Research Centre for Integrated Nanophotonics

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EXECUTIVE SUMMARY

The year 2018 was a period of changes and developments for this Gravitation program and generally for the integrated photonics activities at TU/e and in the Netherlands. In response to the recommendation of the mid-term review, we revised the composition of our strategic advisory board and started a number of initiatives aimed at reinforcing the internal cohesion and collaboration. In the management, Prof. Fiore took over the role of scientific director due to the retirement of Prof. Smit, and more tasks were transferred to younger staff members.

A number of important scientific results were achieved in the past year. In the *Pervasive Optical Systems* theme, high-capacity wireless optical communication using our patented 2D-steered infrared beams technology was extended, and several demonstrations showing real-time high-definition video streaming were given. Spatial-division multiplexing was brought to the next level, with the demonstration of 1 Tbit/s mode-multiplexed transmission over graded-index 50 µm core multi-mode fiber employing Kramers-Kronig receivers. For data centers, record-breaking 720Gbit/s throughput integrated transceiver modules have been realized. A new research line on integrated switches for optical neural networks was started, with encouraging results.

A major step forward was realized within the *Nanophotonic Integrated Circuits* theme, with the demonstration of high-performance distributed-feedback and tunable lasers within the InP-on silicon (IMOS) platform, and particularly a first successful multi-project wafer run on IMOS, incorporating a number of active and passive devices. This marks a turning point for the development of IMOS, where different users and applications can now be targeted. Also noteworthy is the demonstration, within the same platform, of very compact, ultralow-power nanomechanical phase modulators and switches. The integration of nanomechanical switching/sensing with active/passive devices could become a unique feature of this platform.

In the *Ultimate control of light and matter* theme, a major breakthrough is represented by the demonstration of direct-gap emission from SiGe nanowires (work extending across 2017 and 2018). This could open the way to monolithic integration of efficient light emitters on silicon in the long term. The work on photonic/magnetic memories also experienced a major step forward, with the demonstration of 'on-the-fly' all-optical writing of magnetization along a magnetic racetrack. Finally, important progress was made in the control of atomic layer deposition for photonics, and in particular the selective-area deposition of Ru.

On the valorization side, as a result of the intense preparation work of the consortium and of its partners in the last two years, the National Agenda Photonics and the PhotonDelta investment plan was finalized and handed over to the State Secretary in July 2018. This has led to the creation of a dedicated fund for applied R&D in integrated photonics, which will help translating the research results from this program into value for the photonics ecosystem and society as a whole. Several large European programs for increasing the technology readiness level of integrated photonics manufacturing were acquired by the consortium in 2018.

OVERVIEW OF THE RESEARCH OBJECTIVES

Modern society depends on sustained increases in internet bandwidth, connectivity and computational power for business, entertainment, comfort, safety and communications. But the hardware at the heart of the internet consumes an unsustainable amount of energy and projections are showing a relentless increase. The energy consumption limits design and constrains connected bandwidth at every level of the network: inside computer systems, inside fiber-optic routers and at the final wireless connections to the user.

In order to solve these outstanding issues, a radical new technology paradigm is required: we envisage a pervasive end-to-end optical connection between users and computing resources and a radical enhancement in electronic-to-optical conversion efficiencies. This requires the intimate integration of electronics and photonics at both the system level and at the physical layer and a re-engineering of photonics close to the quantum limit. It raises formidable scientific and technological challenges. We focus on the key hardware challenges on all scale levels.

THEME 1 PERVASIVE OPTICAL SYSTEMS

We aim to create new integrated photonic circuits, which connect users optically to the network, keep information in optical form as it passes through data routers in the internet backbone, and handle unprecedented information densities as data streams converge at the servers at the heart of the internet.

The systems must help solve the capacity bottleneck at every network level from the long-haul transmission systems through data-center networks and including down to access networks and in-home networks, where billions of users need fast connections with the local and global internet.

The Gravitation research targets different parts of the communication infrastructure:

- Long haul transmission of data, where photonic integration techniques will be exploited to open new dimensions and increase the amount of data that can be transported over a single fiber.
- Signal routing and processing, where applications of adding versatile photonic circuits to CMOS circuitry are being investigated as well as the introduction of optical switches for energy-efficient and transparent switching and routing of data.
- Closer to the user, the research is aimed at photonic chips as a means to create dynamically reconfigurable indoor access points, a low-cost indoor optical network, and beam-steering techniques for short-range wide-band low-power radio- and optical-wireless connections.

THEME 2 NANOPHOTONIC INTEGRATED CIRCUITS

We aim to intimately integrate active photonic circuits with electronic CMOS circuits using nanophotonic technology to push integration density and power efficiency several orders beyond today's state-of-the-art.

The research line has two parts:

- Creation of a nanophotonic membrane based integration platform that supports integration of compact and energy efficient basic building blocks used in photonic circuits for a variety of applications. These membrane-based photonic circuits are created on top of silicon or CMOS integrated circuits, which contain the electronics for driving and controlling the optical circuits and for processing the electronic data that they generate.
- Creation of compact and ultra-low power components for future integration in the platform. Emphasis is on nanolasers and photonic switches.

THEME 3 ULTIMATE CONTROL OF LIGHT AND MATTER

We aim at ultimate control of light-matter interaction on an atomic scale, to ensure the ultimate in energy efficiency and information density, and to explore ways of manufacturing. The emphasis is on tools to create and analyze optical nanomaterials for efficient nanophotonic devices and to develop and study novel devices for efficient generation and detection of light at the femtojoule (fJ) energy level. We also study the exchange of information between photons and magnetic spin as a route to fast and ultra-dense optically addressable memory.

We are investigating techniques for creating and manipulating structures on the nanoscale, which display properties which are not found in natural materials. One example is the growth of hexagonal Si and SiGe nanowires, the first samples of which show the expected direct bandgap. This novel material may enable efficient emission from silicon, or the monolithic integration of materials with different crystal structure or lattice constant (e.g. III-V on Si or vice versa). This work is made possible by the use of atomic-scale characterization techniques which identify these structures atom-by-atom. Another research line investigates processes where light directly interacts with magnetic properties of matter, which opens ways for optical memories. These are still a major target in the design of optical circuits. Major challenges are encountered and addressed in both the scientific analysis and the manufacturing methods.

All staff members involved in the Gravitation Program "Research Centre for Integrated Nanophotonics" belong to the TU/e Institute of Photonic Integration (IPI). This institute provides the input to a pipeline which brings research to application (see the section on Institutional Embedding).

The focus on new technology hardware offers a unique opportunity to proceed beyond the "proof-of-principle" and tackle both fundamental challenges and opportunities for large-scale applications. On the following pages we give a brief description of the research that we are doing to address the challenges described above, and of the most important results that we have achieved in the fifth year of the project (2018).

In a couple of cases, activities in the Nanophotonic Gravitation program have led to spin-off research. Based on work in the Nanophotonic Integrated Circuits theme, the following PhD projects have been started:

- Rui Ma (PhI group) is working on non-reciprocal photonics.
- Yi Wang (PhI group) is working on LIDAR based sensors.
- Kaylee Hakkel (PSN group) is working on spectral sensors.

WORK PROGRESS AND ACHIEVEMENTS

THEME 1 PERVASIVE OPTICAL SYSTEMS

Theme Coordinator: Ton Koonen

Highlights:

- 1 Tbit/s Mode-Multiplexed Transmission over Graded-Index 50um Core Multi-mode fiber employing Kramers Kronig Receivers [HEI18]
- Programmable Vector Mode Multiplexer – Ongoing collaboration with Nokia Bell Labs and Presented at ECOC Post Deadline [FON18]
- 128x10 Gbit/s-capacity 2D-steered infrared beam optical wireless communication demonstrator [LI_18b]
- Image classification possible through photonic integrated switch matrices [SHI19]

THEME 1.1 **Fiber wireless integration**

Project leader: Ton Koonen

Optical wireless communication indoor network

After concluding the ERC Advanced Grant project BROWSE in Dec. 2017, in 2018 in the newly acquired ERC Proof-of-Concept project BROWSE+ we expanded the demonstration setup of our high-capacity 2D-steered IR-beam optical wireless communication (OWC) system. We published simultaneous downstream transmission of two high-def video streams embedded in 10Gbit Ethernet by two independently steerable IR beams [KOO18b]. We investigated the cooperation of multiple beams in order to create extra link budget for increased reach and capacity, and demonstrated transmission over 1.7m of 20Gbit/s PAM-4 synthesized from two sources [SUN18a]. We designed a localization technique which automatically finds multiple users while requiring only a passive tag at the user side, and demonstrated it in the 10GbE video demonstrator setup [SUN18b].

We demonstrated a bi-directional half-duplex OWC system operating at 10Gbit/s over 1.1m using a single Fabry-Perot laser diode acting both as receiver and transmitter at the user side [LI_18c]. We also showed that our 2D beam steering concept based on high port count arrayed waveguide grating router can be scaled to large beam numbers while suppressing crosstalk between the beams by introducing polarization orthogonality between the odd and even AWGR channels (Fig. 1) [ZHA19]. We presented transmission of a record 30Gbit/s orthogonal frequency division multiplexed (OFDM) signal over a diffuse optical wireless link [CAO18].

Based on our OWC work Ton Koonen was chosen by TU/e as its nomination for the prestigious yearly Huijbregtsen prize, and was among the 6 finalists (out of 40 nominations). A world-wide disseminated IEEE Photonics Society webinar on OWC was given on Feb. 21 [KOO18c].

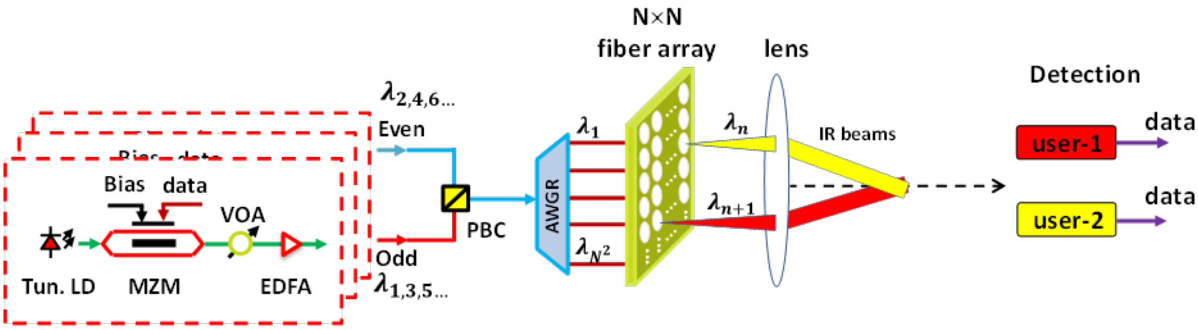

Figure 1 Crosstalk-reduced beam-steered OWC system, enabling scaling to many beams

Optically-controlled radio beam steering

In the Gravitation project we designed a novel optically-controlled true-time radio beam former, based on optical delay lines and optical ring resonators (ORRs). The design was implemented in an InP chip and we demonstrated transmission of 8.0Gbit/s gross (6.7Gbit/s net) per channel [TRI19]. We explored signal modulation schemes with improved bandwidth-efficiency in order to fit high capacity within the bandwidth limits of the ORRs; with Nyquist-shape subcarrier modulation, we achieved up to 9 Gbit/s gross data rate and a delay setting up to 30ps for beam steering [TRI18]. Using a packaged silicon-nitride (Si3N4) optical beam former in conjunction with multicore feeder fiber, for the next-generation 5G new radio (5G NR) mm-wave band we demonstrated a beamforming system which with two antenna elements (AEs) provided up to 21Gbit/s per user, and with 4 AEs up to 16.8Gbit/s per user [MOR19].

In extending our looped-back arrayed waveguide grating architecture, we doubled the radio beam steering resolution by means of a bi-directional optical delay network. Implemented in an InP chip, characterization up to 20GHz showed a tuning range of 13.4+13.1ps with an imbalance of <1ps [ZHA18].

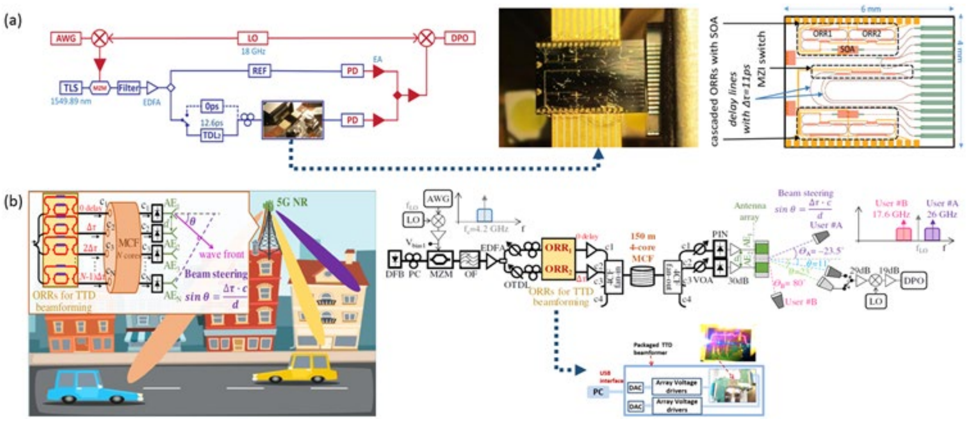

Figure 2 a) InP optical broadband radio beam former using switched delay lines and cascaded ORRs b) packaged Si_3N_4 optical beam former assisted by multicore fiber for 5G NR

THEME 1.2 **Data centers and optical interconnects**
Project leader: Oded Raz

Novel 3D and 2.5D packaging for optics in data centers

This activity was concluded in 2018 with the PhD graduation, Cum Laude, of Dr. Chenhui Li. The technology developed by Dr. Li has been patented by TU/e and the knowhow is being transferred to the TU/e spin-off, PhotonX networks. During the last months of his PhD Dr. Li has published an extended version of his high density interconnect work in IEEE Transactions on Electron Devices [LI_18a] and a report about advanced 200Gb/sec fully integrated transceivers sub-modules [LI_18b].

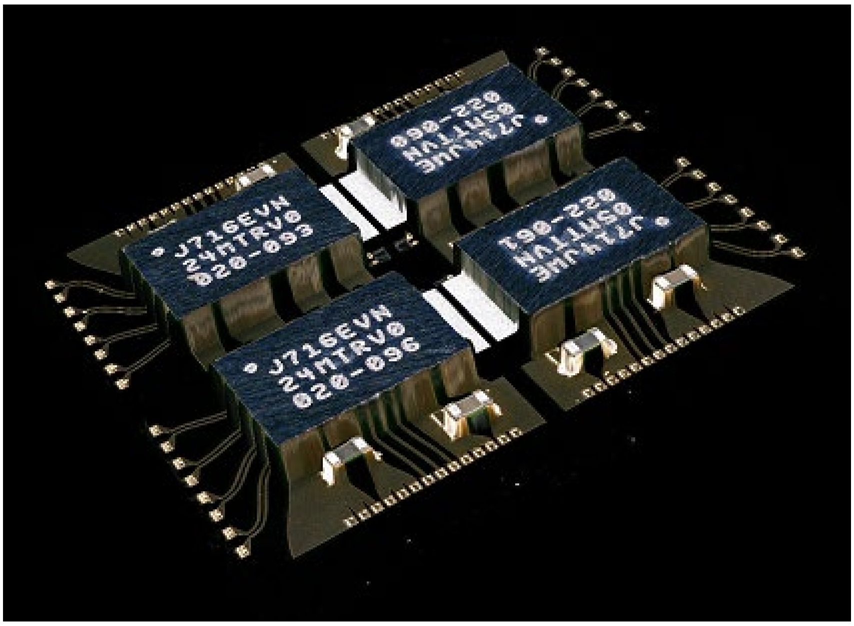

Figure 3 2x8x25Gbps transceiver sub-module supporting up to 200Gb/sec bandwidth (bi-directionally) in an area of ~36 mm2[LI_18b]

Dr. Li has joined the ECO group as a post doc and he is working together with project partners to co-integrated VCSELs with silicon photonics. First results are expected in the first half of 2019 as part of the activities in the H2020 PASSION project.

