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(ICP2DC7)

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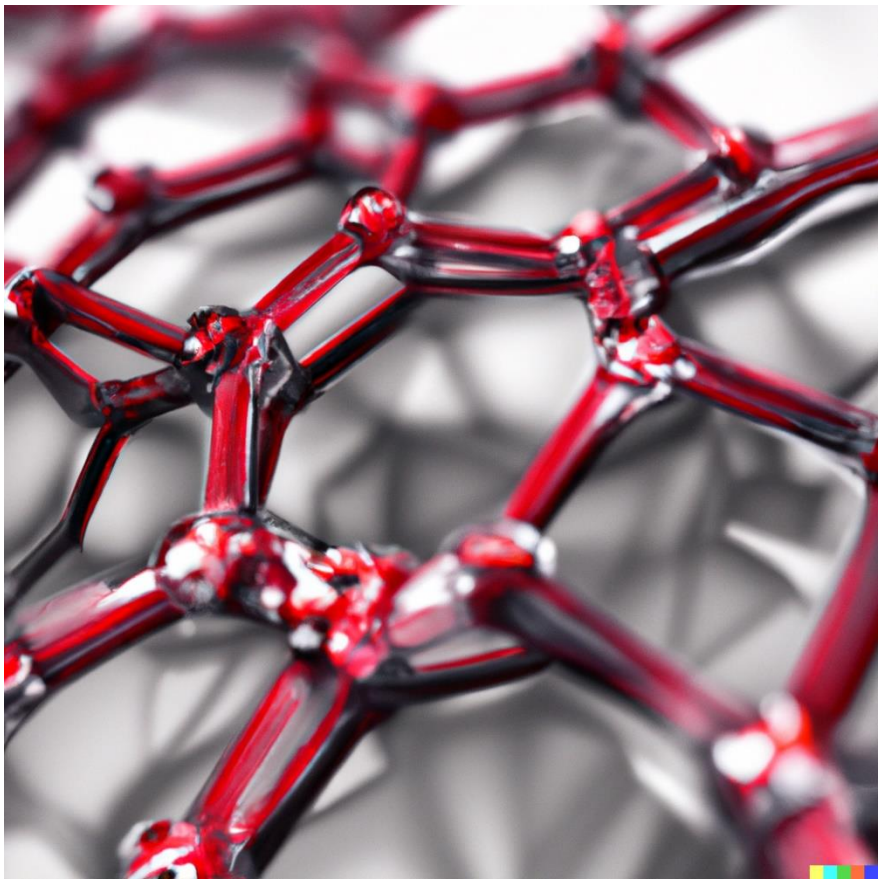

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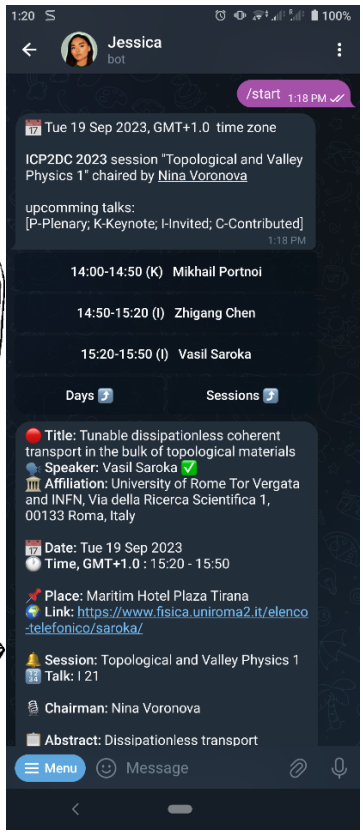
Foreword

Over the past two decades the area of 2D materials has seen a drastic development in terms of breadth and depth. Nowadays the variety of the available systems ranges from mono elemental single layers to complex Van der Waals stacks and twisted moiré structures. The 7-th edition of the International Conference on Physics of 2D crystals (ICP2DC7) has focused on the several key areas of such systems: Excitons and Optics, Characterization Techniques, Collective and Non-linear effects, Fabrication Technology and Quantum Emitters. It provides an overview of the achieved progress as well as it puts forward some novel problems and questions among those are existence of excitonic insulators, limitations of 2D materials usage in metrology, condensed matter simulation in photonic systems, Rydberg states in excitons, photonic nano waveguides, materials for 2D transistors, lossless transport and quantum communication and computing. The ICP2DC7 was a unique academic meeting in terms of adopting digital transformation and paperless technology. During the conference the program was managed using a chat bot. This first attempt of a fully paperless event has demonstrated an impressive outcome. Despite a few reported issues with registration and time zone settings, about 50% of participants had registered in the chat bot before the event and actively used chat bot during the conference sharing information with other participants. While dynamically updated digital program was used during ICP2DC7, these proceedings are meant to support the paperless initiative and maintain in a static digital form the long-term broad-audience availability of abstracts presented at the ICP2DC7.



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Are Xenes excitonic insulators?

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Using a variational approach, the binding energies E_b of the lowest bound excitons in Xenes under varying electric field are investigated. The internal exciton motion is described both by Dirac electron dispersion and in effective-mass approximation, while the screened electron-hole attraction is modeled by a Rytova-Keldysh potential with a 2D electronic polarizability α_{2D}. The most important parameters as spin-orbit-induced gap E_g, Fermi velocity v_F and α_{2D} are taken from ab initio density functional theory calculations. In addition, α2D is approximated in two different ways. The relation of E_b and E_g is ruled by the screening. The existence of an excitonic insulator phase with $E_b > E_g$ sensitively depends on the chosen α_{2D}. The values of E_g and α_{2D} are strongly modified by a vertical external electric bias U, which defines a transition from the topological into a trivial insulator at $U = E_g /2$, with the exception of plumbene. Within the Dirac approximation, but also within the effective mass description of the kinetic energy, the treatment of screening dominates the appearance or non-appearance of an excitonic insulator phase. Gating does not change the results: the prediction done at zero electric field is confirmed when a vertical electric field is applied. Finally, Many-Body perturbation theory approaches based on the Green's function method, applied to stanene, confirm the absence of an excitonic insulator phase, thus validating our results obtained by ab initio modeling of α_{2D}.

Excitons in mesoscopically reconstructed moiré heterostructures

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The rational design of a moiré heterostructure based on two layers of transition metal dichalcogenides [1] makes it possible to control the exciton properties in this structure. In addition to the mismatch of the lattice constants in the layers, or the relative twist of the layers, lattice reconstruction in such materials also changes these properties. We study the mesoscopic reconstruction pattern, which can be understood by combining scanning electron microscopy imaging and modeling of lattice displacement fields. The correlation of the optical response with the observed patterns of reconstruction makes it possible to create a map of exciton features in the reconstructed heterostructures. Reconstruction control opens the way to spatial tuning of the exciton landscape in quantum optoelectronic devices [2].

