. The advantages of using ITO is that is a conductive and transparent material, so that we are only absorbing the NIR region that is resonant with the plasmon. This is a key factor to use such materials in tandem with common solar cells, and so to boost the overall power conversion efficiency.
In order to study the hot electron transfer phenomenon, we employed the so-called pump probe technique, in which a strong pump pulse excite the material and a weak probe pulse track the change in the transmission as a function of the pump probe delay. After the optical excitation, the first

process that takes into place is the plasmon dephasing, the time scale for this process is less than 10fs; the loss of coherence is a result of Landau damping which transfers energy from the plasmon to the Fermi gas. The generation of a hot Fermi-Dirac (FD) distribution is achieved through electron-electron scattering in a time scale of tens of fs. Finally by electron-phonon scattering the hot FD cools to equilibrium exchanging its energy with the lattice as heat, in ITO this process is faster than 1ps. If the plasmon is coupled onto the surface of a semiconductor with a correct alignment of the valence band, the hot electron generated after the Landau damping could overcome the Schottky barrier generated on the ITO-semiconductor interface and transfer into its conduction band. As electron acceptor, TiO2 is a commonly used semiconductor that well matches with our needs. In order to track this electron transfer we need a really high resolution and thus we generated our 1500 nm pump pulse by means of an Optical Parametric Amplifier (OPA) that has a time resolution of about 80fs. The plasmon resonance directly depends on the number of carriers presents in the conduction band of our material. Such an electron transfer is expected to be seen as a redshift of the plasmon resonance of ITO, this will lead to an increase of transmittivity of our sample in the region close to the plasmon resonance as it can be

seen in figure 2. To probe the region close to the resonance (1300 nm -1600 nm) a second OPA was build and tuned at 1200nm, this is then focused into a 6 mm YAG crystal to generate a white light that was able to cover that region. The needs of such a short pulse, lead to peak intensities higher than 100 GW/cm^2. Such a condition may give rise to several Coherent Artifacts (CA), that can completely or partially distort the first hundreds of femtoseconds of the recombination dynamics, and for us covering 1/3 of the whole dynamics. Different CAs can be recognized in ultrafast pump-probe measurements: Two Photon Absorption (TPA), Cross Phase Modulation (XPM), Impulsive Stimulated Raman Scattering (ISRS) and Perturbed Free Induction Decay (PFID). We focused on XPM because is the most disturbing affecting the whole probe spectra and is unavoidable when you have a glass substrate and lo optical density
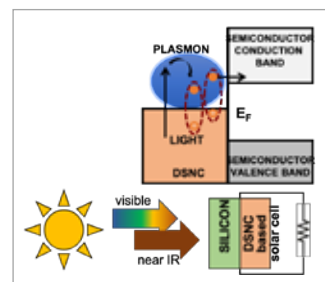
sample. It is a redistribution of the spectral component of the probe pulse induced by the Kerr effect, namely a change in the of the medium refractive index caused by an intense pump pulse.
Simply measuring the XPM on the bare glass substrate and then subtracting it from the signal at every wavelength cannot be a valid solution to get rid of the artifact-related signal distortions. In fact XPM shape is affected by the precise probe spectra and the presence of the sample change its shape and so the artifact change.
We addressed the need to reconstruct the very first event after the pulse excitation by developing a novel AI-driven method to remove XPM artifacts. We propose XPMnet, a Convolutional Neural Network (CNN) able to retrieve directly from pump probe raw data the dynamics embedded in the artifact. We designed and developed the XPMnet
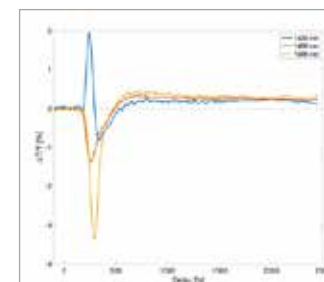
as a supervised Machine Learning (ML) model. The CNN model was trained on a labelled dataset, which featured simulated pairs of XPM-affected pump-probe instances and related extracted dynamics, the latter carrying the physically relevant information about the specimen under investigation. CNNs fall into a peculiar branch of ML, namely Deep Learning (DL), since their structure is composed of sequential layers gives rise to a fairly deep model architecture. According to the universal approximation theorem, artificial neural networks are capable to represent any kind of transfer function.
The generation of the input counterparts of the dataset included the following steps: the fitting of experimentally measured XPM artifacts on glass-substrate and their data augmentation based on fitting parameters; the generation of pump-probe time dynamics via the convolution between the instrumental response function and exponential
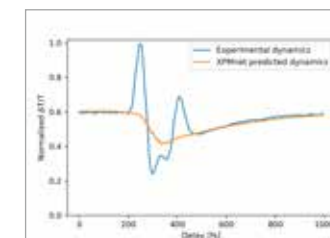
dynamics; the sum of XPM and pump probe dynamics thus obtained, together with the addition of white noise, to generate the final datum. In our experiment we casted the recombination dynamics as a mono-exponential that represent the electron phonon scattering and a constant to take into account the phonon-phonon scattering that take places into much longer time scale and for us can be seen as a constant. Upon training the XPMnet featured a MSE of 5 10^{-5} a mean absolute percentage error of 1% and an R^2 of 0.99 on the validation dataset. The CNN model is able to efficiently and accurately get rid of the coherent artifact and extract the relevant dynamics. The results of applying the XPMnet on experimental measurements are shown in figure 3, where the extraction is performed on an unseen real datum with a new XPM shape. The recombination dynamics is extracted from the XPM and noise-affected input datum. The spatial overlap of the dynamics with the input instance is perfectly managed by the algorithm in terms of baseline and t$_0$ (λ) variations along the time line.

Fig. 1 - Scheme of the plasmon driven hot electron tranfer and Silicon ITO tandem solar cell

Fig. 2 - Recombination dynamics of ITO and TiO2 heterostructure close to the plasmon resonance

Fig. 3 - Predicted dynamics from the XPMnet of an experimental datum

INVESTIGATE CHARGE ACCUMULATION OF HIGH PERFORMANCE SWCNTS FETS BY CHARGE MODULATION MICROSCOPY

Mengting Jiang - Supervisor: Mario Caironi

With the selective polymer-wrapping method, high purification semiconducting Carbon Nanotubes (SWCNTs) is achievable. Depending on the selective wrapping polymer, in general, we could classify SWCNTs materials into two categories, mono-chirality and multi-chirality. Such SWCNTs materials shows lots of profits. First of all, it could be deposited through easily solution-processed techniques such as printing and spin-coating for fabricating the SWCNTs FETs. Secondly, it has been established that the mobility of those devices is one order of magnitude higher than conjugated polymer devices, and its electron and hole balanced mobility indicates the application potential of high-performance CMOS FETs towards the ICs. Moreover, its extraordinary mechanical and optical properties also allow us to explore it to flexible display electronics. Of course, to further adoption in the semiconductor industrial setting, SWCNTs devices still need to be optimized, a better understanding the charge transport in SWCNT networks would benefit.

In this PhD thesis, charge transport in the random SWCNTs networks is investigated through the Charge Modulation Microscopy (CMM) technique. The working principle is the same as the Charge Modulation Spectroscopy (CMS) which is already widely used to investigate the charge transport in polymer. Such setup detects the charge-induced optical transmission variation. A positive CMS signal ($\Delta T/T > 0$) indicates an increased transmission light which is the bleaching of the ground-state absorption, while a negative CMS signal ($\Delta T/T < 0$) is a reduced transmission light due to charge-induced absorption. During the experiment, the source and drain electrode are grounded for a uniform lateral electric field, and an offset DC voltage and modulated AC voltage is applied to the gate electrode. Fixing the AC voltage, we could observe that the CMS signal of SWCNTs FETs first increases with the offset voltage till the plateau, then decreases with the offset potential. It could be explained at subthreshold region the charge modulation carrier density increases with the offset voltage, and above the subthreshold region the modulate signal reduces due to the static exciton bleaching. To avoid complicating the problem, the offset voltage to be applied is at the subthreshold region where the CMS signal, and the charge carrier density, increases with offset voltage.

The CMM technique combines the confocal microscopy with CMS which allows to reach both spatial and spectra resolution where the CMS signal becomes more local. Furthermore, the scanning PZT stage enables to map the local CMS information pixel to pixel. As mentioned above, at the subthreshold region, the CMS signal increases with the carrier density, therefore we could directly visualize the charge carrier density distribution though the CMM map. Moreover, we could selectively map the hole or electron carrier distribution by applying the positive and negative offset voltage. The experiment results show the electron and hole maps are quite consistent with each other which implies there is no selective traps for hole and electron, and the local electrical environments for the electron and hole are the same.