THEME 1.3 **Optical Switching**
Project leader: Patty Stabile

SOA-Based Photonic Switch for Deep Neural Networks

Deep learning neural networks can be applied in image classification, time series prediction, system optimization and data features extraction, but increasing their performance runs into power usage limits. Photonic integrated circuits have recently been considered to realize more efficient deep neural networks. Recently we have demonstrated weighted addition by using InP-based optical switch matrices with a combination of semiconductor optical amplifiers (SOAs) and array waveguide gratings (AWGs) [SHI18a,SHI18b], but no application has been run through it yet.

We now employ an InP optical neural network to solve classification problems. We use the trained optical deep neural network to demonstrate an Iris flower classification among the three species (Setosa, Versicolor and Virginica) and optimize prediction accuracy by adding control feedback loops

[SHI18c,SHI19]. We use 120 instances for training the network from the Fisher's Iris database on the simulation platform TensorFlow.

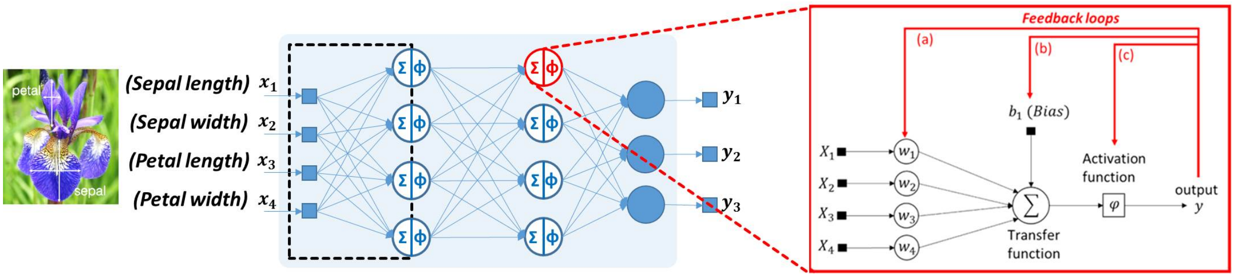

Figure 4 Three layer deep neural network used for Iris classification (blue box). Inset on the right: Basic model of the neuron with feedback loops for fine prediction optimization.

A three layer feed-forward network is aimed for image classification. Four weighted addition functions of the first layer are monolithically integrated on-chip (Figure 5, dashed black line), while a hyperbolic tangent active function is implemented off-chip via software. The second layer and output layer are simulated with the neural network model, which can be implemented by reconfiguring weight matrix on-chip in the near future. The on-chip SOAs provide a wide dynamic range for the weight matrix setting, while the integrated filters reject most of the noise.

The four inputs are encoded into 26 levels in four different laser sources at λ_1=1539.83 nm, λ_2=1543.11 nm, λ_3=1546.26 nm and λ_4=1549.06 nm and are synchronized. The optical data signals are coupled into the chip. There, the WDM signal is split into 4 copies and fed to each of the four weighting stages. At every weighting stage, an AWG filters out the amplified spontaneous emission (ASE) from the SOAs and de-multiplexes the inputs into for different data signals at λ_1, λ_2, λ_3 and λ_4. The 4 SOAs are biased with different (weight) currents by the multi-current controller, in order to control the gain of the corresponding channel and to weight the input data. The weighted signals at each neuron are combined and sent to the chip output for analysis.

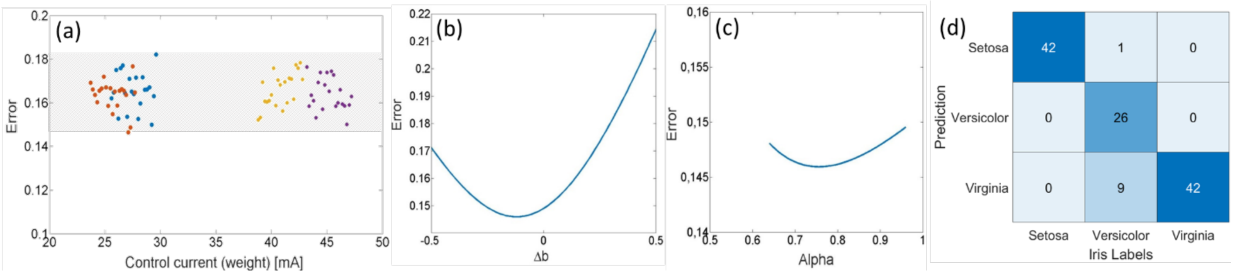

Figure 5 Error optimization of the individual weights at neuron1 (a), of the bias (b) and of the non-linear function shape (c). Figure (d) shows prediction and label mapping.

The classification accuracy is optimized by fine tuning of the control current at the SOAs (Figure 5, right inset - feedback loop a and Figure 6a) and, in a second step, by tuning the bias and the non-linear function shape as indicated in Figure 5, right inset - feedback loop b and c, respectively, and Figure 6b and c). The network classification accuracy is recorded to be 91.6% (see Figure 6d), which is comparable to a trained simulation model on a state-of-the-art processor (93.3%).

THEME 1.4 **Integrated low loss space-division-multiplexed transceivers**
Project leader: Chigo Okonkwo

Ultra-high capacity links: space Division Multiplexing transmission exploiting Kramers Kronig Receivers

In 2018, the key target was to further increase the achievable capacity by exploiting space division multiplexing whilst reducing the overall complexity of the required signal processing through novel techniques. In addition, we are developing compact optical components such as mode-multiplexers and multi-mode amplifiers exploiting integrated photonic techniques. In space division multiplexing, access to amplitude and phase information of the received signal means that coherent reception techniques are required. However, the optical receiver architecture is considered too complex for application in short to medium reach links such as for inter/intra-datacenter communications. With the spotlight on cost-effective inter datacenter links, there has been a resurging interest in Kramers Kronig (KK) receiver schemes. In our work published in 2018, the KK scheme is exploited firstly to allow full reconstruction of the optical phase from a direct amplitude detected signal using a single ended photodiode. Secondly, the KK scheme is exploited to reduce the required receiver structure for receiving each spatial channel with respect to coherent receivers after propagation of the modes over 50um core diameter graded index multi-mode fiber (GI-MMF).

We demonstrated transmission of 100Gbit/s per spatial channel achieving a net transmission rate of 1 Tbit/s after 18km for 12 spatial channels (6 modes, 2 polarizations). Furthermore, we demonstrate 500Gbit/s net transmission for 6 spatial channels (3 modes, 2 polarizations) after 53 km GI-MMF.

Based on this work reported at European Conference on Optical Communications (ECOC) 2018, Sjoerd van der Heide (Zwaartekracht PhD student) was awarded one of the best student paper awards [HEI18]. Further dissemination of this work is planned in an extended journal.

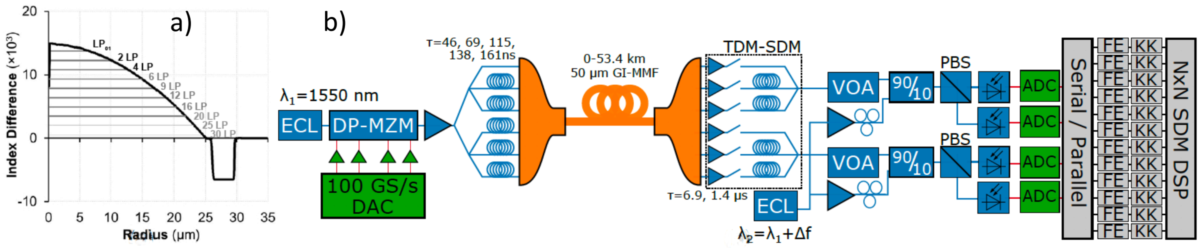

Figure 6 (a) Refractive Index profile of the GI-MMF. (b) Experimental setup: external cavity laser (ECL), dual-polarization Mach-Zehnder modulator (DP-MZM), digital to analog converter (DAC), analog to digital converter (ADC), variable optical attenuator (VOA), photonic lantern (PL), polarization beam splitter (PBS), front-end compensation (FE), Kramer-Kronig algorithm (KK), decorrelation delays are denoted with t, triangles represents amplifiers.

Ultra-high capacity links: Programmable Vector Mode Multiplexer

A key component for space division multiplexing is the development of low loss and compact mode multiplexers. In addition, a reconfigurable mode multiplexing and conversion system that can access the full vector field (polarization, phase, amplitude at every spatial coordinate) will be practical for adapting to different mode couplers, amplifiers and fibers without prior knowledge of the exact modal scheme to be employed.[FON17]

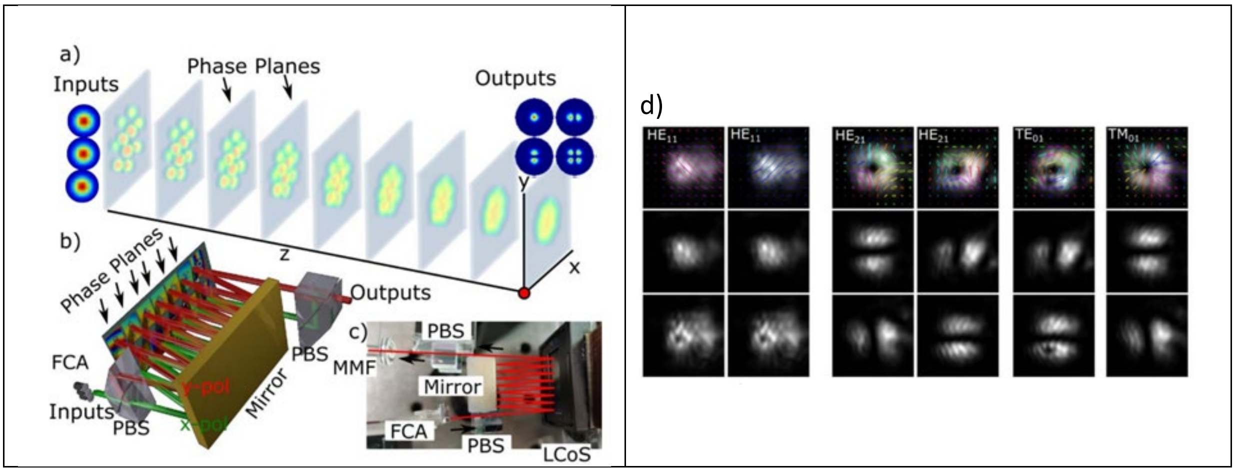

Figure 7 (a) Multi-Plane Light Convertor comprises phase planes separated by free space. b) Dual polarization folded implementation with polarizations vertically offset. c) Experimental realization (d) Polarization direction/ellipticity of vector modes and intensity.

In collaboration with Nokia, we have employed a multi-plane light conversion device to create arbitrary and lossless conversions between sets of spatial modes through a series of phase plates separated by free space. Designing phase planes with smooth profiles produce adiabatic conversions that are inherently fabrication tolerant with wideband operation. Here a proof of concept setup is developed using phase masks fabricated using many types of lithography with the aim of achieving pixel pitches of the order of one micrometer. The Multi-Plane Light Convertor (MPLC) device comprises of a 250 µm pitch fiber array collimator array (FCA) that produces a linear array of 10 beams with 70 µm beam waists, a polarization beam splitter (PBS) to vertically offset the two polarizations on the liquid crystal on silicon (LCOS), a gold mirror and a polarization beam combiner enables combination of both polarizations to the multimode fiber. The measured interference patterns (at 1550-nm) contains the two beams corresponding to the x and y polarization and fringes that encode the phase. Figure 8d shows the measured modes that include the two degenerate linearly polarized HE11 modes, the radially polarized TM01 mode, the azimuthal polarized TE01 mode and the two degenerate HE21 modes with complex spatial polarization. This work was reported at the prestigious post-deadline session at the European conference on optical communications. We continue to investigate the further integration of this functionality.

THEME 2 NANONPHOTONIC INTEGRATED CIRCUITS

Theme coordinator: Kevin Williams

Highlights:

- Successful fabrication of first IMOS MPW wafer [POG18a];
- DFB laser on IMOS platform with more than 60 dB SMSR [JIA18a];
- Compact nano-electro-mechanical switch in the IMOS platform [LIU19]

THEME 2.1 **A high-density generic integration platform for photonic ICs on CMOS**

Project leader: Yuqing Jiao

Based on the twin-guide active-passive integration technology on the IMOS platform, which has been successfully demonstrated in 2017, we have performed a new fabrication run in 2018 including several new features. Firstly, the SOA process flow has been further develope to enable heat sink to silicon carrier. The heat sink penetrates through the bonding layerstacks and connects p-contact metals to the silicon surface. The second feature is the upgrade from chip-based processing to a full 2-inch wafer-scale processing. More uniform resist coating can be achieved with full wafer, therefore improve the lithography qualities.

Recent development in the IMOS platform has attracted much attention, leading to an invited paper in the IEEE journal of Selected Topics of Quantum Electronics in this year [TOL18] as well as an invited featured article in the PIC Magazine [YAO18a].

We have designed and implemented improved laser structures in the wafer [JIA18a]. We take advantage of the active-passive integration and realized a Venier tunable laser based on two micro-ring filters. The picture of the fabricated laser is in Figure 9a. A 21 nm tuning range has been demonstrated by simply shifting the micro-ring resonance wavelength. Another example is a low-noise distributed feedback (DFB) laser, as shown in Figure 9b. We aimed for weakly coupled DFB grating on top of the membrane SOA to obtain millimeter long laser cavity. The long laser cavity helps in reducing relaxation oscillation and suppressing side-modes. The DFB gratings were realized in the shallow waveguide etch step and did not introduce extra processes. The coupling strength κ of the DFB grating is designed for 4, while the fabricated value (deduced from the lasing spectrum) is 4.3. The demonstrated laser has shown a side-mode suppression ratio (SMSR) of more than 60 dB, which is the highest SMSR reported in membrane DFB lasers. It also achieved a high optical output power of 10 mW in the waveguide. The L-I-V curve and the single-mode lasing spectrum can be found in Figure 10. All the various types of IMOS lasers demonstrated have similar threshold current density in the range of 2 – 2.5 kA/cm^2, indicating reliable process technology.

The successful laser development has led to several invited talks in high-level international conferences such as ACP [JIA18a], SPIE Photonics Asia [POG18a] and PIC International [YAO18b] in 2018, as well as confirmed invitations in OFC, ECIO and CSW conferences to be held in 2019.

