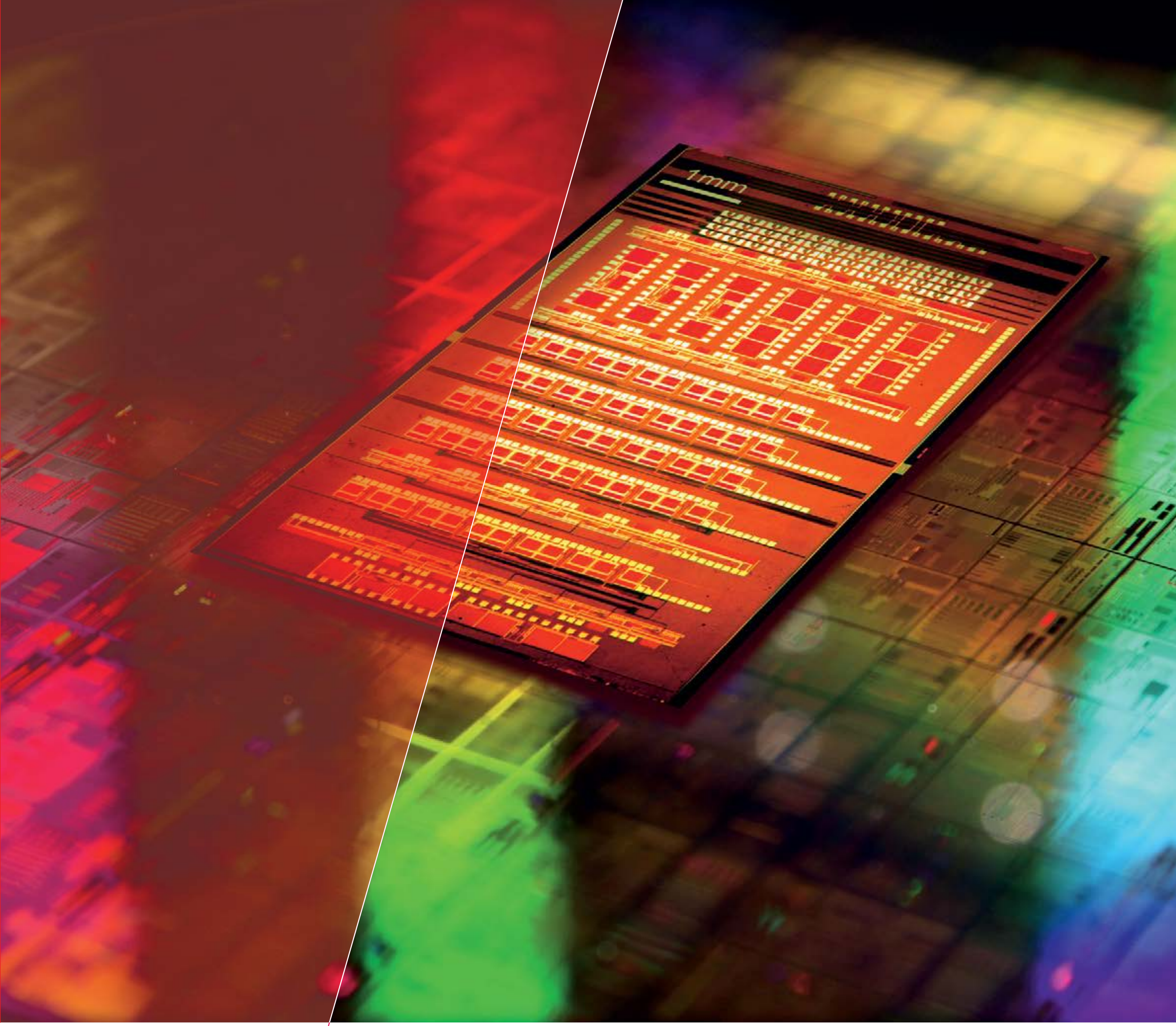

Research Centre for Integrated Nanophotonics

Annual Report 2017

26 April 2018

Technische Universiteit
Eindhoven
University of Technology

Institute for Photonic Integration
Materials • Devices • Systems

Research Centre for Integrated Nanophotonics

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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
Prof.dr. E.P.A.M. (Erik) Bakkers	Semiconductor Nanowires	AND
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Executive summary

In 2017 we made significant progress in all three themes of the Research Centre for Integrated Nanophotonics, which is the largest project of the Institute for Photonic Integration (IPI). The project passed successfully through its midterm evaluation and can continue for another five years. The development of the Photon Delta ecosystem, in which IPI plays an important role, is making good progress and in the coming year we expect significant upscaling of the activities.

In the *Pervasive Optical Systems* we established new records in the capacity of wireless optical links with 2D beam steering, the transmission capacity of data center intraconnect modules and space-division multiplexed transmission in a single-core few-mode fiber. We continued exploration of new concepts for improving mesh-interconnection in large-scale switching matrices and reducing coupling losses to fiber arrays.

In the *Photonic Integration* theme we demonstrated strongly improve SOAs and lasers in our IMOS platform (*Indium-phosphide Membrane On Silicon*). We started to offer access to internal and a few selected external users in an experimental MPW run. We expect to improve the reproducibility of our IMOS platform significantly by introducing 193 nm DUV lithography and high-quality bonding equipment in the processing. The improved process will support fabrication of nanolasers in a standardized generic process. We tested our double-membrane resonators successfully for use in opto-mechanical sensors for measuring force, mass or electric field. We started a new research line on 2D monolayer semiconductors for use in sources and detectors.

In the theme *Ultimate Control of Matter and Photons* we have succeeded in direct measurement of spontaneous emission rate quenching in coupled-cavity systems, which can be used for generating short pulses in nanolasers. We demonstrated all-optical switching of magnetization by single femtosecond laser pulses in an ultrathin film with a potential for integrated photonic memories. We made significant progress in ALD of Co for application in nanomagnetic devices, Ru as seeding layer for metallic vias in the IMOS platform, AlF_3 for optical coatings and Al_2O_3 as anti-stiction layer in nanomechanical membrane devices. Further, we achieved unprecedented performance improvements in passivation of InP nanowires by ALD encapsulation with a PO_x and an Al_2O_3-layer. Finally, we have made significant progress in the growth of direct-bandgap SiGe in nanowires, in which we hope to demonstrated optical gain in the coming year.

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 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 Photonic Integration

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 Matter and Photons

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 fourth year of the project (2017).

Work progress and achievements

Theme 1 Pervasive Optical Systems

Theme Coordinator: Ton Koonen

Highlights:

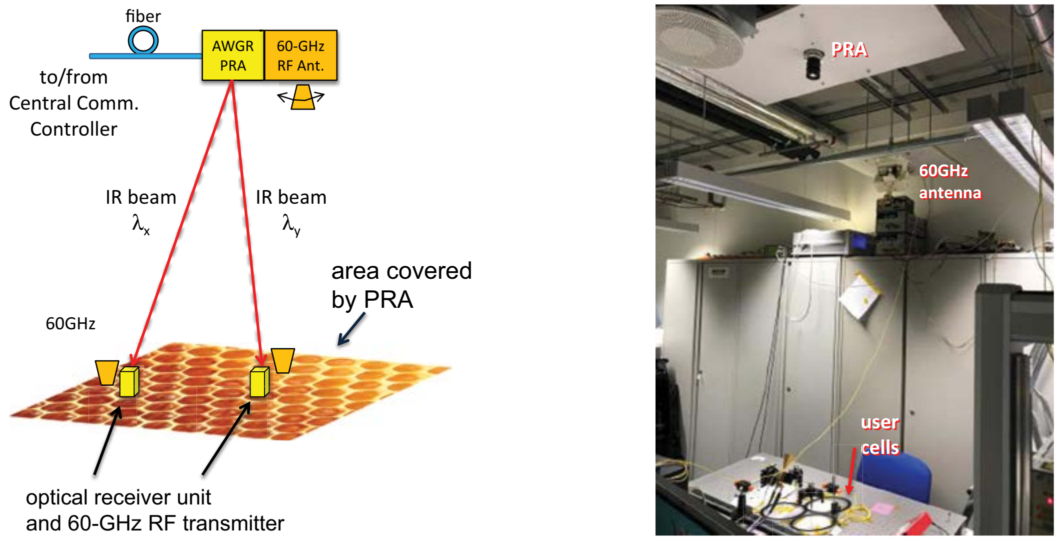
- Record data capacity of 112 Gbit/s per 2D-steered infrared beam
- Record 720 Gbit/s (48 channels × 15Gbit/s) data center intraconnect modules, using VCSELs packaged on a single silicon interposer.
- Record 138 Tbit/s transmission in a single-core few-mode fiber.

Theme 1.1 Fibre wireless integration

Project leader: Ton Koonen

Optical wireless communication indoor network

In the last year of the ERC Advanced Grant project BROWSE, we integrated our novel wavelength-controlled 2D infrared beam-steered optical wireless techniques with radio upstream and device localization techniques and dynamical signal routing in the indoor fiber backbone network.



Beam-steered Optical Wireless Communication (OWC) laboratory demonstrator

Photo of the laboratory demonstrator

Figure 1
Laboratory demonstrator featuring downstream 2D IR beam-steered communication, upstream 60 GHz radio beam-steered communication, and device localization.

We integrated and validated downstream beam-steered communication at 35 Gbit/s over 2.5 m, each beam On/Off Key (OOK) modulated and based on an arrayed waveguide grating router (AWGR), with upstream 60 GHz radio beam-steered communication at 5 Gbit/s (Amplitude Shift Key modulated), and with localization by means of a pan/tilt 60GHz horn antenna receiver [KHA17]. We extended the downstream capacity up to 112 Gbit/s PAM4-modulated per beam, with support for up to 80 beams [GOM17], which brings a 300-fold capacity extension with regard to today's Wi-Fi. We built a comprehensive laboratory demonstrator (see Figure 1) which features downstream AWGR-based beam steering at 10 Gbit/s OOK-modulated per beam for up to 129 beams and upstream

60 GHz radio beam communication at 10 Gbit/s, and demonstrated its performance with real-time transmission of high-definition video streams. We presented this in a keynote to the *Microwave Photonics Conference 2017* [KOO17a]. Eye safety has been verified by an independent external organization.

Downstream optical-wireless communication using the 2D beam steering based on the crossed-gratings principle has been improved to › 50 Gb/s per user [MEK18a]. The upstream link has been implemented using optical and 60-GHz radio free-space links, achieving up to 40 Gbit/s per user in both cases. A dynamically reconfigurable system using an InP optical crossconnect chip, based on semiconductor optical amplifier (SOA) gates, has been built, demonstrating the use of the 60-GHz radio system as a backup to optical-wireless links [MEK18b] [MEK17a] with bidirectional capacity of › 36 Gbit/s per link in both cases. Multicasting functionality is also incorporated in the system in a dynamic manner [MEK17b]. The complete testbed is shown in Fig. 2.

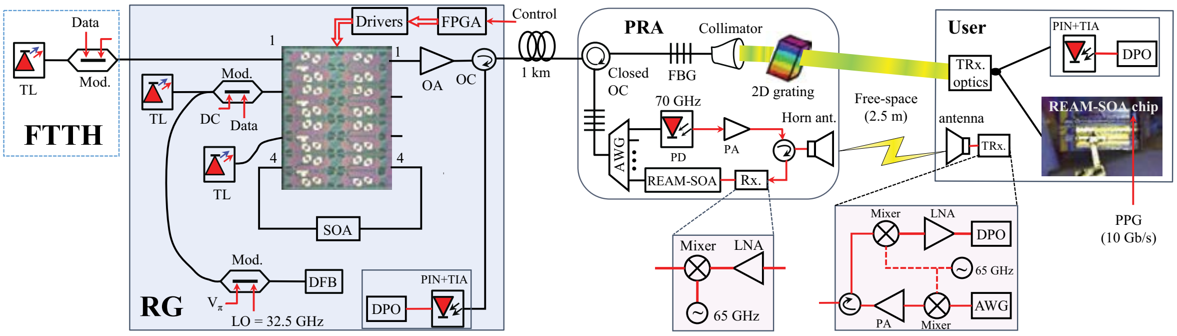


Figure 2
Test-bed for optical wireless communication with optical downlink and radio 60-GHz uplink (with a InP optical cross-connect chip).

