

DFM

*Design of functional materials
for advanced electronic and
photonic properties*



BOOK OF ABSTRACT

WINTER WORKSHOP

Bormio (IT), December 08-13, 2024

Welcome!

It is with great pleasure that we announce the first edition of the Winter Workshop on Design of Functional Materials for Advanced Electronic and Photonic Properties - DFM 2024, to be held in Bormio (SO), Italy, from December 9th to December 13th 2024.

The program will be composed by a combination of invited and contributed talks, given by both established and early-career scientists.

The idea is to create a connection between simulations and experiments in the field of advanced functional materials for electronic and photonic applications, within a stimulating and friendly atmosphere with plenty of opportunities for networking activities.

We look forward to seeing you in Bormio!

The Organizing Committee

Invited Speakers

Simona Binetti (University of Milano Bicocca, IT)
Filippo De Angelis (University of Perugia, IT)
Ahmed Dorrah (Eindhoven University of Technology, NL)
Lorenzo Malavasi (University of Pavia, IT)
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FROM ORGANIC SEMICONDUCTORS ENGINEERING TO EDIBLE ELECTRONICS AND BEYOND

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The employment of organic semiconductors (OSCs) promises to widen the realm of electronics to countless new applications, thanks to the advantageous properties of organics. Effectively, organic electronics, leveraging these OSCs, has been forging ahead from its initial proof-of-concept devices towards increasingly diverse materials and applications.

Kingpin for the development of organic semiconductors has been the study of their structure-processing-property relationships. Here I will discuss how a fine microstructural tuning of OSCs can lead to Organic Field-Effect Transistors (OFETs) exhibiting charge carrier mobilities exceeding $1 \text{ cm}^2/\text{Vs}$.^[1,2] Moreover, I will show how different strategies can be adopted to control the device operation. For instance, doping of OSCs through molecular additives offers great opportunities to adjust the device properties^[3] in OFETs,^[4,5] Organic Solar Cells (OSCs),^[6] Organic Photodetectors (OPDs),^[7] Organic Diodes.^[8] Blending of insulating and semiconducting polymers or molecular and polymeric semiconductors is on the other hand another convenient method to tune the transport properties of OSC.^[4,9,10] Moreover, the introduction of novel architectures^[8] and materials^[11,12] can widen the reservoir of systems from which tapping in towards the development of increasingly diverse and efficient applications.

Further, I will show how the knowledge acquired during the investigation of conventional organic electronics can be applied to the rising field of edible electronics, which aims to develop a technology that is capable to monitor real-time the gastro-intestinal tract. Here, I will show how transistors, the fundamental building block of any circuit, can be reliably fabricated employing edible materials, enabling the achievement of fully edible devices.

Lastly, I will outline the future projects I plan to undertake during my new role at the Physics Department of Politecnico di Milano and in collaboration with the CNST.

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COPPER PHTHALOCYANINE BASED ELECTROCHEMICAL TRANSISTORS FOR FUTURE EDIBLE ELECTRONICS

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Edible Electronics^[1] is an emerging field targeting devices that can be safely ingested and that, after functioning, can be digested, as food. Relevant applications can be envisioned both in the healthcare and the food supply chain sectors, among all: non-invasive monitoring of the gastrointestinal tract, smart and controlled drug release systems, smart tags for safe and direct food tagging and real-time food quality check. One of the main challenges of this research field is represented by the identification of well performing non-toxic semiconductors, to be integrated into low voltage driven (<1V) edible transistors architecture. In this regard, Copper Phthalocyanine (CuPc), also known as C.I. Pigment Blue 15 (CI 74160) is a well-established, biocompatible pigment. While insoluble in most solvents, vacuum deposited CuPc films have been efficiently employed as semiconductor both in solar cells and organic field effect transistors. Nevertheless, its commercial use is mostly associated to its optical and chemical attributes, and it should come as no surprise that it is widely used as teeth whitener into commercially available and popular toothpaste formulations. We recently observed that the average amount of CuPc already safely ingested during daily teeth brushing exceeds by several orders of magnitude the estimated amount needed into our electronic systems, this making CuPc a strong candidate as the semiconductor of edible devices. Of course, its employment requires the individuation of effective, scalable processing strategies, on the one hand compatible with edible substrates, like polysaccharides, which are usually highly soluble and thermally instable; on the other hand forming film nanostructures that efficiently support charge transport. Here we report on the possibility to integrate CuPc films with long-range crystallinity and tunable morphology into fully edible devices, based on a Floating Film Transfer Method. We show that an unconventional solution process, based on reversible molecular protonation, can be used, notably resulting in films with effective ion permeation from electrolytic solutions. Following this strategy, stable electrochemical transistor with hydrogel-based architecture, entirely composed of edible materials, is finally demonstrated. The herein obtained on/off ratios overcoming 10^3 and trans-conductance normalized to channel width up to $\approx 50 \mu\text{S}/\text{mm}$ qualify our devices both as a suitable platform for sensing and bio-sensing and as active components of low voltage edible integrated circuits.

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EXTENDING NANOSCALE SPECTROSCOPY WITH PHOTO INDUCED FORCE MICROSCOPY TO THE VISIBLE RANGE

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Photo-induced Force Microscopy (PiFM) is a compelling alternative to Scanning Near-Field Optical Microscopy (SNOM) for subwavelength imaging, leveraging the mechanical detection capabilities of the cantilever of an Atomic Force Microscope (AFM). This approach simplifies the experimental setup by eliminating the need for optical detectors and complex interferometric techniques for suppressing far-field background signals. However, PiFM relies on laser modulation at the cantilever's intrinsic oscillation frequency (typically hundreds of kilohertz), which is straightforward for mid-infrared quantum cascade lasers, with which PiFM has been extensively demonstrated,^[1] but challenging in the visible and near-infrared ranges. This demanding modulation has been achieved with the use of acousto-optic modulators (AOMs), which introduce wavelength-dependent alignment issues, limiting PiFM's applicability in spectroscopic studies.^[2] To address this, we introduce a novel PiFM setup incorporating electro-optic modulation.^[3] This method eliminates the need for realignment during wavelength tuning, significantly enhancing PiFM's utility for near-field spectroscopy in the visible and near-infrared ranges. We validate our realignment-free approach by imaging waveguide modes in dielectric layers of van der Waals materials, uncovering exciton-polariton phenomena. This advancement positions PiFM as a versatile and powerful tool for subwavelength imaging and nanoscale characterization across diverse spectral regions, opening new frontiers in spectroscopy.

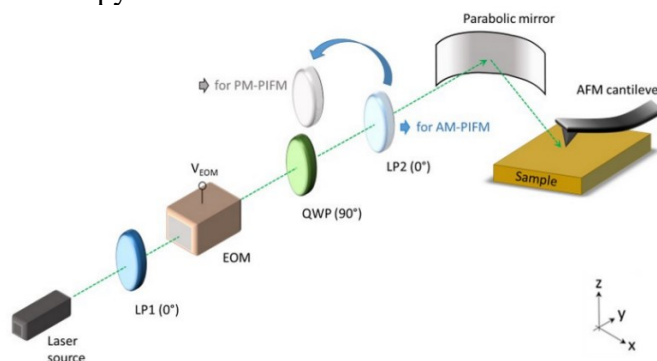


Figure 1: Sketch of the PiFM setup for visible spectroscopy. Linear Polarizer (LP), Electro Optic Modulator (EOM), Quarter Waveplate (QWP)

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TRACKING CHARGE DYNAMICS IN THE LIGHT-DRIVEN OXIDATION OF BENZYL ALCOHOL OVER A SILVER SINGLE-ATOM CATALYST

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Catalysis has become a cornerstone process globally, impacting a wide range of fields including fuel production, the synthesis of molecules for industrial and pharmaceutical applications, energy production, and the reduction of water and air pollution. One of the main drawbacks of most common catalysts are the expensive metals of which they are composed (e.g. platinum, vanadium, palladium and iridium)^[1] and high temperature and pressure required for industrial processes.^[2] Due to these problems, much effort has been spent in recent years on finding greener and less energy-consuming processes. Among the most renowned strategies we can find photocatalysis, in which the catalytic reaction is triggered by the absorption of light by a semiconductor. Understanding charge dynamics after light absorption is crucial for optimizing the efficiency and performance of a photocatalyst, as this directly influences the separation and migration of photo-generated charge carriers, determining the overall reaction rates and product formation.

This study addresses this gap and investigates an Ag-based single-atom catalyst (Ag₁@CN_x) in the photocatalytic oxidation of benzyl alcohol to benzaldehyde. This material displayed efficient performance in the synthesis of benzaldehyde, with a two-fold improvement in catalytic performance compared to state-of-the-art photocatalysts. Time-resolved transient spectroscopic studies were used to monitor the dynamics of photo-generated charges in the reaction, revealing the lifetimes and behaviors of excited states within the catalyst. Specifically, the introduction of silver atoms led to a significant enhancement in charge carrier dynamics, as evidenced by a faster decay of the photo-induced absorption signals in the presence of benzyl alcohol. This indicated that the photo-excited carriers were effectively transferred to the reactant, thereby driving the oxidation process. These novel mechanistic insights were pivotal in spectroscopically elucidating the reaction mechanism and can be practically applied to more rationally design single-atom photocatalysts, targeting target materials that combine both rapid reductive quenching and efficient charge transfer to the metal.

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MATERIALS-DRIVEN STRATEGIES TO ENGINEER BACTERIAL MOTILE BEHAVIOUR: USING LIGHT TO UNDERSTAND AND CONTROL DYNAMIC MEMBRANE POTENTIAL MODULATION

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Understanding and controlling bacterial motility and response to external stimuli is indeed pivotal for leveraging bacteria in the creation of smart and living materials. Recent studies have unveiled the dynamic nature of bacterial membrane potential: it is now evident that membrane potential regulates a wide array of bacterial physiological processes and behaviors, including membrane transport, motility, antibiotic resistance, communication, and environmental sensing. Despite these advancements, numerous questions remain.^[1] Traditional patch-clamp technique, while effective for certain applications, is inadequate for studying dynamic changes in bacterial membrane potential due to the requirement for cell immobilization and the diminutive size of bacterial cells. Consequently, there is an urgent need for developing novel, minimally invasive methods to measure membrane potential dynamics.^[2] Fluorescent molecular probes with voltage-dependent optical properties have emerged as a promising solution for noninvasive studies of membrane voltage. In this context, Nernstian dyes have been widely employed due to their high efficiency and low toxicity. However, estimating membrane potential based solely on fluorescence intensity is fraught with challenges due to various factors such as spatial uniformity of excitation and fluctuations in light source power, which can lead to significant experimental errors. In contrast, fluorescence lifetime is an intrinsic property that depends solely on the local environment of the dye and is independent of many external experimental parameters. Thus, measuring both fluorescence intensity and lifetime can provide more accurate and reliable data. In this study, we investigated the dependency of the fluorescence lifetime of the TMRM dye on the progressive depolarization of membrane potential in both gram-positive and gram-negative bacteria. Our findings demonstrate that this phenomenon is ubiquitous across different bacterial types, underscoring its potential as a robust tool for electrophysiological studies of motile and free-living bacteria in various environments. Furthermore, we employed Fluorescence Lifetime Imaging Microscopy (FLIM) to precisely correlate bacterial motility behavior with membrane potential modulation, using both intensity and lifetime as observables. These advancements enable the use of optical methods in bacterial electrophysiology, providing new insights into the dynamic processes of bacterial behavior and physiology. This approach could also be extended to study the detailed electrophysiology of other small motile cells, such as algae and viruses, which have not been extensively explored before but might serve as a new foundation for developing living materials.

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TAMM PLASMONS FOR THE ENHANCEMENT OF THE LIGHT-MATTER INTERACTION

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Tamm Plasmon mode is a particular type of surface plasmon resonance excited by combining a distributed Bragg reflectors (DBR) and a plasmonic nanolayer made with a noble metal. Exploiting this electromagnetic mode, devices able to act as sensors, actuator and modulator can be manufactured. Starting from the achievements obtained by S. Normani et al.,^[1] a Tamm Plasmon Resonance device is produced by combining a metallic nanolayer, gold, and a Bragg crystal. Functionalizing the external face of the golden layer, the device become capable to create specific interaction with precise species in the external environment. The device has been studied in combination with a photoactive polymer for the enhancement of the photo-driven phenomena of the latter.

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ENGINEERING OF LIGHT SENSITIVITY IN CHLAMYDOMONAS REINHARDTII

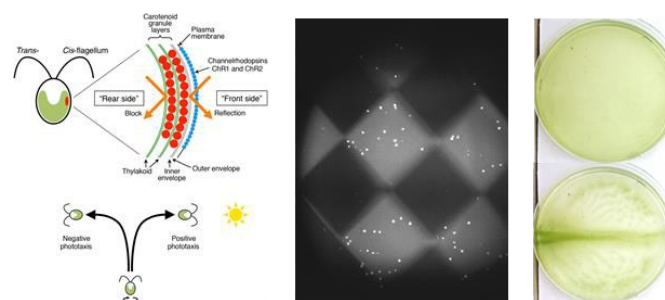
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The evolutionistic competence of certain organisms, such as bacteria and algae, to transform energy into motion can be exploited to perform tasks even in highly viscous and hard-to-reach locations, i.e. human organs and tumours. This implies that control over their motility at high spatiotemporal control represents a formidable challenge, which would enable the development of truly bio-compatible and bio-inspired swimmers that can be used for therapeutics and diagnosis. Furthermore, the study and modulation of motion in these organisms allow the unveiling of essential information about cell motility, cell-cell communication, and response to external stimuli. In our studies, we engineer light sensitivity in algae through exogenous phototransducing materials that can interface with the target organism based on non-covalent interactions only, and without the need for genetic transformation. Our model organism is the unicellular microalgae *Chlamydomonas reinhardtii*, which shows natural fluorescence from chlorophyll and both positive and negative phototaxis.^[1,2] The phototransducing materials are polythiophene nanoparticles and azobenzene photoswitches,^[3] which can transform light energy into electrical potential, thus acting as an artificial eye apparatus. We employ fluorescence microscopy to quantify cell trajectories, migration patterns, and interaction dynamics within the cellular environment with high spatiotemporal resolution.^[4,5] Our research aims at engineering light sensitivity in microorganisms, to uncover the interplay between external cues and cellular dynamics, with implications spanning biotechnology, medicine, and beyond.



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PHOTONIC NANOSTRUCTURED INTERFACES FOR MODULATING KERATINOCYTE ACTIVITY

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The skin is the largest organ in the human body and consists of several layers, the outermost of which is the epidermis. Keratinocytes, the predominant cell type in the epidermis, are essential for maintaining skin integrity and barrier function. During wound healing, the dynamic process of proliferation, differentiation and apoptosis of keratinocytes, which are typically involved in the continuous renewal of the epidermis, is accelerated.^[1]

These processes can be further modulated by nanostructured devices based on conjugated polymers and sensible to the green light to facilitate re-epithelialization of the wound site. Active interfaces with nanoscale components are particularly useful for interfacing and adapting to the complex nanoscale structural features of living tissues. Conjugated polymers are emerging as optimal candidates for interacting with living organisms due to their high biocompatibility and ability to combine the chemical and mechanical advantages of organic materials with the unique optoelectronic properties of semiconductors. Poly(3-hexylthiophene-2,5-diyl) (P3HT) is the chosen organic and photoelectrochemically active conjugated polymer. As a semiconductor, P3HT modulates the cell membrane potential through its interaction with cells, absorbing light in the visible spectrum and supporting charge photogeneration, which sustains both electronic and ionic charge transport.^[2]

In this work we report the synthesis and optoelectronic and morphological characterization of biocompatible and photosensitive platform capable of modulating the epithelial cells physiology. P3HT-based devices have the potential to open new frontiers in regenerative medicine, with significant implications for therapeutic strategies in the treatment of skin injuries and chronic wounds.

