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 (2021-2022)

Alberto Curto, Ewold Verhagen, Andrea Fiore, Jaime Gómez Rivas, Paul Koenraad and Andrei Silov
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 Simone Manche (PSN secretary), 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)

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.
Terahertz Spectroscopy for Extracting Physical Parameters of InGaN Quantum Wells (BSc/MSc project)

Supervisors: Mohammad Ramezani/ Jaime Gómez Rivas
(j.gomez.rivas@tue.nl)

Semiconductor thin films are critical building blocks of many modern devices such as integrated circuits, solar cells, and Light-Emitting Diodes (LEDs). Fabrication of thin films involves many challenges. For example, variations in the growth conditions can influence the electrical and optical properties of these materials, leading to the lack of uniformity in the quality of semiconductors. Among such materials, InGaN quantum wells are critical for generating light in LEDs. The ability to measure physical parameters of InGaN quantum wells such as carrier lifetime, carrier mobility, and carrier concentration is very important for optoelectronics industries. Currently, to extract such parameters, the full device must be fabricated, which involves many time-consuming and expensive steps. Using terahertz spectroscopy, we can extract these physical parameters immediately after epitaxial growth and before entering further fabrication steps. Terahertz spectroscopy relies on interaction of terahertz radiation (0.5 THz – 3 THz) with free charge carriers in semiconductors. By quantifying the amount of transmitted terahertz radiation from quantum wells, we can extract carrier lifetimes, mobilities and concentrations in a non-destructive and contact-free way. In this project, we aim to measure the aforementioned physical quantities of InGaN quantum wells by optically exciting them and measuring the transmitted terahertz radiation as a function of time. Within the context of this project, we will improve the existing laboratory setup to be able to access these materials parameters. Moreover, we will use physical models to fit the experimental results in order to extract the relevant parameters.
Bringing nanophotonics into commercial Light-Emitting Diodes (LEDs) for ultra-high brightness (MSc project)

Supervisors: Mohamed Abdelkhalik/ Jaime Gómez Rivas
(j.gomez.rivas@tue.nl)

The goal of the project is to push solid-state lighting (SSL) into the development of high efficacy and ultra-high brightness LEDs by exploiting fundamental phenomena enabled by the resonant interaction of designed nanostructured surfaces with InGaN quantum wells. For this goal, we will introduce metallic and dielectric nanoparticles with a resonant response at frequencies close to the emission frequency of blue or red LEDs to enhance the emission rate and control the emission direction, thereby reducing the étendue of the LED (i.e. the beaming of the emission). In particular, we will exploit collective resonances in arrays of nanoparticles arising from their coherent radiative coupling to improve the response of the system by optimizing the density of optical states to which the emitters can decay. The proposed approach will be introduced in commercial LED architectures provided by Lumileds Holding B.V.
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.
Chiral molecular sensing with nanophotonics (MSc/BSc project)

Supervisors: Rasmus Godiksen/Ershad Mohammadi/Alberto Curto (A.G.Curto@TUE.nl)

Light gives us information about the chemical and structural composition of matter. Circular dichroism (CD) is one of the most successful and precise optical spectroscopy techniques. It reveals tiny asymmetries in the conformation of nanometric objects of interest like proteins or drugs. CD signals reflect the normalized difference in absorption of a compound when illuminated with light of right- and left-handed circular polarizations. Chiroptical signals are, however, very weak, limiting their potential applications. In this project, you will experimentally investigate the enhancement of chiral light-matter interaction using nanostructures known as optical nanoantennas.

The project revolves around nanofabrication using electron beam lithography and etching of crystalline semiconductor films for achieving high-quality optical resonators. Using circular-polarization-resolved photoluminescence microscopy, the goal of this project is to achieve stronger chiroptical signals by exploiting the optical resonances of the nanoantennas. The ultimate goal of the research line is to increase the sensitivity of chiral sensing to the regime of single molecules.
Beaming light with nanoplatelets (BSc/MSc project)

Supervisors: Bingying You/Sara Elrafey/Rasmus Godiksen/Alberto Curto (A.G.Curto@TUe.nl)

