The emission and absorption of light is the physical basis of lasers, LEDs, solar cells and photodetectors, which have become crucial parts of our daily life. By controlling these processes at a subwavelength scale, we can significantly improve the performance of these photonic devices and develop completely new ones. The Photonics and Semiconductor Nanophysics group investigates the physics of (nano-)photonic structures and materials in five distinct but related research lines, mostly centered around semiconductors, for applications ranging from optical communications to sensing and energy conversion.

Photonics and Semiconductor Nanophysics

Bachelor and Master Research Projects (2022-2023)

Andrea Fiore, Jaime Gómez Rivas,Paul Koenraad, Andrei Silov, Ewold Verhagen

Information on available Bachelor / Master projects in the PSN group

(applies to TU/e students only)

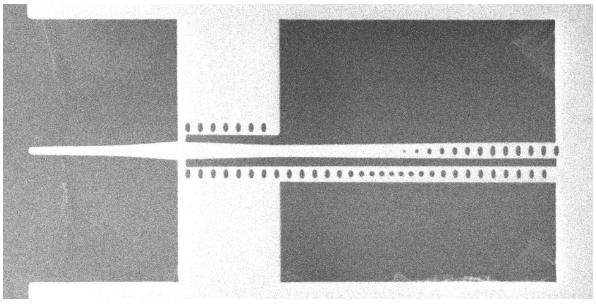
This document presents a short description of the different bachelor (BSc) and master (MSc) projects that can be done in Q4 in the group Photonics and Semiconductor Nanophysics (PSN). Projects for Q1-Q3 can be also defined on demand – you can contact the staff member(s) responsible for the research topics of interest.

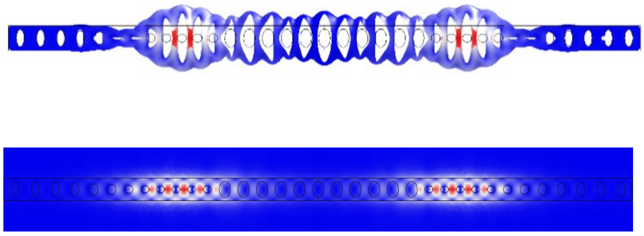
Other useful information is:

- You can find a description of the group's research topics and teams at https://www.tue.nl/en/research/research-groups/photonics-and-semiconductor-nanophysics/
- For general information you can contact the secretary of PSN: secretariaat.psn@tue.nl
- Some of the projects are offered to both MSc and BSc students. The complexity of the projects will be adapted depending on the degree of the students.
- For specific information on the projects and to apply for them, you can directly contact the staff member in charge. All projects can be defined for 10 or 15 ECTS.

Active nano-optomechanics (MSc project)

Supervisors: Matteo Lodde/**Andrea Fiore (a.fiore@tue.nl)**

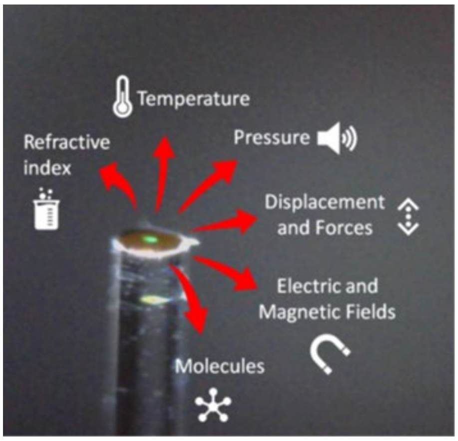


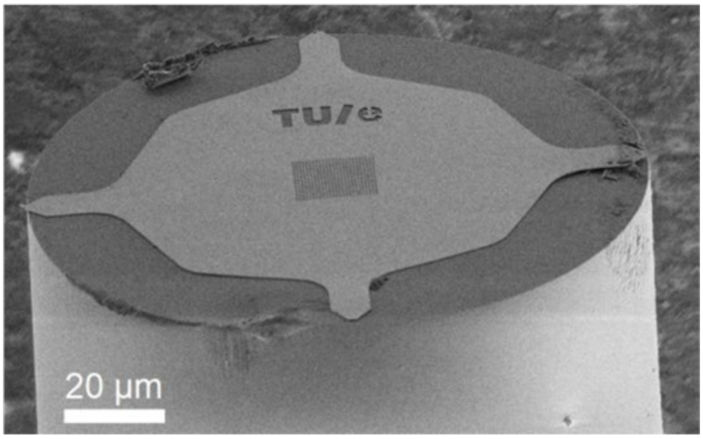


Phonons in solid-state nanostructures form a new toolbox for quantum information processing, and quantum acoustics is a novel field of research. Photon-phonon interaction in optomechanical cavities with co-localized optical and acoustic resonances enables the excitation and detection of phonons, and cooling down to the mechanical ground state. By integrating quantum emitters (e.g. quantum dots) in these systems, it is further possible to introduce a nonlinearity and thereby generate non-classical phonon states, for example single phonons. In this project, structures designed to maximize this emitter-phonon coupling will be experimentally investigated, aiming at a first demonstration of the coupling.