Meanwhile, the CMM setup allows to get the CMM map ($\Delta T/T$) and Transmission map simultaneously. By measuring the incident light intensity , the corresponding map could be calculated. Under the assumption that SWCNTs species have the same distribution of length and the carbon atom per unit length is a constant, the carbon atom concentration could be calculated directly from OD with the following equation: . The carbon atom concentration N is proportional to the network density. Now it is possible to quantitatively build the relationship between the charge carrier density and the network density. Apart for some exceptions, for the mono-chirality, the dense network region is always associated with high CMS signal since the dense network increases the possibility of effective connection such as tunneling, yielding more charge carrier density and vice versa. While for the multi-chirality, there is no clear relationship between the N and the CMS signal which implies the energetic disorder in such networks plays an important role.

Furthermore, CMM experiments for the Mono SWCNTs under different voltages have been performed. In general, the CMS intensity increases with the offset voltage. By subtracting the CMM maps, differential CMM maps could be calculated. A positive signal in differential CMM map indicates an increased CMS signal caused by increased local charge carrier density, while a negative signal means a reduced CMS signal which is associated with the saturated high CMS region. The increased carrier density is because of activating its surrounding connection since the high offset potential overcomes the energetic barrier. In order to exclude the network density effect, CMS/N versus N relationship is used to qualitatively analyze the effective connectivity. Through a mathematic algorithm, the effective connectivity has been assigned to CMM map. The results show that the CMS signal is a complex effect of the local network intensity and the effective connectivity. Further increasing the offset voltage (above the subthreshold region), a CMM map at -2V is achieved with high signal to noise ratio. Comparing the maps, it could be observed that the CMM maps resemble with each other, while the map from a higher offset voltage shows a more homogenous distribution than others since the high potential activates more connections. During this thesis, the charge transport through the random CNTs networks has been investigated. For the mono CNTs, it could be concluded that the charge density is more depended on the network density and the effective connectivity. While for the multi-chirality CNTs, it seems that the energy disorder plays a more important role than other parameters.
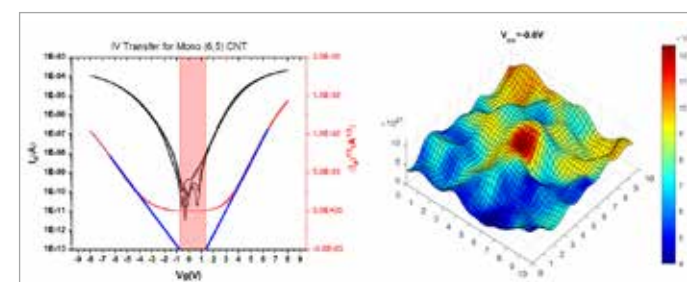

Fig. 1 - Left panel shows the IV transfer curve for Mono CNT (V_{ds} = -0.1 V), the blue curve is for extracting the threshold voltage. Right panel is the CMM map at V_{os} =-0.6V, V_{pp} = 0.2 V, the scan area is 10 μm² contains 40x40pixels.

FUNCTIONALIZATION OF OXIDE-METAL AND MOLECULES-METAL INTERFACES THROUGH MONOATOMIC BUFFER LAYERS

Alessandro Lodesani - Supervisor: Andrea Picone

As famously stated by Herbert Kroemer in his 2000 Nobel Prize lecture "The interface is the device". Indeed, the shrinking of the size of technological devices towards the nanoscale resulted in the quality of interfaces becoming a fundamental and critical factor in determining the efficiency of a device. However, having an atomically sharp interface is quite often a hard task, especially when dealing with very reactive surfaces such as the ones of clean metals. In this work we propose to solve this problem through the insertion of monoatomic buffer layers as a strategy to tailor the properties of interfaces in a reliable and reproducible way. The measurements were structured as a systematic comparison between the samples with and without the buffer layer, where the experimental conditions and the growth procedure have been carefully kept the same.

The first family of interfaces investigated is the one composed by ultrathin oxides grown on a metal substrate. Here, the main problem is linked to the growth procedure, which foresees the exposure of the substrate to molecular oxygen, resulting in the undesired formation of a native oxide. Our interest focuses on interfaces that are relevant for spintronic applications; for this reason, we chose to study the early stages of growth of transition metal oxides on a ferromagnetic substrate, in particular chromium and iron oxides grown on nickel. Ni(111) has been chosen as a substrate since it is the perfect platform to grow high-quality epitaxial graphene by chemical vapor deposition.

The measurements reveal that the graphene buffer layer induces a three-dimensional growth in the case of Fe oxide, instead of the layer-by-layer observed for the same oxide grown on the bare Ni(111) (see fig.1, top row). The results are completely opposite in the case of Cr oxide, where the insertion of graphene induces the stabilization of a highly strained, atomically flat, metastable Cr_2O_3 (see fig. 1, bottom row). Here, graphene also acts as a protective layer for the oxidation of the Ni(111) substrate, which is responsible for a rough morphology in the Cr_2O_3/Ni(111) sample. Moreover, the presence of graphene results in the dramatic shrinking of the surface energy gap, as measured by scanning tunneling spectroscopy. These experiments prove that there is no general rule of thumb for the role of graphene as a buffer layer for metal/oxide interfaces, but it can give rise to very interesting effects.

The second part of the thesis deals with the interface between a ferromagnet and an organic semiconductor, namely spinterfaces. The use of organic molecules in spintronic applications is very promising due to their small spin-orbit coupling, flexibility, low cost, customizability and responsiveness to external stimuli. In spinterfaces the biggest problem is related to the reactiveness of the metallic surface. Indeed, the bonds formed with the first molecular layer can actually destroy the integrity of the molecules. Here, we have investigated the role that a single layer of oxygen (or oxide) has on the early stages of growth of metallo tetra-phenyl porphyrins (M-TPP, M = Co, Ni, Zn) grown on a Fe(001) substrate.

Our study demonstrates that, when growing a single layer of M-TPP on the clean Fe(001), the molecules are indeed destroyed by the interaction with the substrate. By passivating the metallic surface through a single layer of oxygen [namely Fe-p(1x1)O], not only the molecular integrity is preserved, but we also observe the self-assembly at room temperature for one monolayer (ML) of Co-, Ni- and Zn-TPP (see fig. 2). Interestingly, the assembly on the surface varies for different metallic ionic species. Indeed, 1 ML Zn-TPP/ Fe-p(1x1)O displays a 5x5 superstructure parallel to the (100) axis of the substrate. On the other hand, both 1 ML Co-TPP/ Fe-p(1x1)O and 1 ML Ni-TPP/ Fe-p(1x1)O display a 5x5 superstructure with two equivalent domains rotated by $\pm37°$ (see fig. 3). The different assembly is reasonably caused by the larger ionic radius of the Zn^{2+} ion (8% larger than the ones of Co and Ni), which causes a slight distortion of the macrocycle of the molecule, leading to different surface adsorption sites being energetically favorable. Moreover, the magnetic properties of the molecules have been studied by means of spin-polarized photoemission and inverse photoemission spectroscopies, revealing that Co-TPP molecules display a magnetic moment at room temperature. This magnetic moment is localized at the center of the molecule and is linked to the unpaired spin in the dz^2 orbital of Co^{2+}, as also confirmed by DFT simulations.

In conclusion, we have demonstrated that the insertion of monoatomic buffer layers can serve as a valuable strategy for tailoring the morphology and the chemical, electronic and magnetic properties of interfaces in a reliable and reproducible way. In the future, we propose to introduce the monoatomic buffer layer approach in the study of actual working devices. In particular, we propose to study the effect that the insertion of the buffer layer has on organic magnetic tunneling junctions and on interface magnetoresistance devices.
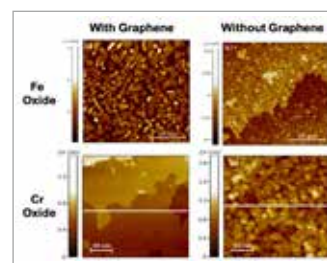

Fig. 1 - STM images of Fe oxide (top row) and Cr oxide (bottom row) grown on graphene/Ni(111) (left column) and on the bare Ni(111) (right column). The presence of graphene induces a 3D growth in the case of Fe oxide while it acts as a template for atomically flat Cr oxide layers.
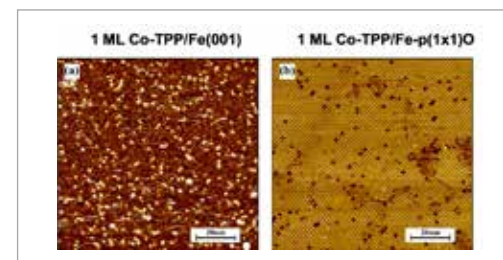

Fig. 2 - STM images of 1 ML Co-TPP/Fe(001) (left) and 1 ML Co-TPP/Fe-p(1x1)O (right). The passivation of the surface results in the self-assembly of the molecules at room temperature.
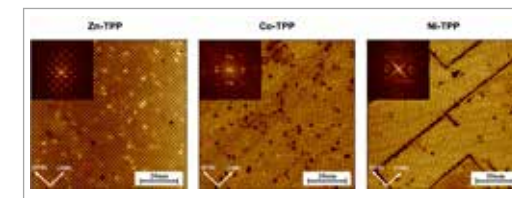

Fig. 3 -STM images and fast fourier transforms of 1 ML of (from left to right) Zn-TPP, Co-TPP and Ni-TPP grown on Fe-p(1x1)O. Zn-TPP displays a 5x5 superstructure parallel to the (100) axis of Fe, while Co-TPP and Ni-TPP arrange in a 5x5 superstructure rotated by 37°.