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Multi-Qubit Photonic Devices

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Semiconductor quantum dots are one of the best on-demand sources of single and entangled photons to date, simultaneously merging the highest brightness and indistinguishability of the emitted photons. They are, therefore, among the strongest candidates for practical single-qubit quantum photonic devices. However, to exploit the full advantage of quantum physics, *multi-qubit* photonic devices are vital. This talk will present our approach to realizing practical *multi-qubit* photonic devices for quantum photonic networks based on novel *crystal-phase quantum dots* in nanowires [1] (see Fig. 1).

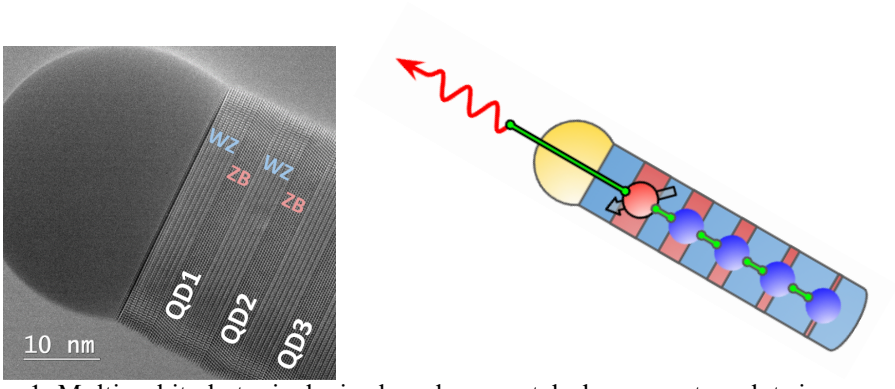

Figure 1: Multi-qubit photonic device based on crystal-phase quantum dots in a nanowire.

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Probing chiral farfield properties of monolayer transition metal dichalcogenides coupled to resonant nanoantennas

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Monolayer transition metal dichalcogenides (1L-TMDCs) are subject to extensive research activity since more than a decade due to their remarkable optical, electrical, chemical, and mechanical properties. Prominently, 1L-TMDCs exhibit strong light-matter interactions driven by excitonic resonances even at room temperature owing to their large binding energies of typically hundreds of meV. In 1L-TMDCs the inversion symmetry of the crystal is explicitly broken giving rise to even-order nonlinearities in their optical material response as well as to valley-contrasting chiral optical selection rules. However, integrating 1L-TMDCs into optoelectronic devices for utilizing these properties is challenging because their ultimate surface-to-volume ratio makes them highly susceptible to their chemical, electronic and topographic environment. In this work, we demonstrate a non-degrative approach to integrate TMDCs with a plasmonic nanostructure, allowing us to investigate the potential of Mie resonances in optical nanoantennas for efficient manipulation of light-matter interaction at the nanoscale [1]. Specifically, we study a hybrid system consisting of 1L-MoS_2 coupled to a resonant gold nanoparticle (GNP) as depicted in Fig. 1a, where we focus on the chiral farfield properties of the hybrid system upon valley-specific pumping.

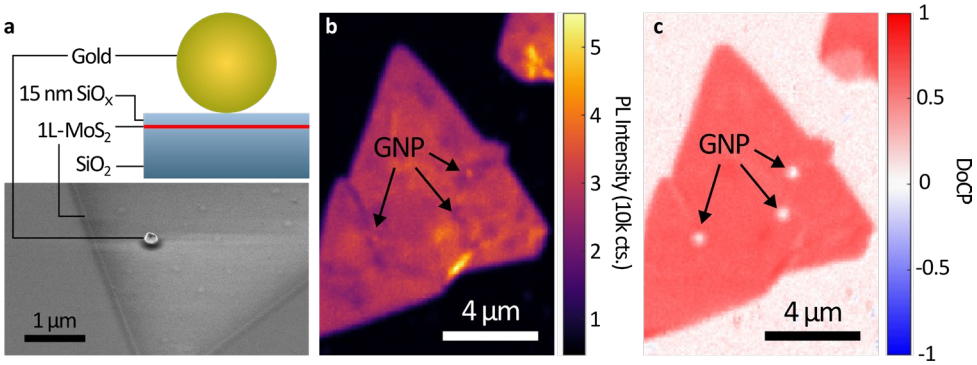

Figure 1: (a) Schematic (top) and scanning-electron micrograph (bottom) of a GNP atop 1L-MoS_2 and separated by 15 nm SiO_x. (b) Photoluminescence intensity and (c) degree of circular polarization (DoCP) images of 1L-MoS_2 decorated with GNPs.

Remarkably, via polarization and spatially resolved white-light and photoluminescence spectroscopy, we find that the chiral farfield properties from valley-specific excitons are lost when coupled to the GNP as shown in Fig. 1b and 1c. We discuss in detail the depolarization effects leading to this behavior, and which insights our observations can give us on the chiral character of TMDC excitons.

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Low-temperature hole-transport layers for p-i-n flexible perovskite solar cells

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Halide perovskite (HP) photovoltaics (PV) demonstrates promising performance with power conversion efficiency > 26% for terrestrial applications. The material shows the following optical and transport properties in micro-crystalline thin-films: diffusion length (>1 μm), lifetime (up to 1 ms), mobility of charge carriers (up to 10^2 $cm^2/V{\cdot}s$), direct-band gap structure. The perovskite solar cells can be realized either on glass or plastic substrates. Light weight, portability, possibility of integration on curve surfaces are the bottom advantages of flexible devices. Flexible solar cells (FSCs) based on silicon, cadmium-tellurium (CdTe), copper-indium-gallium selenide (CIGS) are currently on the market, but there is no well-developed widespread technology for FSCs on perovskites.

Peculiarity of designing perovskite solar cells on flexible substrates is the use of low-temperature conductive layers due to the low thermal stability of plastics limited with annealing at T <150 ºC [1]. Hence, fabrication of charge transporting layers and absorber films should be adopted without negative impact on the output performance, for instance, with use and modification of highly efficient hole transporting thin films based on Nickel oxide, deposition of the small molecule semiconductors etc.

In this work we made complex investigation for the modification of the p-type conductive transport layers with use of organic hole-transport material MeO-2PACz and experimented with NiO_x deposition using ion beam sputtering method with (120–150) ºC annealing. The impact of the HTL type on the output characteristics of flexible solar cells was estimated under the light of a solar simulator. The benefits for the used methods of growth flexible HP solar cells were discussed.

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Spin physics in 2D perovskites

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An overview of our experimental studies of spin-dependent phenomena in two-dimensional (2D) lead halide perovskite materials will be given. Several experimental techniques are used: polarized photoluminescence, optical orientation, spin-flip Raman scattering [1], and pump-probe Faraday rotation with picosecond time resolution [2]. Examples will be given for representative materials $(PEA)_2PbI_4$ and $(PEA)_2PbBr_4$. We evaluate the exciton and carrier g-factors, characteristic spin relaxation times and receive information on spin relaxation mechanisms. Strong anisotropy of the electron and hole Lande g-factors are found and related to structure lower symmetry [1,2]. Negative sign of hole g-factor is identified by means of strong hyperfine interaction of holes with polarized nuclear spins.