Nanophotonic fiber-optic sensors (BSc/MSc project)

Supervisors: Luca Picelli/Arthur Hendriks/Mildred Cano/**Andrea Fiore (a.fiore@tue.nl)**

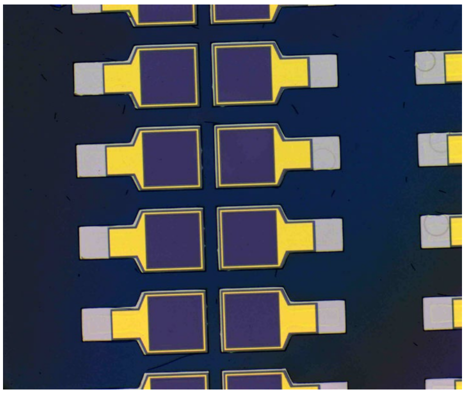




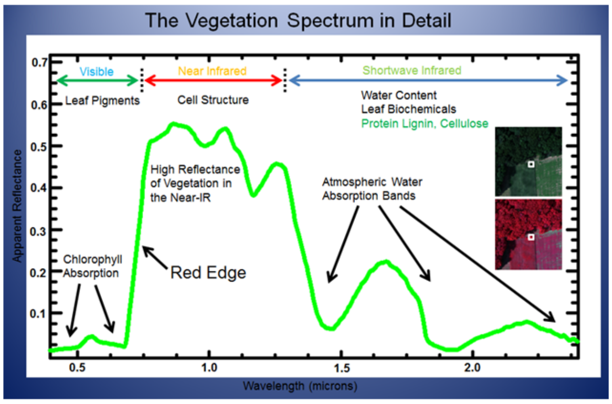
Photonic crystals are nanophotonic structures based on a periodic modulation of the refractive index. They allow defining sharp spectral resonances whose wavelength depends on the environment (temperature, refractive index, force, etc), making them exquisite optical sensors. Our group is exploring photonic crystal sensors placed on the tip of optical fibers and optimized for read-out via the fiber. In this project, you will explore the optical properties of these structures and their application to a practical sensing problem. Depending on timing and personal interests, the project could include the design of optimized structures, the measurement of the reflectance spectrum and optimization of the read-out method, and/or the demonstration of sensing of forces and mass in gaseous or liquid environments.

Integrated spectral sensors (BSc/MSc project)

Supervisors: Anne van Klinken/Don van Elst/Chenhui Li/Fang Ou/**Andrea Fiore (a.fiore@tue.nl)**



TU/e spectral sensors

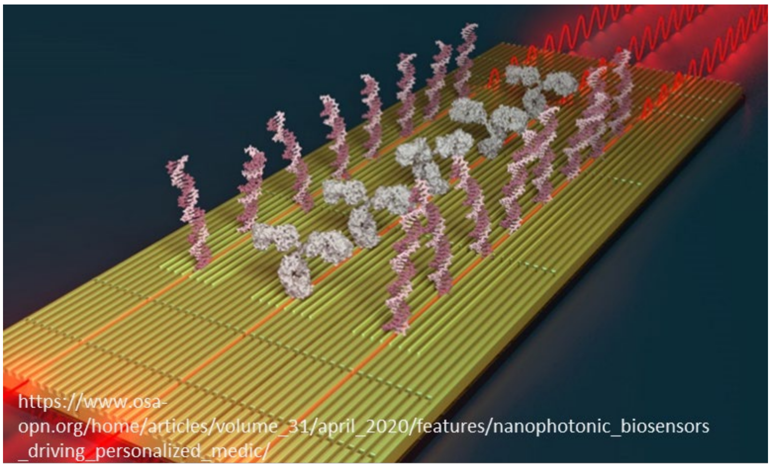


Source: www.markelowitz.com/Hyperspectral

Our group is working on highly integrated spectral sensors for application in the food production and supply chain, for example to monitor the growth of plants and the ripeness of fruit, by measuring the reflection or transmission spectrum. These spectral sensors use advanced nanophotonic concepts to produce narrow spectral responses in an extremely compact and integrated device. In this project you will investigate the optical and electro-optical properties of integrated spectrometers and assess their potential application for near-infrared spectrometry. Depending on the personal interests, the activities could include the design of advanced optical structures, the experimental characterization of their characteristics, and their application in a food sensing experiment.

