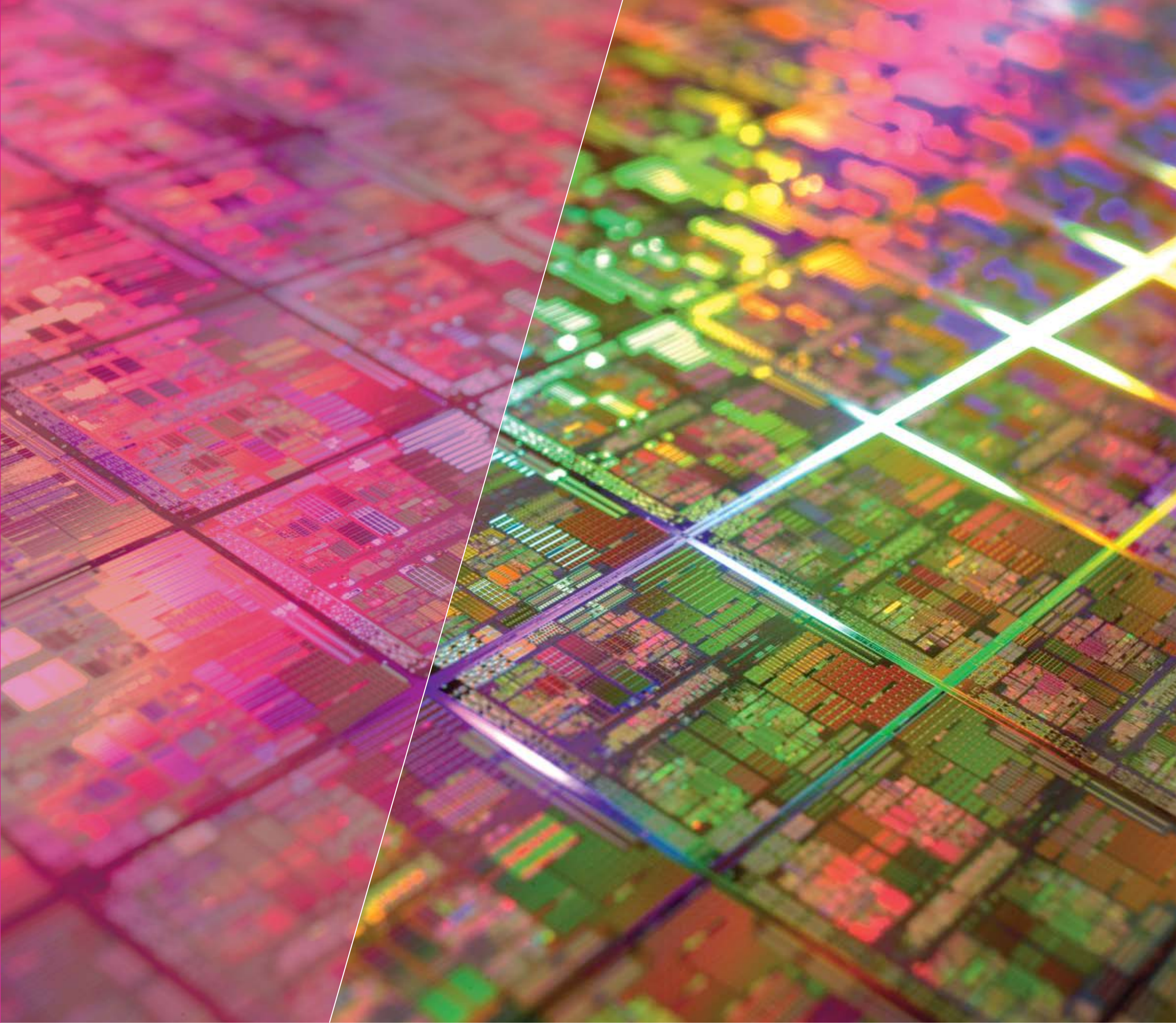

Research Centre for Integrated Nanophotonics

Annual Report 2016

13 April 2017

Technische Universiteit Eindhoven University of Technology

Institute for Photonic Integration
Materials • Devices • Systems

Research Centre for Integrated Nanophotonics

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Contents

Facts

Program	Gravitation (*Zwaartekracht*) 2013
Title	Research Centre for Integrated Nanophotonics
Number	024.002.033
Duration	10 years (January 1st, 2014 - December 31st, 2023)
Budget	€ 12.816.830 for the first 5 years, € 7.327.759 for the last 5 years

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Prof.dr. A. (Andrea) Fiore	Quantum Photonics	PSN
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Executive summary

After a careful planning and alignment phase in its first year, the project is now at full speed. Scientific progress has been made on all three themes addressed by the project, and cooperation between the groups is growing and yielding important novel results.

In the *Pervasive Optical Systems* theme we demonstrated record capacity for indoor wireless networks with 2D-steerable optical pencil beams. For long-haul networks we demonstrated Terabit super-channels over a legacy fiber. Further, we developed a novel architecture for Petabit/s all-optical flat data center networks based on WDM optical cross-connect switches.

In the *Photonic Integration* theme we have been working on further improvement of our IMOS platform (*indium-phosphide membrane on silicon*), the detector that we developed received large international attention. Also in the field of ultra-low power switching using photonic crystal membranes we established record performance.

In the theme *Ultimate Control of Matter and Photons* we have experimentally validated vacuum switching using coupled photonic crystal cavities. We achieved breakthroughs in electrical and optical schemes for switching magnetic elements, which are of key importance for envisioned photonic-spintronic memories but also for future magnetic RAM. Furthermore we achieved record-low surface recombination velocities for InGaAs and InP, and we developed a generic approach for fabricating hexagonal Si and SiGe nanowires with a direct bandgap.

The initial delays in identifying and appointing qualified personnel have been resolved and hiring of new personnel is now back on schedule.

The establishment of the *Institute for Photonic Integration* (IPI), the *PhotonDelta* eco-system and the *Photonic Integration Technology Center* (PITC) are major steps towards effective utilization of the knowledge generated within the IPI, in which the Gravitation Project is embedded. The PITC forms the bridge between the fundamental research in the IPI and the practical applications that are needed by industry and society. It offers an excellent instrument for obtaining continuity in research funding.

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.

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, which keep information in optical form as it passes through data routers in the internet backbone, and which 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 fibre.
- 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 integrate intimately 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, which could feature a direct bandgap and thereby 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.

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 third year of the project (2016).

Work progress and achievements

Theme 1 Pervasive optical systems

Theme Coordinator: Ton Koonen

Highlights:

- Novel photonics-based flat network architecture for data centers *[MIA16]*
- Flexible high-capacity long haul data transport techniques *[RAH16]*
- Novel infrared beam-steered congestion-free optical wireless communication system *[KOO16]*

Theme 1.1 Fibre wireless integration

Project leader: Ton Koonen

Optical wireless communication indoor network

Free-space optical wireless communication (OWC) can offer a solution for reducing the radio spectrum congestion which is already frequently encountered in wireless local area networks (such as wifi networks). Visible Light Communication (VLC) is widely investigated; it deploys LED-based illumination systems which however typically have a very limited bandwidth (few tens of MHz). With visible-light lasers, a higher bandwidth can be achieved but the optical transmitted power is seriously limited by eye safety regulations. As an alternative, we explore OWC with , infrared wavelengths *[KOO16]*. According to eye safety standards (ANZI Z-136 and IEC 60825-1), at IR wavelengths (1400nm-4000nm) the lasers can transmit >200 times more optical power than at visible wavelengths.

As part of both the Zwaartekracht program and the ERC Advanced Grant project BROWSE, optical free-space downlink and radio wireless uplink techniques using photonic integrated chips are designed to realize a highly reconfigurable indoor wireless network. For the downlink, we realized optical free-space transmission with 2-dimensionally-steered infrared optical beams. The beam steering was achieved by tuning the wavelength of the beam. Up to 42 Gbit/s per beam was achieved using a pair of crossed gratings, which is a record data transport capacity for indoor optical wireless networks. Up to 30Gbit/s was achieved using an 80-ports arrayed-waveguide router (AWGR) of which the outputs were arranged in a square matrix followed by a lens.

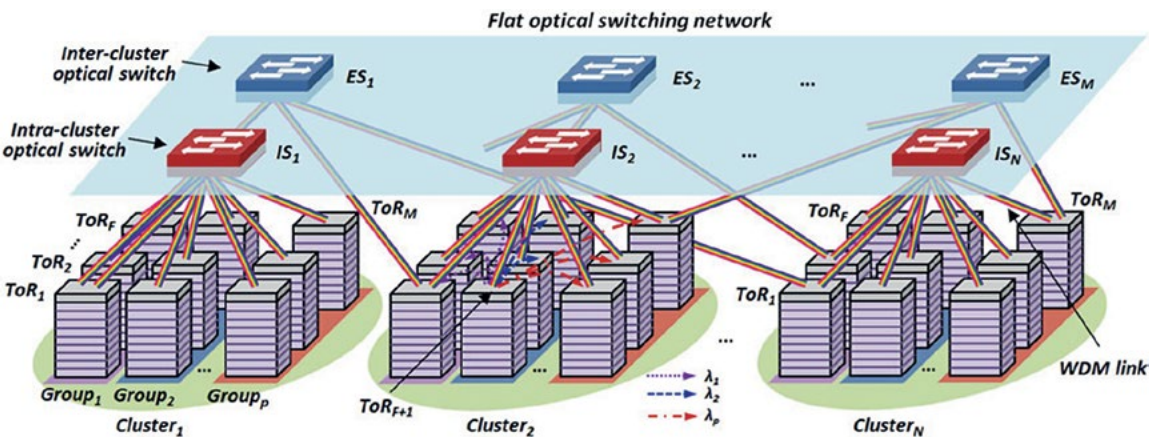

Figure 1
OPSquare flat DCN architecture built on fast WDM OXC switches [MIA16].