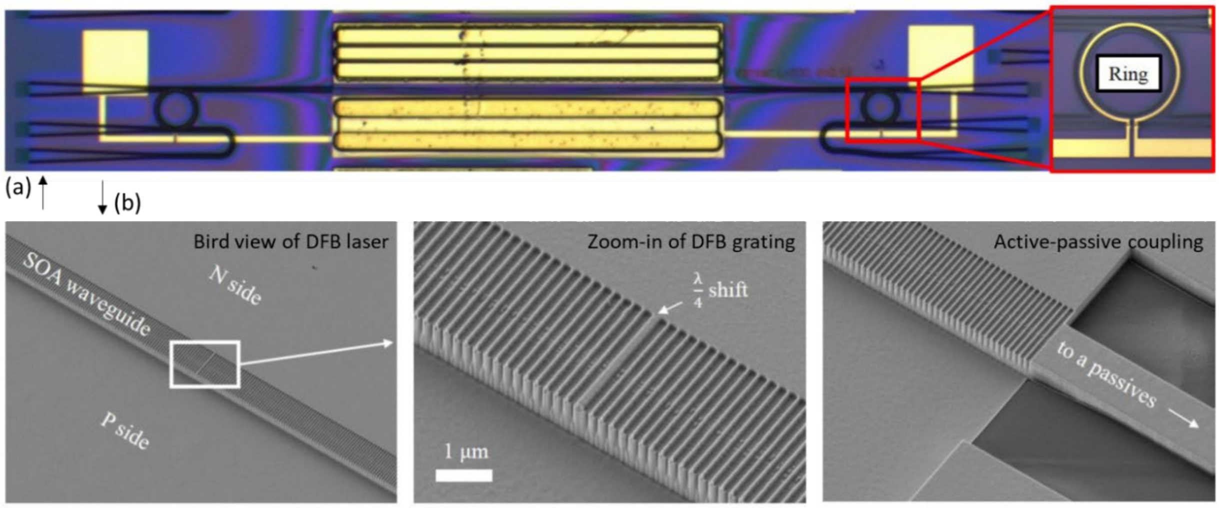

Figure 8 Pictures of fabricated membrane lasers (a) Vernier micro-ring based tunable laser; (b) low noise DFB laser.

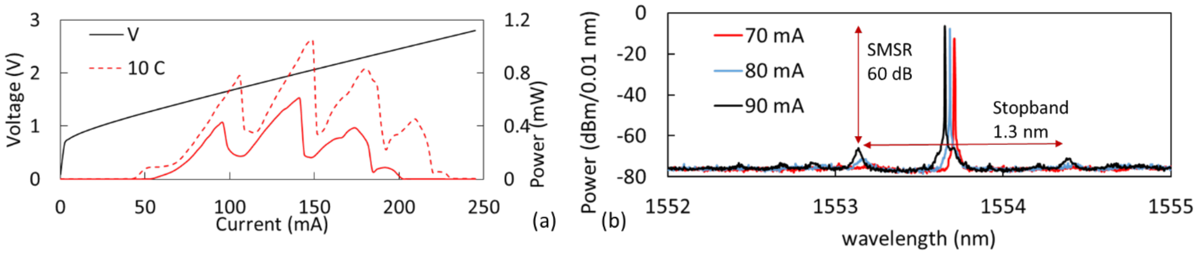

Figure 9 (a) L-I-V curve and (b) lasing spectrum of the fabricated IMOS DFB laser.

Another benefit of going to wafer-scale membrane is the opportunity to open up the wafer space to designers. For this fabrication run, we have organized it as a multi-project wafer (MPW) run with many external designs included [POG18a]. Designers range from PhI, ECO and FNA groups within the university, as well as designers from Bell Labs, USA and Hongkong Chinese University. The fabricated MPW membrane wafer is shown in Figure 10. Currently the wafer is being internally characterized in the PHI group, which has led to several laser demonstrations (see Figure 9). In the near future we will dice the wafer and distribute the chips to the designers.

The wafer-scale bonding technology based on the newly purchased EVG bond system has been maturing over the past year. We have achieved a reliable process for defect/bubble-free and wafer-scale InP to silicon bonding [POG18b]. The successful membrane MPW wafer shown in Figure 10 is based on this bonding technology. This bonding process has been instrumental also for ongoing IMOS-based processes for nanomechanical switches (see Theme 2.2) and spectral sensors (ongoing).

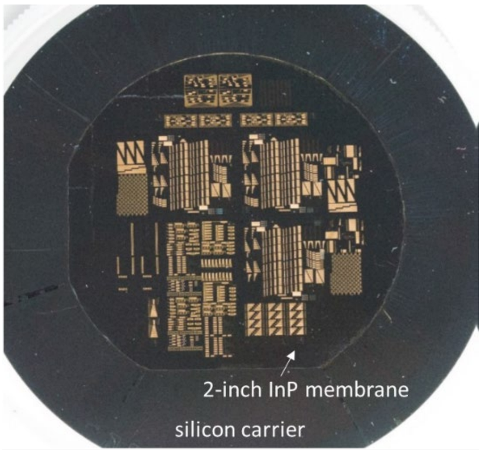

Figure 10 Pictures of fabricated membrane MPW wafer.

In the meanwhile we keep on the collaboration with Lightwave Logic (USA) on EO polymer based optical modulators. We are currently optimizing the process for the EO polymer provided by the company and investigate its process compatibility with the InP membrane material system. We also designed a novel plasmonic slot structure for the EO polymer modulator [KAS18]. The plasmonic slot provides stronger optical interaction with the polymer in the slot and requires less length. Therefore this concept is very promising for high-speed operation.

We have also made progress in incorporating ASML deep UV scanner tool into the fabrication of IMOS circuits. We have developed a reflow process for the deep UV resist, which can significantly reduce the sidewall roughness. The detail of the reflow process and the sidewall improvements can be found in [ENG18]. We have demonstrated experimentally a record low optical loss of 1.8 dB/cm in the InP membrane waveguide, thanks to this new lithography process. The work has been submitted to CSW 2019 conference.

Together with Prof. Hon Tsang, we investigate the nonlinear optical processes in our highly confined InP membrane circuits. We have studied the four-wave mixing process for photon pair generation in InP membrane micro-ring resonators. Thanks to the high Kerr nonlinear coefficient in InP (27×10^{-18} m^2/W, which is nearly 10 times higher than that in silicon), we observed high photon pair generation rate at low optical injection. We were able to obtain a photon pair generation efficiency comparable to the state-of-the-art silicon photonics devices, using an InP mircoring with halved Q factor and doubled radius [KUM19]. This showed promising potential of IMOS platform for integrated quantum computing. At higher optical injection level, we observed that significant two photon absorption and free carrier absorption start to play a role, which is due to the InP material [KUM18, KUM19].

Work continues on integration of polarization elements to IMOS platform, and on dense SOA and phase antenna arrays using IMOS technology for LiDAR application. The advantage of using IMOS over conventional InP platforms is its much higher optical confinement, which can lead to high-performance grating antenna arrays and ultrasmall (10x denser) and energy efficient SOAs integrated monolithically together.

THEME 2.2 **Ultralow-power components**
Project leader: Andrea Fiore

Optical switches based on nano-opto-electro-mechanical systems (NOEMS)

Several types of optical switches, based on the nanomechanical actuation of suspended waveguides, were fabricated on the IMOS platform and successfully tested. The first type consists of a nanomechanical Mach-Zehnder interferometer (Fig. 11). Switching is achieved by tuning the vertical gap between two coupled waveguides through the application of a reverse bias on a p-i-n junction. The switching requires a voltage as low as 4.4V and provides an extinction ratio above 15dB within a 34 nm bandwidth in the C-band. The device also serves as a very efficient optical phase modulator, being able to modify the optical phase by more than 4π with only 6.5V voltage in a 140µm-long waveguide. As compared to alternative MEMS switch demonstrations, mostly involving switching voltages of tens of V, the low switching voltage of our device facilitates the electrical driving.

An alternative switch concept, based on our theoretical proposal [LIU17] and featuring an even smaller footprint (length 60-100 µm) was also successfully fabricated and tested, showing a switching voltage down to approximately 3V, however the reproducibility is presently limited by fabrication imperfections and further optimization is under way.

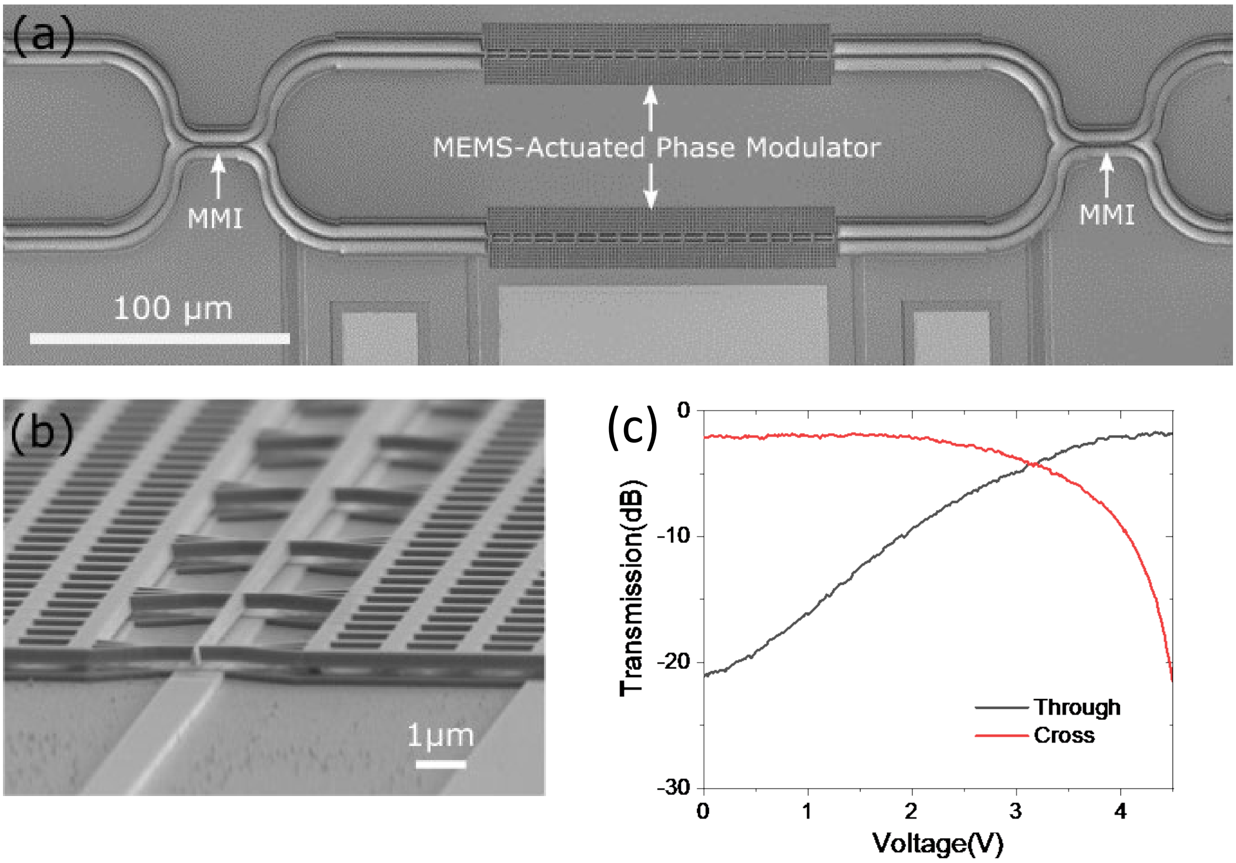

Figure 11 (a) Scanning electron microscope (SEM) image of a 2x2 switch. (b) Zoomed-in SEM image of the MEMS-actuated phase modulator. (c) Measured transmission of the switch as a function of voltage bias at 1530nm.

2D monolayer semiconductors

The overall goal is to push nanophotonics to its ultimate limit, the atomic scale [CUR18], to exploit the tunability and sensitivity of 2D materials in devices. We develop monolayer semiconductors as sources, detectors and modulators for integrated photonics and for other nanophotonic technologies such as sensors. In particular, we exploit novel degrees of freedom of the electron (the spin, the valley index, and the layer number) that could be used as resources to increase the collection efficiency of the emitted photons. For example, recently we have shown that semiconductor antennas [CIH18] can direct the emission of a monolayer semiconductor.

In 2018, we demonstrated three different mechanisms to enhance and control the emission and valley polarization of atomically thin semiconductors. The first mechanism relies on the impact of indirect optical transitions on polarization, whereas the other two mechanisms rely on metal nanostructures (Figure 12). Additionally, in 2018 we have also identified a stable van der Waals material, TiS_3, emitting at telecom wavelengths, as an alternative to environmentally unstable black phosphorus, which was the only 2D semiconductor available in this range so far. When its efficiency is optimized, it would provide a more viable route to applications at telecom wavelengths.

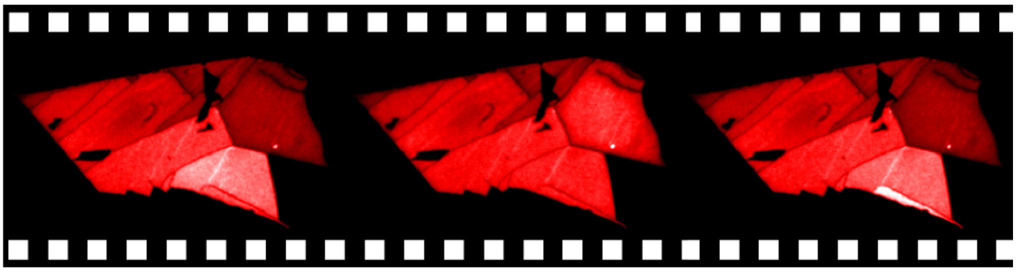

Figure 12 Control of light emission from a monolayer semiconductor using a nanoscale metal. The photoluminescence images of different areas of a 2D semiconductor flake show the time evolution of the emission, as modified by interaction with a metal.

THEME 3 ULTIMATE CONTROL OF MATTER AND PHOTONS

Theme coordinator: Paul Koenraad

Highlights:

- ‘On-the-fly’ all-optical writing of magnetization along the magnetic racetrack [LAL19]
- Radiative emission from direct-bandgap SiGe (publication foreseen in 2019)
- Area-selective atomic-layer-deposition process for Ru (publication foreseen in 2019)

THEME 3.1 **Quantum effects in nanophotonic devices**

Project leader: Jaime Gómez Rivas

In the last year a new activity on strong exciton-photon coupling has been started, under supervision of Prof. Jaime Gómez-Rivas who recently moved his group to TU/e. His group has recently demonstrated strong light-matter coupling of excitons in organic materials with cavity photons in arrays of nanoparticles and the formation of plasmon-exciton-polaritons (PEPs). PEPs can condense into the ground state at sufficiently high densities, which leads to a coherent emission without the need for population inversion. This coherent emission is known as polariton lasing. Quantum effects responsible for condensation and polariton lasing can be exploited to reduce the threshold of non-linear emission compared to traditional lasers, which may lead to the realization of electrically driven organic polariton lasers. This challenging goal will require the optimization of the cavity to maximize the coupling strength. Therefore, we have developed algorithms to optimize structural parameters in nanophotonic cavities to obtain a pre-defined optical response. The traditional approach, consisting on the systematic variation of only one parameter, keeping the others fixed, has limited application in this case as the system is governed by multiple parameters, such as thickness, material composition, geometry of device, wavelengths of illumination/emission etc. An alternative simulation approach has emerged in recent years by using optimization algorithms integrated with numerical electromagnetic methods (such as FDTD or FEM) to explore the parameter space. We have recently integrated the so-called particle swarm optimization (PSO) with the finite-different time-domain (FDTD) method to optimize the transmission spectra of aluminum nanohole arrays for the design of color filters. Figure 13 summarizes the results of the optimization, applied to the case of color optimization in color filtering applications.