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THE IMPACT OF SHALLOW AND DEEP DEFECTS ON CARRIER DYNAMICS IN TIN-IODIDE PEROVSKITES

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Tin halide perovskites (THPs) are promising low-bandgap materials for photovoltaic and light-emitting applications.^[1,2] In lead-based perovskites, iodine chemistry plays a major role in forming deep hole traps. However, in THPs, tin chemistry dominates,^[3] with tin vacancies acting as shallow defects and influencing intrinsic doping, while tin interstitials, and surface Sn(IV) serve as deep electron traps.^[4] Tin-halide perovskites (THP) exhibit complex carrier dynamics due to the coexistence of electronic doping and carrier trapping, which affect device performance.^[5,6] A challenge in evaluating the impact of trap states arises from overlapping timescales between photogenerated electron recombination with dopant holes and trapping. Therefore, solely examining fast dynamics does not provide a comprehensive understanding of trap states' effects. Variations in carrier lifetime and radiative efficiency cannot be unambiguously attributed to changes in trap or doping density. This poses a significant challenge in thin-film optimization, as the effects of compositional engineering cannot be directly assessed.

Here, we use Transient Absorption Spectroscopy across a broad spectral and temporal range, i.e. from visible to near-infrared and from femtoseconds to microseconds respectively, to probe both sub-bandgap and band-edge transitions, while manipulating defect and doping densities via chemical treatments. This approach clarifies the distinct roles of doping- and trap-mediated processes in determining optoelectronic properties.

The dynamics of sub-bandgap trap states at early times reveal two distinct processes: a slow component lasting longer than 1 nanosecond and a fast population of shallow traps lasting tens of picoseconds. The latter repopulates the band-edges and is particularly significant as it may impact the apparent carrier cooling. In time scales of microseconds, we detect long-lived trap states. By separately modulating doping and defect density with additives and intentional air exposure, we identify the spectral features and dynamics of Sn(IV) and tin interstitial (Sni) trap states. These findings are supported by simulations of photoexcited carrier dynamics, which replicate the decay of the transient absorption spectroscopy signal to explain the experimental data.

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CAN ORGANIC SEMICONDUCTORS ENABLE TOUCHLESS CONTROL OF CELL MECHANOTRANSDUCTION?

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Biophysical cues, especially mechanosensation, play a fundamental role throughout life, starting from early embryonic development over function and interplay of cells and tissues in the adult body up to regeneration processes. Tissue regeneration, which includes phenomena like cell division, differentiation, migration and expulsion is triggered by extracellular mechanical cues. Moreover, the body’s capability to regenerate decreases with age, and therefore it impacts our life in sometimes detrimental aspects. Currently available tools to modulate or control mechanosensation often lack features necessary for in vitro and in vivo applications, in terms of efficiency, reliability, reversibility and spatial sensitivity.

Here, we show a novel approach to control mechanosensitive ion channels, through exogenous organic semiconductors. Materials in this class are fully biocompatible, thus offering the perspective for in vivo application, they can be easily processed in several forms, such as thin films, microstructured devices or nanoparticles. Most importantly, they are characterized by distinctive opto-electrical properties, providing excellent visible light responsiveness, as well as electronic and ionic conductivity.

In more detail, we preliminarily explore the opportunity to use organic semiconductors to control the activation of mechano-sensitive ion channels, in a reliable and effective manner. When shone with light, the materials demonstrate a collective movement, thus generating fully controllable shear stress stimulation. Our results may contribute to develop innovative smart materials for tissue regeneration driven by physical cues.

OPTICAL CONTROL OF INTRACELLULAR REDOX BALANCE IN CARDIOVASCULAR CELLS BY CONJUGATED SEMICONDUCTING POLYMERS

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In cell physiology, redox homeostasis is a core concept governing the entire cell cycle, being an imbalance in cellular redox status linked to the onset and progression of numerous diseases. Specifically, Intracellular Reactive Oxygen Species (ROS) concentration plays a crucial role in the fine tuning of several physiological functions.^[1] As a consequence, there has been a growing interest in the emerging field of 'redox medicine' over the past few years.^[2] Currently available treatments to modulate the cell redox balance rely on the employment of chemically controlled methods. However, this strategy often fails to achieve accurate spatial and temporal control, is not reversible and is unsuitable for finely-tuned control of sub-cellular organelles. Employing optical excitation as a stimulus to precisely modulate intracellular ROS concentration at non-toxic levels offers the opportunity to overcome these limitations, but requires the development of novel, photoelectrochemically active transducers. To support the development of new tools for precise, non-toxic, non-invasive and on-demand modulation of intracellular ROS concentration it is therefore necessary to develop new biocompatible materials, characterized by highly tunable electrochemical efficiency and good stability in a biological environment.^[3] Moreover, stimulation protocols should be as minimally invasive as possible. Here, we propose a novel strategy, based on the use of ad-hoc chemically functionalized semiconducting polymers, with enhanced opto-electrochemical properties.^[4,5] We investigate the phototransduction process, highlighting how photoelectrochemical reactions occurring at the polymer/electrolyte interface can modulate ROS concentration on-demand. We successfully employ extra- and intracellular delivery strategies, respectively based on polymer thin films and NPs, to achieve ROS increase within the *eustress* dynamic range in relevant cardiovascular cell models. We demonstrate that photoelectrochemically active organic semiconductors developed in this work satisfy all the requirements for innovative in-vivo redox-based therapies, potentially advancing clinical applications in the redox medicine field. So, we investigate the possibility to exploit photo-activated ROS to activate redox-dependent biochemical pathways with pivotal roles in cardiovascular cells, such as calcium dynamics, nitric oxide modulation, angiogenesis process.^[6,7] These results open up unexplored possibilities for wireless, geneless, and optically driven regenerative therapies in the cardiovascular domain.

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DEVELOPMENT OF TABLE-TOP ULTRAFAST SOFT-X SPECTROSCOPY FOR MATERIAL SCIENCE

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High-order Harmonic Generation (HHG) from intense femtosecond laser interactions with noble gases has led to compact sources of coherent Extreme Ultraviolet (EUV) and Soft X-ray radiation.

This advancement allows ultrafast spectroscopy with attosecond temporal resolutions and chemical selectivity, which is crucial for exploring electronic dynamics and light-matter interactions in molecules and solids.

Transient absorption in the XUV based on table-top sources, despite its promise, faces challenges due to complex setups and low efficiency at high photon energies.

Our work presents a breakthrough in XUV generation using a microfluidic device, crafted via femtosecond laser irradiation and chemical etching. This technique enables precise control over harmonic generation on the micro-scale, achieving high photon flux and phase-matching up to 200 eV.

Moreover, HHG spectroscopy has expanded into solid-state applications, including band structure reconstruction and Berry phase retrieval, highlighting its versatility.

We report on the development of a beamline for HHG spectroscopy and polarimetry in semiconductors for investigating complex electron dynamics during HHG.

This presentation will cover these significant advancements in ultrafast spectroscopy as part of the NFFA-DI PNRR Research Infrastructure at CNR-IFN, emphasizing the method's application potential and transformative impact on materials characterization.

STUDY OF THE EFFECT OF A-SITE CATION ON THE OPTOELECTRONIC PROPERTIES OF TIN IODIDE PEROVSKITES

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Tin Halide Perovskites are promising materials for photovoltaic applications. However, they have received less attention compared to Lead-based Perovskite. In this work we have studied the role of the prototypical A-Site cations (such as FA^+ , MA^+ and Cs^+) on the optoelectronic properties of Tin Perovskites. In particular we considered the effect of different cations on the p-doping of the thin film via self-doping process. Where the low energy formation of tin vacancy defects is the main responsible of the intrinsic doping of tin perovskites. Our preliminary spectroscopic investigation exhibit small differences between the optoelectronic properties of the three perovskites. Consistently, DFT calculations show a minimal modulation of electronic and defect properties with different A-site cations (**Figure 1**).

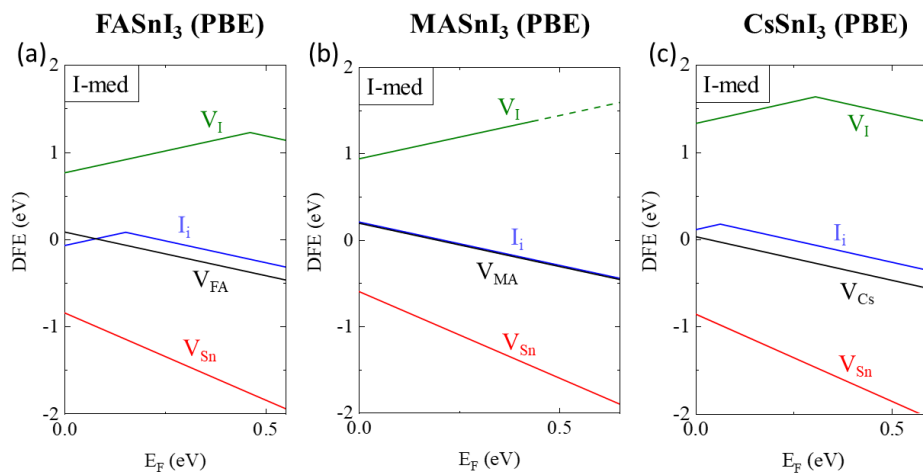


Figure 1: Defect Formations Energies (DFEs) of main defects in FASnI₃ calculated by using PBE functional for (a) I-rich, (b) I-medium and (c) I-poor chemical conditions.

UNVEILING THE BIOPHYSICAL MECHANISM OF CARDIOMYOCYTE EXCITATION-CONTRACTION COUPLING MODULATION BY A MEMBRANE-TARGETED PHOTOSWITCH

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The use of light to control cellular activity presents a promising approach in cardiac research due to its precise stimulus localization and minimal invasiveness. Ziapin2, a membrane-targeted azobenzene compound, has already been identified as an effective tool for light-driven modulation of excitation-contraction coupling (ECC) in hiPSC-derived cardiomyocytes.^[1,2] Its mechanical photomodulation of membrane thickness leads to changes in membrane capacitance (Cm), which are linked to membrane potential alterations that trigger action potential (AP) generation. Despite a robust physical interpretation, a detailed biophysical explanation of this process remains under investigation. To further explore this, we tested Ziapin2 in a more mature model: adult mouse ventricular cardiomyocytes (V-CMs). Using standard electrophysiological techniques and enhanced computational models, we delved deeper into the biophysical mechanisms. Our in vitro results demonstrate that Ziapin2 can photomodulate ECC in mature V-CMs without affecting the main transporters and receptors located within the sarcolemma. Furthermore, we experimentally established the connection between Ziapin2-induced membrane thickness modulation and light-induced AP firing by showcasing the pivotal role of stretch-activated ion channels (SACs) through pharmacological blockade. Our experimental findings were successfully supported by mathematical simulations, incorporating Cm changes and SACs activation due to membrane tension caused by Ziapin2-induced thickness modulation. Together, these results enhance our understanding of the biophysical processes involved, shedding light on the mechanism of action of Ziapin2 as a novel, precise, and non-invasive tool for controlling cardiac electrical activity.

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MODULATION OF ULTRAFAST QUASIPARTICLE DYNAMICS IN TWO-DIMENSIONAL SEMICONDUCTORS

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Two-dimensional transition metal dichalcogenides (TMDs) combine attractive semiconductor properties and mechanical and chemical robustness with exceptionally strong light-matter interaction. As evidence of this, TMD monolayers with sub-nanometer thickness have demonstrated a range of optical phenomena, including photodetection, photovoltaics, saturable absorption, optical gain, photocatalysis, electrooptical modulation, and optical parametric amplification. Their optical spectra are dominated by two main excitonic resonances A and B. The exciton binding energy is several 100 meV in the monolayer, and is sensitive to screening by charge injection or the dielectric environment.

The functional properties of a material are determined by its response to external stimuli, which drive it out of its equilibrium. As far as electronic and photonic functionalities are concerned, the relevant electron and lattice relaxation processes at the origin of such response occur on the femto- to nanosecond timescale. We show the modulation of the electron relaxation behaviour upon the application of two external control parameters. Uniaxial tensile strain applied to a TMD monolayer changes the exciton mobility and hence their migration towards defects, which act as recombination centres, thus modulating the exciton lifetimes. Gating TMD monolayers in field effect transistor configuration enables control of the charge density in the material and tweaking the subtle interplay between photoinduced trion formation and exciton dissociation.

STIMULATED EMISSION OF PEROVSKITE WITH HYPERSPECTRAL IMAGING SPECTROSCOPY

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Hyperspectral imaging is a powerful tool allowing us to visualize the localized spectra of the measured sample, in this presentation, we will demonstrate the working principle of the widefield hyperspectral imaging system and its setup. Then, we will demonstrate how we utilize this technique to study the amplified spontaneous emission (ASE) of lead halide perovskite. we will present a model to demonstrate the spatial origin of ASE in perovskites thin film. From the spatial overlap between the SEM image and the ASE emission map, the ASE was shown to emit from the localized defects at the grain boundaries. Furthermore, by combining the photoemission microscopy with the HSI system, we found that ASE emission areas show a shoulder in the PEEM spectra, which corresponds to trap states. This shows that the ASE emission originated from a more defective region of the thin film.

ENGINEERING BONDING NETWORK IN CHIRAL METAL HALIDES THROUGH LIGAND DESIGN

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Over the last ten years, the role of hybrid metal halide perovskites has received significant attention as suitable materials for various electronic applications. Indeed, their outstanding optoelectronic properties such as high-power conversion efficiency, tunable bandgap, and high absorption coefficient, make them suited for several applications in different devices as photovoltaic cells, photodetectors, light emitting diodes, and sensors.^[2] Starting from the hybrid organic-inorganic perovskites (HOIPs), the introduction of a chiral molecule as organic cation leads to the breaking of the spatial inversion symmetry, allowing new possible designs based on the combination of polarity and chirality.^[1,3] In the scientific scene, this opened plenty of novel applications provided by outstanding chiroptical properties, such as circular dichroism, circular polarized emission, chiral induced spin selectivity and so on. To extend the actual knowledge of these chiral systems, it is important to investigate those parameters which have a major impact on the chirality transfer mechanism, with the final aim to unveil it. From a material chemistry point of view this involve an important work on materials' structure, involving several modulations/substitutions on the latter. More specifically, in this contribution we will present the results of the role of the organic cation, showing the modulation of the optoelectronic properties engineering unconventionally chiral cation. Firstly, we decide to move away from the commercial chiral cation and to synthesize homologous series that can help unveil the role of the chemical nature of the cation on the chiroptical properties. We obtained a new phase (R-/S-AMOL)PbI₃ and the correspondence with the Sn^[4]. The work provides a comparison not only in terms of structural features and chiroptical properties but also in terms of computational modelling, which helps us to deeply understating the role of organic cation and the difference in terms of efficiency moving from a Pb-based perovskites to a Pb-free one. Final aim of this work is to unveil the impact of chemical degrees of freedom on the chirality transfer between the organic cation and the inorganic framework to provide tuning strategies for materials engineering.

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MULTISPECTRAL FLUORESCENCE LIFETIME IMAGING MICROSCOPE BASED ON COMPUTATIONAL IMAGING TECHNIQUES

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Multispectral fluorescence lifetime imaging microscopy (λ FLIM) is a powerful optical technique to investigate biological and material science processes, which generally require long acquisition time. Single Pixel Camera (SPC) is a computational imaging architecture based on Compressive Sensing (CS) techniques which allows to strongly reduce the acquisition time while preserving the information content. In this work we present a λ FLIM microscope based on CS-SPC architecture combined with computational imaging approaches. In particular we have tested the multiscale capability of the system by merging SPC zooming with data fusion and high throughput acquisition.