Integrated photonic biosensors for point-of-care diagnostics **(BSc/MSc project)**

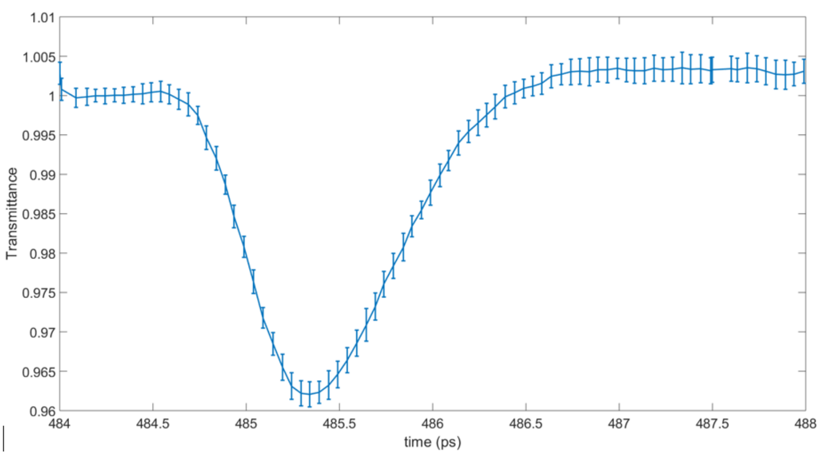
Supervisors: Anne van Klinken/Mathias Dolci/**Peter Zijlstra (p.zijlstra@tue.nl)**/**Andrea Fiore (a.fiore@tue.nl)**

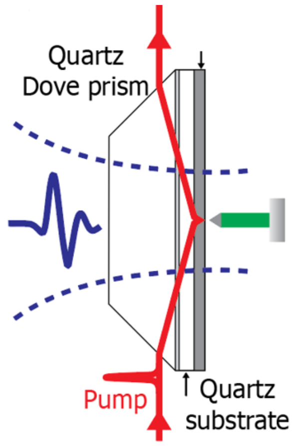


The groups PSN and MBx are working together towards a new generation of optical biosensors of biomarkers for early detection of diseases at the point-of-care. They are based on the combination of nanophotonic structures, integrated interrogation chips and advanced functionalization methods, which could result in extremely compact biosensors, adequate for use by the family doctor and thereby replacing costly lab tests. The project focusses on the experimental characterization of new optical sensors and read-out methods and the measurement of the limit-of-detection for immunoglobulin and other proteins.

Investigating strong light-matter interaction in 2D Materials using terahertz microscopy (MSc project)