DESIGN AND MODELLING OF METAMATERIALS FOR EFFICIENT LIGHT–HEAT CONVERSION

Andrea Mazzanti - Supervisor: Giuseppe Della Valle

Optical devices offer us the capability of controlling electromagnetic field wavefronts operating on polarization, amplitude, and phase of an incoming light beam. Conventionally, the control has been made possible by propagation inside of an optically dense materials (typically dielectric), with the design process being aimed at engineering the shaping of the optical element (as it is the case for conventional lenses or mirrors). Controlling wavefronts by engineering the optical path through refractive optical elements proves to be a powerful approach. However, there is the intrinsic limitation posed by a lower limit to the size of the device itself. The growing interest towards miniaturization of devices is aimed at achieving integrated circuits in a large span of application, ranging from ultrafast information technologies, microscopy, sensing, imaging, and opto-electronics. If our goal is the full control of electromagnetic fields over the sub-micron scale, we need to surpass conventional optics. Metamaterials answer to these needs, being able to induce abrupt changes in wavefronts over a characteristic length of tens of nanometers. Metamaterials are ordered arrangements of basic building blocks (meta-atoms), whose optical response is governed by the resonances of the meta-atoms themselves, rather than grating effects induced by the periodicity. By careful design and

tailoring of the meta-atoms one can achieve the desired optical functionality, being able to control polarization, wavelength, phase and amplitude of the electromagnetic field, with efficiencies larger than their bulk counterparts. The advantage of these platform lies both in their low dimensionality, and in the possibility of having optical features impossible to achieve with natural materials, such as epsilon-near-zero or magnetic permeability (both positive and negative) at high frequencies, allowing us to achieve exotic effects (e.g., negative refraction), paving the way to full control of electromagnetic fields through optical devices as discussed in the field of transformation optics. This

is made possible by the exploitation of resonances at the nanoscale that isolated nanoantennas can sustain, allowing for a new generation of photonic devices. The choice of the platform, whether metallic or dielectric, is but one of the aspects in the overall design process, where shaping of the metasurface unit cell is crucial to excite the resonances of the meta-atom, and fine tune them to the specific application that is being investigated. The increasing need of design requirements in this field is the driving factor behind our studies. Our approach is based on full-wave electromagnetic simulations, and semi-analytical modelling of the carrier dynamics in the active material, allowing for description
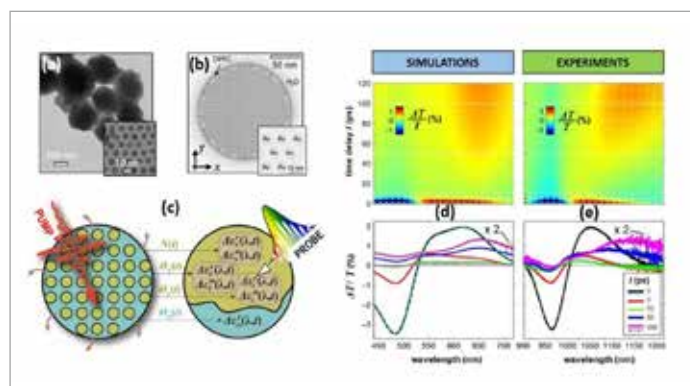

Fig. 1 - (a) transmission electron microscopy of the NC assemblies. Inset shows a zoom of the dried sample to highlight the lattice. (b) 2D model implemented to simulate the assembly response. The inset shows a zoom on the Au NCs. (c) Sketch of photoinduced permittivity modulation mechanism. the assembly, constituted by Au NCs (green) and organic matrix (cyan), is excited by an optical pump pulse (red arrow). The whole system experiences four permittivity variation relative to each of the temperature in our model, these are observed by a probe pulse (rainbow arrow). (d) Simulated and (e) experimental transient transmittance maps.

of the time varying response in the investigated systems. Our modelling accurately retrieves the experimental results for both plasmonic and dielectric based platforms, defining a universal methodology for the design of novel optical devices based on resonant nanostructures. As an example, we present the modelling of the heat release properties of plasmonic nanoassemblies, aimed at either targeted thermal therapy. By combining pump-probe spectroscopy and finite elements analysis (FEA), we can corroborate the claim that nanostructuring of plasmonic nanoheaters increases the light-heat conversion efficiency.

The synthesized hybrid aggregates consist of Au nanocrystals (NCs) of radius r=2.75 nm, embedded in an organic matrix of 1-octadecane-thiol, resulting in aggregates with an average radius R=80 nm (Fig 1a). Visibly, the Au NCs are arranged in a triangular lattice structure with tight packing of NCs. First, we set up a reduced two-dimensional model (Fig 1b) to investigate the presence of a collective plasmonic resonance of the NC assemblies in the visible. Then we estimate the permittivity perturbations by setting up a four temperatures model, which describes the photoexcitation, and subsequent relaxation, of Au non thermalized electrons (N), thermalized electrons (Q_E), Au lattice temperature (Q_L), and organic matrix temperature (Q_O).

Each of these effective temperatures induce a wavelength and time dependant permittivity modulation in the hybrid system (as sketched in Fig 1c). Lastly, combining the linear results of FEA, with the modelled permittivity modulation of the hybrid system, we can calculate the transient transmittance map of the sample in the visible (Fig 1d), and compare it to the experimental one (Fig 1e). Here, the pump wavelength is 400 nm, and the fluence is 2.75 mJ/cm^2. In the first 10 ps, we can observe the fingerprint of transient plasmonic resonance, which exhibits a negative lobe centred around 500 nm (480 nm in the simulation), and positive one around 570 nm (600 nm in the simulation). However, a broader and red shifted revival of the positive lobe is observable starting at 50 ps delay, which steadily builds up (plateau is not reached in the first 120 ps). Interestingly, by disentangling the permittivity modulations coming from the four temperatures, we can claim that the delayed response is ascribable to thermo-optical effects in the organic ligand matrix. Indeed, we report the simulations without accounting for thermo-optical effects in Fig 1d (dotted line). For short time delays, there is no difference with the total spectrum, implying that the effect is negligible at first. On the other hand, at long time delays, the spectrum would be entirely flat without considering the matrix

temperature increase, demonstrating the origin of the delayed signal. Because of the general agreement between experiment and simulations, we can draw conclusions on the assembly temperatures retrieved from the dynamical model. We estimate a temperature increase of the whole assembly of 15 K (peak value of 35 K in the metallic phase) with a time constant of 150 ps. Such values are compatible with hyperthermia of the cell.

TMEK: A LAB ON CHIP DIAGNOSTIC TEST FOR SELECTIVE CAPTURE AND DETECTION OF MAGNETIC FINGERPRINTS OF MALARIA

Francesca Milesi - Supervisor: Andrea Ivano Melloni

Nowadays, according to the World Health Organization (WHO), malaria is one of the most common life-threatening infectious diseases and a global public health challenge. In 2019, around 229 million cases were registered with an estimated 409000 deaths worldwide. The majority of these, around 93%, occurred in the sub-Saharan Africa where the population exposed to the highest risk of death is com- posed by children aged under 5 years old, that are more susceptible to infection and illness because of their low developed immune system, and by pregnant women since placental sequestration of the parasite can lead to maternal anaemia and to an increasing risk of death before and after childbirth. Conventional methods for malaria diagnosis are not suitable for on-field wide screening of the popula- tion. Optical microscopy examination, the time-honored Gold Standard for malaria, asks for an expert operator able to distinguish infected red blood cells (i-RBCs) in a blood smear using a good microscope. It is then an operator-dependent method, requiring about 60 minutes and a laboratory setting. Rapid Diagnostic Tests (RDTs) based on immuno-assay lateral-flow devices require just 15-30 minutes but are not quantitative and suffer from a large number of false negative-positive results, especially in endemic zones. Tests based on polymerase chain reaction (PCR) can detect extremely

low parasite concentra- tions, but the on-field compatible version known as LAMP is not quantitative, has a high cost and long operation times (about 60 minutes) which limit the wide spreading of this technology. To fill the gap be- tween the current technology and the need for a cheap, fast and highly sensitive diagnostic tool suitable to wide screening in low-resource setting, the World Health Organization itself strongly recommends the development of novel RTDs with the same sensitivity of microscopy but with a reduced number of false positives and false negatives with respect to currently available lateral-flow devices. My thesis has contributed to develop an innovative system, named TMek, that provides a rapid and valid alternative up to the actual devices and methods while ensuring a low cost to guarantee its widespread in the poorest endemic countries.