High refractive-index nanostructures can redirect light emission from sources such as molecules and quantum dots to improve collection efficiency (Nature Photonics 12, 284 (2018)). Van der Waals materials have highly anisotropic optical properties due to their atomically layered structure. Bulk crystals are routinely exfoliated in liquid to yield nanoplatelets. Furthermore, materials like hexagonal boron nitride and molybdenum disulfide have high refractive indexes in the range of 2.2-4.5, which allow strong Mie resonances. In this project, you will exploit the optical and geometrical anisotropy of such nanoplatelets to enhance and direct light emission. First, you will elucidate the resonant optical response of individual nanoplatelets using simulations. You will proceed to experimentally characterize the morphological and optical properties of nanoplatelet powders using atomic force microscopy and single-particle optical spectroscopy and fluorescence angular radiation pattern imaging. These materials could be exploited for enhanced light-emitting devices such as OLEDs and random lasers.
Exciton-based imaging sensors in atomically thin semiconductors (MSc project)

Supervisors: Rasmus Godiksen/Alberto Curto (A.G.Curto@TUe.nl)

Nanoscale semiconductors can be sensitive to their surroundings, which in quantum emitters leads to intermittency in the fluorescence of single quantum dots or organic molecules. Our group has recently discovered that the fluorescence of the monolayer semiconductor WS2 is extremely sensitive to charge transfer events (Nano Lett., 20, 4829 (2020)). In this project, you will exploit such exciton fluctuations to exploit the flickering signal for imaging and sensing. The goal is to visualize nonfluorescent nano-objects that are impossible to resolve with conventional optical microscopy using the activated fluorescence of a sensitive semiconductor monolayer.

You will create nanostructures of atomically thin semiconductors and characterize their optical properties. The ultimate aim of this research is to produce an imaging sensor to detect charges, pH, molecules, or chemical reactions with high spatial resolution.
Wide-bandgap semiconductor nanoantennas for ultraviolet nanophotonics (MSc/BSc project)

Supervisors: Ershad Mohammadi / Sara Elrafey / Alberto Curto
(A.G.Curto@TUE.nl)

Light gives us information about the chemical and structural composition of matter. Circular dichroism (CD) is one of the most successful and precise optical spectroscopy techniques. It reveals tiny asymmetries in the conformation of nanometric objects of interest like proteins or drugs. CD signals reflect the normalized difference in absorption of a compound when illuminated with light of right- and left-handed circular polarizations. Chiroptical signals are, however, very weak, limiting their potential applications. In this project, you will experimentally and/or theoretically investigate the enhancement of chiral light-matter interaction using nanostructures known as optical nanoantennas.

Depending on the MSc/BSc character of the project, the tasks will involve experimental nanomaterial characterization (scanning electron microscopy, optical measurements) and/or numerical simulations. You will design nanophotonic resonators tailored for maximum circular dichroism in the ultraviolet, where chiral biomolecules show their strongest response to circularly polarized light. The core of the project is comparing the performance of nanostructures made of different materials such as TiO₂ or diamond. Beyond this target application, confining ultraviolet light to deep subwavelength volumes is relevant for photolithography, disinfection, and photocatalysis.
Theoretical frontiers in chiral light-matter interaction (MSc/BSc project)

Supervisors: Ershad Mohammadi/Alberto Curto (A.G.Curto@TUE.nl)

Optical chirality is a quantity that determines the contrast in light absorbed by a chiral molecule for left and right circularly polarized light. It is proportional to the product of parallel electric and magnetic fields and it is related to the degree of circular polarization of light. It is possible to obtain optical chirality above that of a circularly polarized plane wave (ACS Photonics 6, 10, 2583 (2019), ACS Photonics, 8, 6, 1754 (2021)).