For the crossed-gratings approach, a US Patent has been granted; for the AWGR approach, a provisional US patent has been filed. The latter concept has also been validated for the transfer of real-time 10Gbit/s Ethernet-based data streams *[KHA16]*. In the upstream direction, 60GHz radio technology has been used; up to 5Gbit/s per user has been achieved.

For the upstream wireless link, also optical solutions have been investigated wherein the reversibility principle is deployed by regaining the unmodulated optical carrier from the modulated optical downstream beam by means of a gain-saturated semiconductor optical amplifier (SOA). This regained carrier is subsequently remodulated by the upstream data in an reflective electro-absorption modulator (REAM). Thus fully-optical bidirectional transmission beyond 40 Gbit/s was shown *[MEK16]*.

For OWC systems, at the receiver side a large aperture area and wide angle-of view is needed in order to maximize the light-wave reception. We designed a novel integrated receiver concept (cascaded acceptance optical receiver, CAO-Rx), wherein the light-acceptance function is separated from the light-detection function. Thus each can be optimized separately in order to maximize the overall receiver performance. Surface grating couplers have been designed for the light acceptation, together with a waveguide-coupled ultra-fast uni-travelling carrier photodiode (UTC-PD). In cooperation with the PhI group, a proof-of-concept CAO-Rx has been fabricated on an advanced InP membrane platform *[JIA16]* (see Figure 2). Optical wireless data transfer at 17.4 Gbit/s has been experimentally demonstrated *[CAO16]*. By expanding surface grating coupler area, according to our CAO-Rx concept OWC receivers can be realized with both a large bandwidth and a wide angle-of-view. This concept was a world's first; it was accepted as postdeadline paper presented at OFC2017, Los Angeles, on March 24, 2017.

In a multi-room indoor network, a reconfigurable fiber backbone network is needed to feed the optical beam steerers in each room in response to the fluctuating traffic requests per room. Such a reconfigurable fibre network was realized by means of a 4x4 integrated optical cross-connect *[MIA16]*.

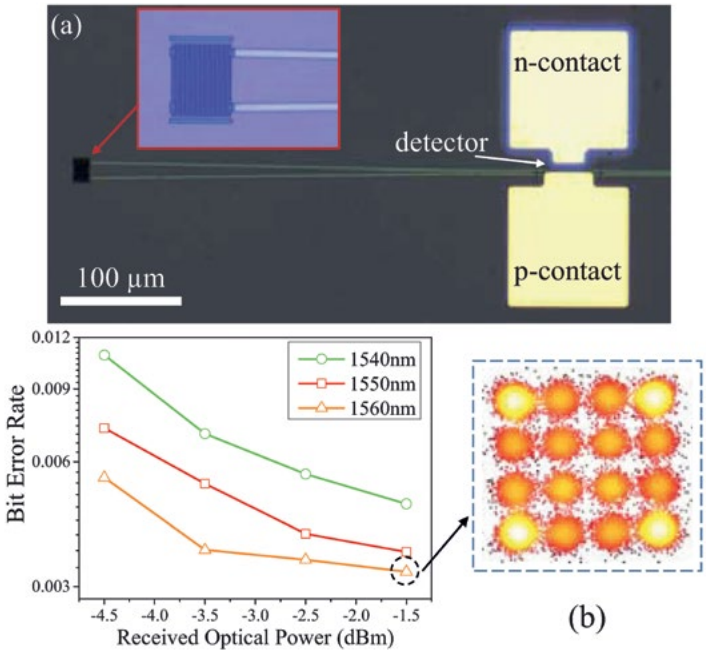

Figure 2
(a) The cascaded acceptance optical wireless receiver (CAO-Rx) made on the InP membrane. (b) The bit error rate curves at three different wavelengths, and the OFDM signal constellation for 1560 nm wavelength and optical power of -1.5 dBm [JIA16].

Fiber-in-the-Home (FITH) techniques for wired/wireless converged service delivery

In the Flexcom FITH project with support from the Zwaartekracht program, we investigated solutions for both wire-bound and wireless delivery of broadband services by means of large-core plastic optical fibre (POF). In a 1mm core diameter POF link of 50 meters, we showed wireless delivery of services in 10 LTE (Long Term Evolution) radio bands over a 3.5m indoor line-of- sight link in combination with wire-bound delivery of multi-level data streams at 1.8Gbit/s *[FOR16]*.

Flex-rate Fibre to the Home (FTTH) networks

In the Flexcom FTTH project, with support from the Zwaartekracht program, we investigated how the data capacity per home can be dynamically adapted to the fibre link conditions by adapting the data modulation format. We designed a duobinary Pulse Amplitude Modulated system with 3 amplitude levels (DB-PAM-3) which can provide up to 37.5Gbit/s with receivers having only 10GHz bandwidth. This solution requires less linearity of the transmitters and has 2dB better sensitivity than PAM-8. In a 10Gbit/s flexible modulation scheme, DB-PAM-3 enables 190% network utilization increase *[LIN16]*. The proposed concept of flexibly adaptive modulation format in time-multiplexed FTTH passive optical networks is a world's first; it has been filed as a US provisional patent.

Optically-controlled radio beam steering

In the Zwaartekracht Freebeam project, we are exploring optical control techniques for steering of radio beams in radio-over-fibre networks. Using phased-array antenna techniques for the beam steering, we have implemented the time delay stages by means of integrated optical ring structures of which the time delay can be adapted by tuning the wavelength of the signal. When two wavelengths are simultaneously injected, two beams are generated by a 2x1 beam-former. We demonstrated that these beams can carry OFDM data with 6 Gbit/s capacity each, with center frequencies at 20 and 23 GHz respectively. The wavelength delay tuning within the ring enables a full scanning range for K-band (18-30 GHz) RF signals *[TES16]*.

Main objectives for 2017:

- An integrated 2D beam-steerer for high capacity optical wireless communication;
- An integrated wide angle-of-view receiver for high capacity optical wireless communication;
- Adaptive modulation integrated transponders for flexible fiber to the home networks;
- InP PIC-based circuits for optically-controlled radio beam steering in beyond-5G networks.

Theme 1.2 Data centres and optical interconnects

Project leader: Oded Raz

New Materials for Programmable Photonic Integrated Circuits (see also theme 2.1)

Planar optical integration technologies offer many capabilities in device design and fabrication. However the methodology used for making PICs is based on fixed devices. The performance of integrated devices cannot be tweaked following the fabrication and can only be tuned actively at the cost of additional voltage/current injection and complex control circuits. If a photonic layer can be created on top or instead of currently used optical materials, one can create new families of PICs with a wide range of applications. In 2016, a project has been started in cooperation with the PMP group to investigate the possibilities of using hydrogenated amorphous silicon (aSi:H) for such a layer. The main idea behind this activity is to exploit a well know and often considered deleterious effect in aSi:H called the Stäbler-Wronski effect (SWE), which results in reduced photoconductivity of aSi:H after exposure to sunlight (also often referred to as light soaking-LS). Once the aSi:H is annealed at several hundreds of degrees C, it regains its original conductivity. Several applications of the SWE are investigated in this project. One concept is the use of light for direct writing of optical circuits. After exposure to light, the refractive index of the exposed and unexposed sections may differ by up to 1-2%, enough for making waveguides and other optical components. Since the process is reversible, by annealing the wafer at high temperature the entire wafer can be erased and prepared for a new writing cycle. A second concept is that of a programmable optical circuit. Here the original PIC can be made of InP or cSi and the aSi:H is deposited as an additional cladding layer. Since the refractive index of the cladding layer changes under light soaking, the function of the entire PIC can be defined after fabrication as the different circuits can be trimmed to give the desired connectivity and functionality. In the 1st year of the project major effort has been devoted to finding the right setting for the deposition of the aSi:H film and the demonstration of the LS and annealing cycle of the film.

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

Based on the theme optically interconnected CMOS switches, and following the demonstration of 3D stacking, work has continued to explore more powerful assembly strategies. Currently we have already demonstrated the use of a Silicon interposer as a platform for the integration of CMOS and Opto-electronic ICs both side-by-side and stacked in the 3rd dimension with performance comparable to commercial devices but with a fraction of the size (Bandwidth densities > 5 Gbps/mm^2). This effort is supported also by two large EU projects (COSIGN and ViDAP) *[LIC17]*.

Main objectives for 2017:

- The first demonstration of programmable optical layers based on the SWE in aSi:H
- Create 2D arrays of emitters and detectors based on 1D arrays by exploiting 2.5D integration techniques.
- Combine the silicon interposer platform with single mode VCSELs and novel Glass interposers to build the world's first Multi Core Fiber 100Gbps transmitter module.

Theme 1.3 Optical Switching

Project leader: Kevin Williams

Today's optical capacity is constrained by the electrical bandwidth of photonic devices. The requirement to resynchronize and demultiplex high capacity optical channels to moderate electrical channel rates at transceivers additionally imposes considerable energy overhead at each network node and this is exacerbated as packet data permeates the network. In this track we create optical switching devices which allow data to remain in the optical domain at network nodes, avoiding electrical bandwidth limitations. The inherent multi-Terahertz bandwidths of amplifiers, splitters, switches and waveguides can therefore be exploited.

This research track leverages both circuit design and fabrication technology expertise, with four key ambitions.

1. Low power consumption: The invention of new switching elements which allow the minimum of switch actuation energy for the maximum optical bandwidth.
2. High connectivity: Monolithic optical switch engines need to be engineered for scaling to many tens of physical connections.
3. Packet compliance: Specifically the photonic and electronic hardware to enable nanosecond programmable reconfigurability across the full switching matrix.
4. Scaling: Such that the number of fibre connections and wavelength channels can grow gracefully as network demand increases.