TMek test is based on paramagnetic properties of malaria i-RBCs and Hemozoin Crystals (HCs) which allow their selective magnetophoretic separation, driven by an external magnetic field gradient. The infected blood corpuscles are concentrated at the surface of gold interdigitated electrodes thanks to magnetic concentrators placed in closed proximity whereas healthy ones sediment under the action of gravity. Then, a change in resistivity,

proportional to the amount of attracted particles (i-RBCs and HCs) is detected as an impedance variation by an electronic circuit. Following a lab-on-chip approach, the test is based on a silicon microchip (Figure 1), that has been fabricated in Polifab, composed by an array of micrometric nickel pillars allowing the magnetophoretic separation and planar interdigitated gold electrodes for the counting of the captured corpuscles. The blood sample to be analyzed is dispensed on a glass slide where a PDMS confinement gasket is prefabricated. In order to perform the experiments in the most reproducible and automated way possible, a mechanical setup has been designed: the chip and the glass slide with the gasket are placed in a cartridge, while a motorized linear stepper motor allows the external magnets to approach the back surface of the chip in a controlled way enabling magnetophoretic attraction. The measurement protocol is based on the magnets motion "downward" and "upward" in order to attract or releases blood corpuscles (Figure 2). An electronic board, a portable power supply and a PC complete the setup configuration. The capability of TMek to perform the selective detection of i-RBCs and HCs has been investigated by multiphysics simulations and tested by means of capture experiments on bovine RBCs treated with $NaNO_2$ to induce the full transformation of hemoglobin in

methaemoglobin and mimicking the behavior of malaria infected ones, and on suspensions of synthetic HCs.

The test has been carried out in different configurations: a horizontal configuration with the chip surface parallel to the floor and facing downwards and a vertical configuration, with the chip surface perpendicular to the floor. Thanks to the higher magnetic susceptibility of HC ($4.1~10^{-4}$) with respect to i-RBCs ($1.8~10^{-6}$) when the chip is operated in the horizontal configuration and the gravity force opposes the magnetic one, only HCs are detected. In the vertical configuration, instead, there is no threshold: the magnetic and gravity force are perpendicular and both HC and i-RBCs can be captured with concentrations down to, respectively, 10^4 HCs/μl and 10

iRBCs/μl in 10 minutes. Preliminary tests on patients with malaria were successfully performed at the Sacco Hospital in Milano and the possibility to perform a follow up of the treatment has emerged. A study on cultured RBCs at different infection stages of Plasmodium (ring, trophozoite, gametocyte) has been done at Istituto Superiore di Sanità in Roma. The results suggest the possibility of a discrimination of the infection stage by analyzing the waveform of the impedimetric signal in response to the application/removal of the external magnetic field. In April 2019, a preclinical validation has been carried out at Hôpital Saint Luc of Mbalmayo, in Cameroon on 75 suspected malaria patients. Using RDT Bioline in parallel limits and performances of the TMek device have been evaluated. Within the limits of this preliminary study,

the lack of false negative results for TMek indicates a high sensitivity, 100% (93.3-100.0), both for venous and capillary samples. This means that the device did not miss any diseased patient, and this is crucial in order to avoid that a patient affected by malaria is not specifically treated with antimalarials. 9 false positive are found in venous samples, leading to a specificity of 69% (49.2 – 84.7) while no false positive results have been detected in case of samples from a finger prick, at least within the limited number of these samples (just 10 due to time limitations in the first prevalidation campaign). Even though the confidence intervals are very large, this preliminary study indicates the potential of TMek as quantitative, stage-selective, rapid diagnostic test for malaria.
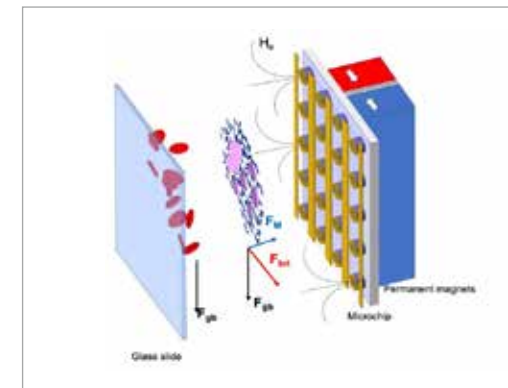

Fig. 1 -TMek schematic concept in vertical configuration: i-RBCs (pink) and HCs (blue) are attracted towards the chip, while healthy h-RBCs (red) sediment.
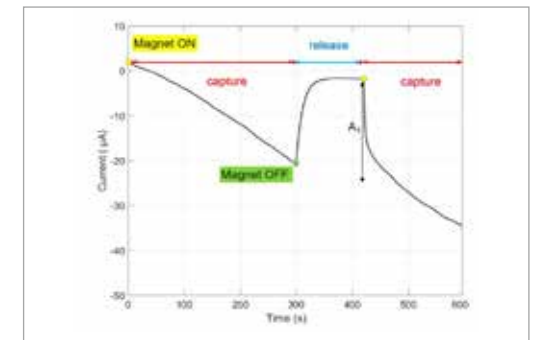

Fig. 2 - Typical shapes of diseased patient current signal vs. time according to the measurement pro- tocol: approach of the external magnets (Magnet ON) and corpuscles are captured, disengagement of magnets (Magnet OFF) and corpuscles are released

TIME DOMAIN NEAR INFRARED SPECTROSCOPY FOR MUSCLE AND CEREBRAL OXYGENATION MONITORING

Thien Le Phu - Supervisor: Shane Eaton

Over the past three decades, the increasing awareness of green and sustainable chemical processes has led to the demand of reducing reagents consumption, wasted production and analysis time. To satisfy these stringent requirements, the most promising candidate are microfluidic system, with inner dimensions are between tens and hundreds of micrometers. Because of the very small inner dimension, microstructure devices have a very high surface-area-to-volume ratio compared to traditional batch reactors, which results in microfluidic devices having high thermal homogeneity and heat transfer efficiency. Additionally, due to the small volume of microfluidics reactors, the diffusion time is very short, leading to improved mass transport and greater control over chemical reaction parameters such as pressure, temperature and flow rate. Many techniques have been developed for fabrication of microfluidics devices such as soft lithography, photolithography and replica molding. Currently, the most popular technique for producing microfluidics devices is soft lithography using polydimethylsiloxane (PDMS) substrate. Soft lithography using PDMS substrates has several key advantages such as low cost, and the ability to produce a large quantity of chips at the same time. However, this method has limited ability to create three-dimensional (3D) microstructure and cannot be exploited to create buried structures.

The simplest method to fabricate 3D buried microstructured channels in transparent materials is by femtosecond laser direct writing. The nonlinear multiphoton absorption driven by focused femtosecond laser pulses inside transparent materials such as glass enables the localized deposition of energy within the sub cubic micrometer focal volume. The modified physical and chemical properties of laser irradiated regions result in the enhancement of the etching rate by hydrofluoric acid (HF) by up to two orders of magnitude compared to the pristine glass. This enables the fabrication of hollow and buried microchannels inside glass. Moreover, glass is an ideal substrate for microfluidics as it is nonporous, chemically resistant, hydrophilic and optically transparent.

Improving energy conversion efficiency has been a goal for decades, which is why several research groups have utilized microfluidics reactor devices for energy applications. Among these applications, artificial photosynthesis is considered as the one most exciting application by many research groups. Photocatalytic water splitting is a research branch of artificial photosynthesis which aims to split water into hydrogen and oxygen using solar energy has received a lot of attention for production of renewable hydrogen. For microfluidic-based hydrogen production, the photocatalyst is usually deposited by the direct coating or sputtering a layer of noble metal followed by electrodeposition. The photocatalyst layers which are deposited by those methods are not stable and uniform on a substrate.

To achieve a homogeneous and firm catalyst layer on the wall of buried micro-channels, one possible solution is immobilizing the photocatalyst in the form of nanoparticles on a functionalized wall. The key idea is attaching some functional groups on the inner wall of the microfluidic channels. Then those functional groups play a role as linker to anchor the nanoparticles by enabling a bond between nanoparticles and functional groups. Immobilization of nanoparticles have the most important advantage is reuse of catalysts which allows for sustainable chemistry. On a glass surface, organosilane is one of the most frequently used for surface modification. The modification is based on the formation of Si-O-Si bonding between Si-OH on the glass surface and the hydrolyzed organosilane molecules. Silane terminated monolayers have good physical and chemical stability, hence we can apply a wide range of chemical reactions or anchor nanoparticles on the monolayer.