Supervisors: Stan ter Huurne/ **Jaime Gómez Rivas (j.gomez.rivas@tue.nl)**

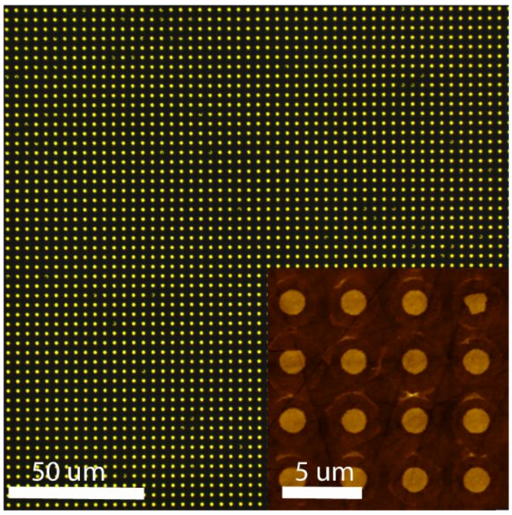


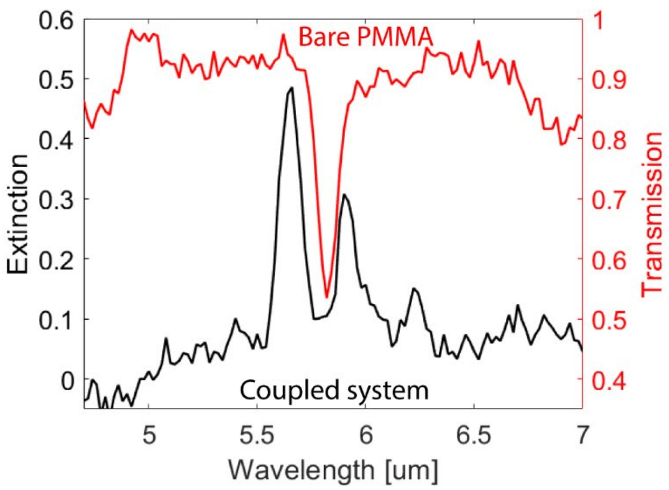


Atomically thin semiconductors have created a lot of interest in the scientific community. They can have very high charge mobilities, optical absorption and transition from indirect band-gap semiconductor in bulk to direct semiconductor at a monolayer thickness. We have recently developed a unique near-field microscope that can generate and detect radiation in the deep infrared region of the electromagnetic spectrum, i.e., the terahertz (THz) frequency range. This microscope detects the time dependent free carrier absorption of materials after photo-excitation with ultrashort optical pulses and with subwavelength spatial resolution, which allows to determine the carrier mobility and free carrier density. In this project, you will investigate the properties of chemically grown and exfoliated 2D semiconductors using THz near-field microscopy and, more specifically, how these properties can be modified and enhanced using resonant (nanophotonic) structures, which interact with the semiconductor. The impact of this research is on improving the performance of organic opto-electronic devices using novel nanophotonic concepts and to use THz microscopy to characterize this improvement. Skills that you will acquire are working with (ultra-fast) laser systems and THz systems, and performing high precision optical measurements.

Design of plasmonic dimers particle arrays for vibrational ultrastrong coupling (BSc/MSc project)

Supervisor: Francesco Verdelli/ **Jaime Gomez Rivas (**j.gomez.rivas@tue.nl**)**

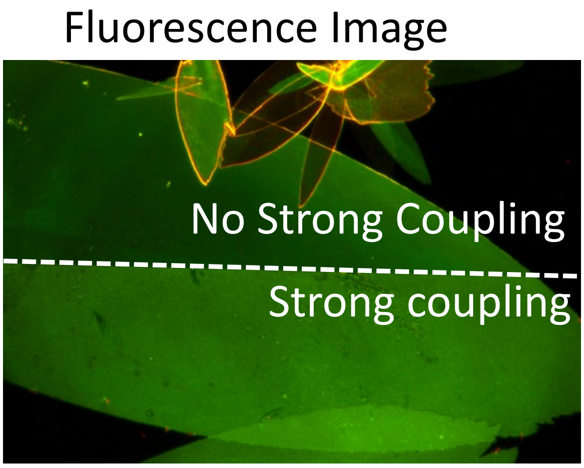




The ultrastrong coupling (USC) regime is established when the energy of the interaction between light and matter is a comparable fraction of the bare energies of the coupled elements (e.g. molecular vibrations and photons). This interaction is governed by the coupling strength between the elements of the system. USC coupling is interesting because it can modify reaction rates of molecules that are strongly coupled to the vacuum field of an optical cavity and enhance the cross section of Raman scattering, which can open new avenues in chemistry and spectroscopy. The coupling strength can be tuned in the infrared using microstructures capable of sustaining huge field enhancements, such as dimers or nanogap antennas. In this project, you will simulate and experimentally investigate possible cavity designs to achieve USC between a molecular vibration resonance and cavity modes in arrays of dimers. The aim is to create a new open platform capable of achieving USC for future studies of polaritonic chemistry. The skills that you will acquire range from designing the microstructures using simulation software to working in a clean room and an optical lab.

Strong light-matter coupling at cryogenic temperatures (BSc/MSc project)

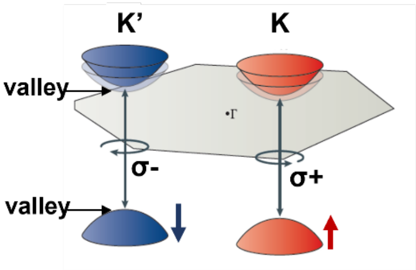
Supervisors: Matthijs Berghuis/**Jaime Gómez Rivas (j.gomez.rivas@tue.nl)**

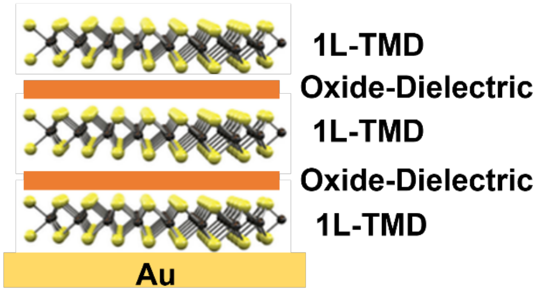


For the design of the best performing LEDs, it is important to understand and improve the light emission efficiency of the semiconductors used in these devices. We have been working on increasing the light emission efficiency in organic semiconductors by coupling the excitons to optical modes in nanocavities. In the past year, we have designed cavity structures for strong light-matter coupling to organic crystals and we have measured enhanced light emission and longer lifetimes. However, due to the complexity of the system the exact mechanism of these phenomena is not yet fully understood. For this project, we want to reduce the 'chaos' in the system by cooling down the sample to very low temperatures around 4 K, reducing the kinetic energy of the excitons and the molecular motion. This will help to simplify the analysis and get a better understanding of the effects associated to strong light-matter coupling.