DETECTION OF CHLORIDE IN SWEAT WITH EXTENDED-GATED ORGANIC ELECTROCHEMICAL TRANSISTORS

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Cystic fibrosis (CF) is the most common progressive, life-limiting genetic disorder affecting multiple organs, caused by mutations in the CFTR anion channel responsible for chloride ion transport and fluid regulation. Diagnosis and personalized treatment for CF rely on monitoring chloride levels in sweat. Currently, the clinical procedure requires sample collection in a healthcare setting, followed by laboratory analysis performed by skilled operators. These technical and logistical limitations highlight the need for accessible, decentralized sweat analysis and personalized diagnostic tools.^[1] Electrolyte-Gated Transistors (EGTs) have recently emerged as a promising technology for biosensing, as they effectively interface with biological samples to transduce weak biological signals into readable electronic outputs. Their high amplification gain, compatibility with low-cost manufacturing, miniaturization potential, and ability to operate at low voltages (<1V) make EGTs well-suited for affordable, point-of-care or wearable devices.^[2] In this study, we present a printed Organic Electrochemical Transistor (OECT) featuring an extended gate made from (poly(2-(3,3-bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-[2,2-bithiophen]-5-yl)thieno[3,2-b]thiophene) p(g2T-TT) with a partially chlorinated silver electrode for chloride ion monitoring. This architecture leverages the transduction and amplification capabilities of OECTs to selectively and accurately convert the potentiometric signal of the sensing element. Initial validation was achieved by conducting standard potentiometry within physiologically relevant chloride ranges (0.1 mM to 100 mM), yielding a super-Nernstian sensitivity of approximately 75 mV/dec. Additional tests using various salts, with and without chloride, were conducted to confirm device selectivity. Finally, the extended-gate OECT sensor was tested under similar conditions, showing a significant response that surpasses previously reported values. This preliminary in vitro validation lays the groundwork for future integration into portable or wearable systems.

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SOLID STATE NMR SPECTROSCOPY OF LOW-DIMENSIONAL PEROVSKITES

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Low-dimensional metal halide perovskites are attracting great interest for photovoltaics and photonics. The optoelectronic properties of this soft class of semiconductors critically depend on their crystal structure, structural distortions and defectivity. Due to the increasing complexity of the materials under development, it is emerging the need to characterize not only their long range structural order by standard X-ray diffraction techniques but also the local coordination environments. Solid state NMR (ssNMR) is a key technique to investigate the local structures at the atomic level. However, the complexity of the spectral output can hamper the analysis and the widespread adoption of this useful technique. Here we show that ^1H , ^{13}C , ^{15}N , ^{119}Sn and ^{207}Pb ssNMR spectroscopy provide clear spectral fingerprints which are characteristic of perovskites with different structural motifs, allowing the identification of their supramolecular spatial arrangements with unprecedented atomic scale accuracy. We further apply spin relaxation dynamics measurements to investigate molecular motions and structural rigidity in 2D perovskites, and discuss their impact on the perovskites' luminescence properties, relevant for lasing and photonic applications. Our studies shed light on how supramolecular engineering can guide the development of improved materials for optoelectronics.

UNVEILING PHOTOLUMINESCENCE QUENCHING MYSTERIES

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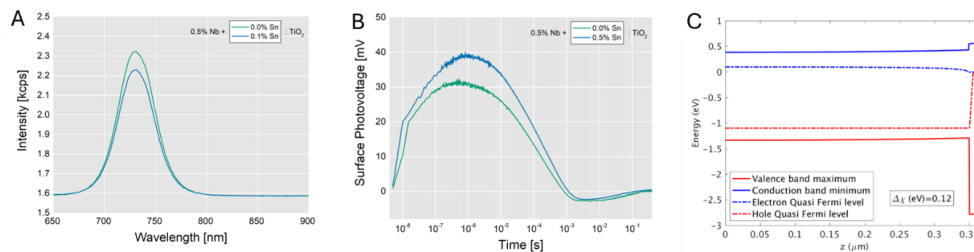
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Among the multitude of characterization techniques, transient (Tr) and steady-state (ss) photoluminescence (PL) asserted themselves as powerful tools for probing optoelectronic properties and the performance of semiconductor devices, owing to their contactless, purely optical nature. Despite the ubiquity of PL, there is still no consensus on the correlation between PL features, such as amplitude and decay time, and device performance: are the former good predictors of the latter? In other words, if a modified structure shows a decrease in PL intensity with respect to the reference (PL quenching), does this imply that this structure yields lower quality or better-quality solar cells? To explore this issue, we choose metal halide perovskites (MHPs), a maturing photovoltaic technology which has been extensively characterized with Tr and ss PL. We complement the analysis with the help of another technique that is sensitive to the spatial separation of carriers, namely transient surface photovoltage (TrSPV).

Previously, we deposited MHP thin films on doped and co-doped TiO₂ layers, and a drift-diffusion (DD) model has been tuned to reproduce TrSPV measurements on the two charge extraction layers.^[1] Here we employ the calibrated model to study the impact of charge extraction and carrier recombination on PL intensity, TrPL decay, and TrSPV. Our findings show that PL quenching is obtained for both enhanced carrier extraction, as well as increased non-radiative recombination at the MHP/TiO₂ interface. These two conditions can be differentiated by employing TrSPV. Beyond this, we reveal the root cause of PL quenching upon charge extraction. Overall, this work provides a deep understanding of the charge carrier



extraction mechanisms in MHPs, paving the way for a fast optimization of semiconductor devices.

Figure 1: PL quenching on a modified MHP/TiO₂ structure (blue curve, co-doped TiO₂) with respect to the reference (green curve, doped TiO₂) (a), accompanied by TrSPV amplitude enhancement (b). In (c), a band-diagram of the DD model used to reproduce the experimental data is shown under light excitation.

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LOCAL STRUCTURE ANALYSIS ON DEFECT PASSIVATED HALIDE PEROVSKITE PHOTOVOLTAIC MATERIALS AND DEVICES

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Metal Halide perovskite have drawn intensive attention due to their remarkable optoelectrical properties as well as low-cost process. Explosive research has been conducted since the first report on stable all-solid-state perovskite solar cells was published in 2012. Presently, 26.7% of certified power conversion efficiency has been reported, which is comparable to that of conventional Si-based solar cells. However, the performance and operational stability of perovskite-based photoelectric devices are still face to challenges, mainly due to the various type of defect resulting from relatively weak binding interactions between metal cations and halide anions. In this presentation, correlation between local structure change after defect engineering and phase stability in solution processed perovskite-based optoelectrical device for highly efficient/stable solar cells will be introduced. First, an effective method for defect passivation on the perovskite films will be suggested.^[1,2] It has been shown that the methodology of defect passivation through intermediate phase post-treatment, additive engineering via iodine-embedded Lewis-base material can improve the perovskite solar cell device performance and stability. Second, extended X-ray absorption fine structure (EXAFS) analysis was employed to investigate the local structure of perovskite thin films, offering higher spatial resolution than conventional X-ray diffraction (XRD).^[3,4] The research highlighted the relationship between the bonding distance of lead iodide octahedra and phase stability of perovskite film, as well as investigation of the correlation between lattice distortion and its impact on changes in phase stability and optical properties. The findings indicated that effective and stable perovskite-based solar cell devices could be achieved through the regulation of defects.

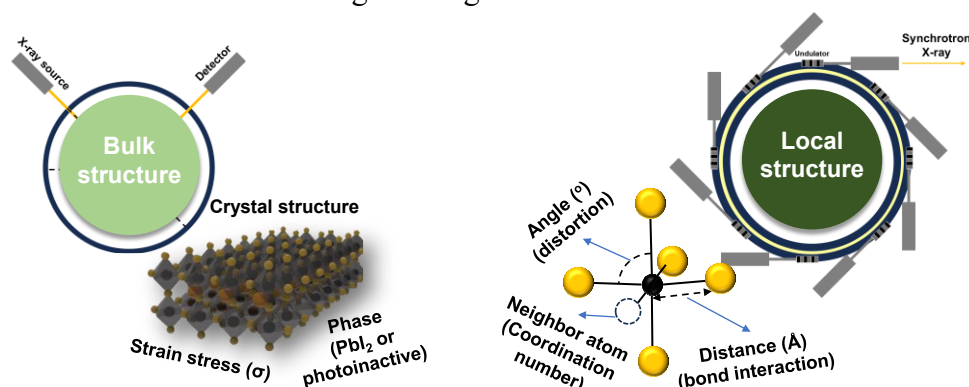


Figure 1: Schematic images of crystal structure of metal halide perovskite and information obtained with XRD and EXAFS, respectively.

Acknowledgements: GoPV commessa EPNZ0130.

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ULTRAFAST SPECTROSCOPY OF NOVEL MEMBRANE TARGETING AZOBENZENES

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Over the past fifteen years, research has increasingly focused on bacteria as dynamic living organisms, beyond their role as potential pathogens. Bacteria exhibit "neuron-like" behavior, relying on electrical signaling for communication.^[1] A key enabler of this behavior is the membrane potential, regulated by ion flux across the cell membrane, which influences motility, pH balance, and nutrient uptake. To modulate bacterial membrane potential, photosensitive azobenzenes offer promising solutions. These organic molecules undergo light-triggered trans-cis isomerization, allowing precise, real-time control of ion flux and electrochemical responses.^[2]

In this study, we present the spectroscopic characterization of four novel hydrosoluble azobenzenes. Using ultrafast transient absorption spectroscopy, we investigated their isomerization dynamics, in a time range spanning from femtoseconds to nanoseconds. Experiments were conducted in water and SDS micelles to mimic biological environments. Our findings highlight the excellent photoisomerization rate of these molecules, also in biological-like environment, offering valuable insights for future stabilization strategies, such as integration into nanoparticles or hydrogels, to advance their application in bacterial manipulation.

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UNDERSTANDING THE PHOTOEMISSION SPECTRA OF LEAD HALIDE PEROVSKITES

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Despite being solution-processed, the defect tolerant property of metal halide perovskites has allowed them to compete in the same league as conventional inorganic silicon solar cells. Though often touted as defect tolerant, proper identification and management of the many defects in the polycrystalline perovskite thin films are nonetheless critical to the achievement of highly performant and stable optoelectronic devices. Among the various techniques used to investigate the properties of these defects, ultraviolet photoelectron spectroscopy and microscopy provide the most straightforward approach to probe the presence of, the spatial distributions, as well as the trapping dynamics of electrically active traps in perovskites.^[1-4] These traps are often characterized by the presence of occupied mid-gap states in the photoemission spectra of perovskites that stretches from the valence band up to the Fermi level. Here we investigate the diffraction patterns and photoemission spectra of a variety of perovskite thin films using spectroscopic low energy and photoemission electron microscopy. By changing the stoichiometry of the perovskite films, we observed a positive correlation between the presence of excess PbI₂ and the photoemission intensity of the mid-gap states. Using microprobe low energy electron diffraction, we found that the presence of the PbI₂ diffraction has a negative correlation with the presence of the photoemission from the mid-gap states. Furthermore, upon laser irradiation, the PbI₂ diffraction weakens and eventually disappear while the mid-gap photoemission appears and increases in intensity. Based on these measurements, we aim to demonstrate the origin of these mid-gap photoemission spectra to be the spectra of metallic Pb, a decomposition by-product of PbI₂.

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EXPLORATION ON THE CHARGE TRANSPORT PROPERTIES OF CUMULENIC SP-CARBON WIRES

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Carbon allotropic forms have gained the spotlight due to their remarkable versatility. Among all, sp-hybridised carbon has been predicted to display unmatched mechanical, thermal, and electronic properties.^[1] Cumulenes, a category of finite sp-carbon-based molecules, are model moieties that have attracted particular attention also in the form of thin films, as they present a tuneable semiconducting nature.^[2,3] Indeed, solution-processed films of tetraphenyl[3]cumulene ([3]Ph) and tetraphenyl[5]cumulene ([5]Ph) have been successfully employed as active layers in p-type organic field-effect transistors (OFETs). [3]Ph-based devices can even reach a field effect mobility exceeding 0.1 cm²/Vs, showing ideal behaviour and operational stability in air in dark conditions.^[4] However, cumulenic charge transport mechanisms remain largely unknown.

We here present an investigation on the electronic properties of [3]Ph, taken as the reference cumulene. Chemical and electrochemical oxidations in solution, supported by UV-Vis and Raman spectroscopy, were employed to probe the charged single molecule, revealing the formation of new transitions related to the localisation of the charge on the sp-backbone. Charge modulation spectroscopy was performed on OFETs based on thin films of [3]Ph to investigate the solid state electronic properties, leading to a good match with the results obtained from the single molecule.

The understanding of the fundamental charge transport mechanism is pivotal to exploiting the full potential of sp-hybridized molecules for large-area organic electronics, and it could also contribute to new insights regarding the infinitely long sp-carbon allotrope known as carbyne.

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EDIBLE SEMICONDUCTORS FOR EDIBLE ELECTRONICS

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Given the increased burden on healthcare workers in recent years, point-of-care medical devices for the gastrointestinal tract that require no external supervision could be pivotal in delivering fast diagnosis, monitoring, and treatment of numerous diseases. Ingestible electronics has thus far been a formidable candidate, with some devices reaching the market in recent years.^[1,2] However, this technology still presents some risks, namely the need to recollect the non-biodegradable devices, which prevent their use in real point-of-care applications. Edible electronics offer a pathway to overcome these retention hazards by providing devices that are not only ingestible but ultimately digestible, thus encompassing the limits of their ingestible counterparts.^[3] A few edible electronic components and devices have already been proposed, including edible batteries.^[4] However, thus far, reliable and stable edible semiconductors, crucial for implementing active microelectronic components, have not yet been identified.

Here, we explore natural/synthetic dyes and pigments with suitable electronic structures and prove their potential as semiconducting materials in edible transistors.

First, we tackle natural carotenoids, commonly present in food and widely employed as food additives. Among more than 1200 carotenoids, only beta-carotene and bixin have been successfully demonstrated as semiconductors, although with poor performances and poor air and light stability.^[5] By applying a structure-property approach and finely tuning their thin film microstructure, we demonstrate field-effect mobilities encompassing 10^{-2} cm²/Vs and devices operating in ambient conditions for up to three weeks alongside the first proofs of carotenoid-based electrolyte-gated transistors (EGOFET).

Second, we explore two different teeth-whitening pigments, Copper Phthalocyanine (CuPc) and Perchlorinated Copper Phthalocyanine (Cl₁₆CuPc), widely used in a plethora of toothpaste and known semiconductors. Although they are not certified as edible, thanks to the ultimate ingestion of the CuPc/Cl₁₆CuPc pigment film left on the teeth, they are excellent candidates for edible applications. In this context, we have developed the first entirely edible p-type and n-type edible EGOFET,^[6] which present air stability for up to 12 months and high reproducibility. With these devices, we have developed three different monolithic, fully edible complementary logic circuits, a NOT, a NAND, and a three-stage ring oscillator, presenting operational stability for up to two months.

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AEROSOL JET PRINTED CONDUCTIVE POLYMER PATTERNS FOR ENDOTHELIAL CELL ALIGNMENT INSIDE A MICROFLUIDIC CHAMBER

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Endothelial cells (ECs) align with blood flow-induced shear stress (2–20 dyne/cm²) to maintain vascular health, with misalignment indicating pathologies like atherosclerosis.^[1] While microfluidics can induce alignment in vitro, excessive stress may harm cells.^[2] Combining microfluidics with methods like substrate patterning ensures proper alignment while minimizing stress and apoptosis. We propose using Aerosol Jet Printing (AJP), a contactless direct-writing technique, to precisely (resolution: 10 μm)^[3] pattern PEDOT:PSS within a microfluidic PDMS chamber for Human Umbilical Vein Endothelial Cell (HUVEC) culture and alignment.^[4] PEDOT, a conductive and biocompatible polymer, promotes ion exchange, enhancing cell proliferation and differentiation.^[5] After oxygen plasma activation for microfluidic device assembly, patterned PEDOT retains its chemical composition, transparency, and conductivity ($\sigma = 340 \pm 126$ S/cm after plasma treatment). HUVECs seeded on PEDOT patterns (6 lines, 50 μm × 8 mm × 100 nm), proliferated along the tracks under both static and capillary flow conditions.

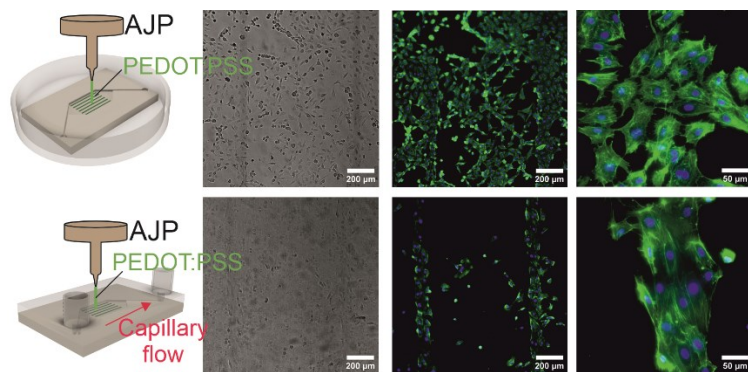


Figure 1: PEDOT-patterns influence on HUVEC adhesion, alignment, and elongation under static (top) and flow (bottom) conditions after one week (cvtoskeleton: green; nuclei: blue). 533349.