In the first phase of the program the activities have been able to leverage a number of ongoing national and international programs, as well as building on the close collaborations between ECO and PhI researchers.

Scalable packet switch technology

Photonic integrated wavelength division multiplexed cross-connect optical switch technology has been devised with cooperations in the EU FP7 projects LIGHTNESS and COSIGN. Here we have designed, fabricated, and characterized a novel photonic integrated 4x4 WDM modular cross-connect switch exploiting SOA technology for nanoseconds wavelength-, space-, and time-switching operation. Lossless operation, crosstalk < -30 dB, and error-free operation, and indications that the architecture could scale to a larger number of ports [CAL16].

Low power consumption packet switch technology

An innovative 4x4 InP switch matrix with electro-optically actuated higher order micro-ring resonators has been devised with input from the VICI project SMARTLIGHT. The cross-point switch contains a 4x4 cross-point grid of third-order ring resonator switch elements (Figure 3, next page). A particular focus is placed on voltage-driven switching of directional couplers for low-energy, nano-second time-scale actuation. Physical layer characterization showed 10- and 20-Gbit/s data routing with sub-10 ns switching times [STA16]. In a follow up experiment, calibrations have been performed to enhance the fidelity of fabricated features reproducibly with deep-UV lithography to enable re-architecting for reduced losses.

Main objectives for 2017:

- Integrated circuit topologies for high-connectivity, low-loss optical packet switch fabrics are to be prototyped exploiting low-optical-loss and low-electrical-loss switch elements.
- The first prototypes for multi-plane monolithic wiring are being planned for low-crosstalk interconnection.
- Create integrated and efficient on-chip optical flow control interfaces for packet contention resolution to fully exploit the nanosecond switching capability of the Optical Cross Connect.

Most important problems/deviations, impact on the planning and corrective actions

The recruiting of high-quality PhD students took longer than expected. Hence there is some lag in the originally planned budget spending.

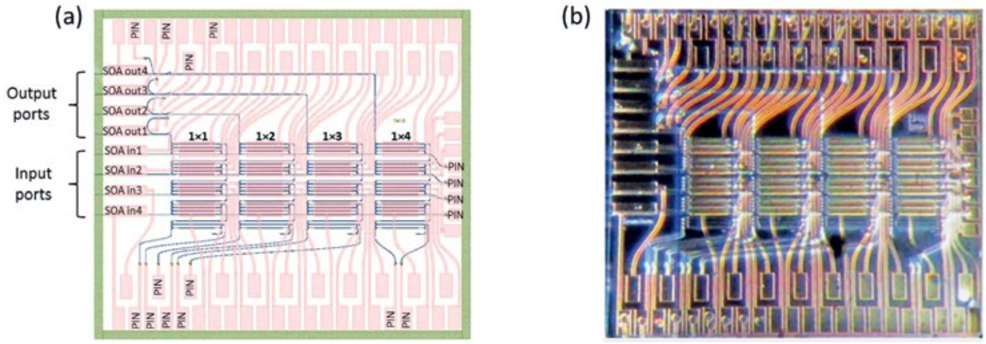

Figure 3
(a) Mask details of the 4x4 switch matrix, including the optical wiring (blue) and the metal wiring (red). (b) Photograph of the full fabricated chip [STA16].

Theme 2 Photonic integration

Theme coordinator: Meint Smit

Highlights:

- The realization of a nanopillar light emitting diode (LED) on the IMOS platform (Indium-Phosphide Membrane on Silicon) was published in Nature Communications *[DOL17]*.
- A stiction-free NOEMS (nano-opto-electro-mechanical system) operation was demonstrated (still unpublished).
- A record (30 nm) tuning range was demonstrated for a NOEMS Photonic Crystal Cavity *[ZOB16]*.

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

Project leader: Meint Smit

Following the demonstration of a membrane based photodetector with record performance last year, we are now working on integration of this detector in our IMOS platform. Further we have started development of a very compact laser source consisting of a short SOA-section with on both sides a 1D Photonic Crystal: a row of 5-8 holes in a photonic wire waveguide. It is depicted in Figure 4. In parallel to the integration of a photodetector and a laser we are exploring novel technologies for further improvement of the platform:

- Replacing zinc (Zn) by beryllium (Be) as p-dopant for the active components. A problem with Zn-dopant is that it diffuses during the epitaxial growth, which is detrimental for the quality of the optical amplifiers in the thin membrane layer stack. Beryllium has a lower diffusion constant and will, therefore, provide superior performance for lasers and optical amplifiers in thin membranes.
- Replacing the present phosphorous-based QW amplifier layer stack by an aluminum-based QW stack. This will enable the Photonic ICs fabricated in the platform to operate at higher temperatures, which is important for many applications, including uncooled operation. Aluminum-based QWs have also other advantages, such as lower linewidth in lasers.
- We have done extensive simulations of a layer structure for a novel type of electro-absorption modulator (EAM), with modulation and loss properties comparable with classical EAMs, but with a much larger bandwidth [ENG16].

PHI and ECO are cooperating to investigate application of IMOS PICs for beam steering in optical wireless networks, and in cooperation with the University of Madrid we are investigating the application of our photodetector in a TeraHertz transmitter.

Main objectives for 2017:

- Integration of a modulator in the IMOS platform;
- Improvement of amplifier performance;
- A first run of platform with integrated high-speed detector.

2.2 Ultralow-power components

Project leader: Andrea Fiore

Nanoscale light sources

A paper about our metallo-dielectric nanopillar LED was accepted for publication in Nature Communications *[DOL17]*. A process for fabrication of very compact low-power photonic crystal nanobeam lasers has been developed (see Figure 4). The first run was unsuccessful due to fabrication issues. A second has been started and will be finished early in 2017.

An important issue in nanolasers is the surface passivation. Because of the large surface/volume ratio in nanolasers, surface effects have a large impact on the laser performance, and very good passivation technology is required for a high efficiency. We developed a novel passivation method for the active layer, based on the combination of sulfur treatment and SiO_x deposition, and we have fully characterized the corresponding surface recombination properties in a collaboration between PhI, PSN and PMP. Record-low values of surface recombination velocity (~260 cm/s) have been obtained, which represents a key step towards low-threshold and high-efficiency nanolasers [*HIG16, HIG17*] (see Figure 5, next page).

Nano-opto-electro-mechanical systems (NOEMS)

A method for avoiding stiction failure in III-V nano-opto-electro-mechanical systems (NOEMS), based on the unique conformal properties of ALD thin layers, has been developed within a collaboration between PSN and PMP. For the first time we were able to operate NOEMS beyond the pull-in limit without failure. This is a major step in the development of reliable NOEMS.

The tuning range of electromechanical photonic crystal (PhC) cavities was extended to 30 nm, which represents a record for this technology. A new concept of random NOEMS spectrometer has been proposed and is presently being tested. A patent application has been submitted on spectrometers and optical sensors based on NOEMS *[FIO17]*. Additionally, we have demonstrated the application of PhC NOEMS in displacement sensing: for the first time the thermal motion of a thin membrane was measured optically through an integrated detector *[ZOB16]*. This potentially opens the way to fully integrated optical sensors of displacement, acceleration and force.

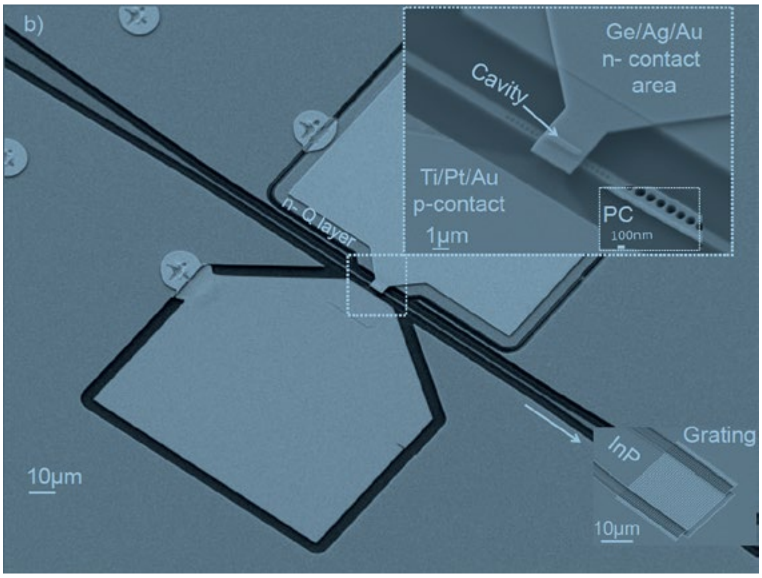

Figure 4
Scanning electron microscope (SEM) photograph of a very compact Photonic Crystal nanobeam laser. The laser consists of a short optical amplifier section, which is situated below the n-contact shown in the center of the photograph. In the upper right inset two Photonic Crystal reflectors can be distinguished at both sides of the amplifier section. The lower right inset shows the grating coupler through which the light is coupled out of the chip.