In the next steps, we will introduce this methodology to simulate and optimize the coupling strength and the lasing threshold of organic polariton lasers. We aim to design cavities formed by nanoparticle arrays with ultra-high Q-factors through the so-called bound states in the continuum (BICs), that can potentially reduce this threshold.

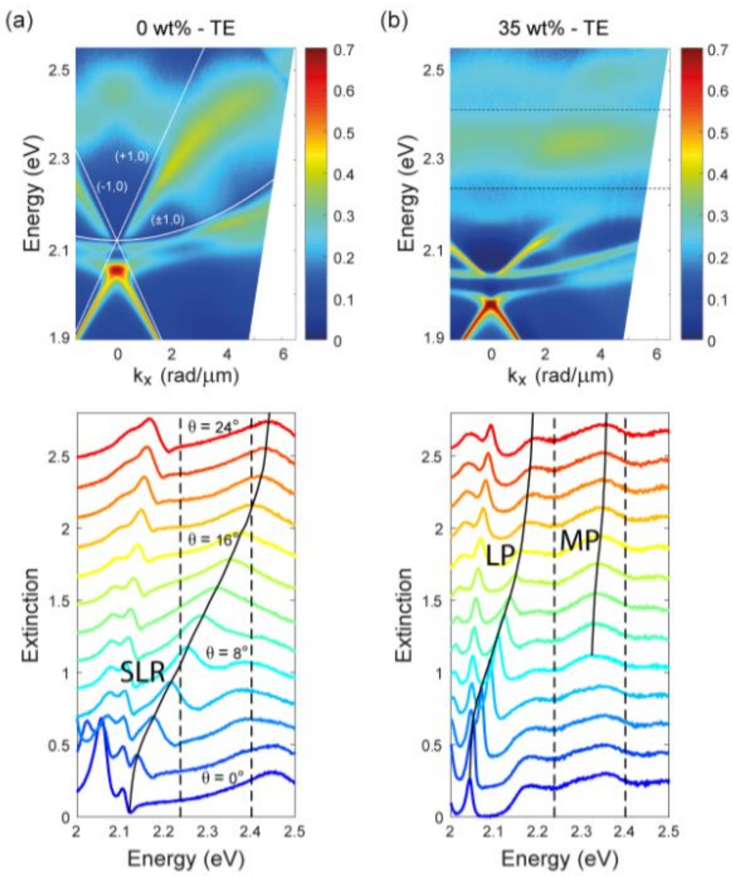

Figure 13 Strong light-matter coupling of excitons in organic semiconductors and photons in semiconductor nanophotonic cavities. Strong coupling is a necessary condition for quantum condensation and polariton lasing. (a) Dispersion extinction measurements of the cavity formed by an array of semiconductor (Si) nanoparticles. The cavity modes follow the dispersion of the diffraction orders of the array. The lower graph illustrates the extinction measurements at different angles. In this graph, the main mode participating in the coupling is also indicated (black curve). (b) Dispersion measurements of a similar array strongly coupled to organic molecules in PMMA (35wt%). The lower graph illustrates the extinction measurements at different angles, indicating also the hybrid lower polariton (LP) and upper polariton (UP) bands. These exciton-polaritons are the result of the quantum superposition of excitons in the molecules and the photons in the nanoparticle array.

THEME 3.2 **Hybrid approaches combining photonics and spintronics**
Project leader: Bert Koopmans

This subproject is driven by our vision to develop the fundamental building blocks for Integrated MagnetoPhotonics, which would provide new dimension to PICs [KOO18a]. More specifically, we aim to create spintronic-photonic memories in which streams of high-data rate optical bits can be copied into a dense magnetic memory, and vice versa, without electronic intermediate steps. This scenario is envisioned to provide a highly energy-efficient scheme. In the first phase of the project we focus on the fundamentals of optical manipulation of magnetic matter, as well as the integration of spintronic and magneto-optical functionality in integrated photonics. More specifically, we focus on a novel approach using photonic waveguides with magnetic claddings that display a perpendicular magnetic anisotropy (PMA), i.e., the magnetization is perpendicular to the thin film plane.

Within the past year we reached a crucial milestone, by combining all-optical writing with current-driven motion of information along a magnetic 'racetrack'. At the basis of the proof of concept demonstration lies our earlier finding of deterministic switching by single 100 fs laser pulses for a Ta(4)/Pt(4)/Co(1)/Gd(3)/Pt(2) film, where numbers between brackets indicate layer thickness in nanometers [LAL17]. For the thinnest Co thickness measured (0.8 nm), an effective switching energy of 50 fJ was demonstrated when normalized to a 50 x 50 nm^2 area. In the most recent work [LAL19], we fabricated magnetic nanostrips with Hall bars for electrical read-out of the magnetization. We explored the current-driven motion of magnetic information in this specific system at velocities up to 10 ms^{-1}, but conservative extrapolations yield velocities of at least several 100s of ms^{-1}, sufficient for high data-rate applications. As to the fs optical writing, we extended existing models for alloys to bilayer systems, and discovered striking differences between the two systems. Finally, we succeeded in establishing a proof-of-principle demonstration of 'on-the-fly' all-optical writing of magnetization while simultaneously propagating the written information along the magnetic racetrack, driven by a DC current, as shown in Figure 14 [LAL19].

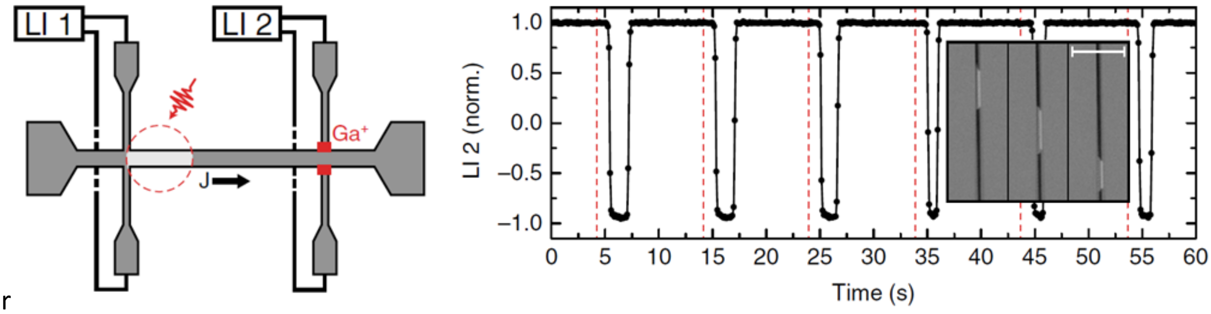

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Figure 14 Demonstration of 'on-the-fly' writing of magnetic information by fs laser pulses. Left image shows the Hall bar, fabricated from a Pt/Co/Gd racetrack. White and grey represents magnetization pointing up- and downwards, resp. A white domain is written by a laser pulse, in the presence of a current density J. The right image shows the arrival of the magnetic domain (signal changing from +1 to -1) as measured by the Hall signal "LI 2". A clear time delay between firing of the laser pulses (vertical dashed red lines) and passing of the domain is seen. The inset shows three stages of domain propagation in a magneto-optical Kerr microscope image. [LAL19]

Collaboration between the groups FNA and PHI on photonic waveguides with magnetic claddings aiming at magneto-optical mode conversion has intensified. We explored the (magneto-)optical parameters of PMA claddings to maximize the Kerr rotation and minimize the optical loss. Samples containing Co layers sandwiched between Pt or Pt and AlO_x were deposited by DC magnetron sputtering on planar InP and Si substrates. Enhancement of the magneto-optical constants due to spin-orbit coupling at Pt/Co interfaces, while not increasing losses, could be quantitatively demonstrated.

In the frame of same collaboration, photonic designs that will enable experimental detection of small magneto-optic Kerr rotations are being fabricated. The designs contained Mach Zender interferometers with components of multi-mode interferometers, polarization converters, and TE and TM grating couplers. Fabrication of the first design was completed in a Multi Project Wafer Run, and optical characterization of the devices has started.

THEME 3.3 **Nanomanufacturing for photonics**

Project leader: Erwin Kessels

The photonics nanomanufacturing research within the Gravitation program is aimed at the atomic scale processing of materials. Most prominently the research focuses on the atomic layer deposition (ALD) of nanolayers, although other deposition and etching techniques, and combinations thereof, are also investigated depending on the specifications of the applications.

One goal within this theme is to have a large set of nanolayer materials available for the application in the photonic devices prepared by the partner groups within the project. This set of nanolayer materials is also continuously extended through the development of new ALD processes. Herein we mainly aim at the development of ALD processes which are challenging either with respect to the materials involved or with respect to the tight specifications of the processing conditions which can be tolerated by the applications.

In addition to the earlier work on Co [VOS18], AlF3 [VOS17] and Ru, in 2018 we have mainly worked on ALD processes for alloys of 2D Transition Metal Dichalcogenide (2D-TMDs) materials. These are expected to find future applications in integrated photonics and closely connect to Theme 2.2. A new ALD process was developed in which MoS_2 and WS_2 were alloyed such that $Mo_xW_{1-x}S_2$ was achieved in which x could be tuned from 0 to 1. The tuning of the band gap by varying x was also studied by photoluminescence spectroscopy and compared to theoretical results obtained from density-functional theory (DFT) calculations. See some of the results below.

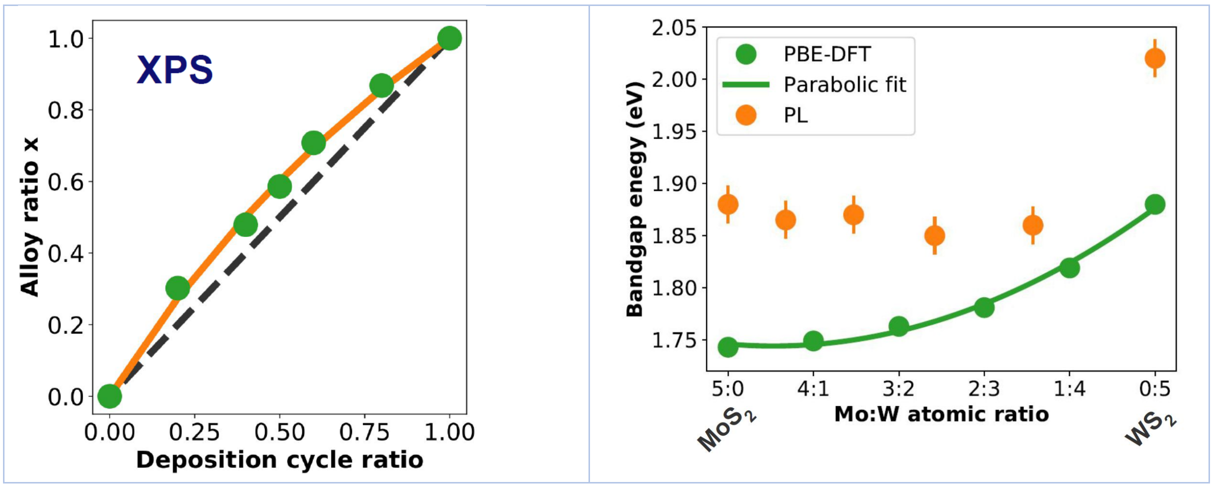

Figure 15 Left: Tunable composition of alloys of the 2D TMDs MoS_2 and WS_2. Right: The electronic bandgap of the $Mo_xW_{1-x}S_2$ alloys as measured by photoluminescence spectroscopy and compared to theoretical values calculated from density-functional theory (DFT) at the PBE level.

A real highlight of 2018 was the development of an area-selective ALD process for Ru. Area-selective deposition is a holy grail in the field of atomic scale processing and it is receiving a lot of attention in the field of nanoelectronics and nanophotonics. Ru is a promising interconnect metal due to its resistance to oxidation, high melting point low bulk resistivity and the ability to build barrierless interconnects (It has already been explored in through BCB vias in photonic circuits in collaboration with the PHI group). Given a surface that consists of areas of different materials, area-selective deposition means that film growth takes place on specific materials and not on others. This enables the local functionalization of complex nanostructured surfaces (also 3D surface topologies) as found in many devices, without extensive and/or complicated lithography steps. In particular, in this work an area-selective ALD process of Ru was developed that combined low-temperature ALD of Ru (from ethylbenzenecyclohexadiene Ru(0) and O_2 and H_2 gas exposure steps) with selective etching steps (using O_2 plasma). By implementing periodic etching steps unwanted Ru on dielectric surfaces could be removed while allowing for the deposition of metal surfaces (metal-on-metal). Using this supercycle approach with etch cycles integrated into the Ru ALD process, the area-selective ALD of ~8 nm of Ru was demonstrated onto Pt/SiO_2 patterns, with no detectable material being deposited on the SiO_2. This work has been submitted for publication.

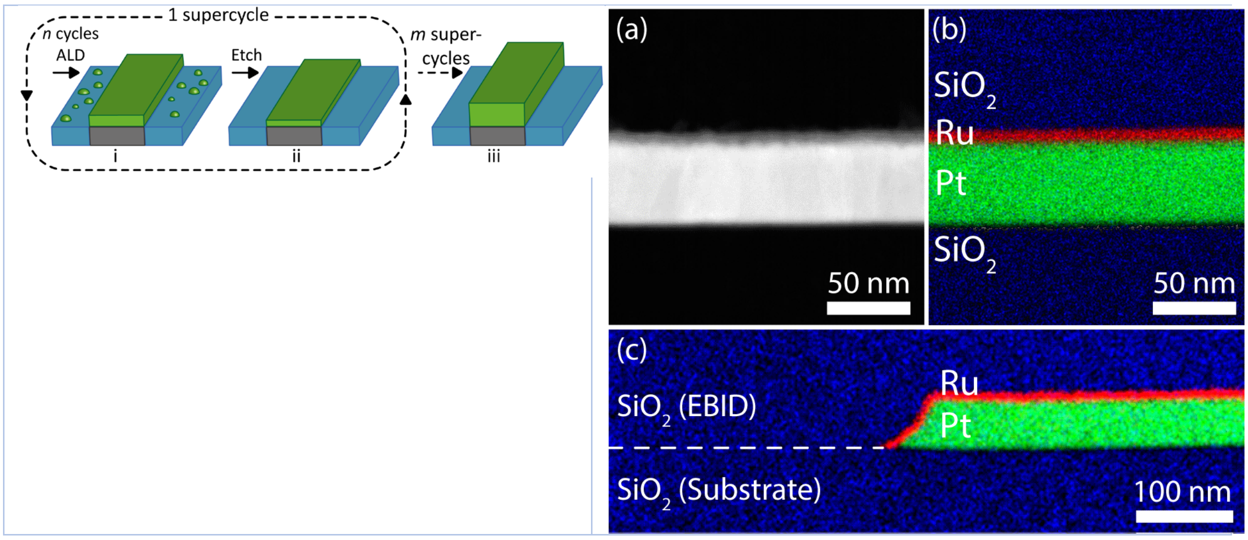

Figure 16 Left: Schematic illustration of the concept of combining ALD with periodic etching to achieve area-selective deposition with a high-selectivity even when some unwanted film nucleation takes place on the non-growth surface. Right: TEM images of Pt line covered with approximately 8 nm of Ru as deposited by area-selective ALD. (a) Cross-sectional HA-ADF scanning TEM image; (b) EDX elemental mapping of the corresponding region; and (c) EDX elemental mapping at the edge of a Pt line showing that no Ru is deposited on the SiO_2.