In close cooperation, the ECO and PHI groups designed and realized a novel architecture for a large-aperture and large field-of-view receiver for optical wireless communication. It deploys a scalable surface grating coupler integrated with a waveguide-coupled uni-travelling-carrier photodiode, achieving an electrical bandwidth of 67 GHz. This Photonic IC was realized in InP Membrane on Silicon (IMOS) technology. Its operation was validated up to 40Gbit/s [CAO17].

An Optical Wireless Communication (OWC) tutorial was given at the *European Conference on Optical Communication 2017* (ECOC 2017) [KOO17b], and a keynote at the *Microwave Photonics Conference 2017* [KOO17a].

Optically-controlled radio beam steering
In the Gravitation program and the STW FreeBeam project we have explored optical control of steering radio beams, in particular for receiving satellite-to-ground K-band signals. A silicon-nitride (Si_3N_4) PIC based on true time delay techniques which enables independent steering of 4 broadband radio beams has been designed, fabricated, packaged, and validated. This chip can also be used for the transmitting function. We achieved an increased channel capacity up to 9.68 Gbit/s of 32-QAM multi-carrier data [TES17].

This optical beamformer has been integrated within a K-band (18 to 27 GHz) antenna system into the final demonstrator of the FreeBeam project [TRI18]. Integration with other system parts led to the final project demonstrator of the FreeBeam project.

In a follow-up, an optical beamformer has been designed in the IMOS platform, containing delay lines and optical ring resonators for providing wide bandwidth and continuous delay tuning, and semiconductor optical amplifiers (SOAs) to compensate on-chip losses. This Photonic IC is designed for indoor applications at 60 GHz and up to 7 GHz bandwidth [TRI17].

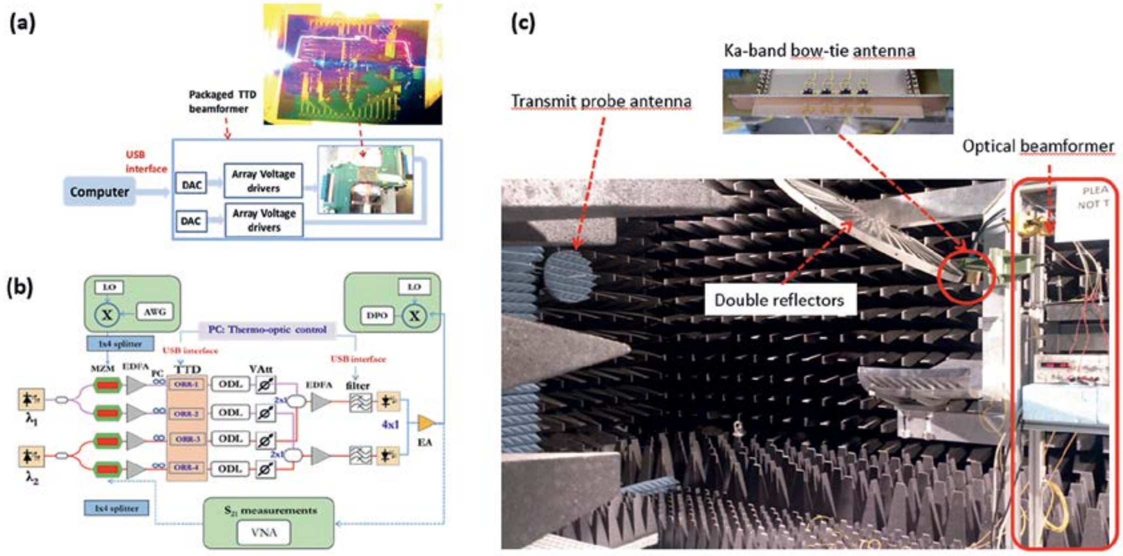


Figure 3
(a) Packaged optical beamformer; (b) Experimental setup for measuring beamforming gain [TES17]; (c) FreeBeam project demonstrator.

Flex-rate Fiber to the Home (FTTH) networks
In the area of FTTH, the Gravitation program and the Flexcom FTTH project mutually reinforce each other. We investigated techniques for dynamic adaptation of the data capacity per home to the fiber link conditions in a power-split passive optical network (PON), by means of adapting the data modulation format. By applying non-uniform hierarchical multi-level PAM formats, FTTH networks can be more resilient to link-dependent signal-to-noise ratios. Thus a higher total system throughput can be achieved, allowing higher capacity for better-positioned users, or an increased flat capacity for all users. Based on real data from a commercially deployed network, the aggregate data rate can be increased from 10 Gbit/s to 19.4 Gbit/s [LIN17, LIN18].

Main objectives for 2018:

- InP Photonic IC high-bandwidth receiver for optical wireless communication with a large aperture (wide field of view)
- InP Photonic IC for wavelength-controlled IR beam steering with increased coverage
- Photonic IC for optically-controlled radio beam steering in 5G pico-cells
- Photonic IC for link adaptation in Fiber-to-the-Home power-split 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)
We studied programmable interconnects on chip to reconfigure a PIC in case of local failures, in order to improve PIC reliability. Work on material research has continued in 2017. The deposition parameters for the optimal material have been further investigated and also alternative direct measurement concepts for testing light induced changes have been suggested based on the fabrication of antireflection (Fabry Perot) layer stacks including aSi:H layers. Initial results from these experiments suggest that the light-induced refractive index change in the 1550nm window is very modest (less than 0.1%). However, for shorter wavelengths reproducible light induced changes in the complex dielectric function have been recorded; see Figure 4. These results were presented in the *27th International Conference on Amorphous and Nanocrystalline Semiconductors* [MAH17] and have been accepted in February 2018 for publication in *Physica Status Solidi (A)* [MAH18]. For 2018 we are aiming to move forward and start the process of designing photonic circuits which make use of aSi:H with the aim of demonstrating resonance shifts of ring resonators and Mach-Zehnder interferometers due to the Stäbler-Wronski effect [STA17].

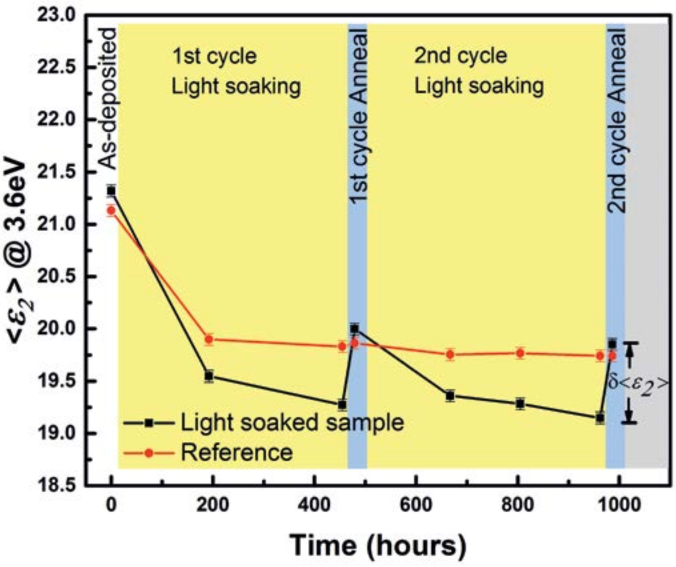


Figure 4
Changes in the imaginary part of the pseudo dielectric function ‹ε2› at 3.6 eV for the reference film (red line) over time and the sample after the 1st cycle of light soaking, the 1st cycle of annealing, the 2nd cycle of light soaking, and the 2nd cycle of annealing (black line).

Novel 3D and 2.5D packaging for optics in data centers
Ongoing work on data communication solutions using VCSELs (Vertical-Cavity Surface-Emitting Laser) has resulted in modules with 48 channels each working at 15 Gb/sec all packaged on a single silicon interposer, a record achievement, improving the previous record by a factor of 2 (see Figure 5). Results have been presented in two conferences and in two journal papers (the *Electronic Components and Technology Conference 2017* (ECTC 2017) [LIC17a], the *European Conference on Optical Communication 2017* (ECOC 2017) [LIC17b], the *Journal of Lightwave technology* [LIC17c] and the *IEEE Transactions on Components, Packaging and Manufacturing Technology* [LIC17d]. Also several provisional patents have been submitted. The packaging concept devised in these projects has more recently been used in an EU project proposal (PASSION) which was awarded to the ECO group and will see further development of the ideas to support cointegration of VCSELs and silicon-photonics chips. Attempts to couple single-mode VCSELs into a multicore fiber were also carried out. Preliminary results were accepted for the *Conference on Lasers and Electro-Optics 2018* [TEN18].

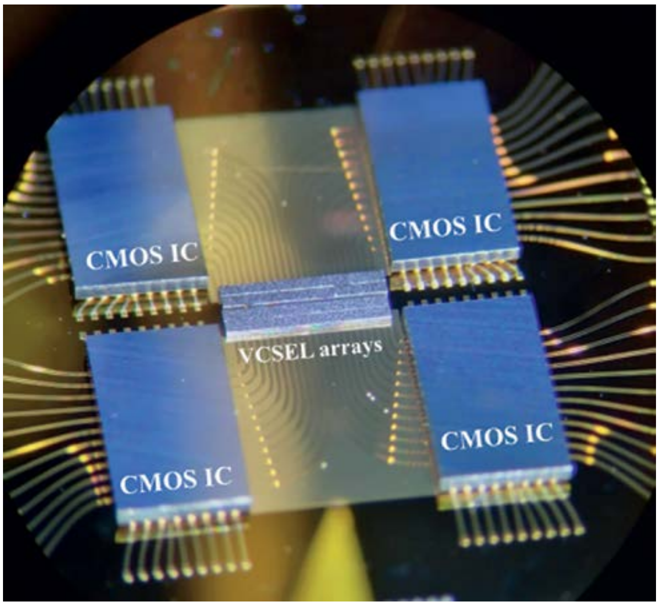


Figure 5
48 channels transmitter sub-module supporting up to 720 Gb/sec bandwidth in an area of ~1x1 cm.

Main objectives for 2018:

- The first demonstration of programmable optical circuit based on the Stäbler-Wronski effect in aSi:H.
- First demonstration of interworking between VCSEL packaging concept and a silicon-photonics chip.

Theme 1.3 Optical Switching

Project leader: Patty Stabile

We have previously investigated photonic integrated switches looking into issues related to energy-efficiency and transparent operation. However the lack of low-loss methods to assemble optical InP inputs/outputs (I/Os) in high connectivity optical switches is still severely impacting the chip performance: optical losses and optical signal-to-noise ratio degradation increase mostly due to the high coupling losses and per-fiber alignment tolerances in the order of sub-microns. When moving from a single to multiple fibers, other issues like fiber core eccentricity and fiber misalignment (0.5 µm best-in-class misalignment) add up to the already strict per-fiber alignment tolerances.

Therefore, we have proposed an innovative design concept for relaxed alignment tolerance and low-loss light coupling for InP-based I/O waveguides, based on the implementation of an on-chip integrated transition from low-to-high refractive index contrast waveguide, in combination with an on-chip embedded polymer I/O waveguide [COO17]. The device concept, based on adiabatic coupling of light from a standard InP waveguide into a wider cross-section polymer waveguide and on the presence of a bottom air-cladding, is firstly designed and then simulated. An insertion loss of the proposed 180 µm long RICT (refractive index contrast transition) device of less than 1.5 dB has been obtained, for a total InP-to-fiber power coupling loss of less than 1.9 dB for TE-polarized light. The broadband operation of the device is promising for wavelength division multiplexing circuit operation [CAL18a].