Up to day 3, cell morphology mirrored the narrow patterns in both conditions. After day 3, elongated cell morphology and alignment were maintained only under capillary flow and cyclic shear stress, along the patterned lines (**Figure 1**). This interplay of topographical constriction and capillary-driven shear stress reshaped ECs without the need for external pumps. Additionally, the PEDOT coating's electrical stability in the microfluidic device allows it to function as a real-time cell monitoring sensor.

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AZOBENZENE-SUBSTITUTED POLY-THIOPHENE NANOPARTICLES FOR THE PHOTO-STIMULATION OF LIVING CELLS

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The use of biocompatible exogenous materials for the stimulation of living organisms avoiding genetic manipulation has been extensively proposed as an effective strategy. Poly-thiophenes have been employed for in vitro and in vivo photo-stimulation in the past years. Polymer nanoparticles in close proximity to the cells can induce a perturbation in the membrane due to a charge displacement in the material, resulting in a physiological response. Similarly, azobenzene-based molecules, able to insert in cells' membrane, can induce modifications in the membrane which can be reverted through photo-switching between trans- and cis-isomer. At the same time, such photochromic molecules have also proved to be effective in interacting with bacteria.

Here, we report the synthesis of a poly-thiophene with simple azobenzene substituents and the fabrication of nanoparticles. The proposed material, in the form of nanoparticles, shows a good affinity with living cells and can also induce a physiological response upon light excitation of the isomerization band. Such a system enables the simultaneous utilization of two different stimulation paradigms which may allow more precise targeting in the case of particularly functionalized azobenzene substituents. In fact, excitation bands of the thiophene and azobenzene substituents are spectrally separated. Tuning of the absorption and selectivity may be obtained with more specific azobenzene derivatives. Combination of the two different stimulation mechanisms may result in increased response when required. Moreover, such approach enables increased spatial resolution due to light confinement and limits inflammatory response associated with more invasive techniques. The electronic and optical properties of those systems also make them interesting for sensing application, since the geometrical conformation of the azobenzene branches has been found to influence the optical characteristics of the poly-thiophene backbone.

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INTRODUCING ML METHODS IN THE DEAR OLD DFT

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Density functional theory (DFT) is one of the most effective methods to obtain optoelectronic properties of materials and molecules. While DFT offers a good compromise between accuracy and computational cost compared to other methods (Coupled Cluster, GW, ...), its use is restricted by computational power to systems of at most a few hundred atoms.

Models of this size are large enough to study pristine materials or simple defective models but are far from reaching the description of realistic or in-operando conditions.

However, to overcome these limits, machine-learning techniques have been developed to pair *ab initio* DFT molecular dynamics simulations with the training of force fields. This allows for obtaining force fields to describe models with thousands of atoms restraining the DFT accuracy.

In this talk, we present some preliminary results about the vibrational properties of the well-studied CH₃NH₃PbI₃ metal halide perovskite obtained using such force fields.

NATURAL HYPERBOLIC POLARITONS AT VISIBLE FREQUENCIES

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The ability to confine and manipulate light at sizes well below the diffraction limit has profound implications for both fundamental science and technology.^[1] Polaritons, which are hybrid light-matter waves, offer unparalleled light confinement due to their subwavelength propagation. In particular, a specific class of polaritons - hyperbolic polaritons - support modes with unbounded wavevectors, enabling a more extreme confinement of radiation. Traditionally, such excitations have been limited to mid-infrared frequencies in natural materials^[2] or rely on lossy artificial structures, i.e. metamaterials, for operation in the visible range.^[3]

In this talk, I will present the first proof of in-plane hyperbolic plasmon-polaritons at visible and near-infrared frequencies in thin films of a natural material: molybdenum oxychloride (MoOCl_2), a van der Waals crystal. Using a combination of theoretical modelling, full-wave simulations, and advanced nanoimaging techniques, the unique polaritonic modes supported by MoOCl_2 are fully characterized. These findings establish MoOCl_2 as an ideal platform for applications in nanophotonics, such as super-resolution imaging, hyperlensing, and quantum emitter enhancement.^[4-6] Unlike previously studied natural materials and metamaterials, this natural crystal embodies a combination of stability in air, low losses, and operation at visible wavelengths, paving the way for novel optical devices with unprecedented performance in the visible spectrum.

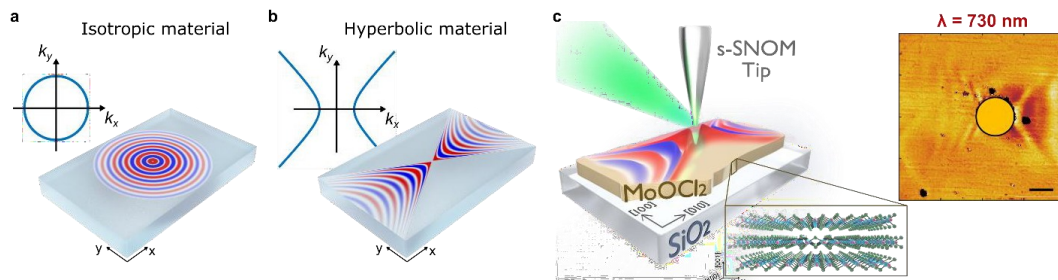


Figure 1: a, b) Comparison of real- and momentum-space features of (a) standard isotropic and (b) hyperbolic polaritons. c) Left: Schematic of the nanoscale imaging principle of scattering-type scanning near-field optical microscopy (s-SNOM) used to study polaritons in MoOCl_2 (crystal structure in the inset). Right: experimental image of hyperbolic polaritons launched by a gold nanodisk (excitation wavelength: 730 nm; scale bar: 500 nm).

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MONOLITHIC INTEGRATED FOOD-BASED LOGIC CIRCUITS FOR FUTURE EDIBLE SYSTEMS

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Conceived as an evolution of ingestible electronics, edible electronics is an emerging research field that aims to realize safe-to-eat devices that would be metabolized after use. They would either perform their function outside the body before ingestion or be consumed as a whole and operate inside the body before being metabolized. This would reduce the need for recollection, retention risks, and the harmful disposal of single-use electronic devices. To this end, food additives, food derivatives, and materials safe for ingestion are being used to fabricate sensors, batteries, and transistors. At this point, the challenge lies in realizing stable edible electronic circuits that can provide synchronization, perform simple computations, and serve as memory using these perishable materials.

This work presents the fabrication and characterization of monolithic integrated edible logic circuits operating at low voltage (< 1 V). Inkjet-printed electrolyte-gated transistors were fabricated using food-based materials and inks. A NOT gate and a NAND gate were successfully fabricated and characterized, proving that any function can be implemented. As proof of concept for more complex edible integrated circuits, multiple edible logic gates were integrated to deliver an edible ring oscillator working at a frequency of up to 1 Hz. Compatibility with edible energy sources was demonstrated, showing that powered edible electronic circuits are possible. This work paves the way for realizing edible systems as the next generation of ingestible devices for healthcare and food-monitoring applications.

POLYMER NANOFIBERS FOR SKELETAL MUSCLE CELLS ALIGNMENT AND PHOTOSTIMULATION

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In tissue engineering, cell-substrate coupling has a crucial role. Its mechanical, chemical, physical and morphological features are decoded by cells as stimuli that strongly affect their behavior.^[1] In muscular tissue engineering, in order to efficiently reproduce the natural muscle organization and achieve contraction ability, cell alignment on a suitably stiff substrate is required.^[2] Here, electrospinning was used as technique to produce polymer nanofibers, used as scaffold for muscle cells. The polymers employed for these nanofibers must be biocompatible, for this purpose we selected polyvinyl alcohol (PVA). Preliminary study of substrate biocompatibility, cells alignment, cells differentiation and photostimulation were conducted on PVA nanofibers. Combing photochromic molecules and biocompatible polymers is it possible to obtain a blend photoactive material that can guide the cells growth and trigger the contraction of a muscle tissue at the same time. To promote muscle cells contraction electrodes are widely used; however, they may produce side effects like unnatural heating, Reactive Oxygen Species production.^[3] Alternatively, photostimulation offers advantages such as better spatial and temporal resolution, low toxicity, and invasiveness.^[4]

In these experiments we tested first PVA nanofibers with different orientation, suitability in promoting skeletal muscle cells differentiation. The next steps will involve the synthesis of photoactive nanofibers through the crosslinking of photochromic molecules on the fibers surfaces. Before the fibers functionalization of the fibers, we characterized the optical properties of the molecules in different solvents, studying absorption properties, emission, and isomerization dynamics. Preliminary studies on the electrophysiology and viability of the photoactuator were conducted on HEK cells to better understand the effects of the molecules on the cells membrane.

The next steps will be to optimize the crosslinking process and verify the properties of the functionalized substrates first on HEK cells and then on muscle cells and to trigger a contraction through photostimulation.

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PHOTOTAMING OF BACTERIAL BIOELECTRICITY

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Recently, bacteria have arisen as excitable cells, exhibiting neuro-like behaviour and extended bioelectric signaling.^[1,2] In the last decade, it has been observed that the regulatory element of such an active behaviour is the electrical potential across the membrane, which governs bacteria electrophysiology, metabolisms and bioenergetics.^[3-5] Light can be a powerful tool in these regards, as one can control the membrane potential and, thus, cell function and behaviour remotely and with relatively high spatiotemporal precision.

I will show that bacterial bioelectricity can be modulate precisely by means of membrane-targeted azobenzene molecules.^[6,7] We found that exposure to visible light induces either hyperpolarisation or depolarisation depending on the excited states deactivation dynamics of the molecules, within a bio-mimetic mechanism reproducing the initial fate of retinal. As a result, we are able to evoke optically bacterial intercellular signaling, to influence their motility and to regulate their responsivity against antibiotics.

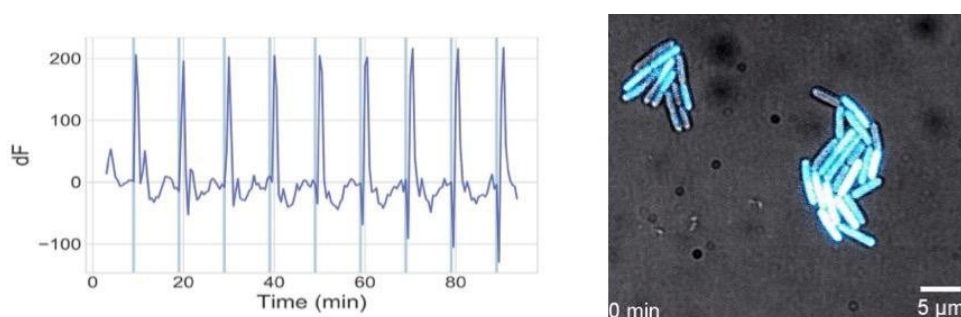


Figure 1: Periodic photo-induced hyperpolarization of a *B. subtilis* microcolony cultured with azobenzene and stimulated by 470 nm light for 10 s every 10 min. Reference: *Adv. Sci.* 2023, 10, 2205007

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CO-DESIGNING LENSES AND AI MODELS: A COMPREHENSIVE REVIEW OF DEEP OPTICS FOR TASK-SPECIFIC APPLICATIONS

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Deep optics is an emerging field where optical lenses and AI models are designed together for specific imaging tasks. This approach integrates hardware and software to optimize both the optical elements and the processing algorithms in a single framework.^[1] Deep optics uses differentiable wave optics to capture complex scene information, enhance applications such as depth estimation, hyperspectral imaging, image reconstruction, and privacy preservation.^[2-5]

Wave optics, based on light propagation principles, treats diffractive optical elements (DOEs) as phase masks that modulate the light field.^[1] By modeling phase shifts as differentiable, AI models optimize these masks, allowing for joint optimization of both lenses and image processing in an end-to-end framework. In the area of privacy-preserving imaging, deep optics embeds privacy features directly into the optical system, unlike software-based solutions that process images post-capture. Deep optics enhances privacy by encoding data optically before the sensor captures the image, reducing the need for vulnerable post-processing and strengthening defense against adversarial threats.^[2-5]

This review synthesizes the latest progress in wave-optics-based deep optics, discussing the methodologies, practical implementations, and task-specific designs. Emphasis is placed on the potential of deep optics to balance privacy concerns while maintaining good task performance.

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SELF-ENCAPSULATED TIN-HALIDE PEROVSKITE THIN FILMS FOR EFFICIENT AND STABLE NEAR-INFRARED LIGHT-EMITTING DIODES

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Tin (Sn)-halide perovskites have emerged as promising candidates for near-infrared light-emitting diodes (NIR-LEDs), with potential applications in biomedical imaging, sensing, photodynamic therapy, and optical communication. However, the intrinsic instability of tin-halide perovskites remains a major obstacle for their further development. In this work, we present a facile yet effective strategy to address this instability. By incorporating a rationally designed molecule (DDS) into the tin-halide perovskite precursors, we in-situ deposit a self-encapsulated tin-halide perovskite film that demonstrates excellent stability when exposed to air. Moreover, the DDS slows the crystallization process, leading to a reduced trap density and decreased p-type doping levels. As a result, the NIR-LEDs achieve a record peak external quantum efficiency (EQE) of 12.4%, alongside a significantly enhanced operational lifetime exceeding 1 hour. This approach offers a promising pathway for the development of high-performance optoelectronic devices based on tin-halide perovskites.

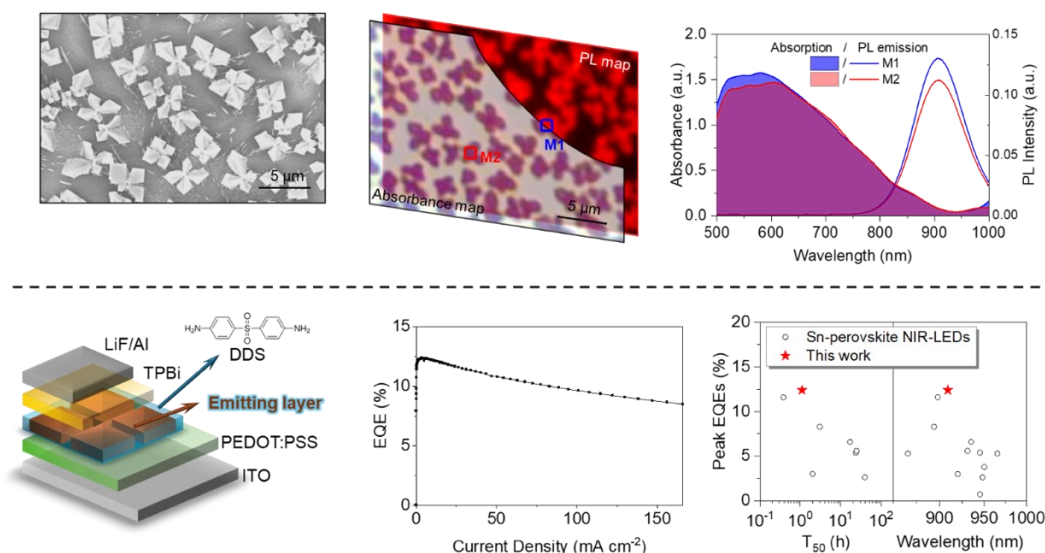


Figure 1: Morphology of the self-encapsulated Tin-Halide Perovskite thin film and the device performances.

INTERFACE OPTIMIZATION FOR EFFICIENT AND STABLE PEROVSKITE SOLAR CELLS

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Over the past decade, the significant increase in the solar-to-electrical power conversion efficiency (PCE) of metal-halide perovskite solar cells (PSCs) has positioned them as a promising candidate for next-generation PVs. These advancements open up exciting possibilities beyond conventional solar plants, including applications in building-integrated photovoltaics, flexible solar-powered electronics, and solar-powered vehicles and aircraft. Among the various PSCs architectures, inverted PSCs (p-i-n structure, IPSCs) stand out due to minimal hysteresis, lower production cost, and superior scalability, stable operation and seamless integration into tandem photovoltaics.^[1] Despite this, IPSCs have historically exhibited inferior PCE compared to the n-i-p structured counterparts, primarily due to the larger deficit in open-circuit voltage (V_{oc}) mediated by nonradiative recombination. The QFLS- V_{oc} match suggests that the majority of energy losses of devices are concentrated at the perovskite/charge transport layers (CTL) interfaces.^[2] The significant reduction of photoluminescence quantum yield of perovskites upon contact with CTL, indicates that the interface creates recombination pathways within the perovskite bandgap. Ameliorating interface recombination and enhance interface durability are paramount for reducing V_{oc} deficit and enhancing stability of IPSCs.