A second goal within this theme is the exploration of nanolayers for the functionalization and passivation of nanopillar- and nanowire-based devices. These nanolayers are prepared by ALD and related CVD techniques in order to provide an excellent conformality on the nanopillars and nanowires. In this respect, a major breakthrough was realized in this project through the development of PO_x/Al_2O_3 nanolayer stacks for the passivation of InP nanowire devices [BLA17]. The process was developed to be feasible at low temperatures (down to room temperature) to avoid P-desorption from the nanowires. The Al_2O_3 encapsulation was important to prevent deterioration of the PO_x which is hygroscopic and therefore unstable in atmosphere.

In the previous year, it has been demonstrated that the PO_x/Al_2O_3 nanolayer stacks can also be used to passivate silicon surfaces [BLA18]. This can be highly relevant for the passivation of nanowires with a hexagonal SiGe shell. It was found that the PO_x/Al_2O_3 stack contained a very high density (> 10^{12} cm^{-2}) of positive fixed charge which provides effective field-effect passivation. However, if a high density of negative fixed charge is desired the PO_x can be omitted and effective field-effect passivation can be achieved by an Al_2O_3 nanolayer.

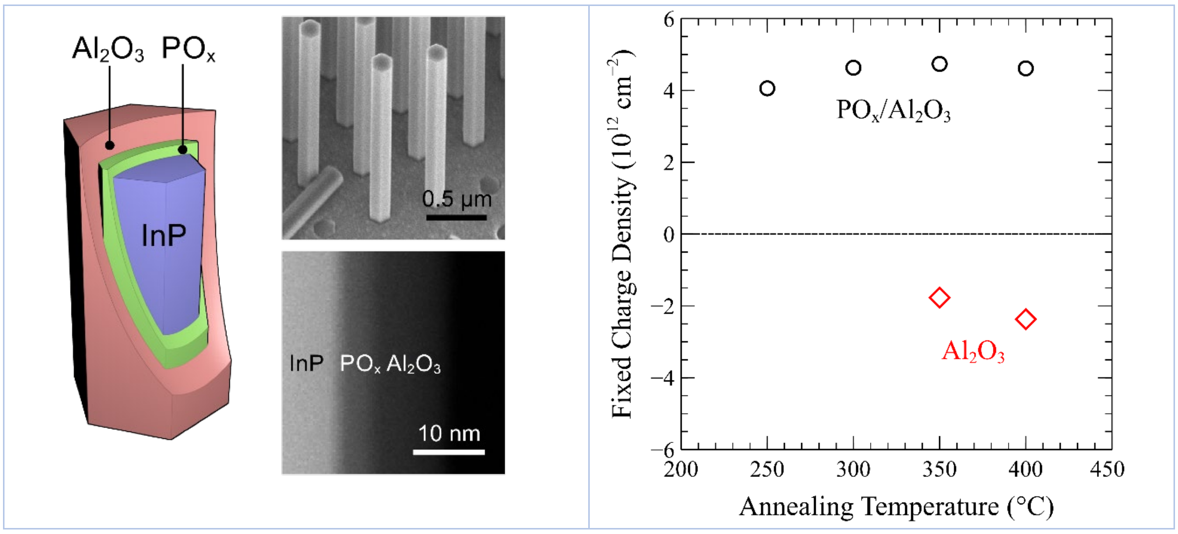

Figure 17 Left: Wurtzite InP nanowires passivated by stacks of low-temperature deposited stacks of PO_x and Al_2O_3 [BLA17]. In addition, the PO_x/Al_2O_3 stacks can also be used to passivate Si surfaces. Right: On these surfaces field-effect passivation is achieved by positive fixed charges in the PO_x/Al_2O_3 stack. Alternatively, when negative fixed charges are preferred, a nanolayer consisting only of Al_2O_3 can be used [BLA18].

THEME 3.4 **Semiconductor Nanowires**
Project leader: Erik Bakkers

In this sub-project, we investigate the optical properties of hexagonal SiGe. Hexagonal SiGe is grown on wurtzite III-V core wires. In order to have a small lattice mismatch between the core wire and the Ge-rich shells, we have developed the growth of defect-free Wurtzite GaAs wires. Figure 18b shows an array of GaAs/Ge core/shell wires with a length of a few micrometer and a diameter of 600 nm.

A small diameter will be relevant for minimizing the strain in the shell. The high resolution TEM image in Figure 18c demonstrates the hexagonal crystal structure. The cross sectional TEM image in Figure 18d shows the GaAs/Ge core shell structure. The precise a and c lattice constants of various hexagonal SiGe compositions have been determined by reciprocal space mapping at the ESRF synchrotron (together with D. Ziss from Linz University). These lattice constants have been used to calculate the exact band structure of the hexagonal SiGe compounds (by S. Botti at Jena).

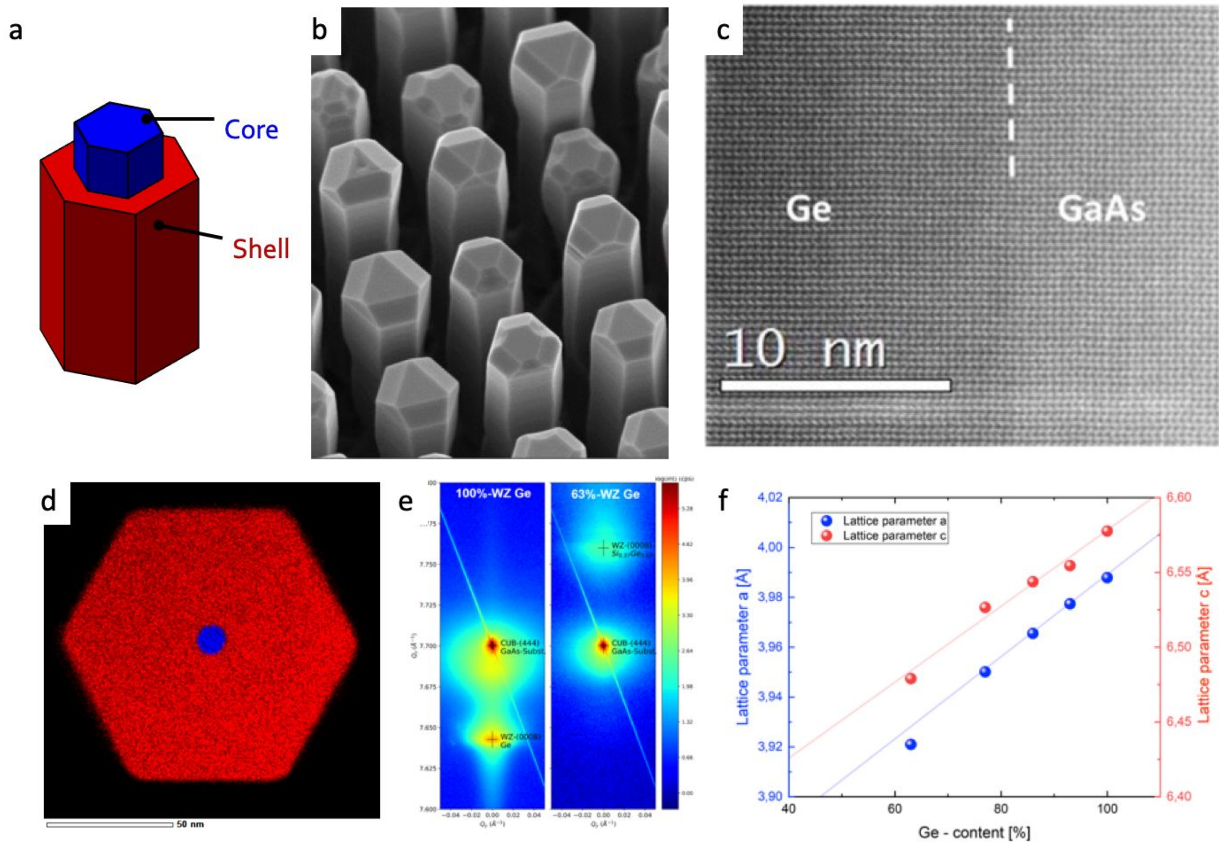

Figure 18 a) Schematic of the GaAs/Ge core/shell structure. B) SEM image of WZ GaAs/Ge core/shell wires. c) High-resolution STEM image of the interface between the WZ GaAs core and the hexagonal Ge shell. From this image the epitaxial relation is clearly visible. d) elemental map of a cross sectional slice demonstrating the core/shell structure. e) reciprocal space maps from which the lattice constants have been determined. f) obtained lattice constant as a function of the composition.

Photoluminescence of hexagonal SiGe

While initial photo-luminescence results were reported last year, in 2018 we systematically investigated the emission from hexagonal SiGe nanowires, leading to strong evidence for direct-gap emission, a major result in view of the future integration of light emitters on Si. The spectra in Figure 19 show emission from low up to room temperature. The peak red shifts with increasing temperature as it is also clear from Figure 19b. The red shift can be described by the Viña equation [Viña et al., Phys. Rev. B 30, 1979 (1984)], which is a first indication for emission from a direct band-band process. The intensity of the peak decreases by a factor of 50 by increasing the temperature to room temperature. This is comparable to direct bandgap III-V semiconductors, such as InP and GaAs.

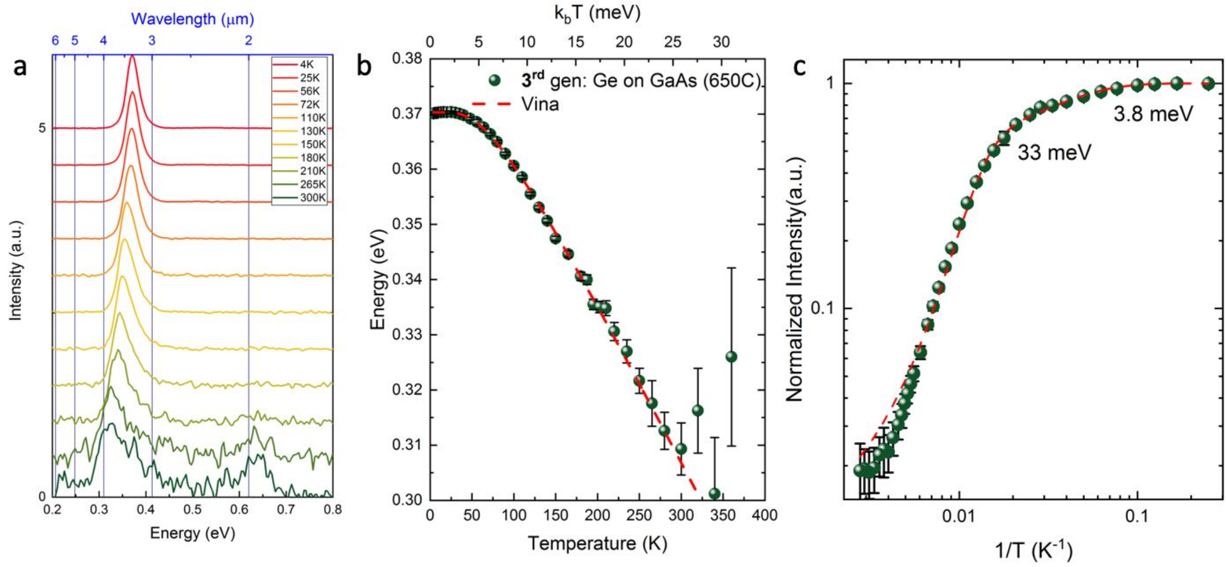

Figure 19 a) Photoluminescence spectra of hexagonal GaAs/Ge core-shell nanowires as a function of temperature. b) The peak energy as a function of temperature. c) The peak intensity as a function of the inverse of the temperature.

The emission energy is tuned by the SiGe composition, as shown in Figure 20. The emission energy increases up to 0.65 eV by increasing the Si content to 35%. In Figure 20b the obtained emission energies are plotted versus the SiGe composition, and compared with the theoretical expected band minima. The agreement between experiment and theory is excellent, substantiating direct band gap emission from these hexagonal SiGe compounds. The emission lifetime has been determined using a superconducting single photon detector. The obtained life times are around 1 nanosecond, which is typical for a direct band gap semiconductor. This work will be published in 2019.

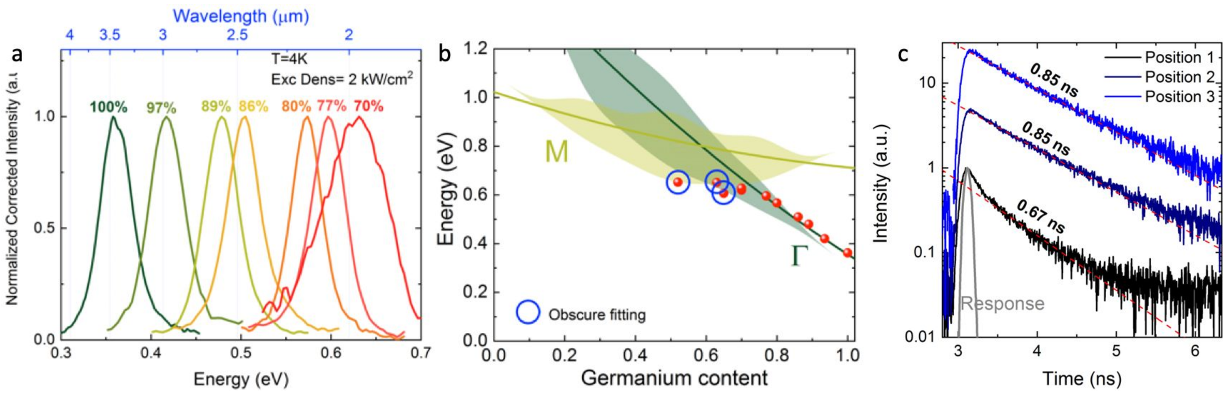

Figure 20 a) Photoluminescence spectra for different SiGe compositions. The % indicates the Ge concentration. b) emission energy peak as a function of the SiGe composition superimposed on the calculated band structure (by Jena University). This shows that the measured emission energy exactly matches witht the predicted trend. c) Measured emission lifetime of the $Si_{0.2}Ge_{0.8}$ sample. This lifetime is indicative of direct band gap emission

In another project we have developed InP nanowire photodetectors. These structures have been etched from a bulk sample, such that wires with a length of 2 micrometer, a diameter of 180 nm, and a pitch of 500 nm are formed (see Figure 21). This geometry is optimimum to have very high absorption (>98%) in a broad wavelength window.