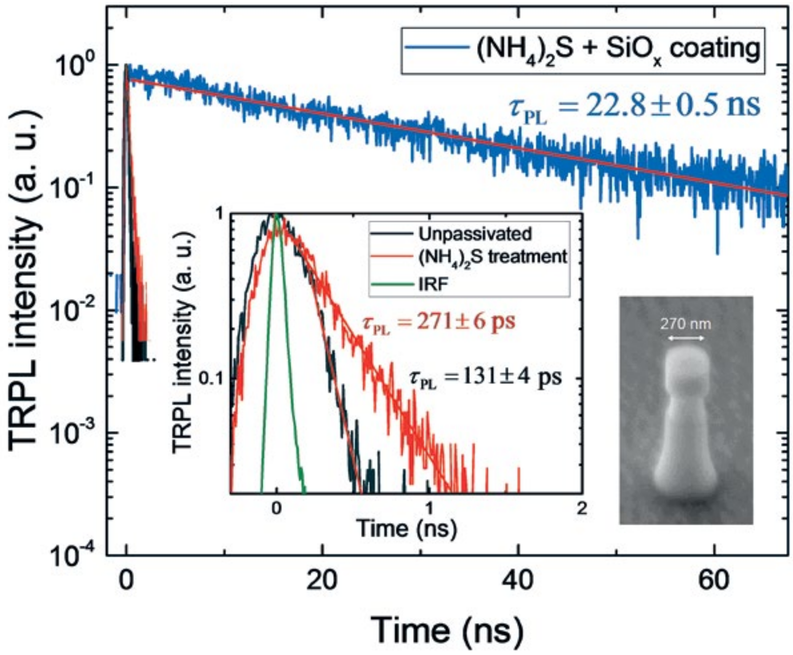

Figure 5
Experimental photoluminescence decay curves of a 275 nm wide InGaAs/InP nanopillar (inset). The corresponding time-resolved photo-luminescence (TRPL) intensity curves before passivation (black color), and after sulfur treatment (red color) and silicon oxide coating (blue color) passivation steps are shown [HIG16].

A new concept of optical switch based on NOEMS on a IMOS platform has been proposed and theoretically analyzed. It is expected to have a small footprint (tens of micrometers) and operate at record-low actuation voltages (a few volts). A provisional patent application has been filed *[LIU16]* and the first fabrication tests are expected for 2017.

Main objectives for 2017:

- The experimental demonstration of a new concept NOEMS spectrometer;
- The experimental demonstration of a NOEMS optical switch.

Most important problems/deviations, impact on the planning and corrective actions

A new research line will target the integration of 2D semiconductors into nanophotonic structures. The coupling between photons and the spin and valley degrees of freedom in these semiconductors may enable application in novel photonic devices. A tenure-track assistant professor and a PhD student have been hired.

Theme 3 Ultimate control of matter and photons

Theme coordinator: Paul Koenraad

Highlights:

- The vacuum field switching using three coupled cavities has been validated experimentally in continuous-wave photoluminescence experiments (publication in preparation).
- Proposal for a novel mechanism for coupling emitters, photons and phonons in nanomechanical structures *[COT16a]*
- The Spin-Hall effect is used to switch magnetic elements without the requirement of applying an external magnetic field, which is considered to be of crucial relevance for future magnetic random access memory (MRAM) *[BRI16]*.
- The development of a generic approach to fabricate Hexagonal Si *[HAU15]* and SiGe *[HAU16]*.

Theme 3.1 Quantum effects in nanophotonic devices

Project leader: Andrea Fiore

The rate-equation model describing nanoLEDs and nanolasers with a correct accounting for the Purcell emission enhancement has been validated by comparison with a number of experimental results and the agreement is very good. A publication is being prepared for 2017.

The concept of vacuum field switching using three coupled cavities has been validated experimentally in first continuous-wave photoluminescence experiments (see Figure 6). The disappearance of the emission from the central cavity at zero detuning is a clear evidence of the effect previously proposed by us. While in these first experiments field switching is used to modulate spontaneous emission, the same effect can be employed to modulate the modal gain in a laser through the confinement factor - i.e., keeping the carrier concentration constant. This would represent a novel modulation method for nanocavity lasers, enabling the generation of ultrafast pulses.

We are now planning to extend the experiments to the most interesting pulsed configuration to demonstrate the ultrafast control of spontaneous emission and laser modulation. In collaboration with Verhagen's group at AMOLF we have also theoretically proposed another application of the three-cavity structure in the context of optomechanical coupling of emitters and phonons via the cavity field *[COT16a]*. This could lead to the nonlinear control of mechanical structures at the single-phonon level. A preliminary experimental evidence of the mechanical control of cavity fields has been obtained in a simpler bended-waveguide structure, showing a record (three-fold) mechanical modulation of the quality factor of a nanophotonic cavity *[COT16b]*.

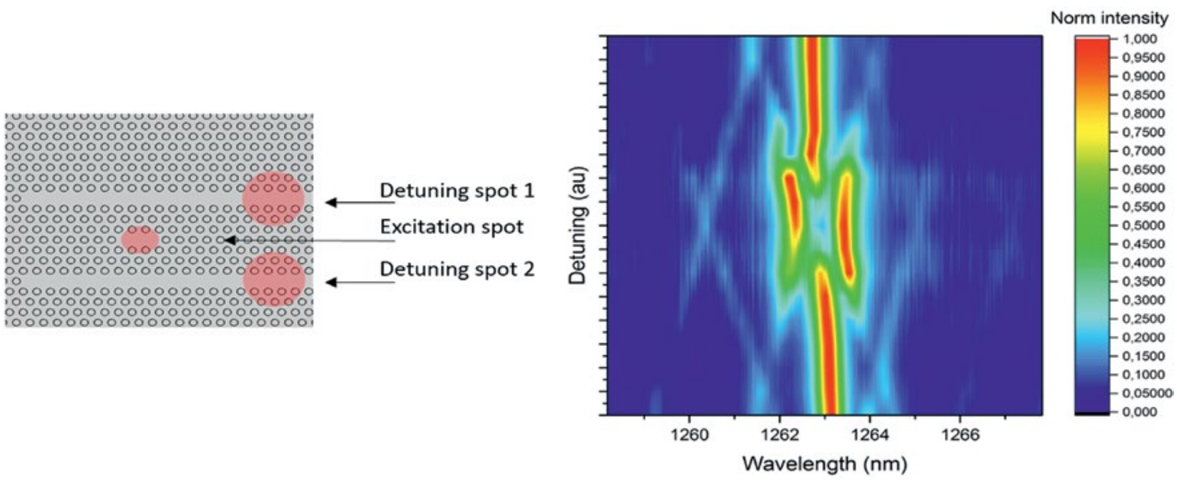

Figure 6
Color-coded micro-PL emission from QDs inside the central cavity of a 3-cavity system as a function of the detuning with the lateral cavities. At resonance the emission in the central mode is suppressed.

Main objectives for 2017:

- Ultrafast switching of three-cavity systems;
- Investigation of lasing in three-cavity systems.

Theme 3.2 Hybrid approaches combining photonics and spintronics

Project leader: Bert Koopmans

The final aim of this subproject is 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.

A relevant mechanism for the optical manipulation of magnetism in specially engineered nano-structures is the creation of charge- and spin currents by (femtosecond) laser pulses. In a collaboration with Nancy University we have demonstrated how optically generated charge currents of ballistic electrons can be used for ultrafast manipulation of magnetism over hundreds of nanometers distance *[BER16]*. Alternatively, optically induced spin currents can apply a magnetic torque (the so-called spin-transfer torque) on a neighboring ultrathin magnetic layer, when generated in a second, magnetic layer that has its magnetization orthogonal to the first one. Recently, we have shown experimentally that such a geometry is ideal for generating THz spin waves *[LAL17]*. This might provide a new route towards integrating ultrafast (integrated) photonics with THz magnonics – another approach towards low power device architectures.

We completed the set-up for all-optical switching and performed pilot experiments on Pt/Co/Pt based systems (see Figure 7 a and b). Experiments have started to explore the role of the so-called 'DMI' interactions, an exchange interaction that prefers non-collinear spin-alignment, leading to chiral textures that are highly relevant for current driven motion of magnetic information, and finite size effects – the latter making use of defining magnetic regions with out-of-plane magnetization using focused-ion beam irradiation. First samples for combining optical writing with current-induced movement of magnetic information in a Hall-bar geometry have been produced and optimized (Figure 7c). Further studies have been performed on magnetic-field and current-induced control exploiting the spin-Hall effect (in which electrons are deflected oppositely depending on their spin orientation) and DMI. Among the highlights we reported on the spin-Hall switching of magnetic elements without the requirement of applying an external magnetic field, as considered to be of crucial relevance for future magnetic random access memory (MRAM) [*BRI16*].

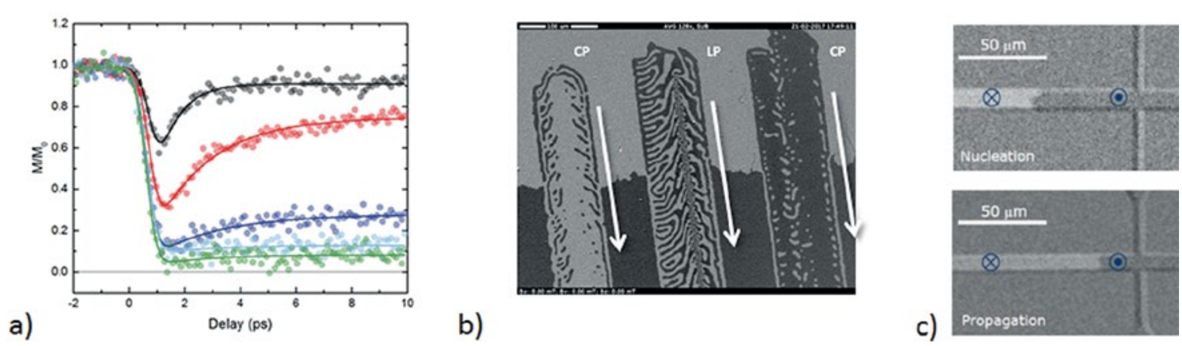

Figure 7
a) Time-resolved change in magnetization of a Pt/Co/Pt film after fs laser excitation at increasing laser fluence (black – green), leading to full demagnetization at high fluence. b) Magneto-optical (MO) microscopy image (light and dark color representing opposite magnetization) of all-optical switching by a train of fs laser pulses from a beam moving up to down across a magnetic domain wall, for right-handed circularly polarized (CP) light, linearly polarized (LP) light and left-handed CP light. c) MO image of a ferromagnetic Pt/Co/Pt magnetic stripe, forming part of a Hall-cross, before and after moving a magnetic domain wall.