Lande g-factor values and characteristic spin relaxation times of 2D perovskites are compared with parameters measured for bulk crystals and nanocrystals [3-6].

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2D-materials mechanical measurements by nanowire precise strain control

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The mechanical properties of two-dimensional materials are subject to completely different laws than the same nanostructured materials such as nanowires or nanosheets. For example, we cite the fact that with the increase in thermal energy, 2D materials usually contract, i.e. they have a negative alpha coefficient. The development of new theories to explain the mechanisms underlying the behavior of two-dimensional materials must be based on measurements that are as accurate as possible, but unfortunately conventional experimental techniques are not applicable to such small components. Here we present a unique new method to control electromechanical forces on quasi 1D nanostructures through static electric fields (GaAs nanowires) directly on the growth substrate. The surface of these NWs acts as an intermediate medium for applying controlled mechanical forces to 2D materials placed as shells.

Evidence for sp^2-like Hybridization of Si Valence Orbitals in Silicene and Multilayer Silicene on Si(111)$\sqrt{3} \times \sqrt{3}$R30°-Bi

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Silicene and multilayer silicene have been synthesised on the α-phase Si(111)$\sqrt{3} \times \sqrt{3}$R30°- Bi [1]. LEED/AES/REELS, grazing-incidence X-ray diffraction (GIXRD), as well as STM and STS have been applied to study the electronic and structural properties of thin and thick Si films. At the Si K absorption edge, REELS revealed two distinct loss structures identified as $1s \rightarrow \pi^*$ and $1s \rightarrow \sigma^*$ transitions, attesting the sp^2-like hybridization of the Si valence orbitals in all Si layers. LEED/GIXRD/STM and STS results confirmed these discoveries.

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Electronic structure of 2D materials probed by photoelectron spectroscopy

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Photoelectron spectroscopy is a powerful technique that exploits the photoelectric effect to study the chemical, electronic and magnetic properties of solids. It is particularly suitable for the study of 2D materials, thanks to its high surface sensitivity, which arises from the strong interaction of electrons with matter. In this talk I will describe the application of photoelectron spectroscopy to two classes of systems having 2D crystalline and electronic structures. MXenes are early transition metal (M) carbide or nitride (X) 2D layers, which derive from bulk MAX phase materials by selective removal of the metal intercalant (A) via chemical etching. This exfoliation procedure saturates the MXene surfaces with variable functional groups. Core-level photoelectron spectroscopy is able to determine the nature and stoichiometry of these terminations and connect them to the functional properties of MXenes. The electronic structure of honeycomb-like 2D materials presents a characteristic feature, the Dirac cone, which defines the electron and spin transport behavior of these systems. Angle-resolved photoelectron spectroscopy gives direct access to the Dirac cone physics. I will show how the Dirac cone properties of C-, Si- and Sb-based honeycomb-like 2D layers (graphene, silicene and antimonene) are strongly influenced by the substrates on which they are grown.

Enhanced Photoresponse in Few-Layer SnS_2 Field-Effect Transistors Modified with Methylammonium Lead Iodide Perovskite

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We demonstrate that decoration with methylammonium lead iodide perovskite ($MAPbI_3$) nanoparticles is an efficient approach to engineer strong visible light photoresponse in electronic devices based on two-dimensional (2D) materials with limited optical absorptivity. This approach was demonstrated using 2D SnS_2, a promising electronic material with a band gap of about 2.3 eV and poor absorption in the visible range of spectrum. Fieldeffect transistors based on pristine 2D SnS_2 show an n-type transport with high on−off ratios. Decoration with isolated $MAPbI_3$ nanoparticles qualitatively retains the transfer characteristics of the devices but dramatically increases their photoresponse in the entire visible range of the spectrum. In particular, the photoresponse of the $MAPbI_3$-decorated devices to the red light is entirely engineered by the perovskite modification of SnS_2, which by itself does not absorb in the red region of the spectrum. The $MAPbI_3$-decorated SnS_2 devices exhibit stable, reproducible photoswitching over numerous cycles with response times of no longer than 12 ms. An analysis of a $MAPbI_3$−SnS_2 heterostructure by Kelvin probe force microscopy resulted in an energy level diagram suggesting a transfer of the photoexcited electrons in $MAPbI_3$ to the conduction band of the n-type SnS_2 channel. The photoresponse characteristics of the perovskite-modified SnS_2 devices were shown to be consistent with the intrinsic optical properties of $MAPbI_3$. The described perovskite decoration approach should be applicable to engineering photoresponse in a variety of other devices based on 2D electronic materials with low optical absorptivity.

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Controllable fusion of electromagnetic bosons in 2D semiconductors: toward efficient sources of strongly-correlated photons and quantum chemistry of light

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In this talk we shall give an overview of microscopic mechanisms enabling control over the interactions of identical electromagnetic bosons - excitons or exciton-polaritons - in 2D semiconductors. Quest of such mechanisms has been inspired by the success of Feshbach resonances in ultra-cold atoms [1]. The crucial ingredient is a coherent link between the "open" scattering channel of interest (a pair of bosons whose interaction one aims to control) and the "closed" bound state (biexciton). We shall discuss the "polaritonic Feshbach resonance" based on the giant oscillator strength model [2], the shape resonance in the case of dipolar bosons [3,4] and the most recent proposal of a fully controllable Feshbach resonance due to the long-range electron-hole interaction [5,6]. In some cases, the bosons exhibit quantum mechanical squeezing at unitarity and may form giant molecules - the so-called quantum halos, possessing non-trivial entanglement properties. We shall also touch upon exotic collective behaviour of resonantly-paired bosons and their molecules in the regime of quantum degeneracy.

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Dynamical screening effects in a hybrid Bose-Fermi mixture of exciton-polaritons and 2D electron gas

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Bose-Fermi mixtures, in particular, hybrid systems of electrons and exciton-polaritons are receiving attention as candidates to host a variety of many-body effects such as supersolidity [PRL **105**, 140402 (2010)], polaron formation [PRX **10**, 021011 (2020)], and superconductivity [J. Nanophot. **6**, 1 (2012); PRB **93**, 054510 (2016)]. If Bose-Einstein condensation (BEC) occurs in the exciton-polariton subsystem, the many-body processes between the condensate and the 2D electron gas (2DEG) become enhanced due to the effect of Bose stimulation.

Here, we consider a multilayer system inside an optical microcavity (the two realisations are shown in Fig. 1a), where one layer hosts Bose-condensed exciton-polaritons strongly coupled to a 2DEG in another layer(s). We address combined effects of intralayer and interlayer interactions between polaritons and electrons, as well as dynamical density responses of both subsystems. We show that, if dynamical effects are taken into account, the spectrum of elementary excitations demonstrates hybridization of polariton Bogoliubov excitations with plasmons in the 2DEG. When damping due to the nonzero imaginary part of the density response function of the 2DEG is taken into account, the lower hybrid mode submerges into the continuum of single-particle excitations (shown by the grey-shaded area in Fig. 1b) and acquires a finite lifetime, broadening the roton minimum. The interference between the lower hybrid mode with the surrounding continuum results in the spectral density demonstrating signatures of Fano resonance (Fig. 1c–e).