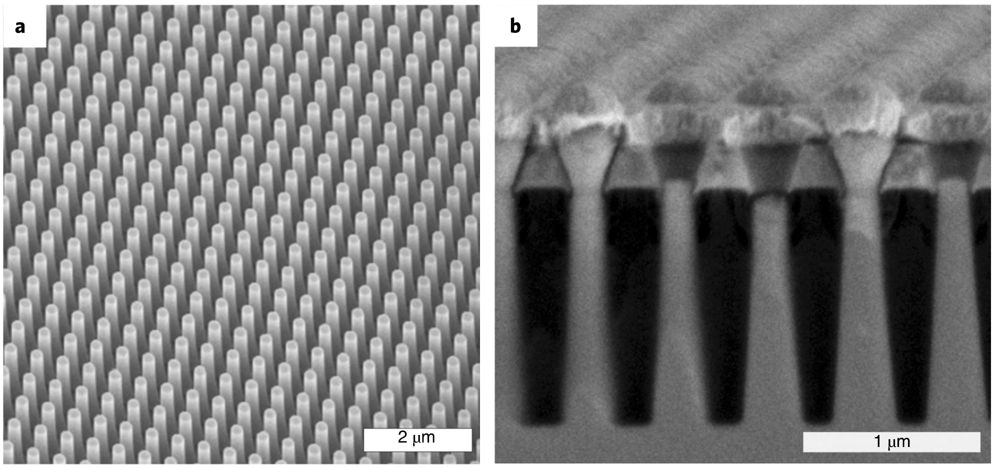

Figure 21 a) SEM imgae of an InP nanowire array etched from a bulk sample. b) SEM side view image of InP wires with a p-n junction and a transparent ITO top contact.

Due to the radial geometry and surface charges, the conductance in the nanowire channel is pinched off, resulting in a very low dark current. This low dark current is shown in Figure 22a. In collaboration with the Univ. Waterloo, we have investigated the detection limit of the device. In figure 22 b-d it is shown that for the lowest excitation powers, corresponding to single photons per pulse, we can still detect a photocurrent at room temperature [Gibson et al., Nature Nanotechnology 14, 473 (2019)]. The detector area is relatively large (300x300 μm^2).

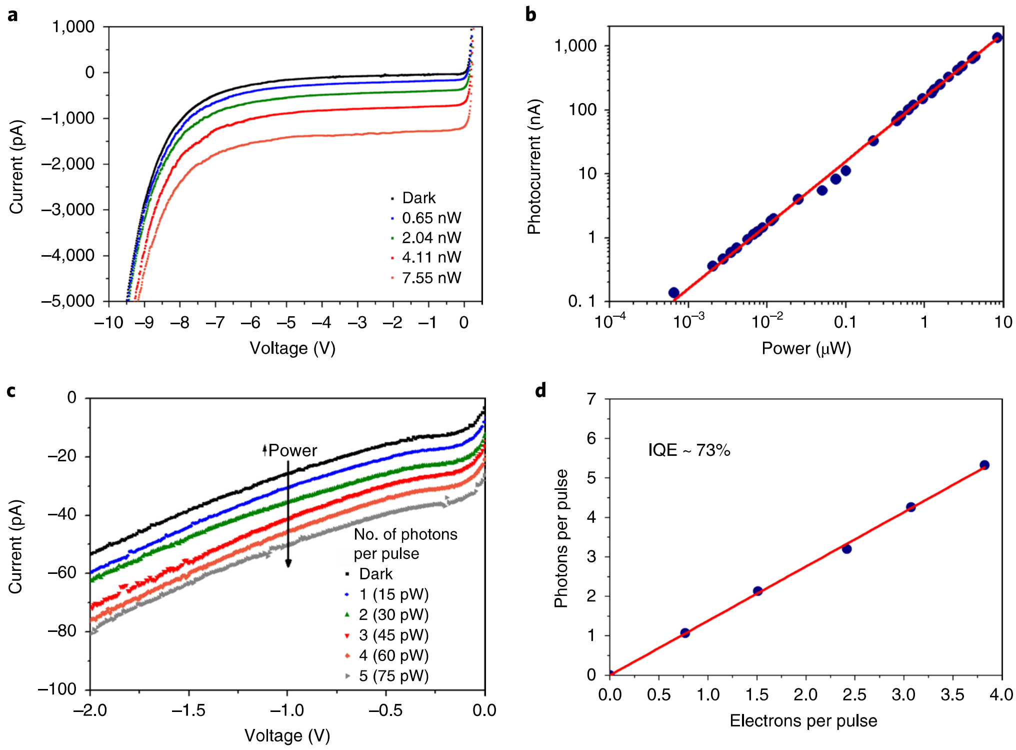

Figure 22 (a) Avalanche threshold voltages measured at 300 K in reverse bias under continuous- wave excitation at 700 nm for varying excitation power. (b) The sub-avalanche photocurrent response, measured at −1.0 V bias, is highly linear over a large dynamic range from microwatts down to picowatts. (c) By attenuating a 40 MHz pulsed laser excitation (3 ps pulsewidth) at 690 nm down to a single photon per pulse, the average photocurrent signal can be distinguished from the dark current. (d) Sub-avalanche photocurrent response measured under pulsed excitation at 690 nm and −1.0 V reverse bias. For this device, an internal quantum efficiency (IQE) of 73% was achieved at room *temperature, corresponding to more than 0.7 electrons per pulse under an illumination of a single photon per pulse.*

OUTREACH & SPIN-OFF

MEDIA COVERAGE OF GRAVITATION PROGRAM AND PEOPLE

- *"Nederland loopt op kop in de race om de licht-chip",* NRC Aug. 10, 2018
- Ton Koonen, on Fibre to the Home broadband in the Netherlands, in TV programme WDR ServiceZeit, Nov. 21, 2018 https://www1.wdr.de/mediathek/video/sendungen/servicezeit/video-internet-in-nrw-100.html (in German)
- Ton Koonen, finalist in Huijbregtsenprijs, in De Avond van Weetenschap & Maatschappij, Oct. 8, 2018, in Ridderzaal, The Hague; NTR video https://vimeo.com/294145868
- Ton Koonen appointed “Short term High level Visiting Scientist at Beijing University of Posts and Telecommunications Oct. 2018 – Dec. 2023”, Beijing, Oct. 30, 2018
- *"New pilot line will be incubator of photonics multinationals of the future*", TU/e press release on new granted EU project, covered by Eindhoven Dagblad and other media, Nov. 30, 2018
- *"236 million for promising integrated photonics technology",* TU/e press release on the signature of the national photonics plan, covered by several media.
- *"New type of low-energy nanolaser that shines in all directions",* TU/e press release on work by Jaime Gómez Rivas, covered by optics.org and other media, Dec. 17, 2018.

WIDE-AUDIENCE PRESENTATIONS

- *Photonics at Eindhoven Science Café*, Ton Backx and Meint Smit, 25 April 2018
- Studium Generale TU/e “Grenzeloze Vooruitgang Begrensd” by Jan Smits & Bert Koopmans, 13 June 2018.
- Lecture *“Quantum & Relativity on the Chip”* for selected international high school students at Young Brainport Summerschool by Bert Koopmans, 15 August 2018.
- *“Nanotechnologie met een Twist”,* lecture and discussion with high-school team leaders of “Ons Middelbaar Onderwijs” as part of the “Palladio” event in Venice, Italy, by Bert Koopmans 1 October 2018.
- *“Optical Wireless Systems: Technology, Trends and Applications”,* webinar by Ton Koonen for the IEEE Photonics Society, Feb. 21, 2018, https://www.photonicssociety.org/education-careers/webinars/optical-wireless-communication-webinar

WIDE-AUDIENCE PUBLICATIONS

- M.K. Smit, V. Calzadilla, B. Romeira en A. Fiore, *"Een nanoled voor gigabit/s optische communicatie",* Nederlands Tijdschrift voor Natuurkunde, May 2018
- R.W. van der Heijden, Z. Zobenica en A. Fiore, *"Met nanofotonica een spectrometer in je handpalm",* June 2018

INVITED PRESENTATIONS

- Haverkort, J.E.M. *“Light emission from direct bandgap hexagonal SiGe”*, IPR Zürich, July 2018.
- Bakkers, E.P.A.M. “*Bottom-Up Grown Nanowire Quantum Devices”,* MRS Boston, November 2018.

- Bakkers, E.P.A.M. *"Light Emission from hexagonal SiGe"*, EMRS, Strasbourg, France, June 2018.
- Bakkers, E.P.A.M. *"Bottom-up Grown Nanowire Quantum Devices" & "Light Emission from Group IV Semiconductors"*, ECS Cancun, Mexico, October 2018.
- Raz O. *"Low cost and high performance packaging solutions for MM based optical interconnects"*, EPIC Meeting on Singlemode vs Multimode Communication in Kessel-Lo, Belgium, 11 June 2018.
- Fiore A. et al., *"Smart sensing with nanophotonics",* Physics@Veldhoven, January 2018.
- Fiore A. et al., *"Tailoring radiative emission in integrated quantum light sources",* CLEO Conference on Lasers and Electro-Optics, San Jose, May 2018.
- Fiore A. et al., *"Spontaneous and stimulated emission in nanoscale light sources"*, European Semiconductor Laser Workshop, Bari, September 2018
- Shi B. et al., *"InP Photonic Circuit for Deep Neural Networks"*, invited paper, Advanced Photonics Congress, Integrated Photonics Research, Silicon, and Nano-Photonics (IPR), July 2019.
- Jiao Y., *"Towards a fully integrated indium phosphide membrane on silicon photonics platform"*, at the SPIE/COS Photonics Asia, 11-13 October 2018, Beijing, China.
- Kessels, W.M.M., *"On-surface interaction during PE-ALD and how it can be used to tailor film properties"* at three occasions: 7th International Conference on Microelectronics and Plasma Technology, Incheon, Korea, July 2018; 9th International Symposium on Plasma Nanoscience and Nanotechnology, New Buffalo, Michigan, August 2018; the European Materials Research Society, Fall Meeting, Warsaw, Poland, September 2017.
- Koonen A.M.J. et al., "*Recent Advances in Optical Technologies for creating Ultra-High Capacity Wireless Indoor Networks*", Asia Communications and Photonics Conference, Hangzhou, Oct. 2018.
- Koopmans, B. *"Spin-lattice coupling in ultrafast magnetization dynamics",* DPG18; Berlin, Germany (13 Mar - 14 Mar 2018).
- Koopmans, B. *"Emission of THz spin waves and all-optical switching by femtosecond laser pulses in multilayered magnetic thin films",* MRS18; Phoenix, USA (2 Apr - 6 Apr 2019)
- Koopmans, B. *"All-optical switching for integrated magneto-photonic memory",* SPIE18; San Diego, USA (19 Aug - 23 Aug 2018).
- Koopmans, B. *"Fs laser-induced switching and spin-transfer",* KITS18; Beijing, China (11 Oct - 15 Oct 2018).
- Koopmans, B. *"Merging spintronics with photonics"* SML18; Beijing, China (16 Oct - 19 Oct 2018).
- Koopmans, B. *"Merging spintronics with photonics - Laser induced spin currents & all-optical switching of spintronic devices",* SPICE18; Mainz, Germany (23 Oct - 26 Oct 2018).
- Gómez Rivas, J. *"Surface Lattice Resonances in Arrays of Metallic Particles: From Enhanced Emission to Induced Transparency",* CDT Metamaterials (Exeter, UK), July 2018.
- Gómez Rivas, J. *"Extended open cavities for polaritonic devices",* Ad70 Symposium (Enschede, the Netherlands), June 2008.
- Gómez Rivas, J., Invited talk at, "Extended open cavities for polaritonic devices", Summer School *Prospects of Plasmonics for Quantum Technologies*, Göteborg, Sweden, June 2018.
- Gómez Rivas, J., *"Strong light-matter coupling in extended open cavities"* QED-M2 *New Landscapes for Molecules and Materials*, Collège de France (Paris, France), June 2008.

INSTITUTIONAL EMBEDDING AND ORGANISATIONAL STRUCTURE

Organizational and Management Structure

The organizational structure has remained the same as last year (see Figure 25), but Prof. Andrea Fiore took over the role of scientific director of the Gravitation program after the retirement of Prof. Meint Smit. Following the recommendation of the mid-term review, organizational responsibilities are increasingly being fulfilled by younger staff members. For example, Oded Raz is leading the initiative on the Photonics MicroMaster, Patty Stabile has taken over the organization of the IPI/ZK quarterly event, the tenure-track assistant professors have jointly defined the program of the annual retreat and Alberto Curto is kickstarting the formation of a local OSA student chapter.

The Strategic Advisory Board (formerly the Steering Committee) has three new expert members. Its current composition is:

- Prof. Rod Alferness (Dean of the College of Engineering, University of California Santa Barbara)
- Prof.dr.ir. Roel Baets (Photonics Research Group University of Gent, IMEC)
- Prof.dr. Polina Bayvel (Optical Communications and Networks University College London)
- Prof.dr. Jonathan Finley (Semiconductor Quantum Nanosystems, Technische Universität München)
- Prof. Sailing He (Director Sino-Swedish Joint Research Center Photonics, ZheJiang University)
- Dr. Patrick de Jager (Senior Director Business Development ASML)
- Prof. Henning Riechert (Director Paul Drude Institut, Berlin)

Management members are:

- Prof. Bart Smolders (Dean of the TU/e Faculty of Electrical Engineering)
- Prof. Gerrit Kroesen (Dean of the TU/e Faculty of Applied Physics)

Chairman of the committee is prof. Frank Baaijens, Rector of the TU/e. Secretary to the committee is dr.ir. Jan Vleeshouwers, who is also coordinator of the Gravitation program.

The groups involved in this program are also planning to further expand. The PHI group is in the process of attracting a new full-time professor, and a number of junior positions in the photonics field have been defined within a "Sectorplan" funding proposal to be submitted in 2019.

Organizational Embedding

The Gravitation project is the largest project of IPI, the TU/e *Institute for Photonic Integration*[1]. Through IPI and Nanolab@TU/e, which is one of the world's most advanced university cleanroom facilities for InP Photonic Integration, it has access to world-class facilities for design, fabrication and characterization of photonic materials, devices, circuits and systems. The IPI benefits from the broad academic and industrial, national and international network of the former COBRA Research Institute.

Photonics is one of the central research themes of the Eindhoven University of Technology, which has been strongly investing in this field for more than two decades. Photonics is one of the key areas in the

[1] https://www.tue.nl/en/research/research-areas/integrated-photonics/

national top sector High-Tech Systems and Materials (HTSM) in which Universities are cooperating with the high-tech industry.