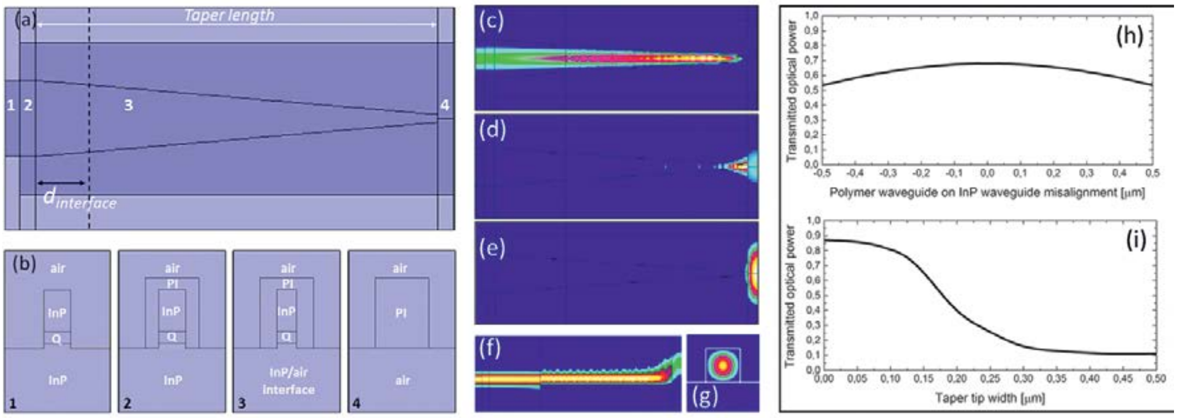


Figure 6

Top view of the taper design (a), including the four waveguide sections (b). The top views of the x-z intensity profile were taken at different depths: (c) 0.25 µm, (d) 1 µm, (e) 1.5 µm, to show how the light couples into the polymer waveguide. Beam propagation side view along the entire RICT device (f) and mode profile at the final polymer waveguide cross-section (g). Fabrication error tolerance for the case of misalignment of the polymer waveguide on top of the InP waveguide (h) and for the case of a taper tip width variation in the range of 0 to 500 nm (i). PI: polyimide, Q: quaternary InGaAsP layer.

The fabrication errors are studied for the foreseen fabrication process flow (Figure 6, h and i). A maximum loss of 1 dB is found for a worst case misalignment of ± 500 nm through photolithography between the polymer waveguide and the InP waveguide. This number is brought down to 0.25 dB worst case loss when using deep-UV lithography. A second source of fabrication error can be derived from the realization of the narrow taper tip. A last source of error comes from the low-to-high refractive index interface placement: as long as we etch the InP bottom cladding layer for a distance which is longer than 180 µm, we manage to keep losses under control [CAL18b]. Overall, the fabrication errors do not add up to notable additional losses as long as high-precision lithography is used. The obtained results open a route to cheap packaging of large port count InP-based photonic integrated chips.

Improved connectivity is crucial for mesh-interconnection in large-scale switching matrices. We are exploring monolithic multi-layer InP integration to enable three-dimensional connectivity for large-scale photonic integrated circuits, potentially offering a step change in optical circuit connectivity and removal of crosstalk at the top-bottom waveguide intersections. Vertical optical vias have been designed to couple two vertically separated guiding layers and move light up and down the layer stack. Methods to isolate the waveguide planes from each other are also proposed for reduced interlayer crosstalk. The dual layer, dual width waveguides also exhibit enhanced chromatic dispersion which can enable photonic circuits for ultrafast optical pulse processing (see Figure 7). Depending on which one of two super modes is excited in this device, the dispersion can be either normal or anomalous with values of -23200 ps/(nm km) or 8200 ps/(nm km), respectively [KJI17]. Mode converters with › 90% efficiency are designed to facilitate selective excitation of one or the other mode. The complete device is expected to be compatible with existing active/passive photonic integration technology in the InP/InGaAsP material system which should allow the creation of monolithic ultrafast optical pulse processing systems. With conventional tools and processes we have demonstrated the creation of the necessary waveguide geometry (see Figure 8).

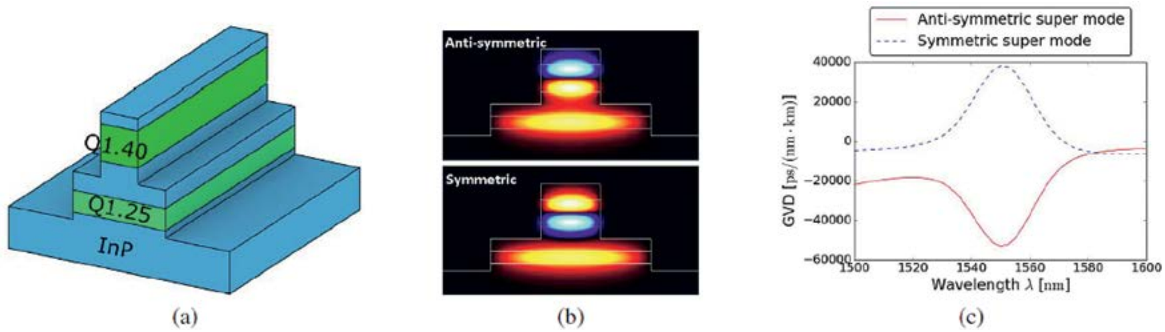


Figure 7
(a) A dual layer, dual width waveguide made from InP and two different InGaAsP composition has (b) supermodes which exhibit (c) resonant giant group velocity dispersion. The layer thicknesses in (a) are (from top to bottom) 650 nm, 1110 nm, and 500 nm.

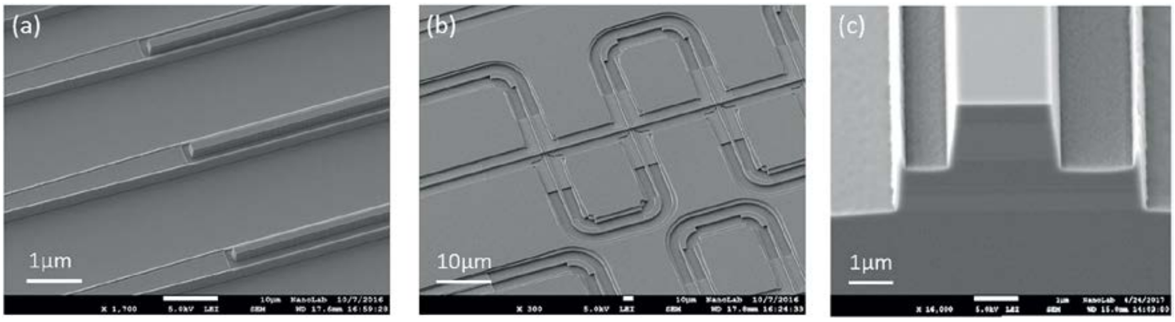


Figure 8
SEM images of the fabricated dual layer, dual width waveguides at the transition to a deep etched, single layer waveguides (a), of serpentines with dual layer crossings and (c) of the dual-layer waveguide cross-section from InP and two different InGaAsP composition.

Main objectives for 2018:

- Identification of the optimal III-V material for robust suspended waveguides and low-loss coupling.
- Wet-etch process development for robust suspended waveguide.
- Investigation of the combination of dual-layer monolithic integration and air-sacrificial layer for improved physical layer mesh-connected switch performance.

Theme 1.4 Integrated low loss space-division-multiplexed transceivers

Project leader: Chigo Okonkwo

Ultra-high capacity per wavelength long reach links
Following previous research in few-moded fiber transmission, we investigated how data capacity can be increased in multi-mode fibers through information theoretic approaches. We proposed a new modulation format exploiting the switching between the spatial channels as another dimension for encoding data; results are shown in Figure 9. Data rate increases of up to 30% exploiting 12 spatial polarization modes were experimentally validated, in cooperation with Prysmian Draka Netherlands and University of Central Florida USA [WEE17a].

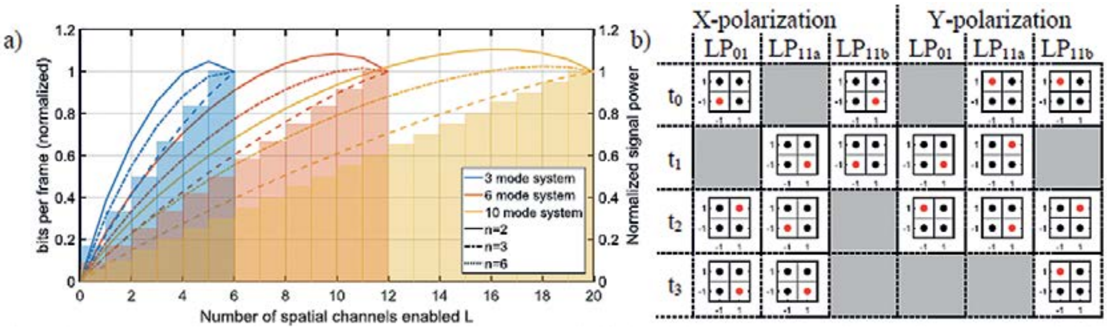


Figure 9
a) Average number of bits per frame using SPPM versus number of spatial channels; b) example of SPPM for 6 spatial channels deploying QPSK symbols.

Extending the capacity of long fiber links with spatially-separated data channels is predominantly limited by transmission effects such as differential mode group delay of the fibers and mode-dependent losses of the optical link components. In addition, viable multi-mode amplifiers with adequate mode-dependent gain are lacking. Working with Nokia Bell labs, OFS Fibers and University of Central Florida USA to carefully engineer the components, we demonstrated multiplexing of 12 spatial channels and 120 wavelengths in the C-band (around 1550 nm) resulting in 138 Tbit/s transmitted over 590 km of 6-moded fiber, with 50 kbits/s/Hz, which is the highest throughput × distance product for C-band transmission in a single-core few-mode fiber reported to date [WEE17b].

Ultra-high capacity per wavelength short-to-medium reach links
With the data-communication sector realizing that the extremely fast growing thirst for Internet bandwidth cannot be easily quenched, Google, Facebook and Amazon are looking for affordable new technology solutions. Hence within the Gravitation program in collaboration with Effect Photonics, we focus on developing Photonic ICs that support high-capacity: beyond 100 Gbit/s towards 400 Gbit/s per wavelength. In addition, power consumption should be kept low through use of low-complexity intensity-modulated formats (such as PAM4), and of direct detection receiver techniques facilitated by digital signal processing algorithms.

At the European Conference on Optical Communication 2017 (ECOC 2017), we reported on a negatively-chirped InP-Mach-Zehnder modulator (MZM, Figure 10) developed by Effect Photonics, modulated by a 1 V peak-to-peak PAM4 signal to enable 112Gbit/s/λ data transmission with reduced digital processing complexity. Operation in standard single mode fiber links longer than 3-km was successfully demonstrated [ALB17]. Also in 2017, we presented a chromatic dispersion and bandwidth pre-compensated 112-Gbit/s single side band signal transmitter over 93 km SSMF at 1550 nm using a dual-drive MZM. The proposed scheme is computationally efficient utilizing only 21 linear and 11 quadratic taps – this has implications on the circuit area required to layout the digital signal processing IC [HEI17].

For 400 Gbit/s/lambda transceivers, improved digital signal processing capabilities are required. Hence, developing improved channel estimators in DSP will in tandem enable enhanced pre-compensation/distortion digital filters to be developed. This work can feed back information on the bandwidth and response particular for electronics and photonic co-integrated components e.g. modulators and receivers.