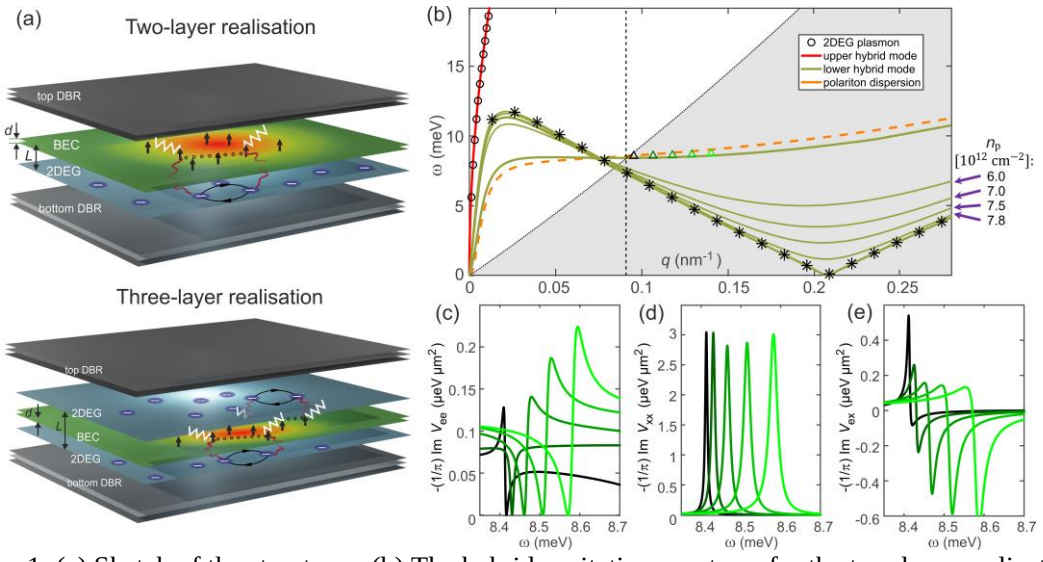

Figure 1: (a) Sketch of the structures. (b) The hybrid excitation spectrum for the two-layer realization. Olive lines show the lower Bogoliubov-like branches at different densities. (c)–(e) Fano lineshapes of the lower hybrid mode, at the momenta corresponding to the green triangles in (b), corresponding to the electron-electron (c), exciton-exciton (d) and electron-exciton (e) interaction channels.

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Superexchange in magnetic van der Waal materials

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Magnetic two-dimensional (2D) materials exhibit many intriguing collective phenomena in spins. Like the other 2D materials, the electronic and spin properties of this material are also highly tunable which can potentially be useful for spintronic applications. However, modeling the exchange interaction of this material, particularly in the moiré bilayer, remains a challenge. Furthermore, the underlying microscopic mechanism is among one of the open questions in strongly-correlated problem in 2D material. Here, we present a microscopic study based on superexchange theory for monolayer chromium trihalides (CrX_3) [1], in Fig. 1(a) and its moiré bilayer [2], in Fig. 2(b). In this study, we not only derive analytically the interlayer Heisenberg exchange and the interlayer Dzyaloshinskii-Moriya (DM) interaction [Fig. 2(c)] accurately for studying the materials' spin physics, but it also provides theoretical insight into the origin of these interactions. In our findings, we reveal the important role of the correlation effects in the X ion's p orbitals, which give rise to a rich interlayer magnetic interaction with remarkable tunability.

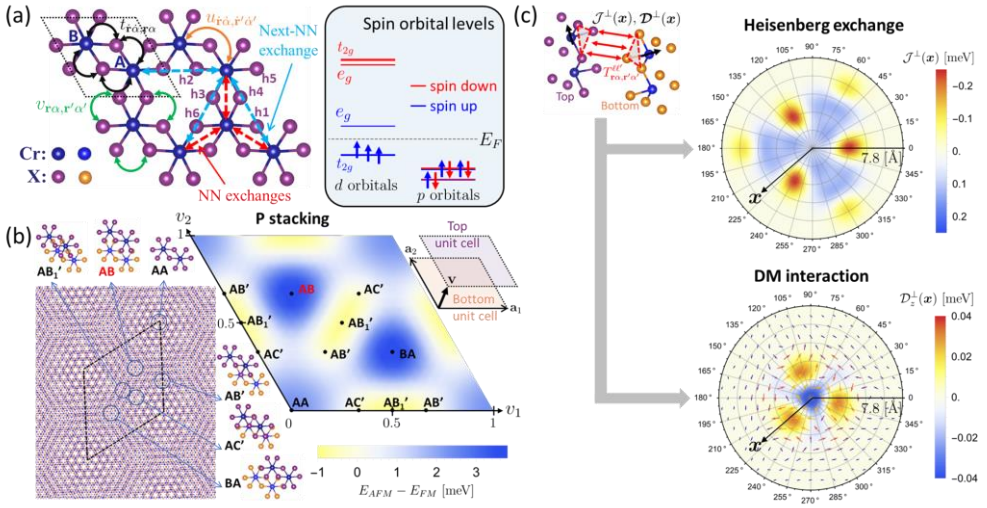

Figure 1: (a) Left: Monolayer CrX_3. Right: the relevant low-energy electronic modes on Cr (d orbitals) and X (p-orbital) ions that mediates superexchange (c) Left: Moiré bilayer and its local stacking order (dashed blue circles). Right: the local magnetic energy gain due to superexchange processes. (c) Top: Interlayer magnetic interaction between two spins (black arrows) with arbitrary in-plane distance $\boldsymbol{x}$ is mediated by the electrons hopping between X ions. Center: $\boldsymbol{x}$-dependent interlayer exchange. Bottom: $\boldsymbol{x}$-dependent interlayer DM interaction (out-of-plane component). The in-plane component is illustrated by the vector field.

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Nonlinear Rybderg exciton-polaritons in cuprous oxide based semiconductor microcavities.

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Rydberg excitons are hydrogen-like bound electron-hole states with high principal quantum numbers in semiconductor materials. The large Bohr radius leads to very strong interactions between Rydberg excitons, which if coupled to light enables strong optical nonlinearity with possible applications in sensing, quantum metrology and quantum optical signal processing. Strong hybridisation between excitons and photons in microresonators or waveguides leads to formation of polariton quasiparticles [1] providing a solid-state platform with very large effective photon-photon interactions required for quantum applications. Here, for the first time we investigate optical Kerr-like nonlinearity for Rydberg exciton-polaritons with principal quantum numbers up to n=7 in cuprous oxide based microcavities. Under pulsed resonant excitation we observe that polariton resonance frequencies are renormalised due to the reduction of the effective photon-exciton coupling with power and the speed of the renormalization (β- factor) increases with the exciton principal quantum number as $\sim n^{4.4}$. The theoretical analysis confirms that Rydberg dipole-dipole interactions play a major role in the increased nonlinearity, whereas contribution from Pauli blockade mechanism is more than an order of magnitude less efficient. The polariton nonlinear β- coefficient or the cavity nonlinear refractive index n2 are found to be comparable or larger than that in the other well-known polariton systems based on GaAs material. Our work makes a fundamental step towards nonlinear Rydberg polaritonics with ultra-high nonlinearities, and opens possibilities for observing strongly-correlated polaritonic states.