Recently, in a concerted effort, FNA and PHI started up new activities exploring the magneto-optical response of photonic waveguides with PMA (perpendicular magnetic anisotropy) ferromagnetic cladding. This study should guide further development of spintronic-photonic racetrack scenarios and assess the feasibility of other devices such as optical isolators.

Main objectives for 2017:
- Establish all-optical magnetic switching in multi-layered magnetic nanostructures and explore the role of DMI and finite size effects;
- Supply a proof of principle of current-driven motion of all-optically written magnetic bits;
- Perform explorative studies of magneto-optical response of photonic waveguides with PMA (perpendicular magnetic anisotropy) ferromagnetic cladding.

Theme 3.3 Nanomanufacturing for photonics
Project leader: Erwin Kessels

Functionalizing nanowire device surfaces by Atomic Layer Deposition (ALD)
The PMP and FSN groups are investigating silicon (Si), germanium (Ge), and III/V nanowires for fundamental properties of various ALD processes on nanowire surfaces. These studies are foundational to current and future work on functionalizing nanowire device surfaces by ALD. This work has highlighted a number of additional considerations that need to be taken into account when performing ALD processes on nanowires as opposed to planar substrates, including possible conformality deviations, material- or geometry- dependent nucleation delay or enhancement, and surface selectivity of deposition. This work has been presented at two scientific conferences *[BLA15, VOS16a]*, and a scientific publication is planned for 2017.

In cooperation with PSN we are studying the (electronic) surface passivation of InP nanowires by ALD. These wires are used by PSN to develop nanowire solar cells with state-of-the-art efficiencies [DAM16], but InP nanostructures are also relevant for other applications such as nanolasers for silicon-integrated photonics [WAN15]. We are using their photoluminescence measurement setup for characterising the effectiveness of our ALD passivation layers on their wires. Through this work we have successfully developed an effective dielectric surface passivation scheme for InP nanowires which significantly reduces the impact of surface recombination. This work will be published in 2017.

In a cooperation between PMP, PHI and PSN we have investigated the effectiveness of ALD dielectrics such as Al_2O_3 and SiO_2 as surface passivation layers for InP/InGaAs nanolaser/LED devices, in comparison with plasma-enhanced chemical vapor deposited (PECVD) SiO_2. Such devices are intended for application as on-chip optical interconnects. This work will lead to a joint publication in 2017, presenting a significant reduction in surface recombination through the use of SiO_2 together with a sulfurization pre-treatment *[HIG17]* (see Figure 8, next page).

In addition we have been working on ALD of cobalt (Co) and platinum (Pt) for magnetic applications, building upon FNA-expertise in deposition and characterization of materials (including Co/Pt stacks) for nanomagnetic devices. Instead of the usual sputtering or evaporation techniques for deposition of these materials, we are investigating the possibility of using ALD for these applications. ALD enables wafer-scale uniformity and ultimate thickness control which could be beneficial for future nanomagnetic devices, although preparing ultrathin, high-purity metal films by ALD is known to be a significant challenge. Recently we presented our work on the ALD process for Co at an international scientific conference *[VOS16b]* and we are currently working on a publication on this topic. Moreover our future plans include the characterization of the ALD films using facilities available in the FNA-group.

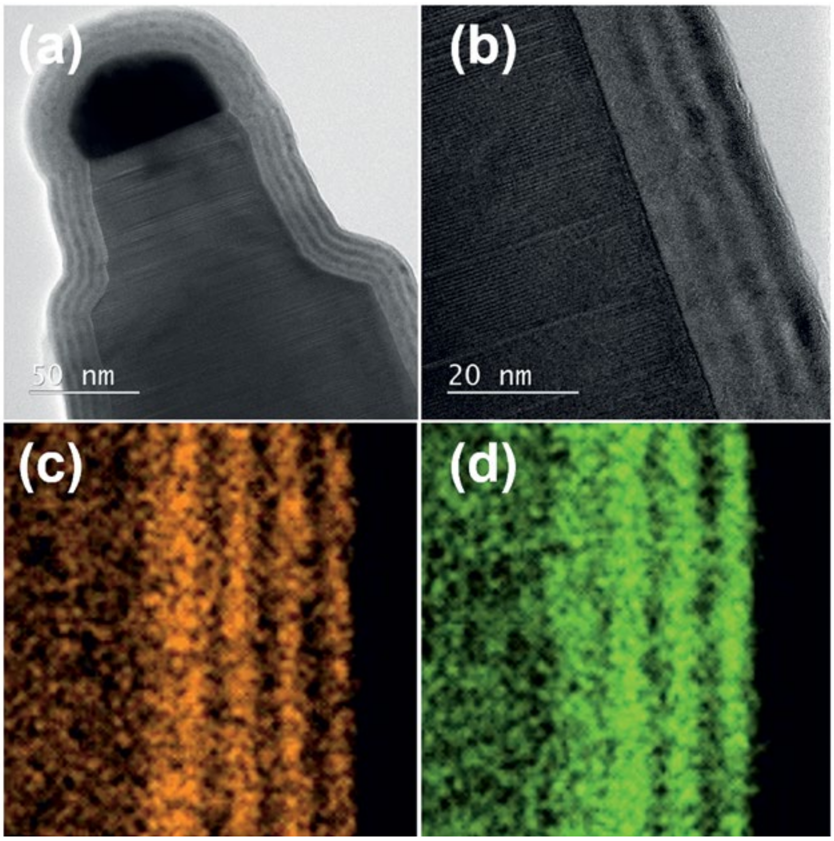

Figure 8
(a) Bright field transmission electron microscopy (TEM) image of a Al2O3/ZnO multilayer stack on GaP. The conformal multilayer was deposited by alternating the ALD processes for Al2O3 and ZnO. (b) High resolution TEM image of the Al2O3/ZnO multilayer. (c) EDS scan of the Al2O3/ZnO multilayer showing the elemental mapping of Al. (d) EDS scan of the Al2O3/ZnO stack for Zn.

Main objectives for 2017:

- Experimentally establish applicability of ALD passivation layers to nanowire devices;
- Investigate ALD of low refractive index, high-transparency materials for (photonic) optical applications;
- Investigate ALD of Co and Co/Pt stacks for application in magneto-optical devices.

Theme 3.4 Semiconductor Nanowires

Project leader: Erik Bakkers

Growth of nanowires

The silicon-germanium (SiGe) alloy with a hexagonal crystal structure is predicted to have a direct band gap with an energy corresponding to common telecommunication wavelengths. As part of this Gravitation program and a VICI project ,we have developed a generic approach to fabricate hexagonal Si *[HAU15]* and SiGe *[HAU16]*. We have analyzed the structure in detail and this is the first time that substantial volumes of a hexagonal group IV semiconductor can be fabricated in a controllable way. In Figure 9 (next page) the approach is illustrated. Wurtzite gallium-phosphide (GaP) nanowires are used as an epitaxial template on which Si is grown as a shell. Because these materials have very similar lattice parameters, the crystal structure is transferred to the shell.
A challenge is to make chemically pure Si and SiGe shells. Due to the high growth temperature Ga and P atoms from the core wire may diffuse into the shell, acting as electrically active dopants. By using the Atom Probe Tomography (APT) facilities available in the PSN-group, we could indeed observe the presence of these impurities in the shell. We will use this technique to further optimize

the shell quality with the goal to demonstrate the direct band gap of SiGe. One route we want to follow is to reduce the growth temperature by using different type of precursors. Another important challenge will be to passivate the surface of these shells. We will develop efficient schemes for surface passivation (see section 3.3) using ALD.

Main objectives for 2017:

- Develop a low-temperature growth scheme;
- Demonstrate the direct band gap of hexagonal SiGe;
- Passivate the surface of hexagonal SiGe.

Most important problems/deviations, impact on the planning and corrective actions

At the start of 2017 the nanowire activities have been organized into a new group “Advanced Nanomaterials and Devices (AND) under leadership of E.P.A.M. Bakkers. The former responsibilities of the team of E.P.A.M. Bakkers within PSN have been transferred to AND without any consequences for the Zwaartekracht program.