Main objectives for 2018:

- Develop methods to enable low-loss coupling between InP waveguides and fiber modes are critical to the design and development integrated mode-multiplexers.

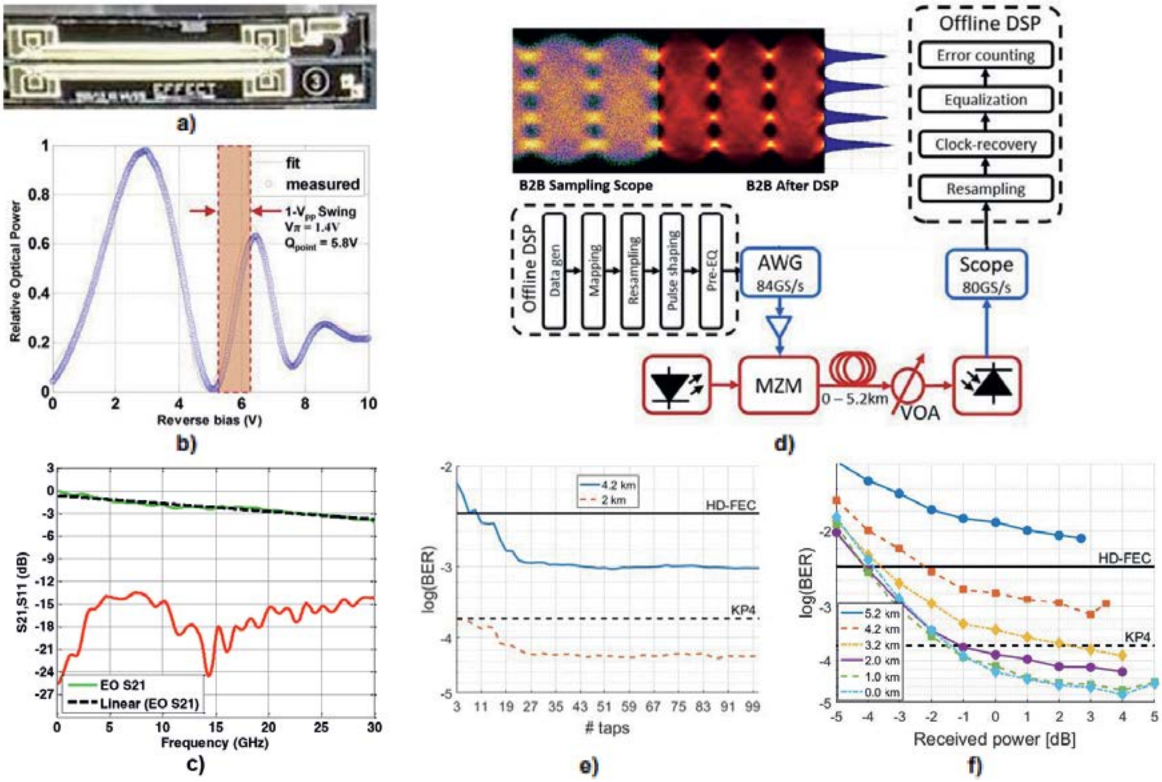


Figure 10

a) Chirped InP-MZM, b) Normalized optical transmission characteristic of the modulator as a function of reverse bias at 1550 nm, c) Measured on-chip EO response of the MZM (3dB bandwidth: 26 GHz), d) Experiment set-up (Pre-EQ: pre-compensation, AWG: Arbitrary Waveform Generator, MZM Mach-Zehnder Modulator, VOA: Variable Optical Attenuator, Scope: Oscilloscope), e) Tap-sweep for a feedforward filter equalizing the signal after 2 km and 4.2 km transmission, f) BER vs received optical power performance for different transmission lengths.

Theme 2 Photonic Integration

Theme coordinator: Meint Smit

Highlights:

- The realization of an optical amplifier building block on the IMOS platform, used for continuous wave lasers [POG17].
- A novel scheme for fast modulator based on band-filling effect [ENG18].

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

Project leader: Yuqing Jiao

We have developed a twin-guide semiconductor optical amplifier (SOA) structure where the active amplifier is integrated on top of a passive nanophotonic waveguide. Compared with silicon platforms our approach offers about 10 times reduction in the length of the transition taper between active and passive sections. It has a high potential to achieve compact lasers. The 3D sketch of this amplifier is given in Figure 11(a). We have successfully demonstrated continuous wave operation of lasers built with such amplifiers together with passive components [POG17]. A fabricated laser is shown in Figure 11(b).

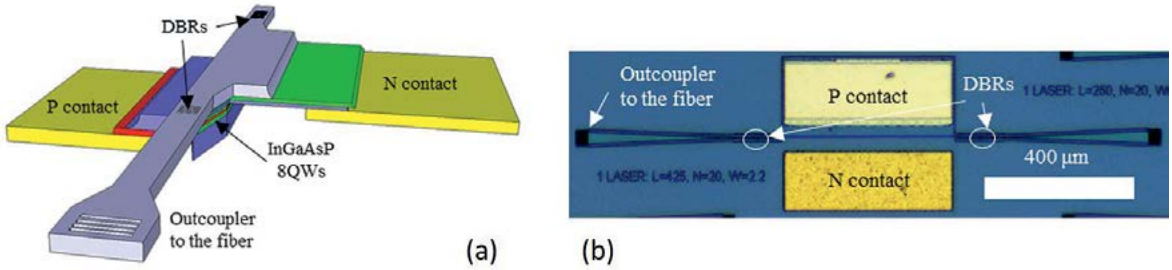


Figure 11
(a) 3D sketch of the twin-guide amplifier in the IMOS platform, integrated with passive waveguide components (8QW: 8 quantum wells; DBR: distributed Bragg reflector). (b) A fabricated laser with gain section made with the twin-guide structure and a laser cavity formed in the passive sections.

Based on the amplifier and demonstrated passive components, we have initiated open access of our IMOS platform for external designers (so-called Multi-Platform Wafer run, MPW). Currently two MPW runs have started, one with active-passive integration and one with only passive functionalities (now in design stage). Both have attracted significant interest and participation from PI's in the research groups PHI, ECO, FNA, as well as external collaborators such as Bell Labs and Hong Kong University.

We have performed a comprehensive study into the band-filling effect in n-doped InGaAs, and proposed a novel electro-absorption modulator (EAM) device with very wide optical bandwidth. The result is published in [ENG18].

In the meanwhile we moved forward with the development of an electro-optic (EO) polymer modulator based on slot waveguides. We established collaboration with Lightwave Logic (USA) on EO polymers. We are currently optimizing the process for the EO polymer provided by the company.

In 2017 we have purchased a new wafer bonding system from EV Group. The system is able to perform wafer-to-wafer bonding with high quality, especially regarding enhanced bonding uniformity, reproducibility and alignment accuracy (1-2 um). We are currently performing bonding tests with 3-inch InP and Si wafers to master the system and improve the bonding process.

We have begun to incorporate the ASML deep UV scanner tool into the fabrication of IMOS circuits. The advantage of the scanner is its high uniformity and high reproducibility. We are developing an optimized process for the scanner lithography on IMOS wafer-scale bonded membranes.

PHI and ECO are cooperating to investigate application of IMOS Photonic ICs for beam steering in optical wireless networks, and have achieved a single receiver device allowing both high efficient light collection and fast data transmission. The results are published in [CAO18] and [JIA18]. Furthermore, PHI and FNA are cooperating on magneto-optic effects in IMOS-waveguides. The first results have been submitted to (and accepted by) two conferences ([HEE17], [KOO18]).

Main objectives for 2018:

- Further miniaturization of amplifiers in the IMOS platform, through butt-joint integration technology;
- Optimized process for IMOS critical lithography steps using an ASML deep-UV scanner;
- MPW runs with lasers and fast detectors integrated.

Theme 2.2 Ultralow-power components

Project leader: Andrea Fiore

Nanolasers

Based on the experimental results of waveguide coupled plasmonic light sources, which yielded good nanoLEDs (published in Nature Communications), but no working nanolasers yet, in combination with theoretical calculations which indicate that Photonic Crystal (PhC) nanobeam lasers promise wall-plug efficiencies a few times higher than plasmonic lasers we decided to focus our research on PhC nanolasers. We have designed PhC lasers consisting of a short SOA section (5 mm) between two PhC nanobeam mirrors with a length of a few mm, with predicted wall plug efficiencies up to 25% at power levels of a few 100 mW, which is very promising for short distance interconnect. We have performed two full fabrication runs, which did not yet show laser operation, however, because the series resistance and the surface recombination of the devices was too high. The novel platform that is developed in theme 2.1 should solve both problems and supports the combination of efficient SOAs with photonic crystals. A next experiment is planned in that platform, which is expected to become operational in 2018.

Nano-opto-electro-mechanical systems (NOEMS)

Substantial progress on the integration of nano-opto-electro-mechanical systems (NOEMS) within the IMOS platform has been realized [MID18, ZOB17]. A suspended InP membrane, defined on top of a InP/SiO_2 waveguide, can be electrically actuated, which produces a change in the effective index of the guided mode and can be used to switch a signal between two different output waveguides [LIU16]. After solving a number of fabrication issues, fully-suspended tunable structures have been realized (Figure 12) .

A novel type of optomechanical sensor, a double-membrane photonic crystal cavity on a fiber tip, has been realized and tested [HAK17]. It consists of a photonic crystal structure, optimized for coupling with the mode of the fiber, patterned on a suspended double-membrane structure, so that the resonant wavelength depends on the displacement. The membrane displacement produced by acoustic waves was measured from the reflectivity, with an estimated sensitivity of 100 fm/$Hz^{1/2}$. This opens the way to fiber-optic sensors of force, mass or electric field, ideally suited for long-distance sensing or environments with high electromagnetic interference.

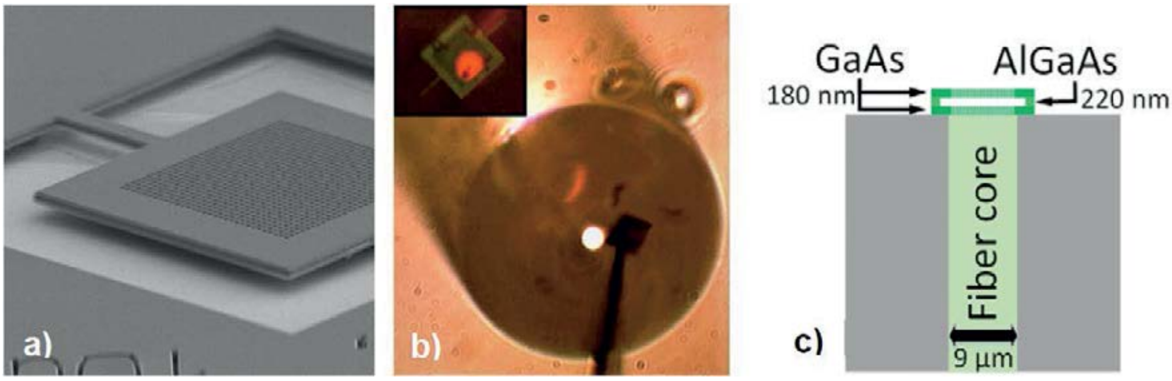


Figure 12
(a) SEM image of the double-membrane sensor on chip. b) Fiber tip & nanomanipulator during pick & place procedure. Inset: Top view of device placed on fiber core with red laser applied via the fiber (note some misalignment). d) Schematic side view of DM on fiber core (not to scale).