At a first step, glass samples were irradiated by focusing a 250 mW average power femtosecond laser beam at a wavelength 515 nm to form the desired geometry inside the glass. Then the samples were etched using 20% hydrofluoric acid at room temperature to obtain hollow structures as shown in Figure 1.
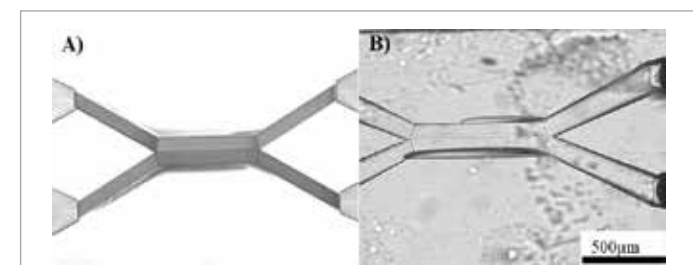
In order to optimize the processes for immobilization of CdSe/CdS core/shell nanorods on micro-channels surface and also for characterization, we first investigated the immobilization of nanorods on glass slide surface using several linkers such as (3-Aminopropyl)triethoxysilane (APTES), carbon disulfide (CS_2) and (3- Mercaptopropyl)triethoxysilane (MPTES). The results from absorption spectroscopy show that MPTES is the best linker for immobilization of nanorods (Fig 2). The nanorods were immobilized on micro-channels surfaces using similar procedure for glass slide, the fluorescene microscope image reveals that the nanorods were deposited successfully on micro-channel surface.

Fig. 1 - Microscope images of microfluidics channel A) before etching, B) after etching
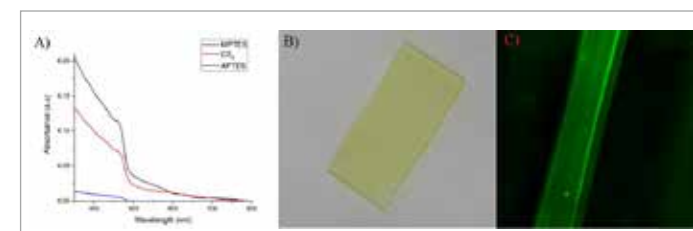

Fig. 2 - A) Absorption spectrums of CdSe/CdS nanorods functionalized glass with different linkers, B) functionalized glass slide using MPTES as linker, C) fluorescence microscope image of functionalized mirco-channel.

SOLUTION PROCESSING OF PEROVSKITE SOLAR CELLS AND TRANSISTORS

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Hybrid metal-halide perovskite (PVK) have been regarded as promising candidates for various optoelectronic applications, especially photovoltaics due to their appealing electronic and chemical properties. These include high charge carrier mobilities, absorption coefficient, longer diffusion lengths, ambipolar nature, solution processing, bandgap tuning etc. Despite they have shown remarkable performance in photovoltaics with laboratory scale efficiencies exceeding 23% within short span of time <10years, several issues are needed to be addressed for their commercialization like their instability towards moisture, oxygen, light, electric field, presence of lead content. High boiling point and toxic solvents are used for dissolving the precursors salts due their solvating power, this also raises the concern for the safe processing at the industrial scale. High boiling point solvents require high temperature annealing and, they are not compatible for ink formulation for large area printing methods. Record efficiencies of these devices are achieved at lab scale, mostly processed in nitrogen box environment. This constraint the industrialization of the material and if these devices processed in ambient atmosphere show poor performances because of oxygen and water during the growth of the film.

PhD work is aimed to address the few such critical issues like ambient air processing, toxicity of solvents, large-area compatible processing method utilizing single solution processing approach. we address these issues, by proposing an alternative route for the precursor salt lead iodide (PbI_2) dissolution using hydroiodic acid (HI) in a low boiling point, less toxic solvent. methylammonium lead iodide ($MAPbI_3$). The prepared solution is deposited with spin- or blade-coating, where we obtain intermediate film Phase comprising PbI_2-HI-H_2O. When the intermediate film is exposed to a methylamine (MA) gas flow, immediate film converts to perovskite. The whole active layer processing is carried out at high RH%, up to 80 %, with optimal conditions at around 65 RH%. One minute of annealing at 100°C is enough to reach the maximum power conversion efficiency (PCE), which do not vary for longer annealing times. For the realization of above films to devices, planar inverted structure was been exploited with poly(3,4-ethylenedioxythiophene): polystyrene sulfonate(PEDOT:PSS) as hole selective layer and phenyl-C61-butyric acid methyl ester and bathocuproine as electron selective layers for device realization. A maximum PCE of 14 % is achieved via spin coating, with a stable output upon light exposure in environmental conditions (~50RH%, 5 minutes maximum power point tracking). Blade coating led to promising (unoptimized) preliminary results with PCEs of ~8

%, demonstrating the compatibility of our fabrication process with high throughput deposition techniques. The chemistry of intermediate film phase PbI_2-HI-H_2O is responsible for high performances of devices even at high humidity levels. Future steps will focus on integrating our perovskite processing technique with different structures, and on developing a deposition protocol for mixed-cation lead mixed-halide perovskites may enable to obtain higher device performances.

Apart from the photovoltaics, PVK semiconductors, mainly 3D PVK could be adopted in field-effect transistors (FET) application, owing to their exceptional electronic properties. In addition, FET is also used to understand the fundamental charge transport behaviour of perovskites, which is not well understood and is still under investigation. In this thesis, we study the transistor characteristics of the PVK FETs. Charge transport in these metal-halide perovskites is mixed combination of both ionic and electronic. FET devices based on 3D perovskite semiconductors, typically show poor performance at room temperature because of ionic diffusion in the material leads to suppression of electronic characteristics of FETs.

To overcome the mentioned issue and to access the electronic charge transport in PVK FETs, in literature, pulsed gate voltage mode operation is utilized. This mode of characterization enabled the successful characteristic curves of FET. But the choice of the pulse duration (fixed 500 μs) seems to be arbitrary and the ionic diffusion is clearly a dynamic process, raises the question on the validity of FET characteristics extracted. In this PhD work, we addressed the issue by studying time-dependent FET characteristics of 3D PVK FETs. Surprisingly, we observed apparent electron mobility decays up to three orders of magnitude with a pulse duration time scale varying from 5 μs to 10 ms. This decay of FET performance with increase of pulse duration is attributed to the accumulation of ions at grain boundaries and hinders the charge transport due to the energy barriers difference between the grains because of local potential generated due to ion accumulation. This study highlights the effect of ions diffusion on the FET characteristics and alarms the consideration of time scales seriously during study of PVK FETs. With this transient measurement, we have also observed the reduction of decay of current, due to the passivation of defects at grain boundaries using PCBM. This transient measurement enables to understand the quality of perovskite material required for the charge transport in FETs.

TOWARDS A MICROFLUIDIC PLATFORM FOR SINGLE CELL ANALYSIS: A DEVICE FOR DETECTING CIRCULATING TUMOUR CELLS

Filippo Storti - **Supervisor: Luigino Criante**

Taking a look at the overall world mortality factors, it is clear how nowadays long-term diseases play a major role. Among these, cancer, due to its insidious and heterogeneous nature, holds a prominent place. Besides the impressive improvements in the field of medicine and diagnostics, the battle against this disease is still harsh. To further increase the chances to win this clash, being able to detect the presence of such a condition in its early stages of development, during its "silent" phase, is a key factor. We still lack a complete picture of the mechanisms that lead to the unnatural and disproportionate growth of tumoral masses. However, it is clear that, for multiple, complex and partially unknown reasons, some cells in our organism, at a given time, may change their behaviour and start affecting the hosting organs. Since the earliest phases of the primary tumoral mass development, some of these cells move from their original site and penetrate the blood circulation to reach distal organs and give rise to new cancerous sites. This mechanism is acknowledged as the cause of the onset of new metastases and the cells responsible for this are called Circulating Tumoral Cells (CTCs). The study and the characterization of these cells – which are very heterogeneous, depending both on their organ of origin and on their development stage – can bring

tremendous advantages in the fight against cancer. They could be easily accessed by a simple blood drawing and their number can be correlated with the presence of an ongoing tumoral growth up to 4 years before other techniques could detect the mass. Furthermore, their occurrence in a blood sample can be linked to the patient prognosis and can be used as an index to monitor therapy efficiency. Lastly, if extracted and analysed, they can unveil precious information that could help to shift towards a more "personalised medicine". However, their detection and extraction are hampered by several factors. Besides their great heterogeneity, their extremely low frequency in a blood sample is a very challenging impediment to overcome. In one mL of whole blood there can be found up to 10^9 erythrocytes, 10^6 leukocytes and only 1-100 CTCs, if present. This means that normal bench-top technologies, used to process great volume of samples, may provide a too low sensitivity to be able to accurately detect the presence of such cells. For this reason, in the recent years, many works have implemented microfluidic strategies – under the name of lab-on-a-chip (LOC) devices – to address this issue. These solutions, thanks to their intrinsic features – i.e., characteristic dimensions of the order of magnitude of the analytes, small sample volume consumption, and high integrability– promise to have the potential to

achieve high-sensitivity, high-specificity, cost-effective and portable performances. However, there is still the lack of a platform able to detect these cells and count them, in a complete label-free way and featuring throughputs high enough to process a blood sample within few hours. For these reasons, the project at the heart of this thesis has been conceived. The underlying concept is the creation of an integrated microfluidic platform for the label-free detection of CTCs in three main steps. The first step implements an in-flow blood filtration to discard as much red blood cells (RBC) as possible, based on their size. Indeed, from the literature it is well known how erythrocytes and CTCs show a significant difference in dimensions – around 6-7 μm for RBCs and 12-35 μm for CTCs. The second step is a hydrodynamic focusing of the remaining particles. This technique allows to manipulate the particle position in a microfluidic channel, by making them flow precisely at the centre of the cross-section. In this way, the cells are aligned and distributed, one behind the other, to significantly improve the performances of the third step. Indeed, in the last stage the platform would perform a single-cell analysis that allows to discriminate between white blood cells (WBCs) and CTCs. Thus, the goal of this thesis has been to carry out a feasibility analysis, design, fabricate and test a proof

of concept for each of the above-described steps. Since the high versatility required, femtosecond laser irradiation, followed by chemical etching (FLICE) technique has been adopted as the main manufacturing process.