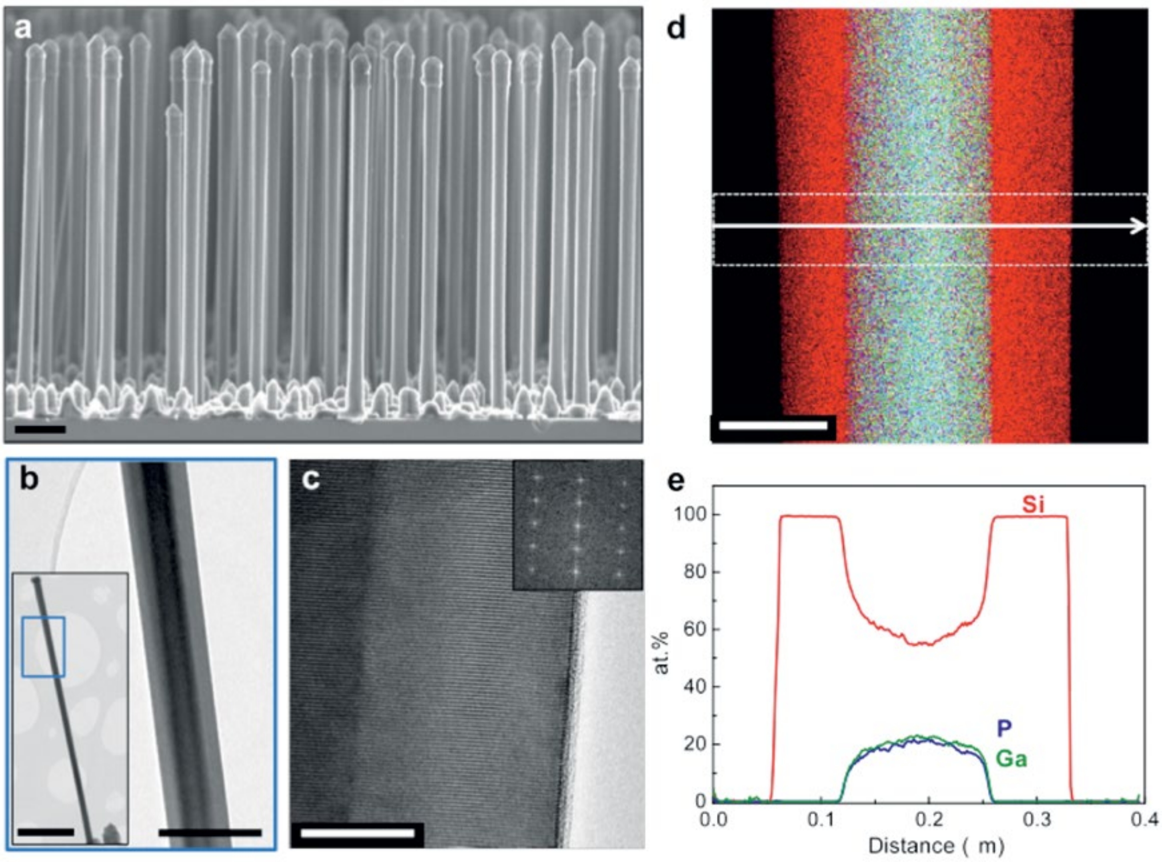

Figure 9

Morphology overview of GaP/Si core/shell nanowires. (a) Cross-sectional scanning electron microscopy (SEM) image of a representative sample of GaP/Si core/shell nanowires. (b) Low magnification bright-field transmission electron microscopy (BF-TEM) image of one of these nanowires exhibiting an untapered shape. Scale bar in (b) is 200 nm (1 μm in the inset).
(c) High-resolution TEM image of the GaP/Si interface with the corresponding FFT in the inset. Scale bar is 20 nm.
(d) and (e) show the energy-dispersive X-ray (EDX) compositional map (scale bar is 100 nm) and the corresponding line scan taken across the nanowire diameter as indicated by the white arrow in (d). The line scan has been obtained integrating the EDX map in the region marked by a white dashed box.

Publications and joint research

The research carried out in the Gravitation Project is tightly related to the current research of the participating groups. In 2016 they published 139 papers on topics related to the Gravitation project, of which 22 were joint papers.

The table below lists the publications of the projects which are referenced in this report.

List of referenced publications

	Publication	Group
BER16	Bergeard, N., Hehn, M., Mangin, S., Lengaigne, G., Montaigne, F., Lalieu, M.L.M., Koopmans, B. & Malinowski, G. (2016). *Hot-electron-induced ultrafast demagnitization in Co/Pt/multilayers.* Physical Review Letters, 117(14):147203	FNA
BRI16	Brink, A. van den, Vermijs, G., Solignac, A., Koo, J., Kohlhepp, J.T., Swagten, H.J.M. & Koopmans, B. (2016). *Field-free magnetization reversal by spin-Hall effect and exchange bias.* Nature Communications, 7:10854	FNA
CAL16	Calabretta, N., Miao, W., Prifti, K. & Williams, K.A. (2016). *System performance assessment of a monolithically integrated WDM cross-connect switch for optical data centre networks.* 42nd European Conference on Optical Communication, ECOC2016, 18-22 September 2016, Düsseldorf, Germany (pp. 1-3). VDE Verlag.	ECO PHI
CAO16	Cao, Z., Jiao, Y., Shen, L., Yan, F., Khalid, A.M., Li, T., Zhao, X., Tessema, N.M., Oh, C.W. & Koonen, A.M.J. (2016). *Optical wireless data transfer enabled by a cascaded acceptance optical receiver fabricated in an InP membrane platform.* Optical Fiber Communication Conference (OFC 2016), 20-22 March 2016, Anaheim, California (pp. 1-3). Piscataway: Institute of Electrical and Electronics Engineers Inc.	ECO PHI
COT16a	Cotrufo, M., A. Fiore, E. Verhagen (2016). *Coherent Atom-Phonon Interaction through Mode Field Coupling in Hybrid Optomechanical Systems.* arXiv 1610.05153; Phys. Rev. Lett. 118, 133603	PSN
COT16b	Cotrufo, M., M. Leonardo, M. Petruzzella, Z. Zobenica, F.W.M. van Otten, A. Fiore (2016). *Active control of the vacuum field in nanomechanical photonic crystal structures.* Frontiers in Optics 2016, Optical Society of America, paper FTu3D.7	PSN
DAM16	Dam, D. van, N. J. J. van Hoof, Y. Cui, P. J. van Veldhoven, E. P. A. M. Bakkers, J. Gómez Rivas, and J. E. M. Haverkort. (2016). *High-efficiency nanowire solar cells with omnidirectionally enhanced absorption due to self-aligned indium–tin–oxide Mie scatterers.* ACS Nano, vol. 10, no. 12, pp. 11414–11419, 2016.	PMP PSN
DOL17	Dolores-Calzadilla, V., B. Romeira, F. Pagliano, S. Birindelli, A. Higuera-Rodriguez, P. J. van Veldhoven, M. K. Smit, A. Fiore & D. Heiss (2017). *Waveguide-coupled nanopillar metal-cavity light-emitting diodes on silicon.* Nature Communications 8, Article number: 14323 (2017)	PHI PSN

ENG16	Engelen, J.P. van, Shen, L., van der Tol, J.J.G.M., Roelkens, G.C. & Smit, M.K. (2016). *A novel optically wide-band electro-absorption modulator based on bandfilling in n-InGaAs.* Proceedings of the 18th European Conference on Integrated Optics (ECIO 2016), 18-21 May 2016, Warsaw, Poland	PHI
FIO17	Fiore, A., R.W. van der Heijden, L. Midolo and Z. Zobenica, T. Liu. (2017). *Integrated spectrometer and optomechanical sensor*. Patent application PCT/EP2017/050262	PSN
FOR16	Forni, F., Shi, Y., van den Boom, H.P.A., Tangdiongga, E. & Koonen, A.M.J. (2016). *LTE-A multiband and ethernet over Large-core diameter GI-POF for wired and wireless in-home networks.* 42nd European Conference on Optical Communication Proceedings, September 18 – 22, 2016, Düsseldorf, Germany Berlin: VDE Verlag GmbH.	ECO
HAU15	Hauge H.I.T., M.A. Verheijen, S. Conesa-Boj, T. Etzelstorfer, M. Watzinger, D. Kriegner, I. Zardo, C. Fasolato, F. Capitani, P. Postorino, S. Kölling, A. Li, S. Assali, J. Stangl, and E.P.A.M. Bakkers (2015). *Hexagonal Silicon Realized.* Nano Letters 15, 5855 (2015)	PSN
HAU16	Hauge H.I.T., S. Conesa-Boj, M.A. Verheijen, S. Koelling, E.P.A.M. Bakkers (2016) *Single-Crystalline Hexagonal Silicon–Germanium.* Nano Letters, 16, 85 (2016)	PSN
HIG16	Higuera Rodriguez, A., Smit, M.K., Fiore, A., Patarata Romeira, B.M., Black, L.E., Birindelli, S., Kessels, W.M.M. & Smalbrugge, E. (2016). *Ultra-low surface recombination for deeply etched III-V semiconductor nano-cavity lasers.* Proceedings Advanced Photonics 2016 (IPR, NOMA, Sensors, Networks, SPPCom, SOF) Vancouver: OSA Publishing.	PHI PSN PMP
HIG17	Higuera-Rodriguez, A., B. Romeira, S. Birindelli, L. E. Black, E. Smalbrugge, P. J. van Veldhoven, W. M. M. Kessels, M. K. Smit, and A. Fiore, *Ultra-low surface recombination velocity in passivated InGaAs/InP nanopillars.* Nanoletters, Submitted for publication.	PHI PSN PMP
JIA16	Jiao, Y., Shen, L., Cao, Z., Latkowski, S., Bente, E.A.J.M., van der Tol, J.J.G.M., Smit, M.K. & Williams, K.A. (2016). *III-V photonic integrated circuits for beyond-telecom applications.* 2016 25th Wireless and Optical Communication Conference (WOCC 2016 Piscataway: Institute of Electrical and Electronics Engineers Inc.	PHI ECO
KHA16	Khalid, A.M., Torres Vega, M., Mekonnen, K.A., Cao, Z., Liotta, A. & Koonen, A.M.J. (2016). *Real time 10Gb-ethernet transmission over 2D indoor passive beam steered optical wireless system based on high port arrayed waveguide gratings.* 42nd European Conference on Optical Communications (ECOC 2016) IEEE.	ECO
KOO16	Koonen, A.M.J., Oh, C.W., Mekonnen, K., Cao, Z. & Tangdiongga, E. (2016). *Ultra-high capacity indoor optical wireless communication using 2D-steered pencil beams.* Journal of Lightwave Technology, 34(20):7482669	ECO
LAL17	M.L.M. Lalieu, P.L.J. Helgers & B. Koopmans (2017). *Absorption and generation of femtosecond laser-pulse excited spin currents in non-collinear magnetic bilayers*. arXiv:1704.03746v1, submitted to Phys. Rev. B.	FNA
LIC17	Li, C., T. Li, G. Guelbenzu, B. Smalbrugge, R. Stabile and O. Raz. (2017). *Chip Scale 12-Channel 10 Gb/s Optical Transmitter and Receiver Sub-assemblies Based on Wet Etched Silicon Interposer.* Accepted for publication in May/June 2017.	ECO PHI
LIN16	Linden, R. van der, Yin, Xin, Tran, N.C., Bauwelinck, J., Tangdiongga, E. & Koonen, A.M.J. (2016). *Demonstration of upstream flexible 2-/4-PAM formats for practical PON deployments.* ECOC 2016 : 42nd European Conference on Optical Communication: Düsseldorf, September 18 - 22, 2016 (pp. 430-432).	ECO