Exploring Valley Polarized Exciton-Polaritons in 2D Superlattices (MSc Project)

Supervisors: Simrjit Singh/Sara Elrafey/**Jaime Gomez Rivas** (j.gomez.rivas@tue.nl)

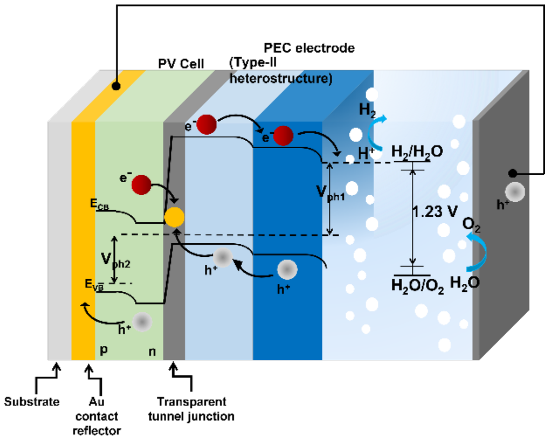




Atomically thin 2D semiconductors possess a variety of intriguing properties thereby, offering unique opportunities for quantum information processing applications. The inversion symmetry breaking and spin-orbit coupling leads to a strong spin-valley locking effect at two distinct K and K' valleys in the electronic band structure that can be selectively addressed using circularly polarized light. A carrier population imbalance created in these two valleys, termed as valley polarization, can be used to store the binary information. Furthermore, the formation of hybrid quasiparticles i.e. exciton-polaritons, can be realized in these semiconductors when the valley addressable excitons are strongly coupled to the optical resonances. In this project, we would explore the formation of exciton-polaritons and their valley selectivity in artificially designed 2D superlattices consisting of an alternate stack of monolayer 2D semiconductors and thin dielectric spacers. The 2D superlattices are recently explored structures for light manipulation in future high-performance opto-electronic and photonic components however, the emergence of exciton-polaritons and their valley selectivity is largely unexplored in these structure. This project would include the fabrication of superlattice structures, the measurement of the reflectance, photoluminescence, circularly polarized photoluminescence and lifetime measurements at room as well as cryogenic temperatures. A part of your efforts will also be focused on numerical simulations.

2D/3D Tandem Devices for Solar Hydrogen Generation (MSc Project)

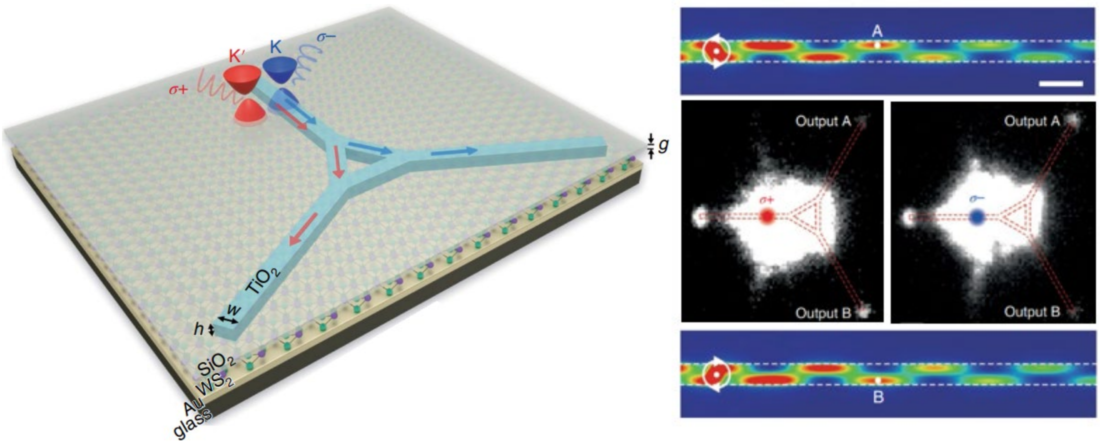
Supervisors: Simrjit Singh/**Jaime Gomez Rivas** (j.gomez.rivas@tue.nl)



Efficient self-powered solar hydrogen generation, a pathway to store solar energy in the form of chemical bonds, using tandem photoelectrochemical/photovoltaic (PEC/PV) devices, requires the optimization of front PEC electrode which is limited by the low photocurrent generation. The present project is targeted on the fabrication of PEC/PV tandem devices utilizing ultrathin 2D materials and 3D semiconductors with appropriate bandgaps as PEC electrodes and PV cells. Photocurrent in the PEC electrode will be maximized through optical engineering such as by using hybrid conductive distributed Bragg reflector geometry and/or 3D ordered macro-mesoporous scaffold for enhancing light trapping and absorption in the PEC electrode. This project will include the fabrication/assembly of tandem device structures, photoelectrochemical measurements such as I-V, Impedance spectroscopy and Mott-Schottky etc., and a part of your efforts will also be focused on numerical simulations for the optimization of the device structure.