Regarding the first step, hydrodynamic filtering has been selected as optimal strategy to implement the required functionality. By carrying out numerical simulations and microfluidics experiments, a new crossflow filtering geometry has been developed, showing high throughputs (up to tens of mL/h) and a completely clogging-free operativity. The efficiency in the separation ranges from 63%-75% for a single round of filtering, but it can be improved up to 94% by taking three rounds subsequently. Instead, the recovery rate of larger particle is 100%. To achieve a precise 3D alignment of particles within a microfluidic channel, a unique geometry has been designed, fabricated, and tested. The great 3D potentialities of FLICE technique have been exploited to fabricate a channel nested within a larger channel, attaining the precise alignment of particles of different sizes – 15 μm, 6 μm, and 1μm –, by using the same device, and the minimum focused flow has reached a cross-section of 9 μm x 5 μm.

For the single-cell analysis step, two main strategies have been identified: deformability assessment of cells

and on-chip Raman spectroscopy. Since tumoral cells show a different deformability with respect to the other blood cells, an easy-to-use, high throughput, and robust optofluidic device has been manufactured to measure it. The geometry consists in a straight channel with a bottleneck to force cells to deform and two pairs of optical fibres to measure the cell transit times. Thus, this quantity can be correlated with their deformability. A proof of concept has been carried out by flowing breast cancer cells (MCF-7) and by measuring their transit times. In a second test, the deformability of the cells has been modified, increasing it, by treating them with a drug (Latrunculin-A). The comparison of the transit times has showed that drug-treated cells require 0.1-0.3 ms more to cross the bottleneck.
 Regarding the on-chip Raman spectroscopy, a new strategy has been proposed. Since the Raman signal is well known for its weakness, the proposed solution is to integrate, near to microfluidic channels, optical structures to increase the solid angle of acquisition. From the literature, it is known that the maximum value of harvested solid angle reaches 28% in the case of a water immersion objective. In this thesis it has been demonstrated, through numerical simulations, that structures such as parabolic mirrors, could improve this value to 56%. Thus, such optical

structures have been designed and fabricated, introducing an optical polishing step, by means of a CO_2 laser, to enhance the quality of the created elements. Thanks to this additional step very high-quality optical structures have been fabricated (RMS of 3 nm) and a focal spot of 50 μm has been obtained. The same fabrication process has been used to fabricate elliptical mirrors as well and, in this case, the spot is ∼ 30 μm wide.

In conclusion, in this thesis the versatility of FLICE technique has been exploited to design and fabricate a wide range of innovative elements, that can be integrated on the same platform to reach a micro total analysis system (μTAS) for CTCs detection and counting.

VOLTAGE-TUNABLE DUAL-BAND GE/GESN PHOTODETECTOR

Enrico Talamas Simola - Supervisor: Luigino Criante

The spectral region comprised between 1.0 and 3.0 μm, known as short-wave infrared (SWIR), holds information of particular relevance for a wide variety of different applications, such as imaging, automotive, remote sensing etc. The ability to accurately detect and analyze such spectral window is therefore highly prized. The detectors most commonly employed to cover the SWIR are based either on III-V semiconductors, specifically InGaAs, or HgCdTe. Although they display good performances with respect to specific detectivity, those technologies suffer from a difficult integration with silicon, and by extension CMOS technology, resulting in high costs and low volumes of production. This constitutes a bottleneck hampering the exploitation of the SWIR spectral range in optoelectronic systems and its diffusion to other applications. Group IV materials such as Ge and GeSn, on the other hand, are relatively cheap and Si-compatible, as they can be grown epitaxially on a standard Si substrate. Silicon itself covers the spectral window corresponding to visible (VIS, 0.4-0.7 μm) and near infrared (NIR, 0.7-1.0 μm), while germanium's detection window extends in the SWIR up to 1550 nm, responding to both the 1330 and 1550 nm wavelengths used by optical fiber communication systems. Finally, the bandgap of GeSn can be tuned by controlling the tin content of the alloy,

where a higher concentration pushes the cutoff wavelength further in the infrared.
During my PhD I designed, modeled, fabricated and characterized dual-band photodetectors based on group IV materials. The architecture of the devices consists in a pair of p-i-n diodes of different materials stacked on top of each other, sharing a common, highly doped region in the middle. The device is controlled by applying a voltage to the whole structure, which reversely polarizes one of the diodes, forward biasing the other, such that the dark current of the whole device is always limited by the dark current of whichever of the two diodes is reversely polarized. Since only the reversely polarized diode detects photocurrent, it is possible to select which diode to employ for detection by switching the sign of the applied voltage. The device is illuminated from the side of the higher bandgap diode, which acts as low pass optical filter for the other diode, yielding spectral selectivity. The device's dual-band operation challenges more traditional approaches to multispectral imaging by combining the different optical bands at a pixel level, with no need for dispersive elements. While this architecture has been previously demonstrated with III-V semiconductors and HgCdTe alloys, the work presented here focuses on extending it to group IV materials.

We demonstrated a voltage-tunable dual-band photodetector based on Si and Ge, covering the VIS and NIR spectral ranges with the silicon diode and the SWIR up to 1600 nm with the germanium one. The device constitutes a p-i-n-i-p structure and is obtained from a high resistivity, 300 μm thick, intrinsic silicon wafer. On one side of the wafer a highly doped p-type region is created by spin-on-dopant, while on the other side the n-Si, i-Ge and p-Ge layers are grown epitaxially by low-energy plasma-enhanced chemical vapor deposition. The fabrication is CMOS compatible and realized by means of optical lithography, reactive ion etching and electron beam physical vapor deposition. The responsivity of the device at the applied biases of ±2V is reported in figure 1, showing dual-band operation and low λ-crosstalk. A second device based on Ge and GeSn and targeting exclusively the SWIR was also demonstrated. Starting from a standard 200 mm p-type silicon substrate, the n-Si, i-Ge, p-Ge, i-GeSn and n-GeSn layers composing the n-i-p-i-n structure are epitaxially grown by reduced-pressure chemical vapor deposition. The fabrication is carried out by means of optical lithography, chlorine-based reactive ion etching and sputtering, and is entirely CMOS compatible. The dark current densities are limited by the deposition of an Al_2O_3 passivation layer by molecular beam epitaxy.

The responsivity of the device at the applied biases of ±0.5V is reported in figure 2. The device is illuminated from the back of the silicon substrate, which acts as an optical low pass filter for the device, filtering anything below 1.1 μm. The Ge diode covers the spectral range in between 1.1 and 1.6 μm, while the GeSn one detects from 1.6 to ~2.4 μm. The tail below 1.6 μm displayed by the responsivity at +0.5V is attributed to the insufficient thickness of the i-Ge layer, which allows a significant fraction of the incoming light to be transmitted. Using GeSn for one of the diodes introduces a degree of freedom consisting in the choice of the tin content of the alloy. By tuning such tin content, it is possible to tailor the

absorption edge of the device, trading off a higher dark current for a wider bandwidth in the SWIR.
Several possible applications of the dual-band Ge/GeSn device have been explored, in the fields of imaging and spectroscopy. Using a single-pixel imaging system, several images of different subjects have been taken in the 1.1-1.6 μm and 1.6-2.4 μm bands, highlighting information not available from the visible spectrum.
Given the strong dependence of the device's responsivity from the applied voltage, is it possible to consider such responsivity as a 2-dimensional matrix, function of wavelength and applied voltage. For any given power spectrum, the measured photocurrent will be a function of the applied

voltage. It is theoretically possible to invert the relation between incident optical power and detected photocurrent by calculating the inverse of the responsivity matrix, employing the photodetector as a spectrometer. This possibility has been investigated both theoretically and experimentally, obtaining the spectral reconstruction of up to 10 different wavelengths.
An analytical model to simulate the dual-band devices has also been developed as part of my PhD, its results yielding good agreement with the experimental data.
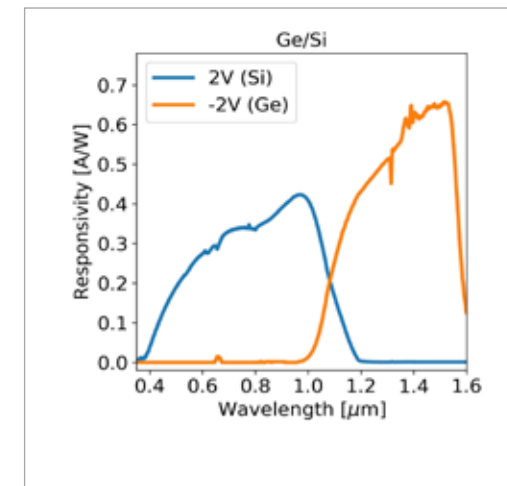

Fig.1 - Responsivity of the Ge/Si voltage-tunable dual-band device measured at the applied biases of ±2V.