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The 2D and 2D/3D strategy for performing new generation solar cells

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In this talk I will review the recent progresses made in the use of 2D material to tune interface properties in new generation solar cells such as Dye Solar Cells and Perovskite solar cells. In particular, the use of 2D material can tune the workfunction, improve charge transport, reduce ion migration and improve conduction of the layers. The use of 2D materials has been extended also to 2D/3D combination where a 2D layers of a 3D crystals are used to ameliorate the photovoltaic properties of a solar cell.

To the theory of the quantum Hall effect

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The quantum Hall effect (QHE) stands out as one of the most notable topology-driven physical phenomena observed in two-dimensional (2D) condensed matter systems. For nearly three decades following its discovery [1], the QHE was associated with ultra-low-temperature environment. However, this perception changed when the QHE was observed at elevated temperatures, even under ambient conditions, in the remarkable 2D material known as graphene [2]. This breakthrough opened up the potential for QHE resistance standards to be accessible to a wider scientific community, extending beyond a select few national institutions. Indeed, Landau level separation, which has to exceed significantly the system temperature for the QHE to be observed, corresponds in graphene to ~2000 K at B=30 T. In stark contrast to the conventional low-temperature QHE, where lattice vibrations are suppressed and the dissipative conductivity is dominated by disorder, at room temperature there is a significant population of acoustic phonons with a wave vector of the order of the inverse magnetic length. In this regime, dissipation in the quantum Hall phase is governed by electron-phonon scattering, which forms the central focus of my presentation.

In this keynote lecture, I will highlight the principal distinctions between the QHE in conventional semiconductors and in 2D Dirac materials including graphene. Subsequently, I will elaborate on the predictions arising from our theory of two-phonon scattering of electrons in graphene in the QHE regime [3]. These predictions have been remarkably validated by recent experiments involving room-temperature QHE observed in graphene encapsulated within hexagonal boron nitride [4].

I will then engage in a succinct exploration of additional scenarios where electron-phonon interaction becomes significant under QHE conditions. Particularly, I will briefly outline our theory of phonon-mediated dissociation of magnetorotons [5] elucidating the outcomes of phonon spectroscopy experiments in the fractional QHE regime [6]. I will also describe how phonon spectroscopy can be used to probe quantum Hall ferromagnets [7] and extract spin-orbit interaction parameters [8]. Finally, I will present the theory of electron-phonon interaction and phonon-induced electron spectrum renormalization near the Lifshitz topological transition at the crossing of Landau levels corresponding to distinct size-quantization subbands in finite-width quantum wells [9].

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Novel phenomena in photonic graphene

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Graphene has attracted immense attention due to its fundamental interest and highly exploited applications. Apart from carbon-based monolayer graphene materials, various synthetic honeycomb lattices (HCLs) have been employed as artificial graphene for electrons, atoms and photons [1]. In particular, photonic graphene - an HCL of evanescently coupled waveguide arrays, has been proposed and demonstrated as an ideal platform for investigation of unconventional edge states [2,3] and pseudospin angular momentum [4], among other intriguing phenomena. In this talk, I will present a few examples of our recent demonstrations on light control and manipulation in laser-written photonic graphene-like structures, including a generic type of graphene edge states exhibiting topological flat band [5] and a universal mapping of topological singularity that leads to periodic conversion of angular momentum mediated by pseudospins [6-8].

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Biography:

Zhigang Chen is currently a specially-appointed Chair Professor at Nankai University, China. He earned his Ph.D. from Bryn Mawr College in 1995. After two years of postdoctoral work, he was promoted to the rank of senior Research Staff Member at Princeton University before joining the faculty at San Francisco State University. His research interests include nonlinear photonics, topological phenomena, soft-matter and biophotonics. Dr. Chen is a Fellow of the Optical Society of America and a Fellow of the American Physical Society. He has served as an Editor / Founding Editor for several journals including Light Science & Applications, Optics Letters, Science Bulletin, Scientific Reports, Frontier in Photonics, and Advances in Physics X, and as a Chair/Organizer for many conferences including 2016/2018 Program/General Co-Chair for CLEO-Fundamental Science.

Tunable dissipationless coherent transport in the bulk of topological materials

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Dissipationless transport of charge carriers is key to reducing heat dissipation in electronic chips. The search for energy efficient materials and architectures is urged not only by the needs of modern electronics but also by numerous emerging applications in neuromorphic computing and artificial intelligence including natural language processing and data mining. Currently, there exist two mechanisms for achieving dissipationless transport: superconductivity and the quantum Hall effect. Here we reveal that dissipationless transport is theoretically achievable in an upcoming generation of metallic graphene-based organic materials. Breaking the usual assumption of commensurability leads to electronic modes capable of dissipationless coherent transport in the bulk, rather than on the edges. The resulting transport is thus expected to be free from thermal gradients that are harmful to nano-electronic chips. The dissipationless transport undergoes a pitchfork bifurcation marking the onset of a novel cubic dispersion phase. All these phenomena can be demonstrated in real systems by molecular synthetic design or by artificial structuring of metamaterials. These results open up a new research avenue for the design of energy efficient information processing and higher-order dispersion materials.

Topological interlayer superconductivity mediated by magnons

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Many proposals to realize topological superconductivity rely on exploiting the properties of a topologically trivial superconductor through the proximity effect. An alternate route is to search for systems where the pairing interaction directly gives rise to topologically non-trivial superconductivity. We show that magnon-mediated superconductivity in heterostructures of transition metal dichalcogenides coupled to magnetic insulators provides a promising route to this end. Considering a trilayer heterostructure consisting of an antiferromagnetic insulator sandwiched between two transition metal dichalcogenides, we show that magnons can mediate topologically non-trivial interlayer superconductivity.

Exploring the possibility of synthesis of 2D ultra-wide bandgap Ga_2O_3 semiconductor

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Currently, there is a growing interest in Ga_2O_3, an emerging semiconductor with an ultra-wide bandgap of ~5 eV. The great potential of Ga_2O_3 for applications such as thin film transistors, solar cells, and solar-blind detectors can be understood in terms of Baliga's figure of merit, which demonstrates that Ga_2O_3 can outperform silicon by more than 3000 times in high power and high-voltage devices.

Among various polymorphs of Ga_2O_3, monoclinic β-phase is the most stable, making it one of the most important transparent conductive oxides for fabrication of transparent electrodes in smart windows technology, photovoltaic devices, liquid crystal displays, chemical sensors and light emitting diodes. For the use as transparent electrodes or thin membranes, Ga_2O_3 films could have polycrystalline structure, which makes the synthesis processes less demanding and significantly cheaper than, for example, epitaxial growth. Given the significance and unique properties of 2D materials like graphene and transition metal dichalcogenides, there is interest in synthesizing and studying the properties of 2D β - Ga_2O_3, even though its bulk properties are rather well-established.