Separation and propagation of WSe_2 valley polarized emission in integrated photonic circuits (MSc project)

Supervisors: Minpeng Liang/**Jaime Gómez Rivas** (j.gomez.rivas@tue.nl)



Chen, Yang, et al. "Chirality-dependent unidirectional routing of WS_2 valley photons in a nanocircuit." *Nature Nanotechnology* 17.11 (2022): 1178-1182.

Valley-dependent excitation and emission in transition metal dichalcogenides (TMDCs) such as WSe_2 and WS_2, have emerged as a new avenue for optical data manipulation, quantum optical technologies, and chiral photonics. The valleypolarized electronic states can be optically addressed through photonic spin-orbit interaction of excitonic emission. However, transferring the valley information with high fidelity, high efficiency and over long distance is still challenging. Here we propose a project which will work on this direction.

The project includes the design and optimization of waveguide structures (simulation), the nanofabrication and the optical characterizations of the devices. The goal of this project is to achieve a waveguiding device which can separate and propagate the chiral signal with high efficiency as it is needed for potential applications in quantum communication.

Atomic scale observation of dopants in semiconductors (MSc project)

Supervisors: Tom Verstijnen/**Paul Koenraad (p.m.koenraad@tue.nl)**

Does observing and manipulating solid state materials on the scale of single atoms sound interesting to you? Semiconductor materials are essential for our society, since they power LED's, computer chips, solar panels and much more. A very important method to control the properties of semiconductors is through doping. Doping introduces new atoms in the material, which can supply extra charge carriers and even change the bandgap of the host material. A good understanding of doping is required to semiconductor devices even further. We use scanning tunneling microscopy (STM) to study these materials at the atomic scale. With this we can look at the effects and properties of single doping atoms. This allows us to see the displacement of single atoms and even to observe their electron wavefunctions. Our main interest is in iso-electronic impurities, these do not introduce extra carriers but change the properties of the host materials through strain and other effects. Examples of iso-electronic doping are Nitrogen (N) and Bismuth (Bi) in Gallium Arsenide (GaAs). Below you can see a typical image that we can make with the STM, where we can see single Bi (bright dots) and N atoms (dark rectangles) in GaAs. Possible projects could be studying the spatial distribution of these iso-electronic dopants or looking at their local electronic interaction with the host.

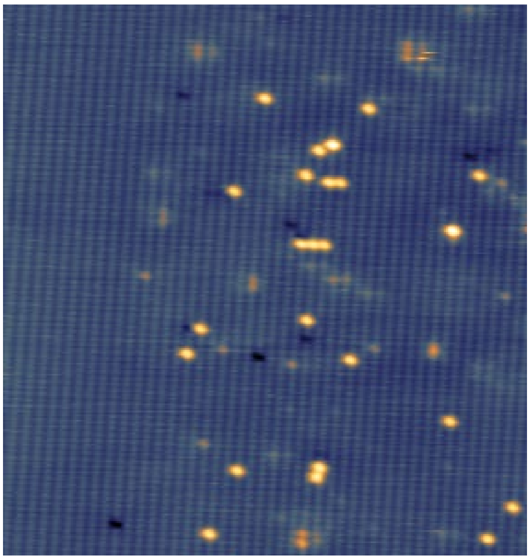
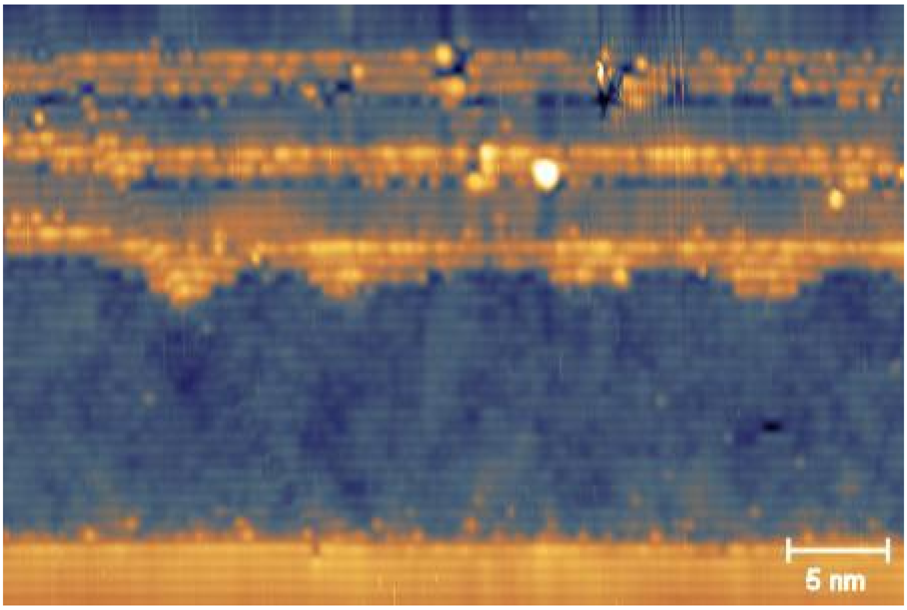