LIU16	Liu, T., A. Fiore and F. Pagliano, *Nanomechanical optical switch*. Patent application: n.62/385380	PSN
MIA16	Miao, W., Yan, F. & Calabretta, N. (2016). *Towards petabit/s all-optical flat data center networks based on WDM optical cross-connect switches with flow control.* Journal of Lightwave Technology, 34(17), 4066-4075.	ECO
MEK16	Mekonnen, K.A., van Zantvoort, J.H.C., Tangdiongga, E. & Koonen, A.M.J. (2016). *Experimental characterization of a reflective amplified modulator for analog applications.* In G. Roelkens, N. Le Thomas & P. Bienstman (Eds.), Proceedings of the 21st Annual Symposium of the IEEE Photonics Society Benelux Chapter, November 17-18, 2016, Gent, Belgium (pp. 243-246). Gent: Universiteit Gent.	ECO
RAH16	Rahman, T., Rafique, D., Spinnler, B., Calabro, S., de Man, E., Feiste, U., Napoli, A., Bohn, M., Khanna, G., Hanik, N., Pincemin, E., Le Bouëtté, C., Jauffrit, J., Bordais, S., Andre, C., Dourthe, C., Raguenes, B., Okonkwo, C.M., Koonen, A.M.J. & de Waardt, H. (2016). *Long-haul transmission of PM-16QAM, PM-32QAM and PM-64QAM based terabit superchannels over a field deployed legacy fiber.* Journal of Lightwave Technology, 34(13), 3071-3079.	ECO
STA16	Stabile, R., Dasmahapatra, P. & Williams, K.A. (2016). *4x4 InP switch matrix with electro-optically actuated higher order micro-ring resonators.* IEEE Photonics Technology Letters, 28(24), 2874-2877.	ECO PHI
TES16	Tessema, N.M., Cao, Z., van Zantvoort, J.H.C., Mekonnen, K.A., Dubok, A., Tangdiongga, E., Smolders, A.B. & Koonen, A.M.J. (2016). *A tunable Si_3N_4 integrated true time delay circuit for optically-controlled K-band radio beamformer in satellite communication.* Journal of Lightwave Technology, 34(20):20	ECO
VOS16a	Vos, M.F.J., L.E. Black, R.H.J. Vervuurt, M.A. Verheijen, E.P.A.M. Bakkers, W.M.M. Kessels, *Thermal and plasma ALD on semiconductor nanowires.* ALD Conference, 25-27 July, 2016, Dublin, Ireland.	PMP PSN
VOS16b	Vos, M.J.F., N.F.W. Thissen, A.J.M. Mackus, and W.M.M. Kessels (2016). *A novel ABC-type ALD process for cobalt using CoCp2 and N2 and H2 plasmas*. Presented at American Vacuum Society 63rd International Symposium, 6–11 October 2016, Nashville, Tenessee, USA.	PMP
WAN15	Wang, Z., B. Tian, M. Pantouvaki, W. Guo, P. Absil, J. Van Campenhout, C. Merckling, and D. Van Thourhout (2015). *Room-temperature InP distributed feedback laser array directly grown on silicon*. Nature Photonics, vol. 9, pp. 837-842, Oct 2015.	PMP
ZOB16	Zobenica, Z., R.W. van der Heijden, M. Petruzzella, F. Pagliano, R. Lijssen, T. Xia, L. Midolo, M. Cotrufo, Y. Cho, F.W.M. van Otten, E. Verhagen, and A. Fiore (2016). *Fully-integrated nanomechanical wavelength and displacement sensor.* Conference on Lasers and Electro-Optics 2016, Optical Society of America, paper STu4H.6.	PSN

Budget and personnel

Summary

After some delay in the first two years due to difficulties in finding highly qualified PhD and tenure track candidates, and the unexpected passing away of prof. Dorren, one of the leading principal Investigators, the project is now running at full speed. The solid line in Figure 10 shows the originally planned appointment level, the bars show the actual appointment level in the participating groups and the commitments for the following years. The light blue bars on top indicate the planned additional appointments, which have to be implemented in the coming years. Figure 10 shows that we have reached the planned effort level in 2017. In 2018 and following years we expect to exceed the planned effort level in order to catch up for the delays in the first two years. We are trying to strengthen our permanent staff. For that reason, we have exchanged two postdocs for an assistant professor. If there are opportunities, we may consider a similar exchange in the future. Apart from that, we have not changed the original plans.

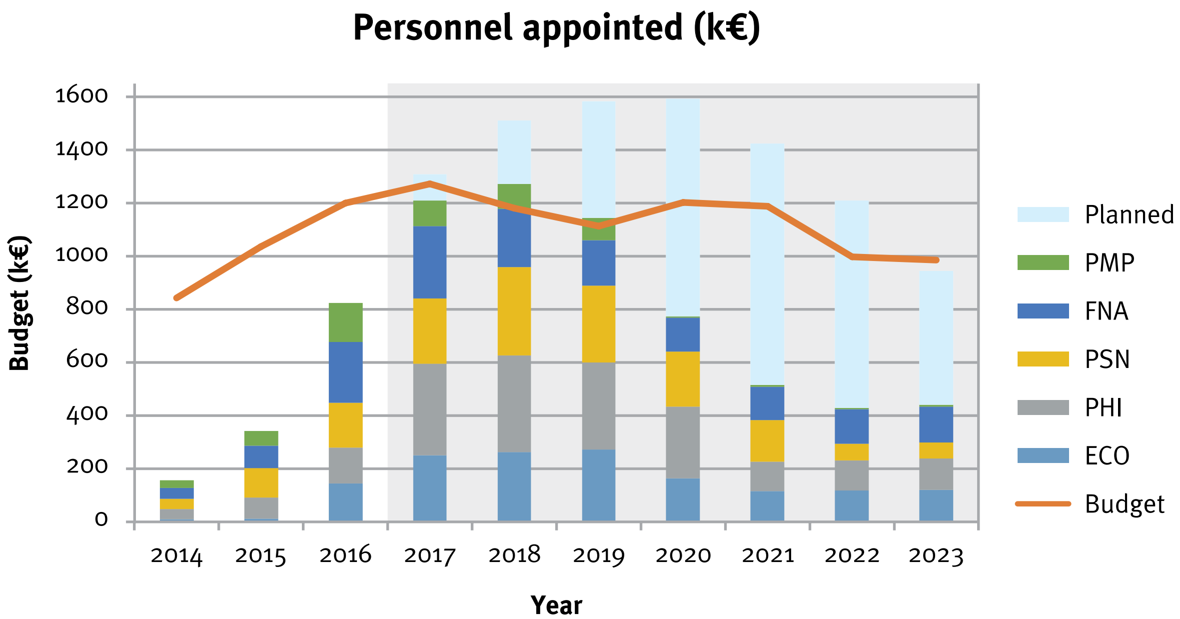

Figure 10
Personnel budget, realized and planned.

Figure 11 shows the difference between the planned cumulative budget and the cumulative spending and commitments so far. Dark blue bars on a grey background indicate reservations for currently hired personnel. Light blue bars indicate plans for 2017 and following years.

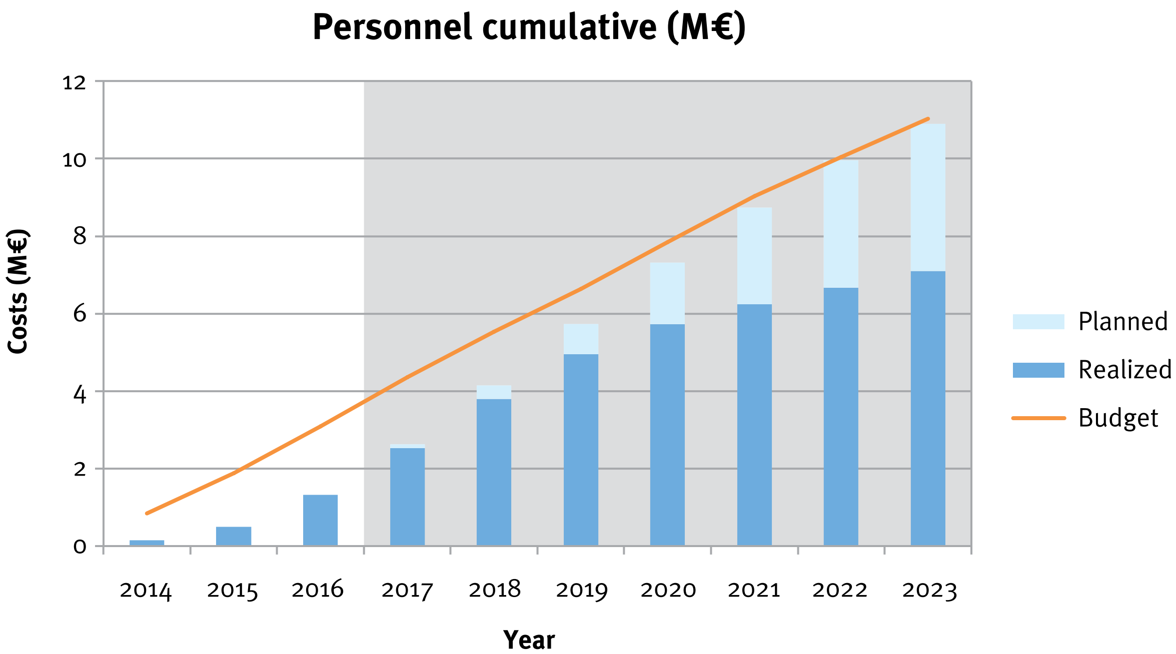

Figure 11
Cumulative personnel budget: realization and planning.