According to theoretical calculations, β-phase has a monolayer thickness of 1.2 nm along the *a*-axis. Due to strong anisotropy, the charge density distribution deviates in different directions. Experimental findings have demonstrated that β-Ga_2O_3 can be exfoliated in the (100) direction. However, due to the relatively strong ionic bond, although mechanical exfoliation of β-Ga_2O_3 is possible, the obtained nanomembranes possess a quasi-2D nature with a thickness of ~ 100 nm, resulting in physical properties similar to bulk Ga_2O_3. Another approach for producing 2D Ga_2O_3 involves passivation, although such studies have been conducted on a theoretical basis. In experimental investigations, thermal oxidation of 2D GaSe nanoflakes has shown promise in yielding β-Ga_2O_3 nanosheets with a thickness of ~ 6 nm. We have synthesized both β-Ga_2O_3 nanostructures and layers using halide vapor phase epitaxy [1, 2] and in this work, we discuss different approaches for the synthesis of 2D β-Ga_2O_3.

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Main challenges for integration of 2D FET technologies into FAB process lines: thermal budget, oxides, reliability

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Recent research advances at fabricating FETs with 2D semiconductors have inspired the industry to begin with integration of these new technologies into FAB process flows [1-4]. For instance, Intel already has 300mm FAB process for MoS_2, WS_2, WSe_2 and $MoSe_2$ at CMOS compatible temperatures [3] and recently reported complementary integration of MoS_2 n-type FETs and WSe_2 p-type FETs [2]. Imec has also demonstrated functional MoS_2 and WS_2 FETs produced using their 300mm FAB lines (Fig.1) [1].

However, the transition of new 2D technologies from research labs to FAB process lines is still very challenging [4] due to a number of open questions, such as the need to satisfy CMOS thermal budget below 450°C, top-gate integration by growing 3D oxides on 2D channels and reliability limitations due to charge trapping near the channel/oxide interfaces.

In this talk I will summarize recent progress made by the industry at integrating 2D FETs into FAB lines, discuss the main challenges which arise on this way, and try to benchmark reliability limitations of first FAB 2D FETs based on our recent experimental results obtained for imec devices with the layout shown in Fig.1.

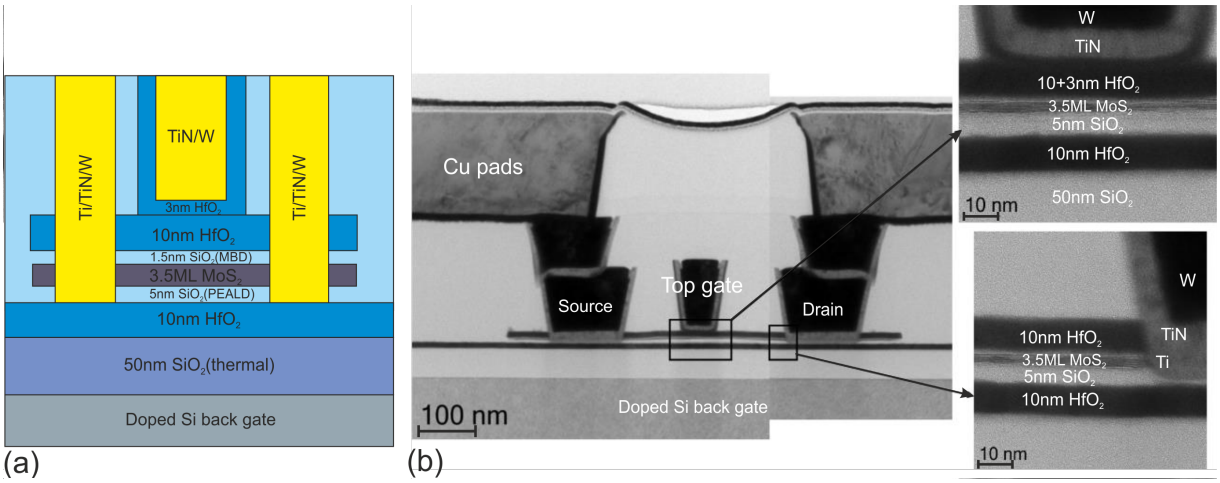

Figure 1: Schematic layout (a) and TEM image (b) of the channel cross-section of 300mm FAB MoS_2 FETs produced by imec.

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Laser MBE synthesis of WS_2 and WSe_2 on CaF_2

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2D materials are of great interest for the further scaling of traditional electronics [1]. One of the main limitations of performance of 2D electronic devices lies in the lack of dielectrics: thin layers of traditional dielectrics are amorphous which leads to a high concentration of traps at interfaces with 2D materials. A promising substitute for silicon oxide as an insulator is calcium fluoride (CaF_2) [2]. The possibility of creating of field effect transistor based on combination of MoS_2 and CaF_2 has been demonstrated in [3]. However, the described procedure involved transfer of MoS_2 layer onto the insulating surface. In this work, we demonstrate a direct synthesis of 2D semiconducting crystals WS_2 and WSe_2 on the CaF_2/Si (111) substrate.

The synthesis was carried out using laser molecular beam epitaxy setup (SURFACE, Germany). For ablation, a CompexPro 201 KrF excimer laser (Coherent, USA) was used. Polycrystalline targets made of WS_2 and WSe_2 were used as a source material. The morphology and composition of films were characterized using atomic force (AFM) and scanning electron microscopy (SEM), Raman spectroscopy, and reflection high-energy electron diffraction (RHEED), measured directly during synthesis of WS_2 and WSe_2 films.

The preliminary experiments were carried out using Al_2O_3 (0001) as an available substrate. At this stage, buffer gas pressure (Ar), substrate temperature, laser energy density on the target, and laser pulse frequency were optimized. The main attention was paid to the relationship between film morphology and growth conditions. Thus, it was shown that an increase of the buffer gas pressure to 0.1 mbar leads to the growth of vertically oriented nanowalls (as observed in [5]), and an increase in the growth temperature to 700 °C leads to the formation of nanowires on the Al_2O_3 surface while the RHEED patterns and the Raman scattering spectra of these structures have characteristic features of WS_2. It was shown that the reduction of buffer gas pressure to 0.05 mbar is sufficient to suppress vertical growth. The smoothest films were obtained at a growth temperature of 500°C followed by heating to 700 °C and Ar pressure of 0.05 mbar.

At the second stage, WS_2 and WSe_2 was synthesized directly on CaF_2/Si (111) substrates preliminarily grown by molecular beam epitaxy. The optimal film growth conditions found for the case of Al_2O_3 (0001) substrate were used as a starting point for growth experiments in this step. At this stage, the main attention was paid to growing thin (1 to 5 monolayers) WS_2 and WSe_2 films and characterizing their morphology, composition, and crystal structure. The post-annealing temperature was lowered to 500 °C since the films grown on CaF_2 were degrading starting from the annealing temperature of ~600 °C. The RHEED patterns of the films showed clear streaks of WS_2 and WSe_2 with slightly more noticeable texture in the case of WS_2. However, Raman spectroscopy results suggest formation of nanocrystallites during film growth [6], which may stem from non-stoichiometric transfer of material from target.