Our team is currently studying several new approaches to increase chiral light-matter interactions. We have several theory projects to offer on the topics of gain for chiral sensing, topological photonics for chiral sensing and nanophotonics-enhanced optical rotation. The methods include Mie scattering theory, numerical methods using COMSOL, and semi-analytical techniques. Get in touch with us to discuss open possibilities.
Atomic scale observation of iso-electronic dopants in semiconductors (BSc and MSc project)

Supervisors: Douwe Tjeertes/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 nm² STM image of GaAs containing both Bi (bright dots) and N atoms (dark rectangles)](image-url)
Atomic-scale characterization of III-V semiconductor Quantum Dots (MSc project)

Supervisors: Raja Gajjela/Paul Koenraad (p.m.koenraad@tue.nl)

A 30×30 nm² filled-state topographic STM image of InAs QD in InP (https://doi.org/10.3390/nano11010085)

Semiconductor quantum dots (QDs) are nanostructures that can confine charge carriers in all three spatial dimensions providing a set of discrete energy levels with various applications in optoelectronics and quantum information technology. The optoelectronic properties of QDs are therefore strongly influenced by the size, shape, and composition of the QDs. The precise structural analysis is essential for the better understanding of growth mechanisms and to optimize QDs for various applications. Cross-sectional scanning tunneling microscopy (X-STM) can directly visualize the atomic structure of the surface and so precisely determining the size and shape of the embedded QDs. The structural and compositional changes after overgrowth such as intermixing, segregation and morphological changes in QDs can also be studied by X-STM. In this project we have multiple QD systems to be analysed by X-STM e.g. InAs/InP QDs grown by local droplet etching, InAlAs/InAs coupled QDs, GaAs/AlGaAs QDs grown on GaAs(111) substrates. The project involves the high resolution imaging using X-STM, image processing and data analysis to provide a detailed feedback to the growers.
Optomechanical Faraday effect (MSc project at AMOLF, Amsterdam)

Supervisors: Roel Burgwal/Ewold Verhagen (verhagen@amolf.nl)

By placing a crystalline slab between two mirrors, light bouncing between the mirrors can couple to standing mechanical waves in the crystal through the process of electrostriction. The excited mechanical waves occur at GHz frequencies, as there the light and sound wavelengths are matched. We have recently predicted that using this photon-phonon interaction, the polarization of laser light reflected from the cavity can be controlled by a second laser. In this project, you will perform optical experiments that seek to demonstrate this effect. You will construct the high-quality optical cavities containing suitably designed crystalline samples. In your experiments, we will look for an optomechanical analogue of the Faraday effect: Breaking the two-way symmetry of light propagation similar to the way that a magnetic field in an optical isolator creates one-way optical transmission. This project is carried out in the Photonic Forces group at the AMOLF institute in Amsterdam.
**Topological phonons in optomechanical chains (MSc project at AMOLF, Amsterdam)**

Supervisors: Javier del Pino/Ewold Verhagen ([verhagen@amolf.nl](mailto:verhagen@amolf.nl))

The field of optomechanics explores the interaction of confined light fields and macroscopic mechanical oscillators via radiation pressure forces. These systems offer excellent optical control over phononic (mechanical) interactions and straightforward scalability, paving the way towards macroscopic simulation of solid state physics on a chip. Our group has recently explored a platform where the (linear) interaction of two phononic modes is tailored through an input laser, imprinting behavior on the phonons that is reminiscent of electrons in a magnetic field (the Aharonov-Bohm effect). Even more exotic phenomena, such as formation of non-bosonic particles, has been predicted if non-linearities are present. In this theoretical project, you will analyze a simple model system, gaining analytical insight and learning how to calculate numerically the phonon states of the system in the presence of light fields. With the know-how acquired you will extend this study to a one-dimensional phononic chain of resonators. There, you will explore how so-called topological phases emerge, allowing states with special properties not normally observed in mechanical systems. You will learn how to characterize these in terms of physical observables. This project is carried out in the *Photonic Forces* group at the AMOLF institute in Amsterdam.
Ultra-coherent nano-optomechanical resonators (MSc project at AMOLF, Amsterdam)

Supervisors: Jesse Slim/Ewold Verhagen (verhagen@amolf.nl)

By measuring a mechanical resonator’s oscillating position with extreme precision – at femtometer level – one could resolve mechanical quantum fluctuations and gain control over the quantum state of the resonator. In this project, you will develop new photonic crystal cavities that confine light at subwavelength scale to sensitively read out the motion of suspended nanomechanical strings. By making these strings out of silicon nitride, we aim to reduce mechanical damping to very low levels. This would boost the mechanical decoherence time such that characterization and preparation of quantum states of the string come in reach. 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.