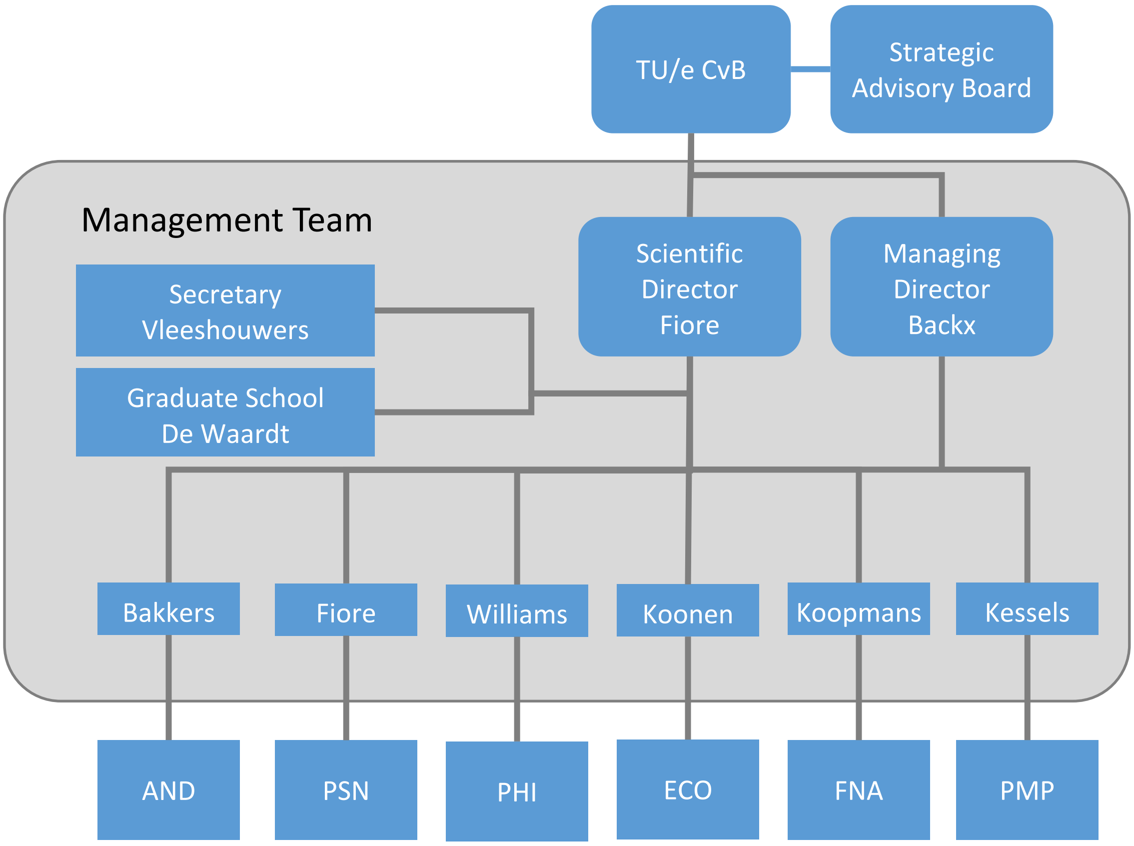

Figure 23 Management Structure of the Research Centre for Integrated Nanophotonics

In order to facilitate transfer to industry (see Figure 26), the IPI is setting up the *Photonics Integration Technology Center* (PITC), a private entity fully owned by the TU/e holding. The PITC should become the intermediary between the IPI research at low technology readiness (TR) levels and the applications envisioned by the companies represented in the photonics ecosystem, which require high TR-levels. The PITC offers an effective channel for using knowledge generated within the Gravitation Project in commercial applications. The detailed implementation plans for the PITC will be finalised in the course of 2019, and according to expectations it will be kickstarted based on the funding allocated by the national and regional governments for the development of applied R&D in the photonics area (see Knowledge Utilization section). The industrial side of the pipeline is organized by *PhotonDelta*[2].

Educating and attracting talent

Photonics is present in the TU/e education curriculum through a number of Bachelor and Master courses in both the Applied Physics (AP) and in Electrical Engineering (EE) departments. Some older dedicated training programs for Master and PhD students (Master program in Broadband Telecommunication Technology and the NWO Graduate school on Photonics), are phasing out, while new initiatives, more adapted to the present training needs and teaching methods, are being developed. A special subtrack in Photronics (integration of Electronics and Photonics), within the EE Master track Connected World Technologies is planned to start in 2020-21. The new Master track will provide the necessary training program for electronic-photonic co-design.

[2] https://www.photondelta.eu/

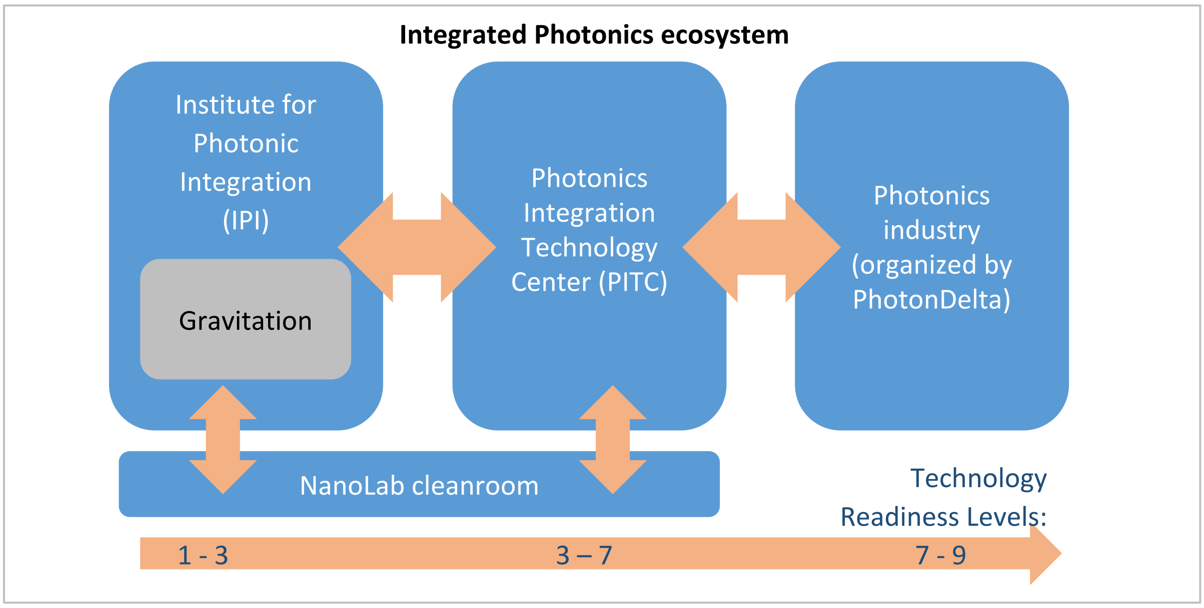

Figure 24 Integrated Photonics ecosystem

A major new development is the initiative of an online MicroMaster in Photonics, proposed and coordinated by dr. Oded Raz. It will consist of three courses, given by teachers of the IPI groups, on different aspects of photonics: Fundamentals of photonics, Photonic integration and Photonic systems. The plan is to have the MicroMaster operational in the fall 2020, subject to the availability of internal funds for the development. One of the goals of this online program is to increase the visibility of the IPI and thereby its capacity to attract promising oversea students, for PhD positions as well as for the local photonics industry. In the long term the availability of this online program should also be reflected in the traditional Master programs of the AP and EE departments. In particular, the Master in Applied Physics is going to be adapted following the redefinition of the department research tracks, where photonics is now more visible in the "Nano, Quantum and Photonics" track. It is therefore expected that photonics will play a more prominent role in the AP curriculum in the coming years.

Finally, at the PhD level, the quarterly IPI/Gravitation quarterly events and the Annual Retreat (which has taken place in May 2019 for the first time), with talks from both guest speakers and IPI students, and poster sessions, represent the main vehicle for broadening the scientific background of PhD students involved in the Gravitation program. A new initiative is the foundation of an OSA Student Chapter, starting in 2019 under the initiative of Alberto Curto.

Figure 25 Question session during quarterly IPI/Gravitation event.

KNOWLEDGE UTILISATION

The IPI cooperates with the growing regional, national and international industrial ecosystem to translate research results into products. The IPI spin-offs SMART Photonics and EFFECT Photonics have enjoyed strong growth in the last couple of years, with a combined personnel above 150 ftes, while Alkmaar-based SME Technobis is rapidly ramping up its activities on sensors for the aviation industry, using InP photonic integrated circuits for the read-out. The Eindhoven-based European platform JePPIX plays a key role in the development of applications based on the InP generic integration concept developed at the TU/e. In 2018 two major TU/e-led projects were acquired for the establishment of a PIC pilot line: InPulse (EC, 14 M€) and OIP4NWE (Interreg North-West Europe, 7.4 M€). This will lead among others to a substantial upgrade of the equipment available for PIC development within the NanoLab@TU/e cleanroom. While the pilot line will initially be based on the more mature generic InP platform, it is expected that the further development of the nanophotonic IMOS platform will also strongly benefit from these developments.

A major recent development is the development of the National Agenda Photonics[3], of which the IPI was an initiator and primary contributor, which has been followed by an agreement, signed by all relevant parties in December 2018, making 60 M€ available for applied R&D activities in integrated photonics. The first projects are now being defined and will start in the summer 2019, giving a further boost to the further development of innovative products based on the IPI PIC technology. The World Technology Mapping Forum is developing a global photonics roadmap.

Figure 28 World Technology Mapping Forum 2018 (photo: Eric Brinkhorst)

[3] https://nationaleagendafotonica.nl/wp-content/uploads/2018/12/National_Agenda_Photonics_spreads_EN.pdf

PUBLICATIONS AND JOINT RESEARCH

In 2018 we published 175 papers on topics related to the Gravitation project, of which 19 were joint papers (multiple groups withing IPI). Half of these papers were published in journals, the other half at conferences. About 50% of the publications related to Theme 1, 30% to Theme 2 and 20% to Theme 3.

The key publications for 2018 are listed below.

THEME 1: PERVASIVE OPTICAL SYSTEMS

Journal publications

	Publication		
KOO18b	Koonen, T., Gomez-Agis, F., Huijskens, F., Mekonnen, K. A., Cao, Z., & Tangdiongga, E. (2018). High-capacity optical wireless communication using 2-dimensional IR beam steering. Journal of Lightwave Technology, 36(19), 4486 - 4493. DOI: 10.1109/JLT.2018.2834374	ECO	1.1
LI_18c	Li C., X. Zhang, E. Tangdiongga, X. Dai, C. Tsai, H. Wang, Y. Xiang, G. Lin, Z. Cao, and T. Koonen, Cost-efficient half-duplex 10 Gbit/s all-optical indoor optical wireless communication enabled by a low-cost Fabry–Perot laser/photodetector. OSA Optics letters, 2019, 44(5): 1158-1161.	ECO	1.1
LI_18a	Li, C., Zhang, X., Li, T., Raz, O., & Stabile, R. (2018). 48-Channel matrix optical transmitter on a single direct fiber connector. IEEE Transactions on Electron Devices, 65(9), 3816 - 3822 . DOI: 10.1109/TED.2018.2859264	ECO	1.1, 1.2, 1.3
MOH18	Mohammed, M. A., Melskens, J., Stabile, R., Kessels, W. M. M., & Raz, O. (2018). Light-induced reversible optical properties of hydrogenated amorphous silicon: a promising optically programmable photonic material. Physica Status Solidi (A) Applications and Materials Science, 215(12), [1700754]. DOI: 10.1002/pssa.201700754	ECO PMP	1.2
MOR19	Morant M., A. M. Trinidad, E. Tangdiongga, A.M.J. Koonen, and R. Llorente, Experimental Demonstration of mm-Wave 5G NR Photonic Beamforming Based on ORRs and Multicore Fiber. IEEE Transactions on Microwave Theory and Techniques, pp. 1-8, Feb. 2019.	ECO	1.1
SHI18a	Shi B., N Calabretta, R. Stabile, WDM weighted sum in an 8x8 SOA-based InP cross-connect for connect deep neural networks. Proc. Photonics in Switching in Computing Conference, Cyprus (2018).	ECO	1.3
	Van Weerdenburg, J. J. A., Ryf, R., Alvarado-Zacarias, J. C., Alvarez-Aguirre, R. A., Fontaine, N. K., Chen, H., ... Okonkwo, C. M. (2018). 138-Tbit/s mode- and wavelength-multiplexed transmission over six-Mode graded-index fiber. Journal of Lightwave Technology, 36(6), 1369-1374. DOI: 10.1109/JLT.2018.2791100	ECO	1.4

Conference publications

	Publication		
CAO18	Cao Z., X. Zhang, I. Vellekoop, T. Koonen, Non-Line-of-Sight Beam Reconfigurable Optical Wireless System for Energy-Efficient Communication. Proc. European Conference on Optical Communication 2018, pp: 1-3 (2018).	ECO	1.1
FON17	Fontaine N.K. et al., Programmable Vector Mode Multiplexer. 2017 European Conference on Optical Communication (ECOC), Gothenburg, 2017, pp. 1-3. doi: 10.1109/ECOC.2017.8346099	ECO	1.4
FON18	Fontaine, N. K., Chen, H., Ryf, R., Neilson, D., Alvarado, J. C., Van Weerdenburg, J., ... Carpenter, J. (2018). Programmable vector mode multiplexer. In 43rd European	**ECO**	**1.2**

	Conference on Optical Communication, ECOC 2017 (pp. 1-3). Piscataway: Institute of Electrical and Electronics Engineers (IEEE). DOI: 10.1109/ECOC.2017.8346099		
LI_18b	Li, C., Raz, O., Kraemer, F., & Stabile, R. (2018). Silicon interposer based QSFP-DD transceiver demonstrator with >10 Gbps/mm2 bandwidth density. In 2018 European Conference on Optical Communication (ECOC) [8535470] Piscataway: Institute of Electrical and Electronics Engineers (IEEE). DOI: 10.1109/ECOC.2018.8535470	**ECO**	**1.2, 1.4**
SHI18b	Shi B., N Calabretta, R. Stabile, Continuous weight tuning for WDM-based neuron addition in an SOA-based InP cross-connect. IEEE Photonics Benelux Symposium, Brussels (2018).	ECO	1.3
SHI18c	Shi B., N Calabretta, R. Stabile, Integrated semiconductor optical amplifiers based photonic cross-connect for deep neural networks. Cognitive computing conference: emerging concepts to hardware, Hannover (2018).	ECO	1.3
SHI19	Shi B., N Calabretta, R. Stabile, SOA-based photonics deep neural networks for image classification. CLEO conference, submitted (2019).	**ECO**	**1.3**
	Stabile, R. (2018). Optical signal processing in InP photonic integrated circuits. In Signal Processing in Photonic Communications, SPPCom 2018 [SpW2G.1] Optical Society of America (OSA). DOI: 10.1364/SPPCom.2018.SpW2G.1	ECO	1.3
SUN18a	Sung J-Y., F. Gomez Agis, A.M. Trinidad, E. Tangdiongga, and A.M.J. Koonen, Coordinated Multi-Source Transmission for Optical Wireless Communications. Proc. European Conference on Optical Communication, 2018, Rome, paper Th2.65.	ECO	1.1
SUN18b	Sung J-Y., F. Gomez Agis, A.M. Trinidad, P. Mitchell, K. Solis-Trapala, B. Docter, E. Tangdiongga, A.M.J. Koonen, Real-Time High-Definition (HD) Video over 10-GbE Optical Wireless Communications (OWC) Supporting Simultaneous Access to Multiple Users. Proc. European Conference on Optical Communication, 2018, Rome, paper Th1B.4.	ECO	1.1
TRI18	Trinidad A.M., N. Tessema, X. Zhang, Z. Cao, E. Tangdiongga, and A.M.J. Koonen, Evaluation of PAM-4, DMT, and Nyquist-SCM for Multi-Gbps Transmission on Bandwidth-limited ORR-based Beamformer. Proc.European Conference on Optical Communications (ECOC), 2018.	ECO	1.1
TRI19	Trinidad A.M., Z. Cao, J.H.C. van Zantvoort, E. Tangdiongga, and A.M.J. Koonen, Broadband and continuous beamformer based on switched delay lines cascaded by optical ring resonator. Proc. Optical Fiber Communications Conference and Exhibition (OFC), 2019.	ECO	1.1
HEI18	Van der Heide S. et al., Single Carrier 1 Tbit/s Mode-Multiplexed Transmission Over Graded-Index 50um Core Multi-Mode Fiber Employing Kramers-Kronig Receivers. 2018 European Conference on Optical Communication (ECOC), Rome, 2018, pp. 1-3. doi: 10.1109/ECOC.2018.8535491	**ECO**	**1.4**
ZHA19	Zhang X., C. Li, Y. Jiao, H. Boom, E. Tangdiongga, Z. Cao and T. Koonen, Crosstalk-free AWGR-based 2-D IR beam steered optical wireless communication system for high spatial resolution. Proc. Optical Fiber Communication Conference 2019, paper Th1F. 5 (2019).	ECO	1.1
ZHA18	Zhang X., M. Zhao, Y. Lei, K. A. Williams, X. J. M. Leijtens, Y. Jiao, S. Huang, Z. Cao, T. Koonen, An Integrated Stepwise Tunable Optical mm-wave Beam Former with Doubled Delay Resolution. Proc. European Conference on Optical Communication 2018, paper Tu3H.4.	ECO PHI	1.1