Figure 1 20x20 nm^2 STM image of GaAs containing both Bi (bright dots) and N atoms (dark rectangles)

Atomic-scale characterization of antimony based III-V semiconductor devices and materials (MSc project)

Supervisors: Aurelia Trevisan/**Paul Koenraad (p.m.koenraad@tue.nl)**

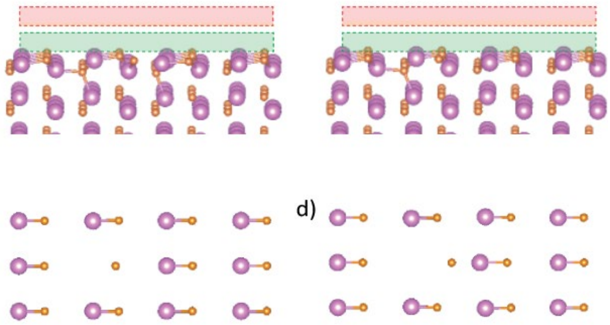


STM image of an ULTRARAM device

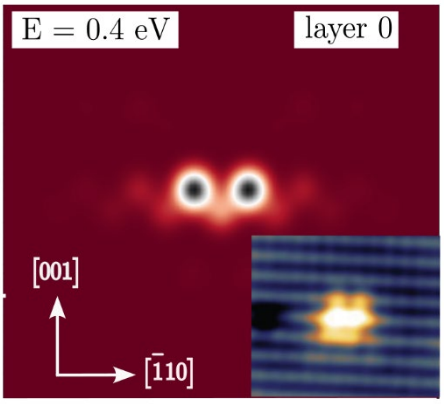
Antimony based III-V semiconductors have a wide range of applications in Electronics, Optoelectronics and Quantum information technologies. We offer the opportunity to observe these materials at the atomic scale using cross sectional scanning tunnelling microscopy (X-STM). Here we study what these materials actually look like at this scale and how devices that are grown are actually formed. You can study many characteristics of these materials. For instance interface qualities, defect distribution and individual dopant behaviour. If you have ever wondered what the devices that lie at the basis of cutting edge technology look like at the smallest scale this is the way to find out. Some examples of materials and devices we study are Sb distribution and wave function in GaAs and the study of ULTRARAM devices, alongside many more Sb based materials. An example of the ULTRARAM device is shown in the figure where you can see how clearly we can identify layers of different materials and interface quality and the rich world of these semiconductors at the atomic scale.

Studying individual dopants in III-V semiconductors using cutting edge simulation techniques (BSc, MSc project)

Supervisors: Tom Verstijnen/ Julian Zanon /**Paul Koenraad (p.m.koenraad@tue.nl)**



DFT Simulations of the relaxation of the Ga vacancy in GaN

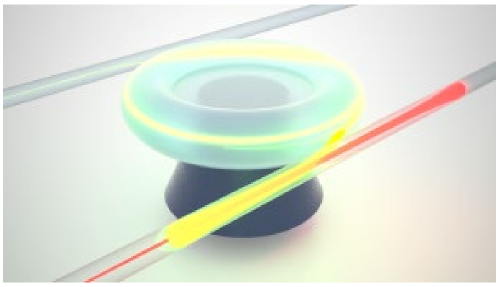


Tight-Binding simulations of the B wave function in GaAs

Semiconductor materials are the foundation on which many technologies are built nowadays. The size of our devices has been decreasing rapidly over the last decades. This has been made possible by the fact that we can now control these materials at the atomic scale. We use cutting edge simulations methods to characterize how individual dopants behave in III-V semiconductors. We work closely with experimental results from our group to directly compare these simulations to experimental results. Dopant characteristics we study include dopant distribution, wave function shape, energy levels of dopant states and material relaxation around dopants. The simulation techniques we have available include Density Functional Theory (DFT), Tight-Binding simulations (TB) and the QuTip package of python. Some examples of systems we study are the wave function and energetic state of Boron in GaAs, the bi stability of the Ga vacancy in GaN and nitrogen-hydrogen complexes in GaAs.