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Three degrees of quantum confinement in Wurtzite InGaAs/AlGaAs nanostructures

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Polytypism in nanowires represents a unique characteristic allowing for the engineering of band structure within a single material [1]. The wurtzite phase is not commonly observed at ambient conditions in bulk $A^{III}B^{V}$ materials, except for nitrides, but nanowires can be engineered to exhibit the wurtzite phase, and this aspect has huge potential technological implications [2].
AlGaAs nanowires are a promising system for the design of innovative devices. By incorporating the Al component into GaAs, the emission can be tuned over a wide range of wavelengths, allowing for the creation of quantum devices . Recent advancements in the accurate control of crystal-phase variation in these structures have enabled the growth of strain-free polytypic nanowires along the growth direction, also at sizes small enough to fabricate quantum dots [3]. Quantum dots in nanowires are one of the most promising systems for numerous applications in quantum nanophotonics. In this work a new type of structure is presented, a wurtzite AlGaAs nanowire with an InGaAs quantum dot and quantum well embedded, a structure that realizes three different types of quantum confinement.

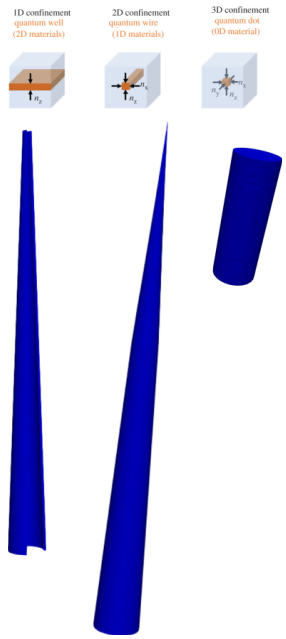

Figure 1: The three structures: the nanowire (middle), the quantum well (left) and the quantum dot (right).

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Giant optical anisotropy in van der Waals materials: perspectives and challenges

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Materials with high optical anisotropy are of great importance in technology and science [1]. Recently, one of the largest birefringence in the visible and near-infrared intervals up to 0.8 was reported in quasi-one-dimensional crystal $BaTiS_3$ [2]. However, anisotropic nanophotonics requires optical anisotropy of about 1.5 to fully exploit advantages of anisotropic properties [3, 4]. Inspired by this challenge, we focused on two-dimensional materials and their bulk counterpart – van der Waals (vdW) materials. Our findings showed that their fundamental difference between interlayer strong covalent bonding and interlayer weak van der Waals interaction leads to unprecedented high birefringence with values exceeding 1.5 in the infrared and 3.0 in the visible spectral intervals (for example, see optical constants of MoS_2 in Figure 1). Thus, our studies enable a new field of vdW anisotropic nanophotonics.

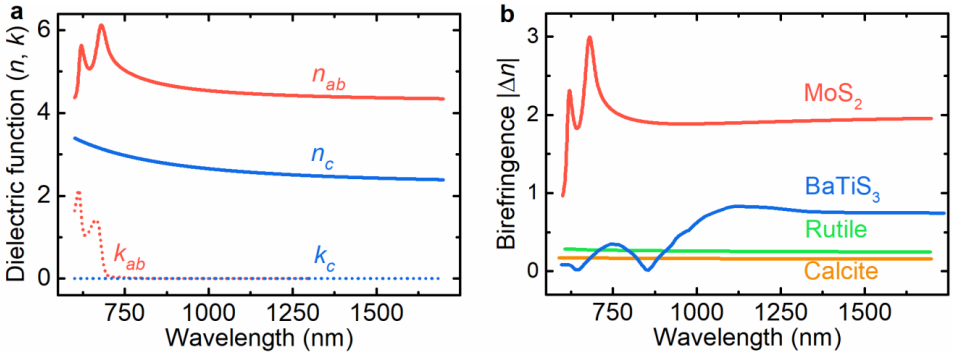

Figure 1: **a.** Optical constants of MoS_2. **b.** Birefringence of MoS2 in comparison with other anisotropic materials.

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Color center ins diamond and in hexagonal boron nitride

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Color centers is diamond found a lot of applications in various sensors, including ones of magnetic and electric field, rotation, temperature and strain. Big fraction of these sensors is based on so-called optically detected magnetic resonance of NV centers, which enabled detection of spin state using fluorescence of a diamond. It appears, that relatively large contrast of optically detected magnetic resonance is rare phenomena, till recently only know in diamond. But, discovery of color centers in hexagonal boron nitride changed this situation. Apparently entire family of color center in hexagonal boron nitride demonstrates noticeable optically detected magnetic resonance. Perspective of utilization of this color centers in censing applications is under active discussion today.

In my lab we actively study color centers in diamond from point of view of sensing applications. Recently we also started activity in hexagonal boron nitride. In my talk I will focus on utilization of NV centers for detection of diamond impurities using so called doble electron-electron resonance, including detection of concentration of the decried impurities and optimization of its spectra. I will also discuss our resent result with color centers in hexagonal boron nitride and discuss potential of this color centers.

Strain tuned non-classical light emission from localized quantum states in 2D layered semiconductors

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Efficient production and manipulation of single-photons are crucial prerequisites for quantum light applications. Among various available non-classical light sources, localized defect states in two-dimensional (2D) van der Waals (vdW) materials, including semiconducting transition metal dichalcogenides (TMDCs), gallium selenide (GaSe) and insulating hexagonal boron nitride (h-BN), have emerged as a promising physical system for scalable quantum technologies. The weak interactions between 2D monolayers enable these materials to be easily exfoliated and integrated with other structures, thereby allowing the development of complex on-chip photonic and optoelectronic devices. Furthermore, their small stiffness for out-of-plane displacements and high elastic strain limit offer exceptional opportunities for nanoscale strain engineering of spatially varying three-dimensional potentials confining the excitons, thus opening the door to large-scale creation of site-controlled quantum emitters. However, in spite of significant advances in the field, the exact nature of these emitters is still under debate. Also, quantum emitters in 2D materials deliver photons at random energies, which severely limits their suitability for any practical future applications in quantum photonics. Therefore, developing post-fabrication tuning methods capable of controlling the quantum light emission energy is of fundamental importance. Elastic strain engineering of the material's band structure is a promising strategy to accomplish this task, as previously demonstrated in quantum dot systems. To date, spectral tuning of the optical emission from non-classical light sources in vdW layers has only been demonstrated experimentally over a few-meV-wide range by static strain. Here, we report on the dynamic real-time control of the photon emission wavelength from individual vdW light sources subjected to the radio frequency surface acoustic waves (SAWs). These experiments were performed on individual atomic-scale defects in h-BN. The direct visualization of the defects structure using atomic force microscopy under ambient conditions combined with density functional theory calculations of their band structures and electronic properties made it possible to associate the existence of several single-photon optical transitions to the observed defects, thus shedding light on the origin of quantum emitters in h-BN [1]. We then showed that when perturbed by the propagating SAW-induced elastic vibration, these h-BN defects are periodically strained and their optical transitions are modulated by the acousto-mechanical coupling within a ~2 meV bandwidth [2]. This SAW-mediated spectral fine-tuning is further combined with spectral detection filtering for temporal control of the emitted photons. In this way, both spectral tunability and on-demand emission of single-photons are achieved simultaneously.