Other publications

	Publication		
KOO18c	T. Koonen, Optical Wireless Communication. Webinar of the Institute for Photonic Integration, Eindhoven University of Technology, Eindhoven, The Netherlands, date: 2018-02-21. https://www.photonicssociety.org/education-careers/webinars	ECO	1.1

THEME 2: NANONPHOTONIC INTEGRATED CIRCUITS

Journal publications

	Publication		
CIH18	Cihan, A. F., Curto, A. G., Raza, S., Kik, P. G., & Brongersma, M. L. (2018). Silicon Mie resonators for highly directional light emission from monolayer MoS2. Nature Photonics, 12(5), 284-290. DOI: 10.1038/s41566-018-0155-y	PSN	2.2
CUR18	Curto, A. G., & Gómez Rivas, J. (2018). Confining light to the atomic scale. Nature Nanotechnology, 13(6), 442-443. DOI: 10.1038/s41565-018-0166-3	PSN	2.2
KUM19	Kumar R.R, Raevskaia M., Pogoretskii V., Jiao Y. and Tsang H.K., "Entangled photon pair generation from an InP membrane micro-ring resonator", Applied Physics Letters, vol. 114, pp. 021104, 2019.	PHI	2.1
LIU17	Liu T., F. Pagliano, A. Fiore, Nano-opto-electro-mechanical switch based on a four-waveguide directional coupler. Optics Express, 25(9), 10166-10176.	PSN	2.2
	Midolo, L., Schliesser, A., & Fiore, A. (2018). Nano-opto-electro-mechanical systems. Nature Nanotechnology, 13(1), 11-18. DOI: 10.1038/s41565-017-0039-1	PSN	2.2
	Romeira, B., & Fiore, A. (2018). Purcell effect in the stimulated and spontaneous emission rates of nanoscale semiconductor lasers. IEEE Journal of Quantum Electronics, 54(2), [2000412]. DOI: 10.1109/JQE.2018.2802464	PSN	2.2
	Utrilla, A. D., Grossi, D. F., Reyes, D. F., Gonzalo, A., Braza, V., Ben, T., ... Ulloa, J. M. (2018). Size and shape tunability of self-assembled InAs/GaAs nanostructures through the capping rate. Applied Surface Science, 444, 260-266. DOI: 10.1016/j.apsusc.2018.03.098	PSN	2.2
TOL18	Van der Tol, J. J. G. M., Jiao, Y., Shen, L., Millan-Mejia, A. J., Pogoretskiy, V., van Engelen, J. P., & Smit, M. K. (2018). Indium Phosphide Integrated Photonics in Membranes. IEEE Journal of Selected Topics in Quantum Electronics, 24(1), [6100809]. DOI: 10.1109/JSTQE.2017.2772786	PHI	2.1
YAO18a	Yao, W., Jiao, Y. and Williams K.A., “Nanophotonics Enables Future InP PIC Scaling”, Featured Article in PIC Magazine, Issue 11 - October 2018. [Invited Article]	PHI	2.1

Conference publications

	Publication		
JIA18a	Jiao Y., High confinement InP photonic membrane. Asia Communications and Photonics Conference (ACP), 26-29 October 2018, Hangzhou, China (invited talk).	PHI	2.1
	Jiao, Y., van der Tol, J. J. G. M., Pogoretskiy, V., van Engelen, J. P., Kashi, A. A., Smit, M. K., & Williams, K. A. (2018). Towards a generic nanophotonic platform based on InP membrane. In ECIO 2018 Proceedings [ID 113]	PHI	2.1
KAS18	Kashi A.A., J.J.G.M. van der Tol, Y. Jiao and K.A. Williams, Development of Plasmonic Slot Waveguide on InP Membrane. Proceedings of the 23nd Annual Symposium of the IEEE Photonics Society Benelux Chapter, 15-16 November 2018, Vrije Universiteit Brussel, Brussel, Belgium.	PHI	2.1
LIU19	Liu T., F. Pagliano, P.J. van Veldhoven, V. Pogoretskiy, Y. Jiao and A. Fiore, Low-Voltage InP MEMS Optical Switch on Silicon, European Conference on Integrated Optics ECIO 2019, 24-26 April 2019, Ghent, Belgium	PSN, PHI	2.1
POG18a	Pogoretskiy, V., van Engelen, J. P., van der Tol, J. J. G. M., & Jiao, Y. (2018). Towards a fully integrated indium-phosphide membrane on silicon photonics platform. Invited paper. In Z. Zhou, & K. Wada (Eds.), Nanophotonics and Micro/Nano Optics IV [1082308] (Proceedings of SPIE; Vol. 10823). Washington: SPIE. DOI: 10.1117/12.2503544	PHI	2.1
POG18b	Pogoretskiy V., J.P. van Engelen, J.J.G.M. van der Tol and Y. Jiao, Adhesive Wafer Bonding of 2 inch InP to 3 inch Silicon Wafers for a Membrane Integrated Photonics Platform. Proceedings of the 23nd Annual Symposium of the IEEE Photonics Society Benelux Chapter, 15-16 November 2018, Vrije Universiteit Brussel, Brussel, Belgium.	PHI	2.1

KUM18	Ranjan Kumar R., M. Feng, M. Raevskaia, V. Pogoretskii, Y. Jiao, H.K. Tsang, Influence of Nonlinear Losses on Spontaneous Four Wave Mixing in InP Membrane Micro-Ring Resonator. IEEE Photonics Conference (IPC 2018), 30 September - 4 October 2018, Reston, VA, USA.	PHI	2.1
ENG18	Van Engelen J.P., J. Bolk, M.K. Smit, K.A. Williams, J.J.G.M. van der Tol and Y. Jiao, Reflow of Deep UV Resist for Line Edge Roughness Reduction in InP Membrane Waveguides. Proceedings of the 23nd Annual Symposium of the IEEE Photonics Society Benelux Chapter, 15-16 November 2018, Vrije Universiteit Brussel, Brussel, Belgium.	PHI	2.1
YAO18b	Yao W., Jiao Y. and Williams K.A., (10-11 April 2018), “III-V Photonic Integrated Circuits for Telecoms and Beyond”, in the 3rd PIC International Conference, Brussels, Belgium. [Invited Talk]	PHI	2.1

THEME 3: ULTIMATE CONTROL OF MATTER AND PHOTONS

Journal publications

	Publication		
BLA17	Black L. E., A. Cavalli, M.A. Verheijen, J.E.M. Haverkort, E.P.A.M. Bakkers and W.M.M. Kessels. Effective Surface Passivation of InP Nanowires by Atomic-Layer-Deposited Al2O3 with PO_x. Interlayer. NanoLetters 2017, 17, 6287-6294.	PMP AND	3.3
BLA18	Black, L. E., & Kessels, W. M. M. (2018). POx/Al2O3 stacks: Highly effective surface passivation of crystalline silicon with a large positive fixed charge. Applied Physics Letters, 112(20), [201603]. DOI: 10.1063/1.5029460	PMP	3.3
	Gagliano, L., Kruijsse, M., Schefold, J. D. D., Belabbes, A., Verheijen, M. A., Meuret, S., ... Bakkers, E. P. A. M. (2018). Efficient green emission from wurtzite AlxIn1-xP nanowires. Nano Letters, 18, [3543-3549]. DOI: 10.1021/acs.nanolett.8b00621	AND PSN PMP	3.3, 3.4
	Krammel, C. M., Nattermann, L., Sterzer, E., Volz, K., & Koenraad, P. M. (2018). Structural and electronic properties of isovalent boron atoms in GaAs. Journal of Applied Physics, 123(16), 1-9. [161589]. DOI: 10.1063/1.5011166	PSN	3.1
LAL17	Lalieu M.L.M., M.J.G. Peeters, S.R.R. Haenen, R. Lavrijsen and B. Koopmans, Deterministic alloptical switching of synthetic ferrimagnets using single femtosecond laser pulses. Phys. Rev. B 96, 220411(R) (2017).	FNA	3.2
LAL19	Lalieu M.L.M., R. Lavrijsen, and B. Koopmans, Integrating all-optical switching with spintronics. Nature Communications 10,110 (2019).	FNA	3.2
VOS17	Vos M.F.J., H.C.M. Knoops, R.A. Synowicki, W.M.M. Kessels, and A.J.M. Mackus, Atomic layer deposition of aluminum fluoride using Al(CH3)3 and SF6 plasma. Applied Physics Letters 111, 113105 (2017).	PMP	3.3
VOS18	Vos M.F.J., G. van Straaten, W.M.M. Kessels and A.J.M. Mackus, Atomic Layer Deposition of Cobalt Using H2-, N2-, and NH3-Based Plasmas: On the Role of the Co-reactant. J. Phys. Chem. C 2018, 122, 22519−22529	PMP	3.3
	Wang, S., Le-Van, Q., Peyronel, T., Ramezani, M., van Hoof, N., Tiecke, T. G., & Gómez Rivas, J. (2018). Plasmonic nanoantenna arrays as efficient etendue reducers for optical detection. ACS Photonics, 5(6), 2478-2485. DOI: 10.1021/acsphotonics.8b00298	PSN	3.1

Conference publications

	Publication		
KOO18a	Koopmans B., Y.L.W. van Hees, M.L.M. Lalieu, F.E. Demirer, J.J.G.M. van der Tol and R. Lavrijsen, Towards Integrated MagnetoPhotonics using Claddings with Perpendicular Magnetic Anisotropy. ECIO 2018, IEEE (2018).	FNA	3.2
	Sharma, A., V. Vandalon, M. Shirazi, W. M. M. Kessels, A. A. Bol (2018). Plasma-enhanced atomic layer deposition of MoS2: from 2-D monolayers to 3-D aligned nanofins, PCSI45, Kona, HI, USA, Jan. 2018 (invited)	PMP	3.3

	Thissen, N., R. Vervuurt, A. Sharma, W. M. M. Kessels, A. A. Bol (2018) Atomic layer deposition for the synthesis and integration of 2D materials for nanoelectronics, AiMES, Cancun, Mexico, Oct 2018 (invited)	PMP	3.3
	Van Engelen, J. P., Bolk, J., Smit, M. K., Williams, K. A., van der Tol, J. J. G. M., & Jiao, Y. (2018). Reflow of deep UV resist for line edge roughness reduction in InP membrane waveguides. In Proceedings of the 23rd Annual Symposium of the IEEE Photonics Society Benelux Chapter (pp. 165-168)	PHI	3.3

GLOSSARY

5G	5^{th} Generation Wireless Mobile systems, operating in the mm-wave range, intended to provide performance up to 10 times that of the 4G-network
AHE	Anomalous Hall Effect
ALD	Atomic Layer Deposition
AND	Consortium group: Advanced Nanomaterials and Devices
APT	Atom-Probe Tomography
ASK	Amplitude-Shift Keying
AWGR	Arrayed Waveguide Grating Router
BCB	Benzocyclobutene
BROWSE	Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication (https://cordis.europa.eu/project/rcn/103158_en.html)
CMOS	Complementary Metal Oxide Semiconductor: most common Si-based technology for fabricating integrated circuits
ECO	Consortium group: Electro-Optical Communication
EO-polymer	Electro-Optic polymer
ERC	European Research Council (https://erc.europa.eu/)
f, femto	10^{-15}
FITH	Fiber in the Home
Flexcom	Flexible Broadband Communication project funded by Technologiestichting STW.
FMM	Film Mode Matching
FNA	Consortium group: Physics of Nanosctructures
FTTH	Fiber to the Home
IEEE802.11n	IEEE wireless-networking standard with a data rate up to 600 Mb/s
IMOS	InP Membrane On Silicon: a technique to integrate InP-based photonic circuitry with Si-based electronics
IPI	Institute for Photonic Integration
IR	Infrared
JKU	Johannes Kepler Universität (Linz, Austria)
LED	Light-Emitting Diode
LTE-A	Long Term Evolution is a standard for mobile communication which also defines frequency bands, such as the LTE-A band
MPW	Multi-Platform Wafer
MZM	Mach-Zehnder Modulator
NOEMS	Nano-opto-electro-mechanical system
OOK	On-Off Keying
p, pico	10^{-12}
PAM	Pulse Amplitude Modulation: PAM4 uses four pulse amplitude levels
PHI	Consortium group: Photonic Integration
PI	Principle Investigator
PIC	Photonic Integrated Circuit
PITC	Photonic Integration Technology Center
PL	Photo-luminescence
PMA	Perpendicular Magnetic Anisotropy
PMP	Consortium group: Plasma Materials and Processing
PON	Passive Optical Network
PRA	Pencil Radiating Antenna
PSN	Consortium group: Photonics and Semiconductor Nanophysics
QAM	Quadrature Amplitude Modulation: modulates amplitude of two orthogonal carriers
QD	Quantum dot

Q-switching	Create laser pulses by changing the Q-factor of the optical resonator
RF	Radio Frequency
RICT	Refractive Index Contrast Transition
SEM	Scanning Electron Microscopy (combined with TEM into STEM)
SOA	Semiconductor Optical Amplifier
TCP	Ethernet Transmission Control Protocol
TEM	Transmission Electron Microscopy (combined with SEM into STEM)
TE-polarized	Transverse Electric polarized (perpendicular to the plane of incidence)
TE-TM-conversion	Conversion from Transverse Electric polarization to Transverse Magnetic or vice-versa
TRL	Technology Readiness Level
UTC	Uni-Travelling Carrier photo diode
UV	Ultraviolet
VCSEL	Vertical Cavity Surface Emitting Laser
WSN	Wireless Sensor Network, operating according to the IEEE802.15.4 standard for low-rate wireless personal area networks.
XRD	X-ray Diffraction

Chemical elements