One-way light propagation on a photonic chip (MSc project at AMOLF, Amsterdam)

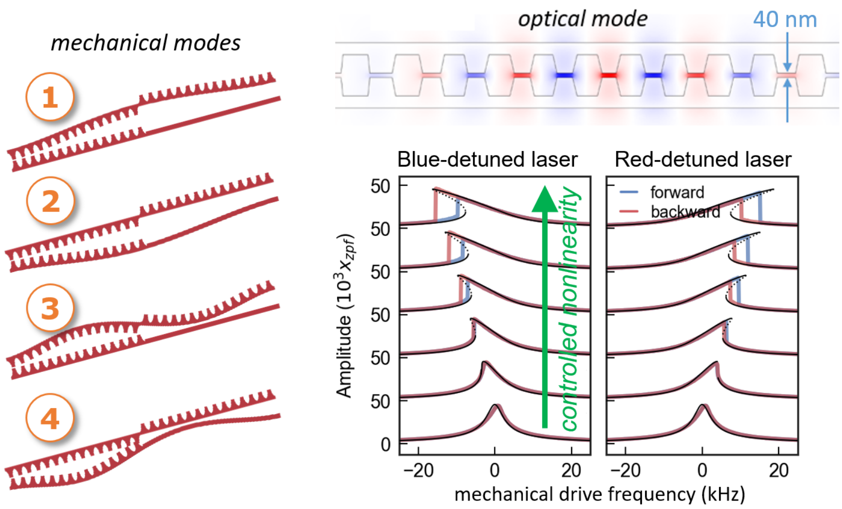
Supervisors: René Barczyk / **Ewold Verhagen (verhagen@amolf.nl)**



Light can normally propagate in two directions through a waveguide, or any optical system, equally well: the principle known as reciprocity. Non-reciprocal functions like isolation or circulation are extremely useful, as they allow protecting against the detrimental effects of backscattering and efficient routing of optical signals. However, this requires magneto-optic materials that cannot be integrated on a photonic chip. In this project, you will use sound waves to break the symmetry of light propagation and create non-reciprocity. We will investigate new materials for efficient generation of sound and interaction with light. You will fabricate the devices in the AMOLF cleanroom and test the envisioned effects in optical experiments. This project is carried out in the *Photonic Forces* group at the AMOLF institute in Amsterdam.

Computation with nano-optomechanical resonators (MSc project at AMOLF, Amsterdam)

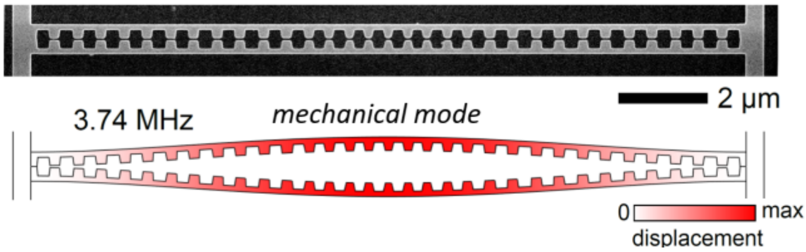
Supervisors: Marc Serra Garcia / **Ewold Verhagen (verhagen@amolf.nl)**



There is a high interest in investigating alternative paradigms for computing, for specific applications related to analog simulation and artificial intelligence, and to study fundamental thermodynamic principles that govern the performance of information processing systems. Under the right conditions, computational tasks can be encoded in the response of nonlinear resonators. We have recently discovered that very strong nonlinearities can be induced in nanomechanical resonators through their radiation pressure interaction with laser light. In this project, we will explore if we can configure different types of logic gates in the nanomechanical domain through by choosing smart temporal modulations of laser light that controls the system response. Through sensitive optomechanical readout of the motion, we aim to test computation performance at the thermal noise limit. You will fabricate these optomechanical devices and demonstrate in proof-of-principle experiments that they can be used as small computing elements. This project is carried out in the *Photonic Forces* group at the AMOLF institute in Amsterdam.

Controlling the quantum state of an ultracoherent nanostring with light (MSc project at AMOLF, Amsterdam)

Supervisors: Menno Jansen/**Ewold Verhagen** (verhagen@amolf.nl)



Even macroscopic objects can exhibit the strange behavior associated with the laws of quantum mechanics. In this project, you will cool a nanostring vibrating at MHz frequencies close to its quantum ground state of motion, using the forces exerted by laser light combined with very sensitive measurement. To do so, you will develop new on-chip nanomechanical resonators made from silicon nitride, in which mechanical decoherence can be extremely small. In a cryogenic setup, we will then seek to test a new theoretical prediction that a short, intense laser pulse could induce a special 'squeezed' quantum state in the mechanical string. You will design the systems, fabricate them in the cleanroom at AMOLF, and characterize their performance in high-precision optical measurement. This project is carried out in the *Photonic Forces* group at the AMOLF institute in Amsterdam.