To address these challenges, we have developed effective surface optimization strategies to facilitate the charge transport and ameliorate interface recombination at the perovskite/CTL interface of IPSCs. (1) Surface reconstruction by 6-maleimido-hexanehydrazide trifluoroacetate/isopropanol achieves the charged defect passivation and a favorable gradient heterojunction for electron extraction of IPSCs. Specially, the coordination between carbonyl (C=O) and Sn^{2+} realizes the Sn-related defect passivation and serves as surface dipole layer for reducing electron transport barrier at the perovskite/ C_{60} interface. (2) In-situ construct a dual-interface 1D/3D perovskite heterostructure realizes low contact-interface losses and internal encapsulation of IPSCs. The dual-interface orientedly aggregated 1D perovskitoids serve as full-scale passivation and mechanically protective layer, in which intermolecular π - π stacking organic spacer cations stabilize the fragile Sn-I octahedral frameworks through trapping the unpaired and delocalized electrons originating from Sn/I surface ions and vacancies. (3) π -conjugated additives are introduced into the Me-4PACz as hole transport layer to form the molecular hybrid buried interface, greatly improving the interface charge extraction and operational stability of devices.

By integrating surface reconstruction, perovskite dimensional modulation, and buried interface optimization, we demonstrate substantial improvements in V_{oc} , operational stability, and overall device performance of IPSCs. These innovations contribute to bridging the efficiency gap with n-i-p devices, positioning IPSCs as a viable solution for scalable, stable, and high-efficiency PV technologies for diverse applications in energy and sustainability.

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ALL-PRINTED PLANAR PHOTOCONDUCTORS FOR X-RAY DETECTION

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Metal halide perovskites are a groundbreaking family of semiconductors finding applications on several areas of the optoelectronics field. They have attracted attention for their bandgap tunability, long carrier lifetimes, high defect tolerance and solution processable fabrication.^[1,2] Specifically for ionizing radiation detection, their large absorption coefficient allows efficient beam absorption even for low thicknesses, associated with the large-Z elements in their composition (Sn, I, Cs, Pb, Bi). In fact, they have already overcome the state-of-the-art X-ray detectors becoming a serious candidate for the next generation of radiation detectors.^[3]

From the possible device architectures, we focus on lateral photoconductors. Unlike standard vertical photodetectors, in this geometry the absorber layer is irradiated vertically, while photogenerated carriers (electron and hole pairs) are collected laterally due to the coplanar electrodes. The non-uniform electric field adds complexity to the generation of signal (photocurrent) and hinders the carrier collection efficiency, resulting in a sensitivity drop. On the other hand, this is compensated by gain at low radiation fluxes, which depends on the asymmetry of electron-hole pairs in space (due to the non-symmetric geometry) and time (related to defect chemistry, specifically unequal lifetimes). Another interesting feature of these radiation detectors is the porous absorber layer. This thick absorber (10 - 100 μm) is composed of perovskite microcrystals of adjustable size and composition, whose morphology impacts the onset of gain, and the quality of the interface (contact area) with the electrodes.

Together, the planarity of electrodes and the porosity of the absorber layer pave the way for flexible and all-printed radiation detectors, resilient to bending stress, low cost to fabricate, and easy to upscale. We demonstrate the performance of all-printed devices and aim to discuss the parameters that influence gain in the two relevant colour palettes: visible light and X-rays.

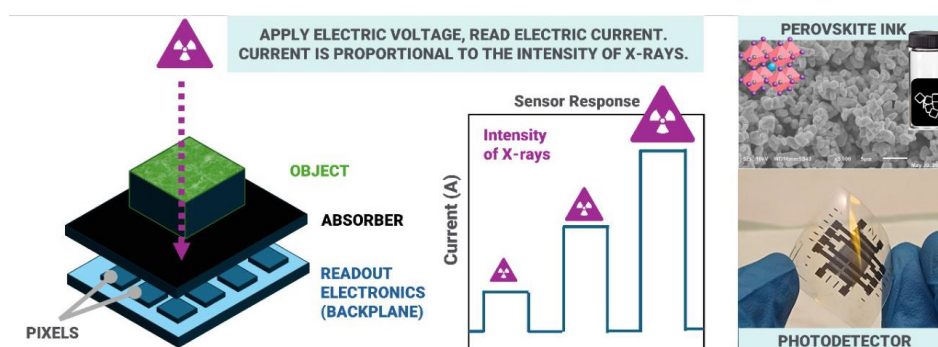


Figure 1: Summary of Ionizing Radiation Detectors sensing mechanism and illustrative device pictures.

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PEROVSKITES AND DERIVATIVES FOR OPTOELECTRONICS

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Halide perovskite materials are promising candidates for photoabsorption applications thanks to their tunable chemical composition, which allows them to be optimized for both photocatalytic and photovoltaic technologies. However, two key challenges for the widespread adoption of these materials are the reliance on harmful solvents and non-scalable synthesis techniques, which hinder the commercial scalability of devices and materials.

We address these concerns by focusing on the sustainable synthesis of halide perovskite and pseudo-perovskite materials using green solvents. We aim at comparing green solvothermal synthesis methods with solvent-free techniques, such as mechanochemical synthesis. We explore traditional lead-based perovskites such as MAPbI_3 and MAPbBr_3 , as well as lead-free inorganic pseudo-perovskites like $\text{Cs}_2\text{AgBiBr}_6$, $\text{Cs}_3\text{Bi}_2\text{I}_9$, and $\text{Cs}_3\text{Bi}_2\text{Br}_9$.

To ensure the scalability of these materials we also investigate the use of slot-die coating as an up-scalable technique to deposit functional thin films. We focus on a single-step deposition process and optimize the coating parameters, such as the solution concentration and dispense rates, to obtain uniform and homogeneous thin films.

This work paves the way for future advances in large-scale production of halide perovskite materials and halide perovskite-based devices and supports the development of green technologies for energy conversion and storage applications.

OPTOELECTRONIC ENGINEERING OF FORMAMIDINIUM LEAD TRIHALIDE PEROVSKITE USING PRECURSOR CHEMISTRY

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Organic metal trihalide perovskite (MTP) has been designated as a photoactive material due to its exceptional optoelectronic features, including a high absorption coefficient and low exciton binding energy.^[1] Notably, formamidinium lead triiodide (FAPbI₃) perovskite exhibits impressive solar cell performance, with a power conversion efficiency of 26%, comparable to that of crystalline silicon solar cells. Given that perovskite can be fabricated at a lower cost compared to its inorganic competitors, numerous efforts have been made to broaden its applicability in various electrical and photoelectronic devices. Nonetheless, drawbacks of FAPbI₃, including elevated defect densities, limited carrier concentration, and inadequate electrical reliability, have constrained its practical uses. To be extensively utilized as a foundational material, like to Si, in optoelectronic and electronic devices, it is imperative to conduct fundamental research on methods to alter FAPbI₃ from its intrinsic optoelectronic properties.^[2] Many studies have been done on the optoelectronic properties of FAPbI₃, but there have been few publications about fine-tuning of precursor chemistry to improve the optoelectronic characteristics of FAPbI₃.

We propose advanced precursor engineering to modulate optoelectronic attributes concerning defect concentrations, carrier concentrations, and electrical reliability. Firstly, precise precursor treatment enables reduction of defects concentration by uniaxially directed perovskite growth, leveraging the complexation of the precursor. Moreover, manipulating the off stoichiometry of precursors to enhance the electrical dependability of FAPbI₃ in solar applications. Finally, electronic doping of FAPbI₃ introduces shallow dopant states while alleviating the adverse impact of impurities that may function as deep-level defects.^[3] This fundamental research on the regulation of optoelectronic structures by precursors will enhance the practical applications of FAPbI₃ as a promising material for electrical and optoelectronic devices.

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PRECISION FABRICATION WITH VAN DER WAALS MATERIALS – AN OVERVIEW

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Van der Waals materials, also known as two-dimensional (2D) materials, such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN), have garnered significant attention for their unique optical, electronic, and mechanical properties. The fabrication of 2D materials involves several key processes, each tailored to optimize material quality and applicability. Exfoliation techniques, including mechanical and chemical methods, enable the isolation of atomically thin layers from bulk crystals, ensuring high crystallinity and minimal defects. Transfer processes play a crucial role in relocating exfoliated or synthesized 2D layers onto desired substrates, often involving polymer-assisted techniques that balance precision and minimal contamination. Stacking methods allow the vertical integration of multiple 2D layers, creating heterostructures with novel interlayer interactions and emergent properties, often controlled with precise rotational alignment to engineer moiré patterns.^[1,2] Finally, nanostructuring techniques, such as lithography, etching, and laser patterning, enable spatial customization, paving the way for devices with tailored functionalities.^[3,4] Together, these fabrication approaches form the backbone of advancing applications in photonics, electronics, and quantum technologies, while ongoing innovations aim to enhance scalability and integration.

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METAL HALIDE PEROVSKITES (& DERIVATIVES): THE PLAYGROUND FOR MATERIALS CHEMISTRY

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Metal halide perovskites (MHPs) are attracting a huge interest for their potential use in different applicative fields ranging from photovoltaics to photocatalysis. The most investigated MHPs possess the archetypal ABX₃ crystal structure, where A= protonated monocationic amine or monovalent inorganic cation, B= Pb, Sn or Ge, and X = Cl⁻, Br⁻, or I⁻. By playing with the nature of the different chemical constituents on the different perovskite sites, it is possible to tune and modulate the optoelectronic properties of the final material and provide materials suitable for different applications. Moreover, by changing the dimensionality of the perovskite structure, *i.e.* moving towards low-dimensional perovskite such as 2D systems, an immense playground for materials chemistry and structural chemistry can be accessed.

In the present contribution, we will present some selected examples in the field of MHPs where, through a rigorous structure-property correlation approach, it was possible to design novel materials with tailored functional properties. This aim requires to devise, synthesize, and characterize rational series of samples to unveil the role of the various chemical degrees of freedom on the optoelectronic properties. We will show how it is possible to design photocatalytically active MHPs to be used in the photogeneration of hydrogen and in the photofixation of nitrogen. This was achieved by selecting suitable amine ligands as well as by understanding the role of central metal ion.^[1-4] The reaction mechanism at the basis of their photocatalytic activity will be also presented, including the role of defect chemistry on the redox activity. A similar materials-design guided approach will be presented for perovskite derivatives used in efficient photodetectors and in the understanding of the chirality transfer mechanisms in chiral perovskite.^[5-6]

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POLYMER ASSISTED TIN-BASED PEROVSKITE SOLAR CELL FORMATION

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Tin halide perovskite solar cells (PSCs) offer a promising low-toxicity alternative to lead-based perovskites but face challenges in achieving optimal stability and efficiency. Control over the crystal morphology is essential to enhance optoelectronic quality and long-term stability. We introduce the use of pyridine-based polymer additives, which form strong complexes with tin and enable controlled crystallization with an antisolvent-free approach. This method improves film reproducibility, resulting in elongated crystals encapsulated within a polymer matrix, forming a perovskite-polymer composite film. Although increased film thickness initially posed challenges, combining these polymers with a low molecular weight pyridine molecule allowed precise control over crystallization with minimal polymer content, enhancing charge transport and reducing grain defects. Through optimized polymer concentrations, we achieved significant efficiency improvements, underscoring the potential of polymer-perovskite composites for stable, efficient, and environmentally friendly photovoltaic technologies.

QUANTIFYING THE EFFECT OF INTERFACIAL DIPOLES ON THE ENERGY LEVEL ALIGNMENT OF METAL-HALIDE PEROVSKITES

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Surface passivation of metal-halide perovskites (MHPs) using organic molecules is a proven strategy to reduce surface defects and enhance device performance.^[1,2] This study employs Density Functional Theory (DFT) calculations to explore how functionalized anilines influence the energy level alignment in methylammonium lead iodide (MAPbI₃). The adsorption process involves both electrostatic interactions and charge transfer, which together modulate the electronic properties of the perovskite. While the dipole moment of the passivating molecule plays an important role, adsorption geometry and surface coverage also critically impact energy level alignment at the perovskite interface. A linear relationship is observed between the dipole moment of the surface-passivating molecule and the perovskite valence band maximum (VBM) energy: increasing dipole moments lower the VBM. Substituents on the aniline have a pronounced effect—electron-withdrawing groups reduce electron density at the interface, weakening the Pb-NH₂ bond, while electron-donating groups strengthen this bond and promote charge transfer from the molecule to the perovskite.

The findings emphasize the dual role of chemical passivation and molecular dipoles in tailoring the perovskite's electronic properties. Chemical passivation raises the VBM by passivating lead ions, while molecular dipoles oriented away from the surface lower it. Treating MAI-rich perovskite surfaces with polar molecules containing electron-withdrawing substituents is proposed as a strategy to optimize energy level alignment, potentially improving charge extraction efficiency in perovskite solar cells. This work provides critical insights into the interplay of molecular and interfacial factors affecting energy level alignment, contributing to the design of more efficient and stable perovskite-based optoelectronic devices.

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CONDUCTIVE THIOPHENE-BASED FIBERS ASSEMBLED BY LIVING CELLS AS NOVEL BIOELECTRONIC MATERIALS

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In recent years, it has been observed that living cells can be employed as active synthesis platforms for the assembly of intrinsically biocompatible bioelectronic materials. This process, which lies at the interface between living and non-living matter, is of fundamental interest since self-assembly in-vivo could allow circumvention of the blood-brain barrier, enabling the delivery of large aggregates or even devices to the brain. Within this context, thiophene-based compounds are pivotal materials for organic bioelectronics, owing to their biocompatibility and their capability for both electronic and ionic conduction.

Here, we report on the cell-mediated assembly of semiconductive nanofibers composed entirely of dithienothiophene-S,S-dioxide (DTTO) aggregates. This molecule spontaneously penetrates the cell membrane, and fibers originate inside cells with the aggregation of the DTTO. These fibers grow “through” cells, reaching and piercing the plasma membrane in one cell to penetrate the adjacent cell, without causing cell death. We extensively characterized the photophysics of DTTO molecules during the various stages of fiber production through steady-state and time-resolved spectroscopy. We observed that the fibers are formed entirely from DTTO aggregates, which dictate the conductivity of the nanostructured material, and described the interaction between DTTO molecules and the protein scaffold. By complementing the spectroscopic data with theoretical calculations, single crystal X-ray diffraction and electrical conductivity measurements, we discovered an extended polymorphism of DTTO in the solid state. Our results suggest that the aggregation occurring in living cells is somewhat unique to the biotic phase, involving at least part of the cell machinery. As the fibers exhibit electrical conductivity, they present a method to directly stimulate cells or to induce artificial gap junctions between cells, potentially affecting signal propagation as occurs in cardiomyocytes, or in general, influencing cell population behavior.

Further studies on the fiber production process are in progress, aiming to pave the way for a wide range of new cell-mediated syntheses of materials or devices.

LASER-ASSISTED MICROMACHINING

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When a complete device is only slightly larger than a human hair, its fabrication could be very tricky to achieve by conventional manufacturing methods. An effective way to overcoming this difficulty is to use a direct writing technique based on pulsed lasers. Their use in micromachining has proven to be extremely versatile, as the principle of their operation is guided by the physics of light-matter interaction: photon energy and wavelength, material band, absorption and energy transfer.^[1] Of all the available regimes (cw or pulsed [ns-ps-fs]), femtosecond lasers represent a clear technological breakthrough, including their ability to generate large electromagnetic fields and to extract large amounts of energy in the form of coherent light. In addition, as the time scale on which the electrons are excited is smaller than the electron-phonon scattering time (about 1 ps), the thermal effect on the material is minimised by increasing the accuracy of the modification.^[2]

Ultrafast laser micromachining has exciting potential for many applications and has led to impressive advances in the study of light-matter interactions. These “fantastic” fabrication tools have an excellent ability to perform three-dimensional processing, particularly in transparent materials such as crystals, glass and polymers, based on a non-linear absorption process that leads to a permanent change in the material structure. This has opened up the possibility of using a powerful laser-assisted tool for micromachining 3D electro-optical- μ fluidic devices where rapid, maskless, high-resolution fabrication is required.