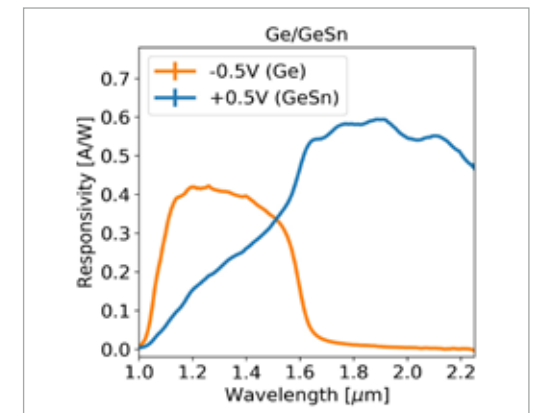**Fig.2 - Responsivity of the GeSn/Ge voltage-tunable dual-band device measured at the applied biases of ±0.5V. Even though the device responds up to 2.45 μm, the measurement stops at 2.25 μm because of the intrinsic limitations of the experimental setup.**

ADVANCES IN COHERENT RAMAN SCATTERING

Carlo Michele Valensise - Supervisor: Dario Polli

Raman Scattering is a powerful non-linear optical technique that allows one to identify chemical bonds in samples without the need of any external label, exploiting light as a probe of molecular vibrations that directly maps into chemical bonds. Raman Scattering worth a Nobel prize in 1930. Since then, it has become a well-grounded research field in both its spontaneous and coherent version. Coherent Raman Scattering (CRS) presents some advantages over the spontaneous, especially with respect to possible applications, despite the need of more complex optical setups and technologies. In fact, CRS is a non-linear optical technique, and requires at least two laser pulses (pump and Stokes) to probe the matter: a broadband (hundreds of femtosecond) and a narrowband (a few picoseconds) one, together with a non-trivial optical setup to synchronize and spatially overlap the two beams. Moreover, the detection of the tiny signals associated to molecular vibrations, and so to chemical bonds, is very challenging and technologically demanding. In the last two decades a huge research effort has been devoted in this respect, with great achievements and outstanding results. The final goal of research in CRS is the application of the technique at the biomedical level, especially for what concerns the identification of tumoral masses within tissues. This is the current front of the research.

The VIBRA laboratory of Physics Department at Politecnico di Milano, is one of the most advanced European CRS laboratory. In the last years we developed a number of setups and technique that tackle the challenge of probing simultaneously multiple molecular vibrations, in a reasonable amount of time, keeping in sight the need for real-time applications. There are two signals (see Figure 1) that are mainly studied in CRS, the Coherent Anti-Stokes Raman Scattering (CARS) and the Stimulated Raman Scattering (SRS). A broadband SRS signal is constituted by very small intensity gains or losses, depending on the configuration (see Figure 1) on the broadband pulse used to excite the molecular vibrations. As these variation intensities are rather small (down to one part per million) complex schemes based on modulation transfer are required to reduce the noise and being able to detect meaningful signals. This technique require the use of lock in amplifiers, that are superb electronic devices, enabling the detection of very tiny signals. However, perform lock-in detection on a broadband pulse is rather challenging. In collaboration with the Electronics Department we developed a multichannel lock-in amplifier, allowing to simultaneously measure 32 channels, so to reconstruct very good spectra. We also developed a technique that employs a single detector, onto which the broadband light is scanned by means of a mirror,

after it has been dispersed in space, through a grating.
On the other hand CARS signal is homodyne, produced at a higher frequency with respect to both pump and Stokes fields. This aspect simplify the detection chain with respect to SRS, as it is just necessary to filter out the excitation components, and record the signal with a conventional spectrometer or a CCD, without the need of demodulation and lock-in detection. Nevertheless the limiting factor of this technique is a parasitic signal that interferes with the vibrationally relevant one, an has to be taken out in order to obtain reliable chemical information. This signal is called Non-Resonant Background (NRB), and it has two main consequences on the signal. On one side, it degrades the shape of the vibrational spectrum producing also a shift in the peak position (see Figure 2); on the other side it acts as a local oscillator for the weak Raman resonances that are in turn amplified, and made visible. Several strategies have been investigated by scholars to reduce this effect, both dealing with peculiar experimental setups, to prevent NRB from degrading the measurement, and numerical methods, to process the spectrum after the measurement has been carried out, leveraging the presence of NRB itself to reconstruct the information. In this respect our proposal was to employ deep Neural Networks (NNs)

to solve this problem. As the inverse problem (going from a spectrum with NRB to a NRB-free one) is mathematically well defined, NNs are a natural candidate tool to solve it. In fact, we employed a Monte Carlo technique to generate a synthetic dataset onto which perform the training of a deep Convolutional Neural Network (CNN), inspired to the most classical CNN applied in computer vision field, to produce a NRB-free spectrum, from a noisy one. We applied the technique to spectra collected from test samples, and the results pretty good. The technique promises to be very effective also in a microscopy setting. In Figure 2 an example is reported: the red curve is the CARS spectrum distorted by NRB; the green one is the output of the CNN that is in good agreement with the orange curve, that is the spontaneous Raman reference spectrum.
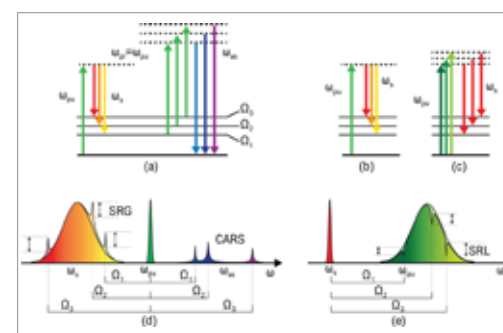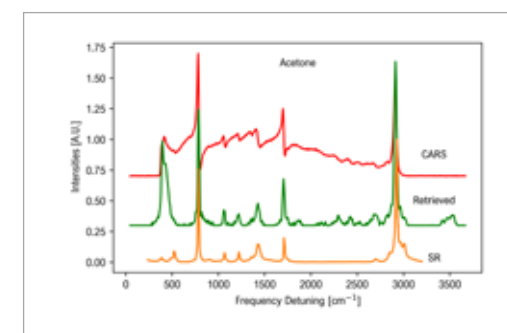

Fig.1 - Scheme of CRS signals

Fig.2 - CNN used to denoise CARS spectra

HIGH-RESOLUTION SPECTROSCOPY BY OPTICAL FREQUENCY COMBS

Edoardo Vicentini - Supervisor: Gianluca Galzerano

For more than half a century, laser spectroscopy has been the main tool to identify and measure molecules and their dynamics.

In the last twenty years, high-resolution and broadband spectroscopy performances could accelerate due to the advent of the optical frequency comb, an optical pulsed source that can be represented by thousand narrow line continuous wave laser all equally spaced, which frequencies can be known with a fractional accuracy of or better.

Two main groups of techniques have emerged for frequency combs spectroscopy. In the first group, the optical frequency comb assists a continuous wave (CW) as an absolute frequency reference. Once the CW laser is locked to the n-th comb mode, it can be precisely scanned across a desired molecular absorption by fine tuning of the comb mode spacing frequency. These kinds of techniques are preferable when few absorption lines have to be measured with the highest frequency precision and sensitivity.

The second groups of techniques employ the optical frequency comb to directly probe samples. Its advantage relies on the large number of comb components which allows a massive parallel detection to acquire spectroscopic information with fast acquisition times.

This PhD research was aimed to develop novel spectroscopic methods in the near- and mid-infrared spectral regions based on optical frequency comb sources that combine high frequency precision, high sensitivity, ultrabroad bandwidth and high measurement speed in a single powerful analytical tool for high-fidelity mapping of the internal atomic and molecular energy structure.

Both direct and assisted comb spectroscopy approaches have been investigated, using fiber frequency combs and quantum cascade lasers (QCL).

QCL are, now, a key tool for mid-infrared and terahertz ranges. These are spectroscopic regions where many strong absorption lines are accessible, stronger than the near-infrared counterparts, offering a high sensibility in detecting most of the molecules.