We also demonstrate a scalable and lithography-free approach toward creating large areas of localized emitters in 2D semiconductors. The proof-of-concept was achieved by placing tungsten diselenide (WSe_2) and GaSe flakes over polystyrene or luminescent rare-earth ion doped micro/nano-particles.

Altogether, this study opens the door to the use of static and dynamic strain engineering for scalable integration of vdW emitters in nanophotonic and related quantum information technologies.

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Ultrafast quantum optics with single-photon emitters in hBN

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The availability of efficient and robust quantum light sources in large numbers and their optical coherent control are key challenges in the development of quantum networks and communications. Recently, single-photon sources in atomically thin transition metal dichalcogenides and other 2D van der Waals materials joined the family of solid-state quantum light emitters [1]. In the 2D insulator hexagonal boron nitride (hBN), optically active states in the band gap have been found, which efficiently emit single photons even at room temperature. The wide variability of the emission wavelength, narrow emission lines and tunability makes this emitter particularly interesting for quantum sensing and wavelength division multiplexed quantum communications.

We demonstrate the fabrication of rectangular arrays of tens of thousands of commercially available hBN nanocrystals hosting single-photon emitters, using the of capillary assembly technique [2] with high positioning yields of up to >95 % (Fig 1a). Our method offers the possibility of deterministically fabricate photonic nanostructures around individual emitters. Besides, it opens the way for a systematic optical characterization of easily addressable single-photon emitters.

Indeed, photonic microstructures and components can be created using 3D direct-laser writing. In this way, polymer microlenses of various shapes can be printed to effectively collect and direct light from embedded light emitters. However, the auto-fluorescence of commercially available photoresins limits the application for quantum optics. Here, we present microlenses that are 3D-printed from an ultra-low-fluorescence photoresin using direct laser writing onto individual hBN quantum light emitters (Fig 1b). The microlenses are designed to collect light effectively from the emitters and collimate the single-photon emission into a low-divergent beam (Fig 1c) [3].

Furthermore, we demonstrate the coherent state manipulation of a single hBN quantum emitter with ultrafast laser pulses using a double-pulse experiment [4]. The coherence properties of the two-level system are detected by measuring the emitted photons as a function of the pulse delay. Our joint experiment-theory study reveals the effects of different sources of spectral jitter on the ultrafast coherence dynamics. We also demonstrate that coherent control can not only be exerted resonantly on the optical transition but also phonon-assisted, which provides profound insight into the internal phonon quantum dynamics.

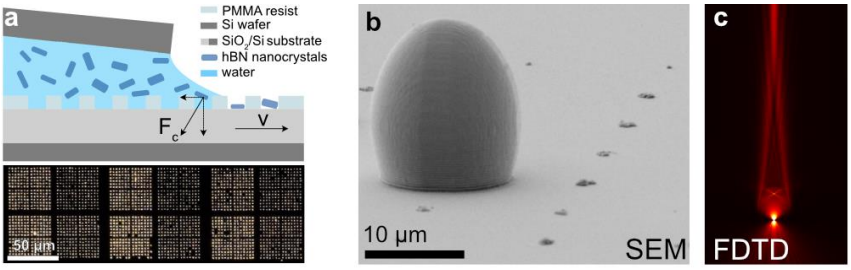

Fig.1 (a) Sketch of the capillary assembly scheme and darkfield optical microscope image of a part of a typical sample demonstrating the high yield. (b) Scanning electron microscope (SEM) image of an individual polymer lens printed on an array of hBN nanocrystals. (c) FDTD simulation of a dipole emitter inside the lens.

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Monolayer-based single photon source in a liquid-helium-free open cavity featuring 65% brightness and quantum coherence

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Solid-state single photon sources are central building blocks in quantum communication networks and on-chip quantum information processing [1]. Atomically thin crystals were established as possible candidates to emit non-classical states of light [2,3], however, the performance of monolayer-based single photon sources has so far been lacking behind state-of-the-art devices based on volume crystals. Here, we implement a single photon source based on an atomically thin sheet of WSe_2 coupled to a spectrally tunable optical cavity [4]. It is characterized by a high single photon purity with a $g^{(2)}(0)$ value as low as 4.7 ± 0.7 % and a record-high first lens brightness of linearly polarized photons as large as 65 ± 4 %. Interestingly, the high performance of our devices allows us to observe genuine quantum interference phenomena in a Hong-Ou-Mandel experiment.

Our results demonstrate that open cavities and two-dimensional materials constitute an excellent platform for ultra-bright quantum light sources: the unique properties of such two-dimensional materials and the versatility of open cavities open an inspiring avenue for novel quantum optoelectronic devices.

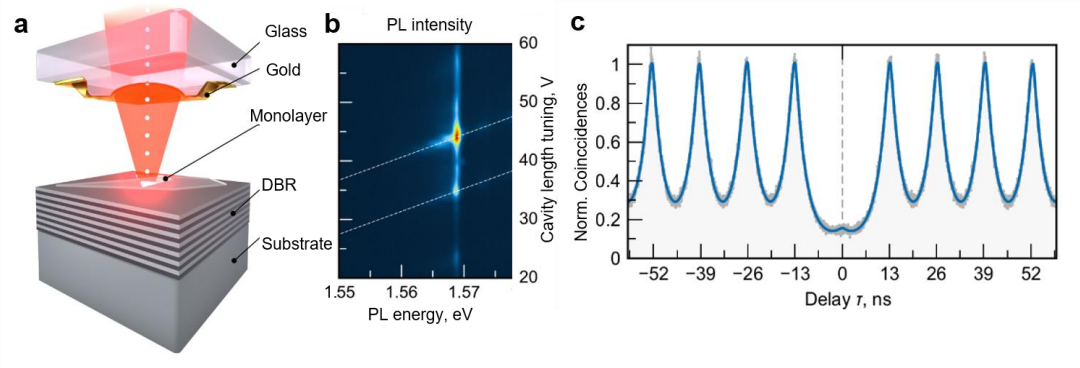

Figure 1: **a** Single photon emission from a monolayer in a plano-convex open cavity under optical excitation. **b** Photoluminescence spectra upon tuning the cavity optical length for above-bandgap excitation at 532 nm. Cavity modes are highlighted by dashed lines. **c** Second order autocorrelation function of single photons measured in a Hanbury-Brown-Twiss experiment with 76.2 MHz pulsed excitation.

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