There are many permanent modifications that can be made to various materials: modulation of the refractive index, direct ablation of the material, sintering, material phase change and breaking of specific chemical bonds with periodic induction of the material's density (nanocrack - nanograting). In this context, the laser-assisted wet etching fabrication technique has opened new frontiers in the optofluidic lab-on-a-chip, i.e. complex and easy-to-use microsystems capable of integrating multiple physicochemical processes on a single platform to replicate specific chemical, biological and medical tests typically performed in a laboratory. These miniaturised multifunctional laboratories exploit the synergy between the high sensitivity of optics and the unique ability to manipulate small quantities of microfluidics to develop a new frontier of analytical devices. To demonstrate the potential of this new detection platform, we report on some challenging studies: the detection of micro-objects^[3] (cells, *Escherichia coli* bacteria or microplastics) and Raman analysis of blood, in flow.

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CELL MECHANOTRANSDUCTION DRIVEN BY BIO-ORGANIC OPTOELECTRONIC DEVICES

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Biophysical cues, especially mechanosensation, play a fundamental role throughout life, starting from early embryonic development over function and interplay of cells and tissues in the adult body up to regeneration processes. Tissue regeneration, which includes phenomena like cell division, differentiation, migration and expulsion is triggered by extracellular mechanical cues. ^[1,2,3] The body's capability to regenerate decreases with age and therefore impacts our life in sometimes detrimental aspects. Currently available tools to modulate or control mechanosensation often lack features necessary for *in vitro* and *in vivo* applications, in terms of efficiency, reliability, reversibility and spatial sensitivity.

Here, we show a novel approach to control mechanosensitive ion channels, through exogenous organic semiconductors. Materials in this class are fully biocompatible, thus offering the perspective for *in vivo* application, they can be easily processed in several forms, such as thin films, microstructured devices or nanoparticles. Most importantly, they are characterized by distinctive opto-electrical properties, providing excellent visible light responsivity, as well as electron and ion conductivity.

In this work we explore the opportunity to use organic semiconductors, and in particular conjugated polymers, to remotely control the activation of mechano-sensitive ion channels, in a reliable and effective manner. We critically discuss results obtained with different tools, including polymer thin films and microstructured devices.

Our results may contribute to develop innovative smart materials for tissue regeneration driven by physical cues.

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ACTIVITIES ON SUSTAINABLE ELECTRONICS IN THE PRINTED AND MOLECULAR ELECTRONICS GROUP OF IIT

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In this contribution I will expose the main research activities on-going in the “Printed and Molecular Electronics” group of IIT within the sustainable electronics field. Such activities are tightly related to the IIT Flagship Programme “Technologies for Sustainability”, and are supported by several different European projects. In particular, I will discuss two new projects that are awarded within the EIC Pathfinder Challenge “Responsible Electronics”, one of which is coordinated by IIT. Such projects address future electronics technology with a drastically reduced impact throughout the entire life-cycle, from sourcing of materials to end-of-life of products.

NOVEL PHOTOACTUATORS FOR MITOCHONDRIAL AND BACTERIAL MODULATION: DESIGN, SYNTHESIS AND CHARACTERIZATION

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In the field of cellular stimulation, light offers a high spatiotemporal precision control at low invasiveness, and it allows for remote control of biological functions when combined with photoswitches. In this work, different photochromic systems have been designed, synthesized and characterized to target mitochondria and/or bacteria to control their functions. The designed materials are tailored azobenzenes functionalized with donor and acceptor groups to absorb red light in order to guarantee cell viability and deep light penetration for clinical applications. These switches were designed with a lipophilic cation as a targeting group, which also acts as the acceptor moiety. The efficiency of these photochromes to target mitochondria was investigated by performing colocalization assays using confocal imaging on HEK293 and HUVEC cells. Moreover, absorption and emission spectroscopy measurements were performed for a fundamental characterization of these novel materials.^[1-3] Furthermore, different experiments have been carried out on bacteria (*B. Subtilis* and *E. Coli*) using these switches in order to investigate the possibility to confer light-sensitivity to bacteria so as to create novel biohybrid materials, which can be used in the fields of drug delivery and to minimize antibiotic resistance.

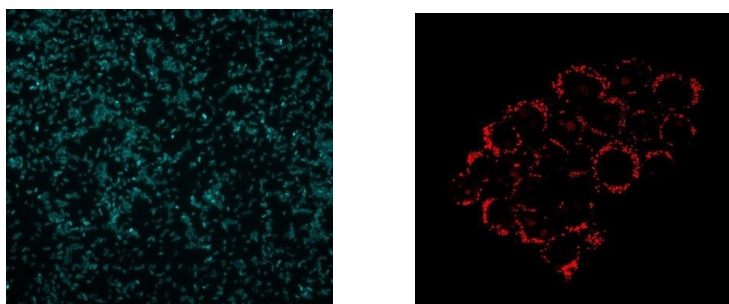


Figure 1: *B. Subtilis* (right) and mitochondria in HEK293 cells (left) stained with novel targeting photoswitches.

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WIDE BANDGAP PEROVSKITE FOR TANDEM SOLAR CELLS APPLICATION

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Metal halide perovskites (MHP) are a class of ionic semiconductors with the formula ABX_3 , where A is a monovalent cation (organic as Methylammonium or Formamidinium, or inorganic as Cesium), B is a bivalent metallic cation (lead or tin), and X is halogen anion (Cl, Br or I). MHP have been used in recent years to fabricate single junction solar cells with efficiencies up to 26.1%,^[1] quickly approaching the radiative limit. The next step to improve efficiency is the fabrication of tandem structures with multiple absorbing layers. Tandem technologies combine a narrow bandgap absorbing layer (bandgap around 1.1-1.3eV) with a wide bandgap (WBG) one (1.7 to 1.9eV). Perovskite, due to its bandgap tunability, is a good candidate for both mixed technologies (for example silicon-perovskite tandems) and all-perovskite ones. WBG perovskites are obtained by crystal site engineering, mainly using a mix of I and Br, in the X site of the crystal. We are working on solving the challenges that their fabrication still poses, regarding mainly the segregation of the halides under illumination and the poor alignment of the charge extraction layers typically used for perovskites with narrower bandgaps.^[2,3]

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FULLY PRINTED FLEXIBLE OFETS VIA INK-JET PRINTING OF ELECTRODES AND A HIGH-MOBILITY ORGANIC SEMICONDUCTING BLEND

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Physical properties of organic materials could allow the development of a distributed, flexible, and wearable electronics, providing solutions to different application fields, including healthcare, security, large-area sensing, and monitoring of goods.^[1] However, large-area, low-cost and sustainable processes are required to transfer research results from a lab-scale scenario to industry.^[2] Inkjet printing is a promising and versatile technique, which allows both conductive metals, semiconductors, and dielectrics to be deposited and patterned directly on the same substrate at low temperatures. Moreover, thanks to the capability of printing large-area complex design related to the drop-on-demand deposition, could enable the fabrication of complementary logic circuits with a CMOS-like configuration. However, fully inkjet printed organic field effect transistors (OFETs) exhibiting mobilities higher than $2 \text{ cm}^2/(\text{Vs})$ have not yet been realized in literature^[3], limiting the final technological scaling-up. Indeed, mobilities higher than $5 \text{ cm}^2/(\text{Vs})$ are fundamental to access a wide range of application, including wireless communication or high-resolution display control, which demand high performances.

Here, we present the fabrication of OFETs via inkjet printing of electrodes and of a high-performing organic blend based on the small-molecule C₈-BTBT and the polymer C₁₆-IDT-BT, reaching the highest mobility and the lowest contact resistance for a system with printed contacts and printed semiconductor. OFETs were fabricated in a top-gate bottom-contact configuration on parylene flexible substrates, and both the gold source and drain electrodes, the semiconductor and the PEDOT:PSS top gate were inkjet printed. With our strategy, OFETs exhibiting a mean field-effect mobility of $8.3 \text{ cm}^2/(\text{Vs})$ in saturation regime, and of $7.7 \text{ cm}^2/(\text{Vs})$ in linear regime were fabricated with a high reproducibility. Such results support the potential of organic printed electronics as a promising candidate for flexible and wearable applications.

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ULTRAFAST DYNAMICS OF SPACE-TIME STRUCTURED LIGHT

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The ability to control and shape light has revolutionized many areas of science and technology, from high-speed communications to advanced imaging. Traditionally, scientists have manipulated the "where" (spatial aspects) and the "when" (temporal aspects) of light separately, each with remarkable precision.^[1] However, recent breakthroughs have shown that combining these two aspects—controlling both the location and timing of light simultaneously—can unlock entirely new possibilities. I will discuss our recent advancements in creating complex spatiotemporal light structures, focusing on the synthesis of novel wave packets that move in spiraling trajectories through space-time.^[2] Using an innovative space-time pulse shaper, which incorporates spatial light modulators and specially designed holograms, we generate light pulses that rotate at ultrafast timescales. These light pulses exhibit unique rotational dynamics, including rapid changes in angular momentum, self-torque, and self-induced angular acceleration.^[3] Furthermore, our technique enables the simultaneous creation and control of multiple complex light patterns, a process known as spatiotemporal multiplexing. This allows us to precisely adjust the timing of each light pulse as needed while ensuring they interact coherently with one another. Our ability to tune the spatial-temporal properties of light on demand opens up new possibilities for exploring ultrafast light dynamics, with far-reaching implications for ultrafast spectroscopy, nano- and micro-structure manipulation, condensed matter physics, and other related areas.

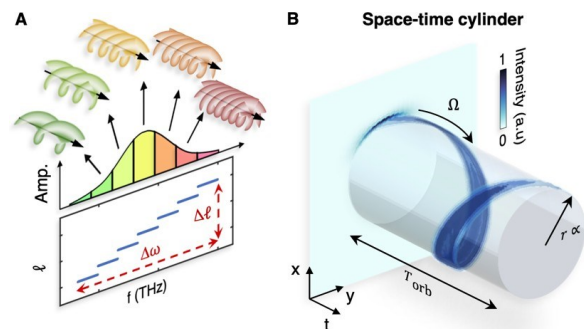


Figure 1: (A) Helical wave packets result from the superposition of vortex modes correlated with an ultrashort pulse's frequency spectrum. (B) Simulation of a helical wave packet, where the mode-frequency correlation determines its angular velocity $\Omega = \Delta\omega / \Delta l$, shaping its helical path within a space-time cylinder.

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CARBON-BASED CATALYSTS IN CATALYTIC OZONATION FOR EFFECTIVE WATER POLLUTANT REMOVAL: INSIGHTS AND FUTURE DIRECTIONS FOR ELECTRICATALYTIC APPLICATIONS

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Carbon-based materials have gained significant attention as catalysts in advanced oxidation processes, particularly for catalytic ozonation^[1] and electrochemical systems^[2] aimed at water pollutant degradation. In catalytic ozonation, these materials enhance the generation of reactive oxygen species (ROS) from ozone, facilitating the breakdown of organic contaminants. Similarly, in electrochemical systems, carbon-based catalysts promote electrocatalytic H₂O₂ formation, contributing to effective pollutant degradation through ROS production.

This study provides a detailed assessment of catalytic ozonation as a treatment method for removing indigo trisulfonate (ITS) due to its environmental persistence, aquatic toxicity, and potential health risks. We focused on the performance of four carbon-based catalysts: activated carbon (AC), multi-walled carbon nanotubes (MWCNT), graphitic carbon nitride (g-C₃N₄), and modified graphitic carbon nitride (C₃N₄-TE). All selected catalysts achieved over 99% ITS decolorization within just 120 seconds of mixing, showcasing the potential of catalytic ozonation as a fast and effective method for dye removal. Mechanistic exploration of the catalytic ozonation process provided insights into the interactions between the catalysts, ozone, and ITS molecules, highlighting the role of ROS in dye degradation. Additionally, adsorption experiments offered valuable information on the role of catalyst surface properties in the catalytic ozonation process. MWCNT, for instance, exhibited the highest adsorption efficiency, removing 43.4% of ITS, while C₃N₄-TE showed lower efficiency at 21.4%, suggesting that surface area, alongside catalytic properties, significantly impacts adsorption efficiency and overall catalytic performance.

Based on these findings, carbon-based materials remain a promising area for further research in water treatment applications. Future studies aim at exploring the integration of carbon-based electrocatalysts in electrochemical systems to generate H₂O₂ in situ, offering an alternative or complementary approach to catalytic ozonation. This electrocatalytic H₂O₂ formation could provide a sustainable pathway for advanced oxidation processes, enabling rapid and efficient degradation of a broader range of water pollutants.

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SPECTRAL MANIPULATION OF QUANTUM EMITTERS IN HEXAGONAL BORON NITRIDE

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Quantum emitters confined in wide-bandgap 2D semiconductors have gained significant attention recently due to their potential as single-photon sources for quantum technologies. Among the various photoluminescent centres, defects in hexagonal boron nitride (hBN) stand out as robust emitters, exhibiting lifetime-limited emission linewidths even at room temperature. However, these emitters often display significant spectral variations depending on the defect type, and reliably generating specific defect types remains a significant challenge, limiting their practical applicability as single-photon sources. In this work, we introduce a method that combines patterned ion implantation with subsequent annealing to simultaneously control the position, type, and emission spectrum of hBN emitters. Furthermore, our approach allows precise selection of the emitter density within the crystal. This method provides unprecedented control over the properties of quantum emitters in hBN, representing a critical step toward engineering emitter ensembles that can be seamlessly integrated into Van der Waals heterostructures and advanced quantum systems.^[1]

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ASSEMBLY OF EDIBLE ELECTRONIC DEVICES AND SMART FOOD MONITORING LABELS VIA A CORN-BASED CONDUCTIVE GLUE

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Edible electronics is a research field focused on developing functional devices wherein all components are designed to be safely ingested and digested by the gastrointestinal track.^[1] Devices that can be handled similarly to food, from a safety and recyclability perspective, have applications as food monitoring systems to prevent spoilage or smart gastrointestinal theragnostic capsules.^[1,2] The swift evolution of the field has already led to edible electronic devices as edible sensors,^[3] antennas,^[4] batteries^[5] and transistors.^[6] However, strategies for the assembly of these components into complex electronics or their interface with food to fulfill the aimed applications while complying with edibility constrains is a fundamental and as-yet-largely unexplored aspect.

Here, we have developed an edible electrically conductive adhesive, made out of zein (a protein from corn) as adhesive matrix and activated carbon (food additive E 153) as conductive filler, with a small footprint and compatible with several deposition techniques. Adding activated carbon to zein does not only confer electrical conductivity, with a resistivity of $3 \cdot 10^3 \Omega \cdot \text{cm}$, but also increases the overall robustness with a twelve-fold enhancement in adhesive strength, reaching up to 2 MPa. As proof-of-concept, our adhesive has been validated in the surface mounting of devices on top of innovative edible substrates and interconnecting state-of-the-art edible devices. Notably, the obtained circuits show good and longtime functioning indicating a lack of resistive load and large time stability of the glue. Additionally, our material easily adheres to fruit, constituting long-term stable adhesive electrode labels, enabling food monitoring (Figure 1). Our findings open thus the door to development of fully edible circuitry and biodegradable edible sensors for agriculture.

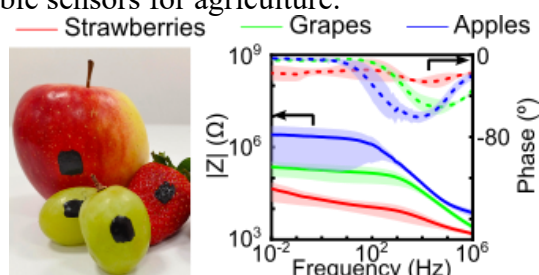


Figure 1: Adhesive edible electrodes on top of fruits. Mean absolute bio-impedance modulus (full line) and phase (dashed line) over three strawberries, grapes and apples measured with edible adhesive electrodes.