2D monolayer semiconductors

This new research line has started in 2017 with the hiring of a tenure-track Assistant Professor, dr. Alberto Curto. The overall goal is to develop monolayer semiconductors of the transition metal dichalcogenide family (materials with a chemical composition of MX_2, with M a transition metal and X a chalcogen atom such a S, Se or Te) as sources and detectors for nanophotonics. Two aspects are under development. First, we have addressed to need the identify efficient and stable 2D materials operating at telecom wavelengths. Instead of unstable black phosphorus (the only 2D semiconductor available in this range so far), we focus on novel materials with bright near-infrared emission.

Second, we aim at gaining access to novel degrees of freedom of the electron (the spin, the valley index, and the layer number) as a resource for the design of nanophotonic components with advanced functionality. In 2017, our preliminary results have shown that it is possible to control valley-polarized light emission using nanophotonics (Figure 13).

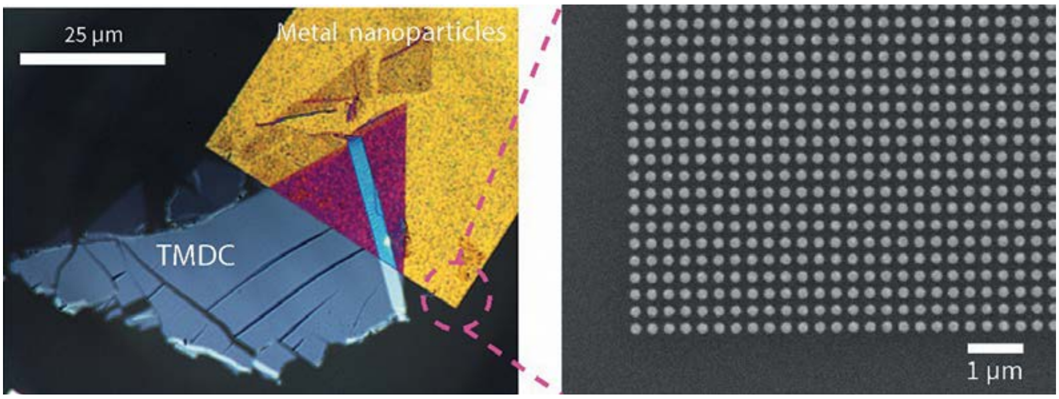


Figure 13
Control of valley-polarized light emission. Left) Optical microscopy reflection image of a transition metal dichalcogenide flake on top of a metal nanoparticle array. Right) SEM image close-up of the metal nanoparticle array.

Main objectives for 2018:

- The experimental demonstration of a nano-opto-electro-mechanical systems (NOEMS) spectrometer;
- Investigation of IMOS-integrated NOEMS as switches and sensors. Experiments and optimization of the contact resistance.
- Observation of highly polarized valley emission with a nanophotonic structure.
- Design and testing of nanolasers in the improved IMOS platform.

Theme 3 Ultimate Control of Matter and Photons

Theme coordinator: Paul Koenraad

Highlights:

- Direct measurement of spontaneous emission rate quenching in coupled-cavity systems [PEL18].
- All-optical switching of magnetization by single femtosecond laser pulses demonstrated in an ultrathin film with potential for integrated photonic memories [LAL17].

Theme 3.1 Quantum effects in nanophotonic devices

Project leader: Andrea Fiore

We have obtained a strong experimental proof of the effect of vacuum field switching in systems of three coupled cavities. The photoluminescence dynamics as a function of the detuning between lateral and central cavities (see Figure 14) provides a direct measurement of the spontaneous emission rate and thereby of the exciton-photon rate g as a function of detuning. A fit with our model reproduces the data very consistently, and further confirms the switching off of the radiative emission at resonance. We have further set up a model for a nano-cavity laser, and observed that a fast modulation of the modal gain via the vacuum field produces ultrafast (~ps) pulses, and a dynamics similar to Q-switching in macroscopic lasers. This may be used to produce short and relatively intense pulses from a micro- or nano-cavity laser. In first experimental tests we have observed lasing in single- and three-cavity systems, and are now proceeding to fast modulation experiments.

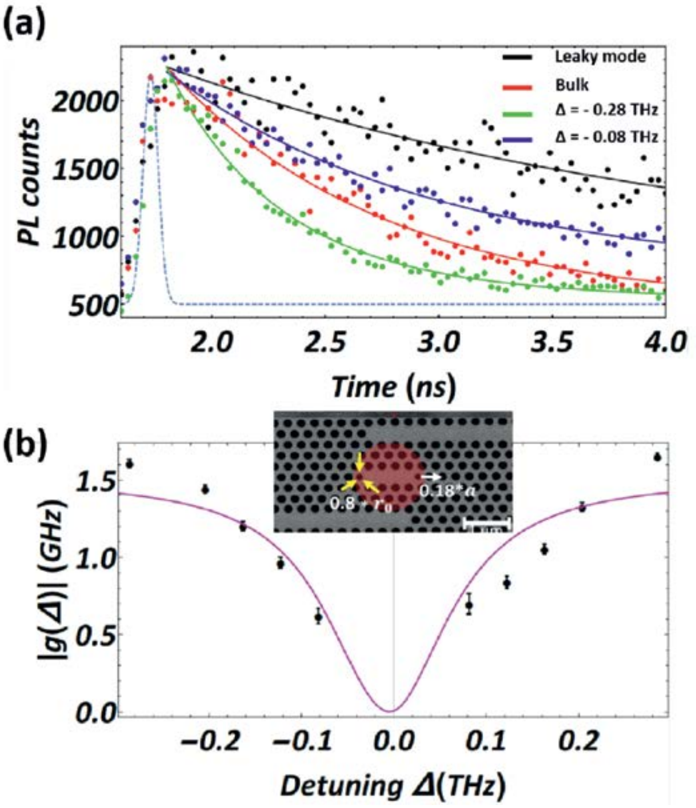


Figure 14
(a) Measured dynamics of the emission from QDs in the central cavity of a three-coupled-cavity system for different detunings Δ; (b) Extracted dependence of the exciton-photon coupling rate vs detuning. Inset: SEM image of the three-cavity system.

Main objectives for 2018:

- Ultrafast switching of lasing via the vacuum field

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. 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.

An important proof of principle relevant for the development of spintronic-photonic memories was established in 2017: all-optical switching of the magnetization by a single laser pulse in a magnetic thin film system that also displays efficient current-driven motion of the magnetic information. Figure 15(a) shows deterministic switching by single 100 fs laser pulses at 700 nm for a Ta(4)/Pt(4)/Co(1)/Gd(3)/Pt(2) film, where numbers between brackets indicate layer thickness in nanometers [LAL17]. A toggle-wise heat-driven switching process is resolved, in which each next pulse reverses the magnetic orientation. For the thinnest Co thickness measured (0.8 nm), an efficiency of 50 fJ per switch when normalized to a 50 x 50 nm^2 area was established. The switching turns out to be highly robust. Figure 15(b) displays repetitive reversal, detected electrically by the anomalous Hall effect in a so-called Hall bar geometry, in which it was found that no deterioration at all was observed within a sequence of 5000 switching events. Furthermore, we quantitatively determined key parameters governing fast current-induced motion of magnetic information in the very same system. Clearly, these results are highly promising for photonic memories.

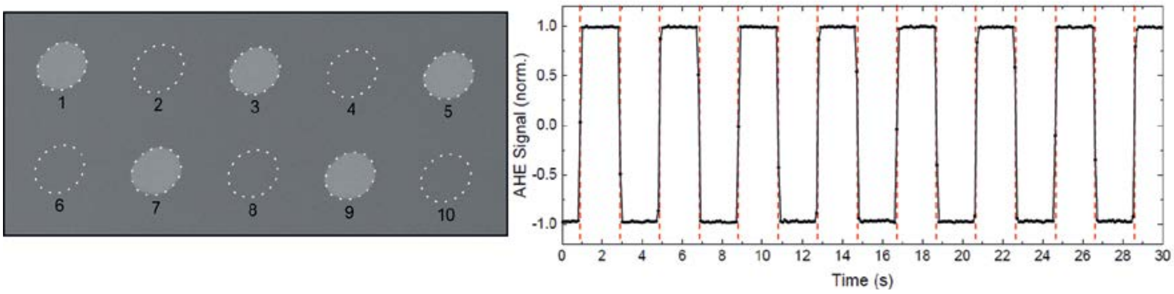


Figure 15
(a) All-optical switching experiment on a Pt/Co(1)/Gd stack, using 100 fs laser pulses. The numbers indicate the number of pulses the region has been exposed to. Black and white represent magnetization down and up, resp. (b) Switching by laser pulses arriving every 2 seconds, electrically measured using the anomalous Hall effect (AHE), where +1 and -1 represent up and down, resp.

The collaboration between the FNA and PHI groups resulted in steps forward in fabricating photonic waveguides with magnetic claddings and exploring the process of magneto-optical reading. Batches of test samples with composition Pt(2)/Co(1)/Pt(2) with PMA were deposited by DC magnetron sputtering on planar InP substrates as well as on InP waveguides (based on the IMOS platform). Standard magnetometry was used to verify proper PMA behavior. Transmission studies resolved an attenuation of 2.4 dB/µm at a wavelength of 1550 nm, in good agreement with 2.0 dB/µm as estimated from 2D Film Mode Matching (FMM) simulations.

Finally, another collaborative effort of FNA and PHI numerically explored possible designs for switchable polarization converters. We introduced a design with periodically poled sections with magnetization up and down, which can be achieved experimentally by using focused ion-beam irradiation to lower the magnetic anisotropy periodically. Thereby, by magnetic fields one can switch between a uniform magnetic state (off-state), and a periodically poled state (on-state).

An enhancement of the TE-TM conversion by a factor 5 was found in the on-state as compared to the off-state for a device with 15 sections, providing a simple proof of concept for the reconfigurability [HEE17]. 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 perpendicular to the thin film plane.

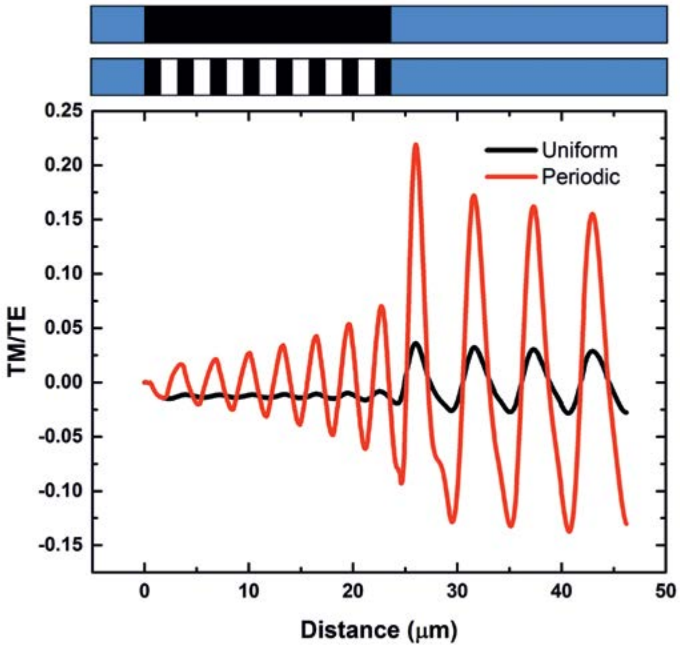


Figure 16
Numerical simulation of a InP-based switchable polarization converter with a PMA cladding. The TM/TE field ratio is plotted as a function of distance along the propagation direction for a uniformly magnetized ("off state") and a periodically modulated ("on state") magnetic strip as indicated above the graph. The blue region indicates the bare waveguide, and the black and white regions indicate the strip with up and down magnetization respectively.

Main objectives for 2018:

- Establishing all-optical writing of magnetic bit patterns in PMA (Pt/Co/Gd) conduits and successive current-induced motion of the same pattern coherently.
- Quantitative measurements of magneto-optical mode conversion in waveguides with PMA ferromagnetic claddings, and optimization of magnetic stack compositions for improved read out.