Institutional embedding and organisational structure

Organisational and Management Structure

Figure 12 shows the management structure of the project, which was described in more detail in the 2014/15 year report and on the website https://www.tue.nl/onderzoek/research-centers/institute-for-photonic-integration/.
In 2016 Prof. Andrea Fiore replaced prof. Paul Koenraad, one of the co-applicants of the Gravitation Projects, as chairman of the PSN group and as PSN delegate in the management team. In 2017, Erik Bakkers' chair in the PSN group will become a separate group: Advanced Nanomaterials and Devices (AND). The group will remain fully committed to the Gravitation program.

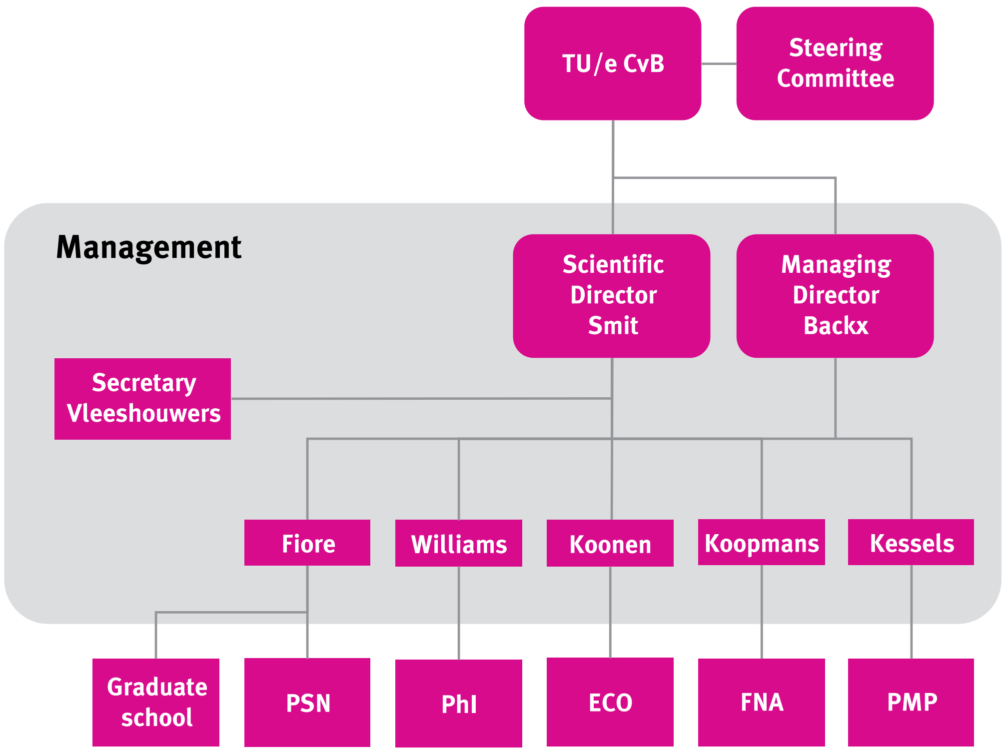

Figure 12
Management Structure of the Research Centre for Integrated Nanophotonics.

Organisational Embedding and Cooperation

As of 2016, the Gravitation project *Centre for Integrated Nanophotonics* is embedded in the *Institute for Photonic Integration* (IPI), which has succeeded the *COBRA Research Institute* in April 2016. The Gravitation project is the largest project of IPI. Through IPI and Nanolab@TU/e, which is one of the world's most advanced university cleanroom facilities for 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 national, European and international network of the former COBRA Research Institute, both in the academic and the industrial world.

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 has recently been recognized as one of the major areas in the national top sector High-Tech Systems and Materials (HTSM) in which Universities are cooperating with the high-tech industry.

The IPI cooperates with *PhotonDelta* to provide company access to research results (see Figure 13). To this end, IPI and PhotonDelta will set up a Research Center based on industrial and public co-funding. This *Photonics Integration Technology Center* (PITC) will be the intermediary between the IPI research on low *technology readiness* (TR) levels and the applications at high TR-levels envisioned by the companies joined in PhotonDelta. Companies participate in Photon Delta through membership of a Cooperative, which gives them privileged access to IPI and PITC research.
The JePPIX activities will become part of PITC from the start. The PITC will offer an effective channel for using knowledge generated within the Gravitation Project in commercial applications.

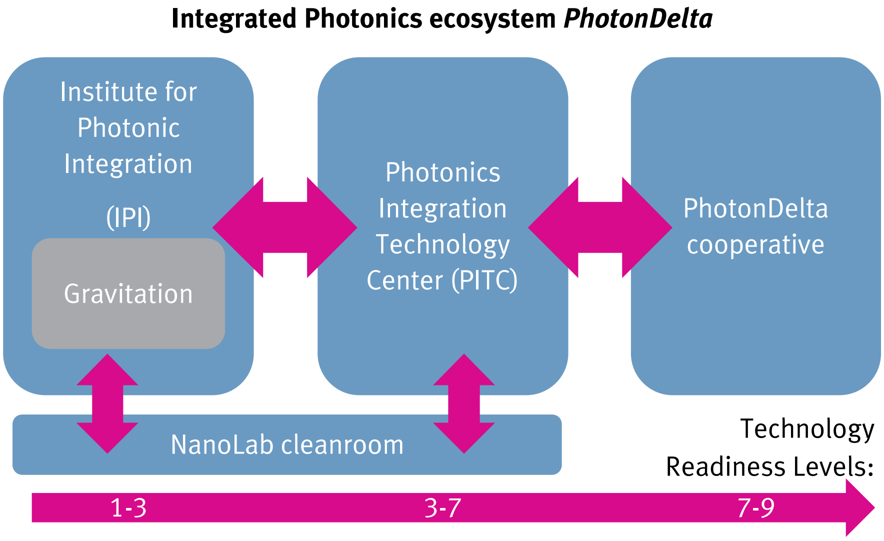

Figure 13
Integrated Photonics ecosystem PhotonDelta.

Educating and attracting talent

Photonics is present in the TU/e education curriculum through a bachelor course, a special Master program in *Broadband Telecommunication Technology* and the *NWO Graduate school on Photonics* established in 2015, which offers a training program for PhD students and Master students in Photonics. A special master track in *Photronics* (integration of Electronics and Photonics) will become available in 2017 or in 2018. This initiative will be key for the development of the field, because all photonic integrated circuits require electronic drivers, receivers, controllers and processing circuitry. The new Master track will provide the necessary training program for electronic-photonic co-design.

In a general context of a shortage of qualified personnel, the institute is successful in attracting highly qualified researchers and excellent PhD students, due to the international reputation of the former COBRA institute and its excellent cleanroom facilities. The Gravitation project offers significant means to strengthen the scientific quality of the IPI staff and students. The PHI group is in the process of attracting a full-time professor for the Gravitation project. Another 3 PhD students have started this year. The PHI group is in the process of attracting a new full-time professor for the Gravitation project. Two new assistant professors have been appointed in the FNA and ECO groups.

Knowledge utilisation

As described in the section on organizational embedding, the Gravitation project is embedded in the *Institute for Photonic Integration* (IPI). IPI is the scientific pillar of the PhotonDelta ecosystem. The research activities in IPI receive a significant impulse as a result of the activities initiated by the ecosystem *PhotonDelta*: the PhotonDelta ecosystem generates research to be conducted in IPI. Main driver for this function is the *Photonics Integration Technology Center* (PITC). This is a commercial entity 100% owned by the TU/e, offering R&D services to industry, funded directly by industry and through public co-funding. The PITC is the important bridge between the outcomes of research and commercial application. The interface function covers the range in *technology readiness levels* (TRLs) necessary for scaling up, proof-of-concept, prototyping, experimental packaging options, condition and duration testing and the required highly sophisticated measurement and testing equipment. The PITC provides the equipment and expertise to prepare a technological innovation in the area of photonic integration for industrial use and integration.

Currently, the PITC has started with hosting the European JePPIX platform and expanding its R&D activities in the field of integration platform technology, and initiating similar activities in the field of system prototyping and materials research. Within JePPIX IPI is closely collaborating with Europe's key players in Photonic Integration and with its own startup companies SMART Photonics and EFFECT Photonics. A number of patents and technologies developed by COBRA, the predecessor of IPI, have already been licensed to JePPIX partners. In the field of materials and systems research we have intensive cooperation with the companies Genexis (fiber-to-the-home and photonic in-home networks), Coriant (high-capacity data transport systems), PhotonX Networks (dense high-capacity interconnects in data centers) and Oxford Instruments (Atomic Layer Deposition). Through the PITC and Photon Delta, we will further broaden and strengthen our contacts with industrial partners.

In 2016, there were over 80 companies and institutions active in the Netherlands in the field of integrated photonics. That number is growing steadily. PhotonDelta will strengthen a collaborative approach to valorisation. The initiative is supported by Eindhoven University of Technology, by its sister universities and by a large number of companies in the Brainport region, Twente and other tech-regions in the Netherlands.