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ULTRAFAST MOLECULAR CHIRALITY: A TOPOLOGICAL CONNECTION

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An object is said to be chiral if it cannot be superimposed on its mirror image by any rotation. The two mirror images of the same chiral molecule are called enantiomers and are often referred to as “left”- and “right”-handed. While the physical properties of the two enantiomers of the same chiral molecule are nearly identical, the geometric property of chirality leads to vastly different chemical properties of the two enantiomers. The need for rigorous selection of a specific enantiomer, a now standard requirement in drug design, is one of the many reasons behind the ever-greater need for improving sensitivity of chiral sensing.

Yet, standard optical methods of chiral detection still use the same principles as the method discovered by Louis Pasteur in the XIX century: the linear interaction between chiral molecules and light, which becomes chiral-sensitive due to the magnetic field component of the light wave.

Ultrafast non-linear spectroscopies promise to increase the enantio-sensitive signal by three orders of magnitude^[1] by removing the need to rely on the interaction with the magnetic field component of light. The second important feature of non-linear light-matter interactions is the opportunity to imprint topological properties of light on matter, presenting an opportunity to achieve topologically robust enantio-sensitive observables.

I will describe our very recent results^[2,3,4] on marrying chiral and topological properties in ultrafast electronic response of chiral molecules in the gas phase, enabling highly efficient and robust chiral observables. I will present three vignettes where topological connection appears in optical or electronic chiral response:

- (i) **Chiral topological light:** a new concept enabling chiral-sensitive and topologically robust properties of high harmonic emission, generated by such light in chiral molecular gases^[2]
- (ii) **Geometry of temporal chiral structures:** a concept encompassing the emergence of geometric fields in electronic response of chiral molecules^[3]
- (iii) **Enantio-sensitive exceptional points:** chiral topology in non-Hermitian chiral systems^[4]

Acknowledgements: ERC-2021-AdG project *ULISSES*, grant agreement No 101054696

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[3] Geometry of temporal chiral structures, A. F. Ordonez, A. Roos, P. Mayer, D. Ayuso, O. Smirnova, arXiv preprint arXiv:2409.02500, 2024

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TOWARDS EDIBLE GAS SENSORS TO REDUCE FOOD WASTE

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According to the United Nations Environment Programme report on the Food Waste Index,^[1] around 18 % of the world's food production is being wasted along the food chain. Moreover, food waste also accounts for about 10% of the world's greenhouse gas emissions, representing a universal challenge for the rising global hunger and climate change. In this context, technologies that constantly evaluate the state of the food are required to prevent its spoilage and consequent waste.

For these reasons, we first focussed on identifying the most relevant target gases produced in the packaging headspace of salmon meat samples during their spoilage. Gas Chromatography-Mass Spectroscopy experiments confirmed that sub-ppm to a few ppm range concentrations of Ammonia and Trimethylamine gases are the main gas products during spoilage. The known gas concentration was also correlated with the total volatile basic nitrogen (TVB-N), a standard indicator for food freshness.^[2] Furthermore, we developed gas sensors based on Organic Field Effect Transistors (OFET) to detect low concentrations (sub-ppm level) of those target gases produced upon food deterioration, which can be used as early indicators of food degradation. Finally, preliminary results on a fully edible gas sensor enable their safe introduction into food packaging without being harmful even in case of ingestion.

Acknowledgements: Pierluigi Mondelli is grateful to Valerio Francesco Annese for his support in Matlab programming.

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MEMBRANE POTENTIAL MODULATION IN BACTERIA VIA PUSH-PULL AZOBENZENE

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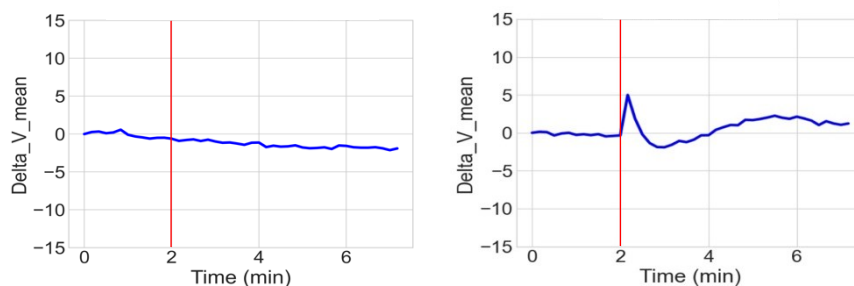
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Optomodulation uses light to artificially alter physiological or metabolic functions in organisms on single-cell basis.^[1,2] In particular we photostimulate *Bacillus subtilis* after exposure to NO₂-2(C₆-Pyr), a recently developed azobenzene molecule. Its exposure to visible light (470nm) leads to a trans-cis isomerisation reaction, accompanied by a strong change in the dipole moment thanks to the electron-donor acceptor moiety (Push-Pull effect). This in turns leads to a decrease of the membrane potential (depolarization) and a subsequent modulation of the cellular signalling. Here, we show that a membrane-targeted azobenzene is able to modulate the membrane potential via visible light stimulation. Specifically we observed, via fluorescence microscopy, a depolarization across the cell wall that occurred within 10 seconds after a 10 seconds light pulse and the recovery of resting membrane potential lasted an amount of time dependant on the concentration of NO₂-2(C₆-Pyr). Furthermore we observed that the exposure to this molecule can also lead to an increase of the antibiotic tolerance, suggesting the involvement of membrane potential in the phenomenon. These results show our capability to influence bacteria membrane potential with optomodulation systems, which will allow us to better understand and analyze microbial physiological mechanisms on quantitative and qualitative basis.

Figure 1: depolarization effect measured during timelapse under exposure to 470nm light pulses.



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ORGANIC THERMOELECTRICS: ENGINEERING MATERIALS TOWARDS APPLICATION

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Organic thermoelectric generators (OTEGs) are energy-harvesting systems exploiting the Seebeck effect of carbon-based conjugated materials to convert thermal gradients into electric energy. The abundance, low-toxicity, and easy tunability of organic semiconducting materials compared to their inorganic counterpart, along with the scalability of the fabrication techniques promise to deliver a safe, low-cost, and adaptable power source to sustainably operate electronic devices and sensors with limited energy demands (1 – 100 μ W), typically required in IoT and wearable applications.^[1]

As the most efficient design of OTEGs requires the use of both p- and n-type materials, the latter constitutes the most challenging obstacle both in terms of thermoelectric properties and environmental stability. Molecular doping is indeed a necessary strategy to improve the charge transport properties of the semiconducting materials. Herein, we provide some new insight on the use of benzimidazoline compounds as n-dopants. Observations acquired from separate investigations on dopant degradation in atmosphere and on the chemical tuning of the benzimidazoline structure can be both interpreted and understood in terms of modifications of the interactions with the semiconductor at the structure-property level. These results pave the way to the development of new synthetic design rules and strategies for molecular doping.^[2,3]

Even if the focus of research is still on the understanding and optimization of thermoelectric properties of organic materials, some promising candidates have recently emerged allowing the development of OTEG prototypes. In this framework, some relevant examples of device design and fabrication strategies devised in our group will be shown. Considering the diverse nature and geometry of the available thermal gradient sources, both solutions with an in- and out-of-plane architecture have been evaluated, leveraging on the facile processability of organics enabling direct-writing deposition techniques on flexible substrates. The use of tailored fabrication methods allows to greatly increase the power output per unit area generated by these devices. The realized OTEGs do not yet meet the requirements to operate commercial electronic devices, providing only a power density few tens of nW/cm², nevertheless they demonstrate that, by combining efficient design rules and fabrication techniques with the expected improvements in material performances, OTEGs constitute a viable and advantageous harvesting system to reduce consumptions.

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[3] F. Pallini, *ACS Applied Energy Materials* **2023**, 5, 2.

ADVANCES AND PERSPECTIVES IN KESTERITE SOLAR CELLS

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This presentation explores the critical role of kesterite $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ (CZTSSe) solar cells in advancing sustainable energy solutions. Kesterites are highlighted for their environmental friendliness, low cost, high stability, and tunable bandgap, making them promising candidates for applications such as tandem devices, flexible solar cells, and indoor photovoltaics. Despite their potential, challenges like the V_{oc} deficit and efficiency gaps compared to commercial CIGS solar cells—the thin-film technology from which kesterites are conceptually derived—persist.

Innovative strategies to address these limitations are examined, including doping, advanced growth techniques, and defect engineering. The development of non-toxic alternative buffer layers using ALD technique and scalable processing methods are also discussed as critical steps towards improving efficiency and scalability. Furthermore, state-of-the-art tandem architectures combining perovskites and kesterites are presented, demonstrating their compatibility and potential for enhanced performance.

This work highlights the pivotal role of CZTSSe among emerging solar cell technologies, emphasizing its evolution from CIGS and its potential to complement and diversify the photovoltaic landscape.

By overcoming current technical challenges and intensifying research activities, kesterites could become one of the key players in the future of photovoltaics, contributing to a more sustainable and decarbonized energy future.

DESIGNING MINIATURISED IMPLANTABLE ELECTRONIC BIOSENSOR FOR CARDIAC HEALTH MONITORING

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Cardiovascular diseases remain a leading cause of mortality globally, underscoring the need for continuous cardiac health monitoring.^[1] With this goal in mind, a recently funded EIC Pathfinder Challenge project named *IV-Lab* (acronym for “In-vessel implantable smart sensing device for personalised medicine”) brings together various expertise across Europe to develop a multi-sensing micro-device to monitor heart disease progression, enabling prompt and personalized treatment by physicians.^[2] Our group will contribute by designing and developing a miniaturized electronic transistor-based biosensor for the detection of cardiac troponin, a critical biomarker for heart injury and disease diagnosis, which is to be integrated within a compact implantable platform measuring just 1-2 cm in length and 2-4 mm in diameter.

Scaling down transistor-based biosensing platform^[3] presents significant challenges related to signal sensitivity, selectivity, and integrity. As the device size reduces, maintaining accurate detection becomes increasingly difficult due to inefficient electrostatic control over the transistor channel owing to reduced capacitive coupling. Furthermore, real-time continuous selective detection of analyte in complex biological fluids, such as blood, requires appropriate selection of biorecognition element. Therefore, ensuring signal integrity demands innovative solutions in material selection, device architecture, signal transduction mechanism, and data interpretation. Here, I will discuss these challenges and potential design rules to guide the development of such a sensing platform along with the initial results.

Acknowledgements: This project has received funding from the European Innovation Council (EIC) under the European Union’s Horizon Europe programme (Project Number: 101115545).

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FABRICATION AND CHARACTERIZATION OF ORGANIC POLYMER-BASED MEMRISTIVE BIOSENSORS

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This work discusses the fabrication, functionalization, and characterization of simple, cost-effective, polymer-based memristive devices for biosensing applications, within the framework of flexible electronics. Memristive devices are considered a promising route for biosensing and have been demonstrated to allow sensitive detection of proteins and viruses.^[1-3] The quantification of analytical signals relies on measuring the voltage gap in their semi-logarithmic hysteretic current-voltage (I-V) characteristics, defined as $V_{\text{gap}} = - (V_{\text{DS}}|_{\text{negative-min}} - V_{\text{DS}}|_{\text{positive-min}})$, where ‘negative-min’ and ‘positive-min’ refer to the current minima in the scans for the I-V measurement in the negative and positive voltage ranges, respectively.

Particularly, a blend of poly(3,4 ethyldioxythiophene) poly(styrenesulfonate) and poly(vinyl alcohol), PEDOT:PSS-PVA, was employed, since it was proven to possess the desired memristive properties.^[4] The analyte of interest was the prostate-specific antigen (PSA), but the devices were also functionalized with an ion-selective membrane for the detection of ammonium ions. PSA is a biomarker of critical importance for prostate cancer, one of the most common cancers diagnosed in men. PSA levels in the bloodstream are considered suspicious when they exceed 4.0–6.5 ng/mL, and a biopsy is recommended if there is an increase of more than 0.75 ng/mL within one year.^[5] Therefore, after functionalization with anti-PSA antibodies, the devices were used to detect PSA in a range perfectly covering the clinical levels.

Ammonium detection proved to be unreliable, exhibiting low sensitivity and a high standard deviation. In contrast, prostate-specific antigen detection was successfully achieved with highly promising results. These devices also represent a pioneering effort and are the first of their kind in this field.

Acknowledgements: This work was funded by the In-Memory Sensing (In-Me) project (project code SNF/200021L204496/1). The authors would like to also thank the EMERGE project (European Union’s Horizon 2020 research and innovation program, grant agreement number 101008701) and the FH Joanneum, Graz, Austria, for their help in providing instrumentation for SEM measurements.

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INVESTIGATING TWISTED HBN MOIRE' SUPERLATTICES BY AFM

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When a marginal twist angle is applied between two layered materials, the atomic reconstruction shapes the interfacial atomic registry providing a moiré superlattice.^[1-3] In this talk I will address how atomic force microscopy (AFM) can be a powerful tool for investigating moiré superlattices in twisted hexagonal boron nitride (hBN). Specifically, I will first present tapping mode phase imaging as a simple AFM technique to visualize moiré patterns without the need for complex setup or sample perturbation.^[4] Then, I will move towards piezo force microscopy as the proper AFM method to study the electro-mechanical properties of twisted hBN moiré superlattices.^[5]

Acknowledgements: Authors acknowledge funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme 'METAmorphoses', grant agreement no. 817794.

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SOLUTION PROCESSED FLEXIBLE UV-VIS-PHOTODETECTOR BASED ON CSPBBR₃ PEROVSKITE-POLYMER COMPOSITE FILM

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This study presents the development and characterization of a flexible, solution-processed UV-vis photodetector employing a composite film of CsPbBr₃ perovskite merged with PVP polymer and covered by a PCBM layer. The device is fabricated with scalable and cost-effective methods adaptable both on rigid and flexible substrates. The active layers are obtained through a facile solution-based deposition on top of ink-jet printed interdigitated electrodes. The presence of the polymer and of the PCBM layer in the composite film improves its surface coverage, surface passivation, light absorption and stability. The optimized CsPbBr₃-polymer based photodetector has a photo-to-dark current ratio of 3.5×10^3 at 5 V applied bias, a responsivity $> 1 \text{ A W}^{-1}$ across the whole visible range, with a peak of 64.4 A W^{-1} at 410 nm and the specific detectivity can be estimated to reach 3.2×10^{12} Jones. The detector, which is symmetric, works along a photoconduction regime, though shows reasonably short rise and fall times of 657 and 835 μs , respectively. The performances of the device are stable over 12 weeks under ambient environmental conditions.

The scalability and compatibility of the solution-processing method hold promise for large-scale manufacturing of cost-effective and flexible UV-vis photodetector devices and opens avenues for the integration of perovskite materials into diverse optoelectronic applications.

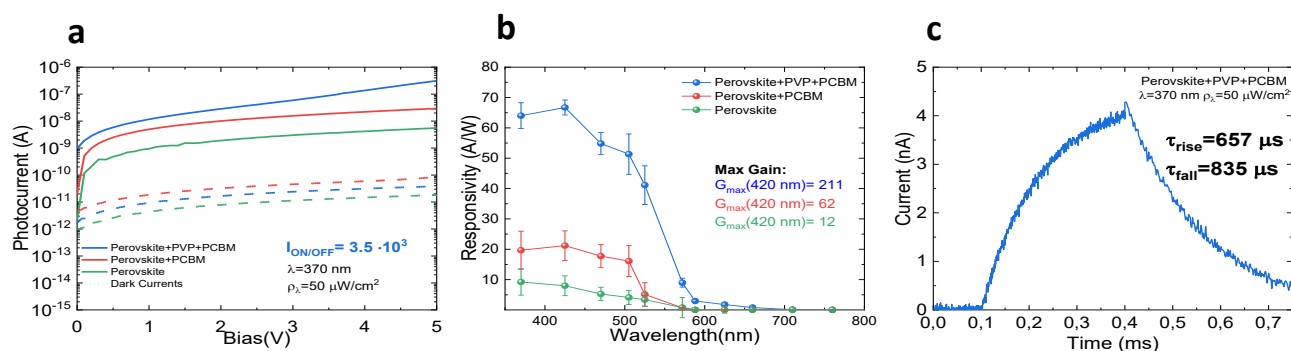


Figure 1: a. Comparison of Dark and Photocurrent measured at $\lambda = 370 \text{ nm}$ and b. Responsivity of devices with plain perovskite, plain perovskite with PCBM layer, and composite perovskite film with PCBM layer. c. Rise and Fall Time of the composite device excited by a $\lambda = 370 \text{ nm}$ light impulse.