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. The latter is mainly aimed at the development of challenging ALD processes, e.g., with respect to materials systems themselves or with respect to tight specifications of the process conditions which can be tolerated by the applications. In the previous period we have developed ALD processes for:

- Co nanolayers which can for example be used in nanomagnetic devices consisting of Co/Pt stacks (researched by FNA) or as metallization in interconnect technology. ALD of Co is particularly challenging but through the use of NH_3 plasma and N_2/H_2 plasma as co-reactant, high-purity, low-resistivity Co nanolayers have been obtained.
- Ru nanolayers which have applications in interconnect technology in photonic and electronic circuits. The application of ALD Ru in through-BCB vias as seed layer for Au electroplating is being investigated through collaboration of PMP and PHI. A highlight of this work is that an area-selective ALD process has been developed.
- AlF_3 nanolayers which have many applications as optical coating in photonic devices due to their high transparency and low refractive index. A novel plasma-based ALD process has been developed which is HF-free and which allows for the preparation of the AlF_3 at low deposition temperatures. This work has been published [VOS17].

Furthermore, nanolayers of Al_2O_3 prepared by ALD have been employed as anti-stiction coating for mechanically tunable photonic crystal devices (collaboration between the PMP and PSN groups, see Figure 17). This successfully prevents stiction failures in these devices which were a real showstopper [PET18].

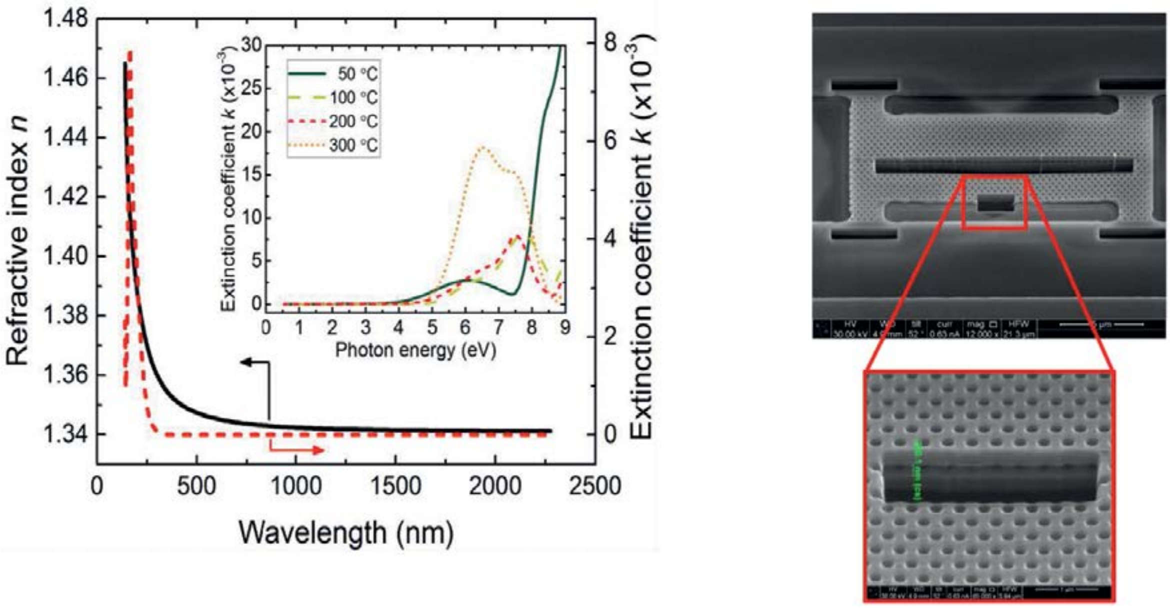


Figure 17
Optical properties of AlF_3 nanolayers prepared by a novel ALD process. A mechanically tunable photonic crystal device in which ALD Al_2O_3 nanolayers have been employed as anti-stiction coatings.

A second goal within this theme is the exploration of nanolayers for the functionalization and passivation of nanopillar- and nanowire-based devices. In this respect, a major breakthrough has been realized in the project in the past period through the development of PO_x/Al_2O_3 nanolayer stacks for the passivation of InP nanowire devices. This work has been a collaborative effort of the PMP and the AND group and it has been published in NanoLetters [BLA17].

A novel approach was developed in which a phosphorus-rich interfacial oxide (PO_x) was prepared and encapsulated by an ALD Al_2O_3 nanolayer. 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 prevents deterioration of the PO_x which is hygroscopic and therefore unstable in atmosphere. Through a photoluminescence study on state-of-the art wurtzite InP nanowires it was shown that an unprecedented level of performance (in terms of internal quantum efficiency) can be obtained for undoped InP nanowires by these passivating PO_x/Al_2O_3 nanolayers (Figure 18). Furthermore, it was shown that the passivation scheme displays excellent long-term stability

(› 7 months) and can substantially improve the thermal stability of InP surfaces (› 300 °C), significantly expanding the temperature window for device processing.

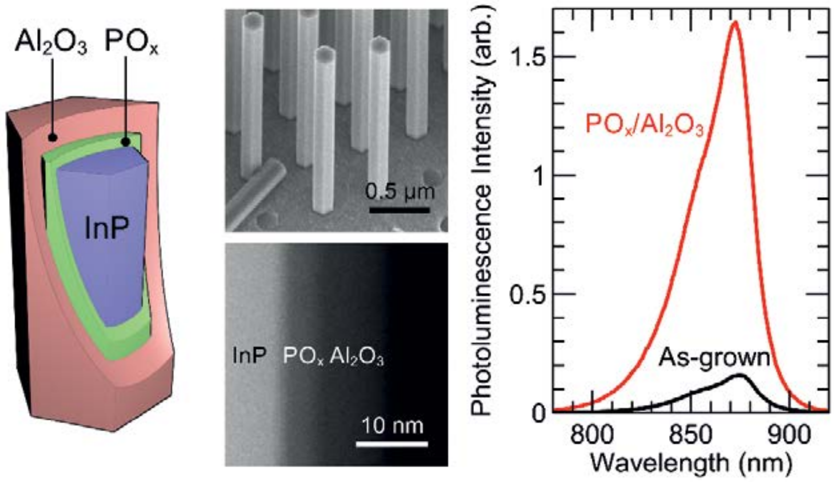


Figure 18
Wurtzite InP nanowires passivated by stacks of low-temperature deposited stacks of PO$_x$ and Al$_2$O$_3$. Through photoluminescence studies an unprecedented level of surface passivation for undoped InP nanowires has been demonstrated.

Main objectives for 2018:

- Experimentally establish applicability of ALD nanolayers to passivate nanopillar- and nanowire-surfaces, in particular hexagonal SiGe surfaces.

Theme 3.4 Semiconductor Nanowires

Project leader: Erik Bakkers

Growth of nanowires

Wurtzite GaP core wires with a diameter of 200 nm have been grown using a Au-catalyst as an epitaxial template for the growth of hexagonal SiGe shells (Figure 19). We have shown that we can grow single crystalline uniform layers of hexagonal SiGe layers up to 80% Ge at a temperature of 600 °C with a thickness of › 50 nm. The stacking fault density in the GaP and therefore also in the SiGe shell is less than ‹ 1 µm^{-1}. These wires have been studied with XRD by JKU. There are however some remaining challenges, which have to be addressed:

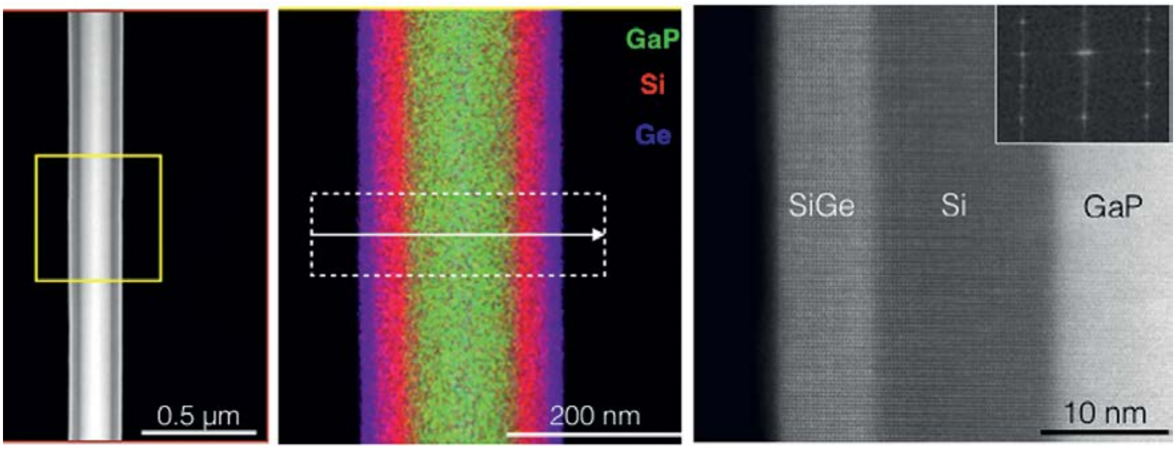


Figure 19
Overview TEM image of a hexagonal GaP/Si/SiGe core/shell/shell wire show the uniformity and defect-free nature of the wire. Elemental map of the wire showing the composition of the structure. High-resolution TEM image of the wire demonstrating the hexagonal crystal structure. We note that a thin wire with a thin shell has been used for imaging, since it is very difficult (impossible) to obtain high resolution images from thicker samples.

- Impurities from the substrate (Ga and P) may affect the optical properties of the hexagonal SiGe. Atom Probe Tomography (APT) has been used to study the presence of these impurities.
- The Ge-rich shells are heavily strained due to the ~4% lattice mismatch with the GaP core. Strain and strain-induced defects will deteriorate the optical properties of the SiGe shells. We therefore investigate the possibility to use Wurtzite GaAs as a lattice-matched core to for Ge.

These issues have been addressed during 2017 and will be discussed below.

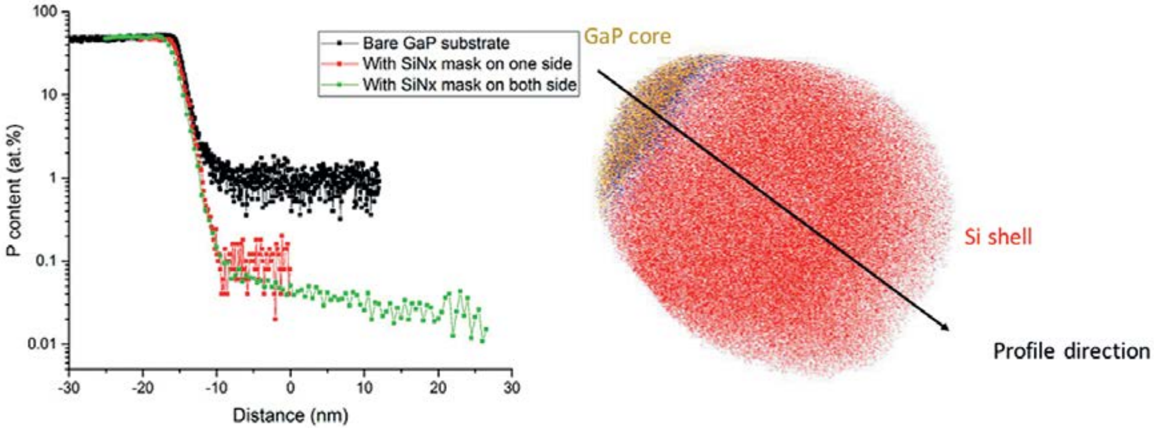


Figure 20
Atom Probe Tomography (APT) line scan of a hexagonal GaP/Si core/shell nanowire. Au and Ga are below the detection limit (1 ppm) of the APT. The P concentration in the Si shell is the highest (1%) when an uncapped GaP substrate is used and the is concentration decrease with the level of capping the GaP substrate.