A part of this PhD research has been devoted to find and test the best stabilization strategies for a QCL emitting at 8.6 m in order to investigate the fluoroform molecule with the highest spectral resolution and accuracy. This molecule presents attractive properties to be later utilized as target for ultra-high-resolution spectroscopy for physical constant variance testing, in particular, the proton-electron mass ratio.

In this work, line center frequencies of 95 transitions have been measured, with a best accuracy of 400 Hz, in relative terms . Thanks to frequency modulation and modulation transfer stabilization methods, the same molecule has been used as a frequency reference. The stability of the QCL locked to the sub-Doppler profile reached a best of , measure limited by the Rb-clock used as a frequency reference.

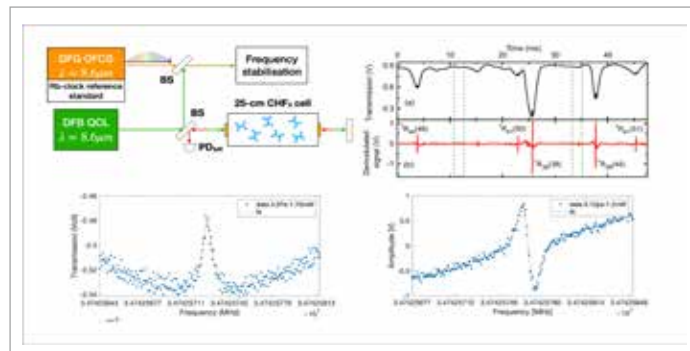A second part of this research has been dedicated to direct-comb-spectroscopy methods in the near-infrared spectral region.

A novel direct comb technique based on a scanning micro-cavity resonator (SMART) has been characterized in terms of resolution and bandwidth. It has been experimentally demonstrated a resolution limited only by the frequency comb linewidth (in the specific experiment 50 kHz over a 4 THz bandwidth).

This simple, compact and accurate method to resolve the mode structure of an optical frequency comb allows a straightforward absolute calibration of the optical-frequency axis with a negligible instrumental line-shape that can be used in any spectral region from UV to THz.

Additionally, a new application for dual-comb spectroscopy has been explored, bringing to the realization of a high-spectral resolution hyperspectral imaging system. Thanks to the multiple frequency component of the frequency comb and, thanks to the acquisition performed on a camera, a multi-parallel detection is possible, allowing to acquire 512 spatial elements at a resolution of 350 MHz over a 0.6 THz bandwidth, with the possibility to coherently average in time at least up to 1000 s.

These novel class of spectrometers could be used in future in different applications, including atmospheric trace gas measurements, astrochemistry, breath analysis, industrial process monitoring and fundamental laboratory spectroscopy.
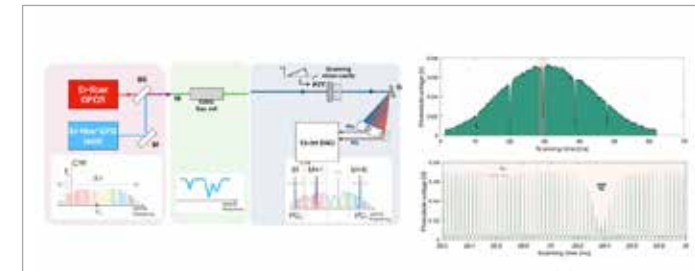

Fig.1 - Comb-assisted QCL spectroscopy of fluoroform.
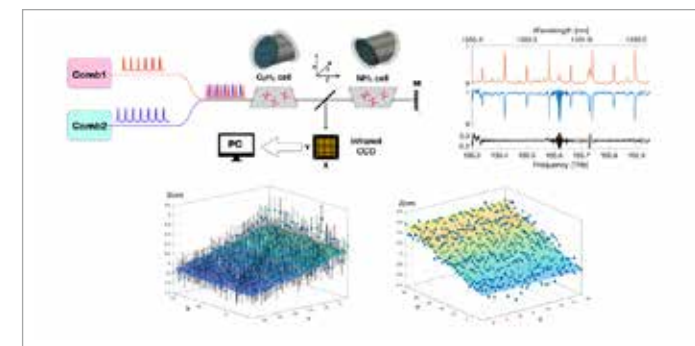

Fig.2 - SMART spectroscopy of acetylene.

Fig.3 - Dual-comb hyperspectral imaging of acetylene and ammonia.

NON GENETIC PHOTOSTIMULATION FOR BIOHYBRID LIGHT-CONTROLLED ACTUATORS

Vito Vurro - Supervisor: Guglielmo Lanzani

The use of light to control and manipulate bio-matter is an appealing and promising approach. Indeed, light can interact with living cells with a high space and time resolution and it can achieve a high selectivity in tissue, free from wiring constrains and with a low reactive oxygen species production due to cell stimulation. The research activity of this thesis is aimed at the development of materials suitable for muscular cell opto-stimulation. The selected materials work as light actuators acting at the living cell interface and transducing light signal into a biological stimulus. In particular, two interfaces exploiting different approaches and based on different materials are evaluated: a planar interface based on an organic semiconductor and a diffuse interface based on a photochromic molecule. The former is an organic polymer well known in the organic photovoltaic field: the poly(3-exylthiophene-2,5-diyl) (P3HT). The polymer is used as a planar phototransducer and it has been demostrated to be able to enhance the contraction behaviour of muscle cells through a photothermal effect. The latter, based on the diffuse interface, relies on an azobenzene photoswitching molecule labelled Ziapin 2. This molecule is designed to dwell in the plasma membrane by means of its amphiphilic properties. Moreover, the azobenzene core works as a switching unit ensuring the ability to

change the isomer conformation due to light excitation. A characterization of both the phototransducers is carried out in order to understand their optoelectronic properties and their compatibility for developing a functional abiotic-biotic interface. The target cells of this research are the muscular cells, which are chosen in order to test the transferability of the stimulation on muscular tissue instead of single cells. The tissues are realized using a bottom up approach that exploit standard tissue engineering techniques. The cells are organized in an ordered anisotropic tissue that reproduces the native muscle tissue properties called microphysiological systems. Moreover, a crucial element of this systems are the mechanical properties of the substrate that should be compatible with cell activity and properties. The final step of the research activity is focused on the photostimulation of muscular tissue, evaluating the integration of the proposed phototransducers with the realized tissue. The planar interface is not suitable for the realization of biohybrid actuators because of the mechanical properties of the realized film. In order to overcome this limitation, a blending approach is used in order to improve the mechanical properties of the P3HT and preserve the optoelectronic one. The diffuse interface is naturally compatible with classic bioengineering methods due to

its diffuse nature and its direct intercalation and interaction with a biological element. Exploiting this approach a simple light-driven actuator is realized.

The realization of this biohybrid device can be very appealing in research fields such as robotics, biomedicine and biotechnology. In robotics the high power-to-weight and the force-to-weight ratio, the native self-repairing ability and the high density energy storage typical of muscular tissue can led to the development of a new generation of actuators. However, this is not yet a fully mature technique because an efficient encapsulating system is required to protect the living engine from the external environment. Moreover, in order to sustain the cells a supporting system is needed to keep the cells viable. Regarding the possible
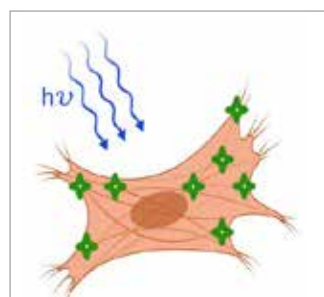

Fig.1 - Schematic illustration of the biotic-abiotic interface between a phototransducer (represented by green stars) and a living cell. The photoactive material are able to absorb light and transform this light signal in a biological stimulus.

medical applications an easier implementation can be imagined, starting from a pacemaking device up to muscle paralysed conditions can be treated with such a method gaining a series of advantages related to the use of light. Moreover, a light-driven microphysiological system could be an optimal platform for pharmacological applications, rare disease studies and the development of the so called personalized medicine (or precision medicine). In all these application a reliable and stable stimulation technique is required and the photostimulation of the microphysiological system could be a very promising platform.
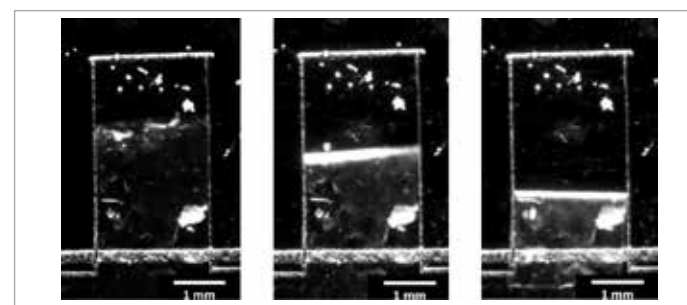

Fig.2 - Series of frame of a biohybrid cantilever contraction. The rectangular thin film is able to contract due to the muscular cells activity.