HIGH-MOBILITY, FLEXIBLE AND LOW VOLTAGE SOLUTION PROCESSED OFETS FOR HIGH-SPEED ELECTRONICS

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Efficient wireless communication at low voltages (≤ 10 V) is an important feature for many applications of distributed electronics such as smart labels, security, healthcare and large-area biosensing. In addition cost-effective fabrication, flexibility and sustainability are of fundamental relevance. In this framework organic electronics has the potential to become a disruptive technology since organic devices can be solution fabricated at low temperature on flexible substrates. However, so far the frequency operation of organic field-effect transistors (OFETs) at low voltages rarely exceed few MHz. One challenge is related to charge injection in solution processed organic semiconductors in which a high level of energetic disorder is present. Another issue is the capability of solution deposit very thin organic insulating layers with good dielectric properties in terms of leakage currents. In this work it is demonstrated the successful integration of a solution processable high-mobility organic blend in OFETs with a 1.3 μm channel and a 1.9 μm gate overlap. Organic blends take the advantage of easy the solution processability of small molecules over large area, retaining at the same time good electrical performances as a consequence of phase segregations. Thanks to the combination of molecular doping (to reduce contact resistance) and the use of a novel ultra-thin all-organic dielectric stack, a mobility as high as 3 $\text{cm}^2/(\text{Vs})$ in such downscaled structures was obtained, allowing a transition frequency of 23 MHz at -8 V. This result is of fundamental importance for the development of high-speed and low-power IoT electronics.

2D OR NOT 2D, THAT IS THE QUESTION

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Surface passivation with ammonium salts, such as phenylethyl ammonium iodide (PEAI), is a well-established strategy to enhance the stability and optoelectronic properties of 3D metal-halide perovskites (MHPs).^[1] PEAi efficiently passivates surface defects and shields perovskite films from environmental stress, while also facilitating the formation of quasi-2D perovskite layers.^[2] Over time, the higher thermodynamic stability of 2D perovskites can lead to the abstraction of PbI₂ layers from the underlying 3D perovskite, resulting in mixed-dimensional structures. To investigate this dynamic, we performed first-principles Density Functional Theory (DFT) calculations, assessing the thermodynamic competition between PEAi surface passivation and the formation of 2D perovskite layers. Our findings demonstrate that hybrid 2D/3D structures are more stable than 3D perovskites passivated solely by PEAi. These results provide valuable insights into the development of MHPs with enhanced stability and optoelectronic performance, highlighting the critical role of processing conditions in optimizing dimensionality.

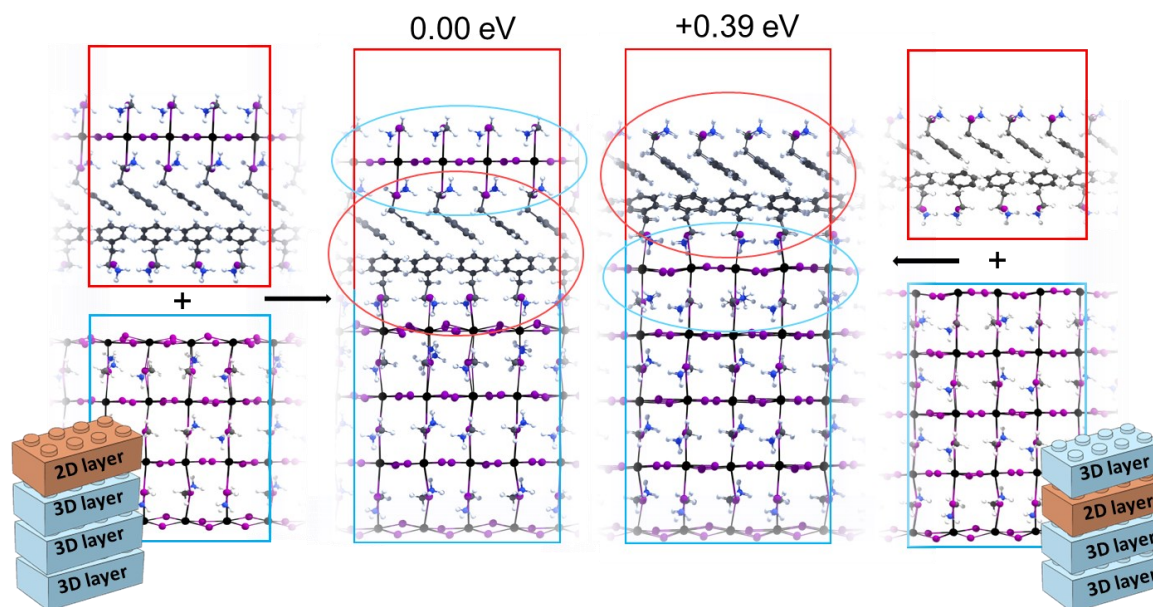


Figure 1: Representation of the assembly of the two modelled structures.

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TOWARDS EDIBLE TECHNOLOGY FOR GASTROINTESTINAL TRACT MONITORING AT THE POINT-OF-CARE

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Ingestible technologies - first introduced in 1957 - are miniaturised swallowable devices that collect diagnostic data in the gastrointestinal (GI). Although these devices have reached a high complexity and produced a \$819 million market in 2022, they are employed in hospital settings rather than at the point-of-care (POC) due to safety concerns over the use of non-degradable, rigid, and potentially toxic materials. Edible electronics is an emerging research area leveraging the electronic properties of food-derived materials to deliver safe-to-eat technology. Their inherent safety and degradability make them ideal for GI tract monitoring as edible systems can be metabolised by the body after performing a specific task, leaving no e-waste, eliminating health risks and removing the need for hospitalisation. Such edible systems would enable POC testing of the GI tract. However, despite recent advances, further research is needed to develop fully edible systems.^[1]

This work presents the concept and latest advancements of an edible POC system for GI tract monitoring, demonstrating H₂O₂ detection – a common intermediate product of enzymatic assays. The system includes microfluidics, transducer, and bioreceptors – all in an edible format. Candidate materials for passive edible fluidics were assessed and capillary microstructures were fabricated using PVA-gelatin-glycerol hydrogels via replica moulding. A partly-edible transistor, using a semiconductive toothpaste pigment,^[2] an ion-gel electrolyte, and gold electrodes, is the transducer. Enzymes and substrates commonly present in food (horseradish peroxidase (HRP) and caffeic acid) were employed as bioreceptors to replicate standard redox enzymatic assays as a biorecognition mechanism. Further cascade enzymatic reactions will be used to implement a biosensor for gastric enzymes. The future integration of these components will pave the way to an unprecedented edible system offering unique advantages for POC GI tract monitoring: this MSCA action ‘EDISENS’ works toward the vision that clinical testing will be as easy as eating candy one day.

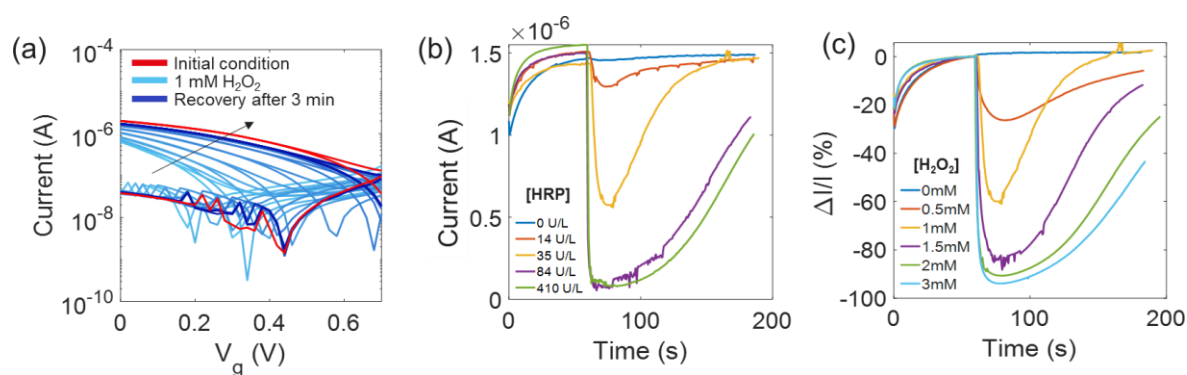


Figure 1: (a) The biorecognition reaction produces a potentiometric signal which modifies the response of the transistor. (b) Sensor current output at a fixed bias point for different concentrations of HRP enzyme at fixed 1 mM H₂O₂. (c) Normalised sensor output for different concentrations of H₂O₂ at fixed 35 U/L HRP.

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EDIBLE RECHARGEABLE BATTERIES

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Edible rechargeable batteries are a new opportunity for energy storage, currently dominated by toxic materials. Being entirely made of food-derived materials and additives, such batteries open the way to electronic systems characterized by unprecedented features. Their intrinsic safety and sustainability can be key in next-generation medical and agrifood low-power electronic devices, replacing traditional batteries and reducing health hazards and environmental impact.

The battery is based on the redox reaction between two molecules commonly found in food, riboflavin and quercetin, with an operating voltage of ~ 0.65 V. All the battery components are fabricated using materials that can be safely ingested, like activated carbon, edible gold leaves, ethyl cellulose, and beeswax. Edible battery stability has been extensively tested, showing a stable capacity of ~ 20 μ Ah over two weeks of storage at room temperature. The possibility of implementing these batteries in different scenarios has been verified by cycling them in various environmental conditions, proving stable performance between 0 and 37 °C. Successful integration with both traditional and edible electronic components has been achieved, indicating a feasible path along the development of edible batteries as critical components in sustainable agrifood IoT nodes and power supplies in future edible electronic systems for medical and food monitoring applications.^[1,2]

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AMPHIPHILIC MOLECULAR PHOTOTRANSDUCER ENABLES CONTROL OF SKELETAL MUSCLES CELLS AND TISSUES CONTRACTION

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Interacting with living cells has always been a challenging problem. Since the biological environment can be associated with an electrolyte, commonly used electrical stimuli tend to spread through biological tissue, losing their localization. Furthermore, the presence of wires, usually required to properly deliver this stimulation, alters the biological environment and introduces issues related to the presence of the wires themselves.

Looking for a contactless and wireless stimulation methods, light represents a clean and spatiotemporal precise tool to achieve effective bio-stimulation.^[1,2]

Material-based light-transducers, such as conjugated molecules and macromolecules, have proven their efficacy at the interface with living cells and tissues. The interaction is made possible thanks to the photophysics, biocompatibility and versatility in chemical synthesis of the molecular actuators.^[3-5]

By exploiting a biomimetic approach a molecular phototransducer will be presented analysing both its photo/chemical properties and its ability to control cell activity. As a case of study an azobenzene-based photoswitch called Ziapin2 has been used for pacing muscle cells contraction. In addition to photopacing, we also evaluate the energy requirements of this approach comparing it to the traditional electrical one.

Finally, we also employ classic tissue engineering techniques for the realization of *in vitro* microphysiological systems. These systems can mimic the native properties of a muscle and can be used for creating bio-hybrid actuator, regenerative medicine tools, drug testing and diseases screening platforms.

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FULLY DEGRADABLE, TRANSPARENT, AND FLEXIBLE PHOTODETECTORS USING ZNO NANOWIRES AND PEDOT:PSS:AG NANOWIRES-BASED NANOFIBRES

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Photodetectors (PDs) are crucial devices for flexible optical-electronic systems and their applications in high-capacity wireless communication and light fidelity (Li-Fi). They also provide attractive alternative solutions for human activity monitoring in a smart home or privacy-sensitive environments. Their transparency, flexibility, and conformability also enable use in wearable technology and smart textiles. Many of them have been developed through conventional microfabrication techniques, such as electron beam lithography, which enable precise patterning but are costly, complex, and produce (planar) rigid devices. To make photodetectors suitable for daily life applications, they need a flexible form factor. One approach involves embedding rigid devices into flexible substrates, yet high deformation can cause functionality loss due to material differences, which leads to detachment. Fully flexible systems, including active layers and electrodes, are needed, ideally developed through simpler, resource-efficient manufacturing methods. Active electronics on textiles have been explored to address the above shortcomings using either printing functional inks on clothes/fabric or yarn and fibre-based devices. The electrospun fibre-based approach is another attractive option which has been used to draw fibres from a viscoelastic fluid. In addition to being cost-effective, it offers scalability, customisability and the capability to successfully produce fibres, with diameters down to tens of nanometres, from various materials, including polymers, ceramics, small molecules, and their combinations.

Considering the above, we report here fully degradable, transparent, and flexible PDs. The developed PDs consist of transparent conductive electrodes based on PEDOT:PSS/AgNWs electrospun fibres, on flexible and biodegradable cellulose acetate (CA) films. With sheet resistance of 11 Ω /sq and optical transmittance of 79 % at a wavelength of 550 nm, the electrospun PEDOT:PSS/AgNW-based fibres, offer an attractive eco-friendly solution for transparent conductive electrodes (TCEs). Alternative facile methods such as dip, and spray coating of various organic/inorganic composites have been reported in the literature to obtain low sheet resistance and flexible TCEs. However, their reproducibility is a major challenge because of uncontrollable fabrication steps. The TCEs here were patterned using a mechanical blade cutter to develop the two sides of the electrodes for PDs. Following this, the photosensitive material, i.e. ZnO NWs, was drop-casted to bridge the two electrodes. The developed PDs showed excellent responsivity (1.10×10^6 A/W). The device demonstrated good stability under dynamic exposure to UV light on both flat and curved surfaces and optical transparency of 70 %. Moreover, the full degradability of devices is an attractive solution for emerging challenges such as electronic waste. The obtained results show the presented devices hold considerable potential for flexible and see-through optoelectronics and wearable systems.

AMPLIFIED SPONTANEOUS EMISSION PROPERTIES OF METAL CATION TWO-DIMENSIONAL PEROVSKITES

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Metal halide perovskites have rapidly emerged as excellent optical gain media with the potential in laser technology. In 2014, room temperature laser emission was first achieved using 3D perovskite materials, underscoring their promise.^[1,2] Additionally, reducing the thickness of halide perovskites enhances the binding energy of excitons, leading to strong light emission even at high temperatures. Specifically, 2D halide perovskites are ideal candidates for highly compact and ultra-low threshold lasers due to their large exciton binding energy, efficient radiative recombination, and excellent environmental stability. Previous studies have reported that mechanically exfoliated 2D lead-based perovskites ($n > 1$) can achieve optically pumped laser emission in the visible light region without the need for an external resonant cavity.^[3] However, the laser properties of 2D lead-based perovskites have only been observed in bulk crystals or under external cavity conditions.^[4] Recent research has also shown that 2D tin-based perovskite films exhibit excellent spontaneous emission amplification properties,^[5] although this behavior has not been observed in corresponding 2D lead-based perovskites. There is still controversy regarding the intrinsic properties of the optical gain medium material itself, generally thinking that 2D lead-based perovskite films have inherent limitations that make spontaneous emission amplification very difficult to achieve, even at low temperatures. Similarly, achieving a stable output ASE signal at room temperature in tin-based perovskite films remains a big challenge. To address these challenges and better understand the properties of two-dimensional perovskites as optical gain media, we selected the commonly used material PEA_2Xl ($\text{X} = \text{Pb}, \text{Sn}$) and employed pulsed lasers for optical pumping. This approach aims to reveal the underlying mechanisms of the spontaneous emission signal, and we have made some progress in this endeavor.

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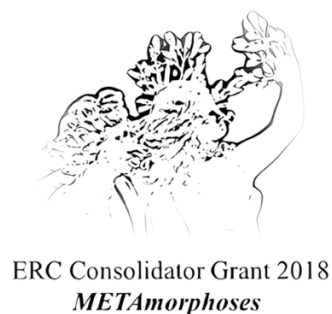


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