Impurities from the substrate (Ga and P)
Possible sources of P and Ga are 1) diffusion from the GaP cores at the high temperatures (900 °C) used during growth of the Si shells, 2) evaporation from the GaP substrate, 3) background pressure in the MOVPE chamber.

APT has been used to chemically analyze the samples. In Figure 20 an APT line-scan is shown from this analysis we find a concentration of 1% P in the Si shell, and Ga is below the detection limit of the APT. In order to reduce this concentration, we have capped the GaP substrate with a SiN_x capping layer. This reduces the P concentration by a factor of 10 when the SiN is only on the top side and by a factor of 100 when both sides of the substrate are covered. This shows that P evaporates from the substrate during the growth of the SiGe shell. In order to further reduce the P concentration in the Si shells, we have investigated alternative precursors (tetrasilane, Si_4H_{10} and disilane, Si_2H_6) which enable growth at lower temperatures. The cracking efficiency is about an order of magnitude higher for tetrasilane compared to disilane in the temperature range between 500 and 700 °C.

We believe we can reach 1-2 ppm impurity levels for the hexagonal core/shell and branch wires by combining all the steps presented above (substrate capping, low growth temperature, and reactor flushing).

Ge-rich shell strains
Ge-rich alloys with a Wurtzite crystal structure are interesting since these are expected to show the direct band gap needed for application in photonics. Ge grown on GaAs is subject to large strains, because Ge has a lattice mismatch of about 4% with GaP. Therefore, we have decided to explore another core material. GaAs has a very small mismatch with Ge and has also been reported in the Wurtzite crystal structure. We have developed the growth of Wurtzite GaAs wires using a SiN mask to cap the substrate and avoid outgassing of As. The SEM image in Figure 21 shows an array of GaAs wires with a length of a few micrometer and a diameter of 150 nm. We can tune the GaAs wire

diameter by the size of the hole opening in the SiN mask and the deposited Au thickness. Smallest possible diameters are around 30 nm. A small diameter will be relevant for minimizing the strain in the shell.

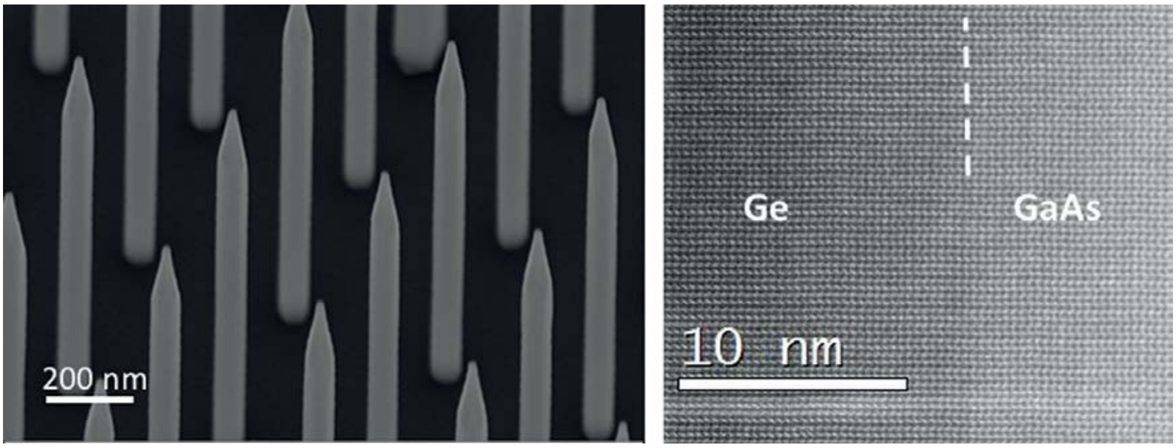


Figure 21
SEM image of WZ GaAs wires. E-beam lithography has been used to define the position of the Au catalysts in a SiN capping layer on a GaAs(111)B substrate. High-resolution STEM image of the interface between the WZ GaAs core and the hexagonal Ge shell. From this image the epitaxial relation is clearly visible.

Photoluminescence of hexagonal SiGe

Photoluminescence measurements are carried out using low magnification Fourier transform infrared spectroscopy (FTIR) with all-mirror optics under a nitrogen purged environment to get the highest sensitivity and avoid aberrations and absorption from moisture in the air. In combination with a lock-in technique this also allows to cancel out thermal background radiation required to measure in the infrared.

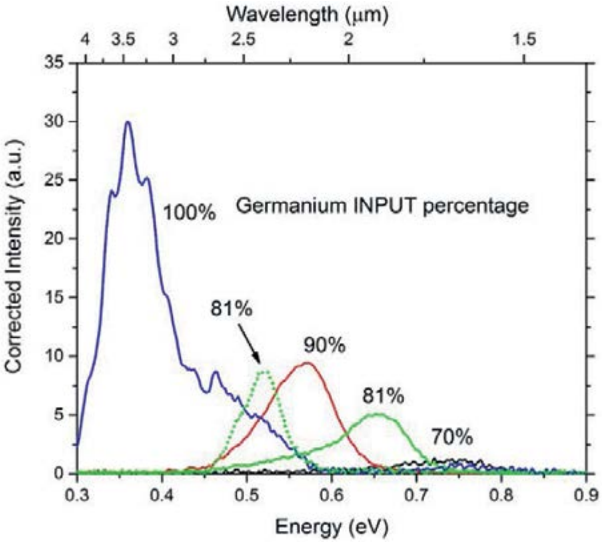


Figure 22
Photoluminescence spectra of core-shell $GaP\text{-}Si_{1-x}Ge_x$ nanowires taken at a temperature of 4K and excited of about 1.0 kW/cm^2 with different compositions. We show the input percentage of germanium atoms into the reactor for growing the wires.

Initial measurements were performed on samples with varying germanium concentrations (see Figure 22). Typically the spectra exist of a broad emission peak that do not allow for accurate deconvolution. This broad emission is probably due to a combination of alloy broadening, germanium content fluctuations and defects induced by the lattice mismatch between GaP and a germanium rich silicon-germanium alloy. However, these first results show the trend that for increasing germanium content the emission shifts to the red and that the total intensity increases.

This indicates that the emission wavelength can be tuned by controlling the germanium content in the material.

Main objectives for 2018:

- We aim to grow Wurtzite GaAsP, which can be lattice matched to SiGe shells. Since the growth conditions of Wurtzite GaP and Wurtzite GaAs wires are comparable, we expect that we can grow high quality cores. Aim is to grow strain free SiGe shells with Ge concentrations › 60%. The strain level will be determined together with JKU.
- We aim to substantiate the direct band gap character of hexagonal SiGe by photoluminescence and absorption measurements. In addition, we want to demonstrate optical gain in hexagonal SiGe.

Publications and joint research

The table below lists the main publication of the IPI groups, which report work done in the Gravitation project, or work done in close collaboration with other projects. In 2017 they published 108 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
ALB17	Aaron Albores-Mejía, Sjoerd van der Heide , Muhammad Usman Sadiq, Saeed Tahvili, Chigo Okonkwo and Boudewijn Docter “112-Gbit/s/λ PAM4 Transmission enabled by a Negatively-Chirped InP-MZ Modulator” in 43rd European Conference on Optical Communication (ECOC), 2017, paper Th.1.C.4.	ECO
BLA17	L. E. Black, 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* Al_2O_3 *with* PO_x *Interlayer*. NanoLetters 2017, 17, 6287-6294.	PMP
CAL18a	N. Calabretta, Isis A. Cooman, R. Stabile, “Low-to-high refractive index contrast transition (RICT) device for low loss polymer based optical coupling”, IOP Journal of Optics, 20, 044001 (2018).	ECO
CAL18b	N. Calabretta, Isis A. Cooman, R. Stabile, “Low-to High Refractive Index Contrast InP Transition for Light Coupling into a Wider Cross-Section Polymer Waveguide”, ECIO 2018.	ECO
CAO17	Z. Cao, et al., “200 Gbps OOK transmission over an indoor optical wireless link enabled by an integrated cascaded aperture optical receiver,” in Proc. OFC2017, Los Angeles, Mar. 2017, post-deadline paper PDP Th5A.6.	ECO, PHI
CAO18	Z. Cao, Y. Jiao, L. Shen, X. Zhao, R. Stabile, J.J.G.M. van der Tol, and A.M.J. Koonen, “Ultra-high Throughput Indoor Infrared Wireless Communication System Enabled by a Cascaded Aperture Optical Receiver Fabricated on InP Membrane [Invited],” Journal of Lightwave Technology, vol. 36, no. 1, pp. 57-67, 2018.	PHI ECO
COO17	Isis A. Cooman, N. Calabretta, R. Stabile, “Air bottom-cladding for low loss polymer based InP waveguide optical coupling”, in IEEE Photonics Benelux Annual Symposium, 2017.	ECO
ENG18	J. P. van Engelen, L. Shen, G. Roelkens, Y. Jiao, M. K. Smit and J. J. G. M. Van der Tol, “A Novel Broadband Electro-Absorption Modulator based on Bandfilling in n-InGaAs: Design and Simulations,” IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, no. 1, pp. 3300108, 2018.	PHI
GOM17	F. Gomez-Agis, S. P. van der Heide, C. M. Okonkwo, E. Tangdiongga and A. M. J. Koonen, “112 Gbit/s transmission in a 2D beam steering AWG-based optical wireless communication system”, in Proc. ECOC2017, Göteborg, Sweden, Sept. 17-21, 2017, Paper Th.2.B.1.	ECO

HAK17	Hakkel K., Z. Zobenica, F. Galeotti, F. Pagliano, R.W. van der Heijden and A. Fiore, *"A nanomechanical photonic crystal displacement sensor on a fiber tip"*, IEEE Benelux workshop (2017)	PSN
HEE17	Hees Y.L.W. van, Tol J.J.G.M. van der, Koopmans B. and Lavrijsen R., *"FDTD simulation of enhanced mode conversion in an InP waveguide with a periodically modulated ferromagnetic cladding with PMA"*, Proc. 22nd Annual Symposium of the IEEE Photonics Society Benelux Chapter, p. 196, 2017.	FNA PHI
HEI17	Sjoerd van der Heide, Aaron Albores-Mejia, Fausto Gomez-Agis, Boudewijn Docter and Chigo Okonkwo "112-Gbit/s Single side-band PAM-4 transmission over inter-DCI distances without DCF enabled by low-complexity DSP " in 43rd European Conference on Optical Communication (ECOC), 2017, paper P2.SC5.8	ECO
JIA18	Y. Jiao, Z. Cao, L. Shen, J. van der Tol and T. Koonen, "Membrane-based receiver/transmitter for reconfigurable optical wireless beam-steering systems," IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, no. 1, pp. 6100506, 2018.	PHI ECO
KHA17	A.M. Khalid, P. Baltus, R. van Dommele, K.A. Mekonnen, Z. Cao, C.W. Oh, M. Matters, A.M.J. Koonen, "Bi-directional 35-Gbit/s 2D beam steered optical wireless downlink and 5-Gbit/s localized 60-GHz communication uplink for hybrid indoor wireless systems, " in Proc. OFC2017, Los Angeles, Mar. 2017, paper Th1E.6.	ECO MSM
KJI**17**	Kjellman, J.Ø., Stabile, R. & Williams, K.A., "Broadband giant group velocity dispersion in asymmetric InP dual layer, dual width waveguides", Journal of Lightwave Technology, 35 (17), 3791-3800, 2017.	PHI
KOO17a	Ton Koonen, Fausto Gomez Agis, Frans Huijskens, Ketemaw Mekonnen, Zizheng Cao, Eduward Tangdiongga, "High-Capacity Optical Wireless Communication using 2-Dimensional IR Beam Steering," submitted to J. Lightw. Technol., Feb. 2018	ECO
KOO17b	A.M.J. Koonen, "Indoor optical wireless systems: technology, trends, and applications, " J. Lightw. Technol., Dec. 2017, DOI 10.1109/JLT.2017.2787614	ECO
KOO18	B. Koopmans, 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," Accepted for European Confernece on Integrated Optics (ECIO 2018), Valencia, Spain, 30/5 to 1/6 2018.	PHI FNA PMP
LAL17	Lalieu M.L.M., Peeters M.J.G., Haenen S.R.R., Lavrijsen R. and Koopmans B., *"Deterministic all-optical switching of synthetic ferrimagnets using single femtosecond laser pulses"*, Phys. Rev. B 96, 220411(R) (2017).	FNA
LIC17a	Li, C., Smalbrugge, E., Li, T., Stabile, R. & Raz, O., "3D packaging of embeded opto-electronic die and CMOS IC based on wet etched silicon interposer", ECTC 2017	ECO
LIC17b	Li, C., Li, T., Stabile, R. & Raz, O., "A platform for 2-dimensional 48-channel optical Interconnects based on wet etched silicon interposer", ECOC 2017	ECO
LIC17c	Li, C., Li, T., Guelbenzu de Villota, G., Smalbrugge, B., Stabile, P. & Raz, O. , " Chip scale 12-channel 10 Gb/s optical transmitter and receiver sub-assemblies based on wet etched silicon interposer", IEEE Journal of Lightwave Technology. 35, 15, p. 3229-3236 2017	ECO

LIC17d	Li, C., Stabile, R., Li, T., Smalbrugge, E., Guelbenzu de Villota, G. & Raz, O. ," Wet Etched 3-Level Silicon Interposer for 3 Dimensional Embedding and Connecting of Opto-electronic Dies and CMOS ICs ",24 Nov 2017 (Accepted/In press) IEEE Transactions on Components, Packaging and Manufacturing Technology.	ECO
LIN17	R. van der Linden, N.C. Tran, E. Tangdiongga, and A.M.J. Koonen, "Improvement on Received Optical Power Based Flexible Modulation in a PON by the Use of Non-Uniform PAM", in 43rd European Conference on Optical Communication (ECOC), 2017, paper W2B3.	ECO
LIN18	R. van der Linden, N.C. Tran, E. Tangdiongga, and A.M.J. Koonen, "Optimization of Flexible Non-Uniform Multi-Level PAM for Maximizing the Aggregated Capacity in PON Deployments", OSA/IEEE Journal of Lightwave Technology, Accepted, 2018, DOI:10.1109/JLT.2018.2809966	ECO
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MAH17	Mahir Asif Mohammed, Jimmy Melskens, Ripalta Stabile, Wilhelmus M.M. Kessels, and Oded Raz, "Metastable above bandgap absorption properties of hydrogenated amorphous silicon through spectroscopic ellipsometry", ICANS 2017	ECO
MAH18	Mahir A. Mohammed, Jimmy Melskens, Ripalta Stabile, Wilhelmus M. M. Kessels, and Oded Raz, "Light-Induced Reversible Optical Properties of Hydrogenated Amorphous Silicon: A Promising Optically Programmable Photonic Material", Wiley press, PSS-a, in press 2018	ECO
MEK17a	K.A. Mekonnen, Z. Cao, N. Calabretta, E. Tangdiongga, and A.M.J. Koonen, "50 Gb/s Indoor Optical Wireless Communication Equipped with Millimeter-wave Backup System and Localization and Tracking", in 43rd European Conference on Optical Communication (ECOC), 2017, paper Th2B2.	ECO
MEK17b	K.A. Mekonnen, N. Calabretta, E. Tangdiongga, and A.M. J. Koonen, "High-capacity dynamic indoor network utilizing optical wireless and 60-GHz radio techniques", in International Topical Meeting on Microwave Photonics (MWP), 2017, paper We2.3.	ECO
MEK18a	K.A. Mekonnen, Z. Cao, E. Tangdiongga, and A.M.J. Koonen, "Towards Dynamic Ultrahigh Capacity Symmetric Bidirectional Indoor Optical-Wireless Communication", in Optical Fiber Communications Conference and Exhibition (OFC), 2018, paper M1F6.	ECO
MEK18b	K.A. Mekonnen, J.H.C. van Zantvoort, N. Calabretta, N.M. Tessema, E. Tangdiongga, and A.M.J. Koonen, "High-Capacity Dynamic Indoor Network Employing Optical-Wireless and 60-GHz Radio Techniques", OSA/IEEE Journal of Lightwave Technology, vol. 36, no. 10, p. 1851-1861, May 2018.	ECO
MID18	L. Midolo, A. Schliesser and A. Fiore, *"Nano-opto-electro-mechanical systems",* Nature Nanotechnology, 13, 11 (2018)	PSN
PEL18	Pellegrino, D., F. Pagliano, A. Genco, M. Petruzzella, F.W. van Otten and A. Fiore, *"Deterministic control of radiative processes via mode field tuning",* submitted	PSN
PET18	M. Petruzzella, Ž. Zobenica, M. Cotrufo, V. Zardetto, A. Mameli, F. Pagliano, S. Koelling, F.W.M. van Otten, F. Roozenboom, W.M.M. Kessels, R.W. van der Heijden, and A. Fiore. *Anti-stiction coating for mechanically tunable photonic crystal devices.* Optics Express Vol 26, No 4, 2018, pp 3882-3891.	PMP
POG17	V. Pogoretskiy, J. J. G. M. van der Tol, A. Higuera-Rodriguez, M. K. Smit and Y. Jiao, "Integrated Photonic Crystal DBR Laser in an InP Membrane Platform", in the 39th Progress in Electromagnetic Research Symposium (PIERS 2017), 19-22 November 2017, Singapore.	PHI

STA17	R. Stabile, “Towards large scale fast reprogrammable SOA-based photonic integrated switch circuits”, MDPI Applied Sciences, 7(9), 920 (2017).	ECO
TEN18	Teng Li, Sander Dorrestein, Wouter Soenen, Chenhui Li, Ripalta Stabile , Xin Yin, Oded Raz, “Low Cost 100 Gbps Multicore VCSEL Based Transmitter Module Platform”, accepted for oral presentation CLEO 2018	ECO
TES17	N.M. Tessema, A.M. Trinidad, K.A. Mekonnen, J.H.C. van Zantvoort, F.M. Huijskens, Z. Cao, E. Tangdiongga, A.B. Smolders, and A.M.J. Koonen, “A photonics-assisted beamformer for K-band RF antenna arrays,” in International Topical Meeting on Microwave Photonics (MWP), 2017, paper Th1.2.	ECO
TRI17	A. M. Trinidad, N.M. Tessema, Z. Cao, E. Tangdiongga, and A.M.J. Koonen, “Ring resonator-based true time delay for indoor wireless communication,” in IEEE Photonics Benelux Annual Symposium, 2017.	ECO
TRI18	A. M. Trinidad, N.M. Tessema, Z. Cao, J.H.C. van Zantvoort, A. Dubok, A.N.H. Al-Rawi, E. Tangdiongga, A.B. Smolders, and A.M.J. Koonen, “Optical Beamformer for K-band Smart Antenna Systems,” in Optical Fiber Communications Conference and Exhibition (OFC), 2018, paper M4J.2.	ECO, EM
VOS17	M. F. J. Vos, 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
WEE17a	J. J. A. van Weerdenburg, A. Alvarado, J.C. Alvarado Zacarias, J.E. Antonio Lopez, J.H. Bonarius, D. Molin, M. Bigot Astruc, A.M.J.Koonen, A. Amezcua Correa, P. Sillard, R. Amezcua Correa and C. M. Okonkwo. “*Spatial pulse position modulation for multi-mode transmission systems*”. 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2017, pp. 1-3.	ECO
WEE17b	J.J.A. van Weerdenburg, R. Ryf, J. C. Alvarado-Zacarias, R. A Alvarez-Aguirre, N. K. Fontaine, H. Chen, R. Amezcua-Correa, A.M.J. Koonen, C.M. Okonkwo “138 Tbit/s Transmission over 650km Graded-Index 6-Mode Fiber” in 43rd European Conference on Optical Communication (ECOC), 2017, *Post-Deadline paper Th.PDP.A.4*	ECO
ZOB17	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 (2017). *“Integrated nano-opto-electro-mechanical sensor for spectrometry and nanometrology”*, Nature Communications, 8, 2216 (2017)	PSN

Budget and personnel

Summary

The project is on track and catching up for the delays which occurred in the first years. The solid line in Figure 23 shows the originally planned appointment level, the bars show the actual appointment level in the participating groups and the contractual commitments for the following years. The hatched blue bars on top indicate the planned additional appointments, which will be implemented in the coming years. Figure 23 shows that we reached the planned budget level in 2017. In 2018 and following years we will 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 positions for an assistant professor. Currently, there are four assistant professors working in the Gravitation program, one of which has obtained a permanent position this year.

A couple of staff have left sooner than expected, which will lead to some minor changes to the original personnel plan in 2018.

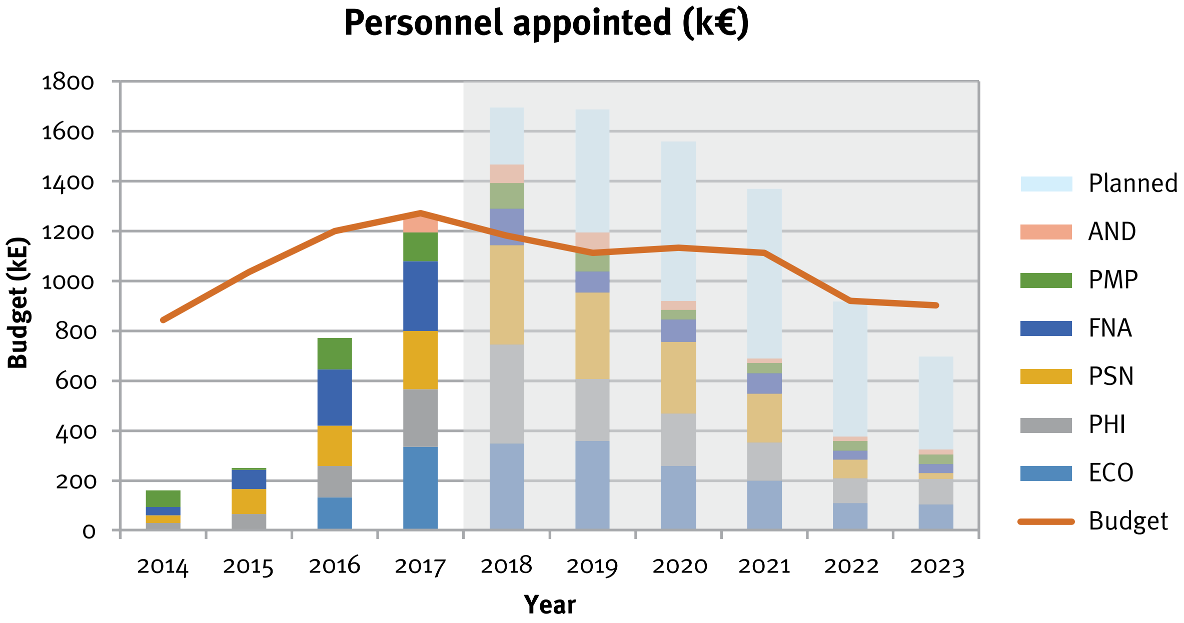

Figure 23
Personnel budget: originally planned budget, realized and budget not yet allocated.

Figure 24 shows the difference between the planned cumulative budget and the cumulative spending and commitments so far. The red bars on a grey background indicate reservations for currently hired personnel. Hatched blue bars indicate plans for 2018 and following years.

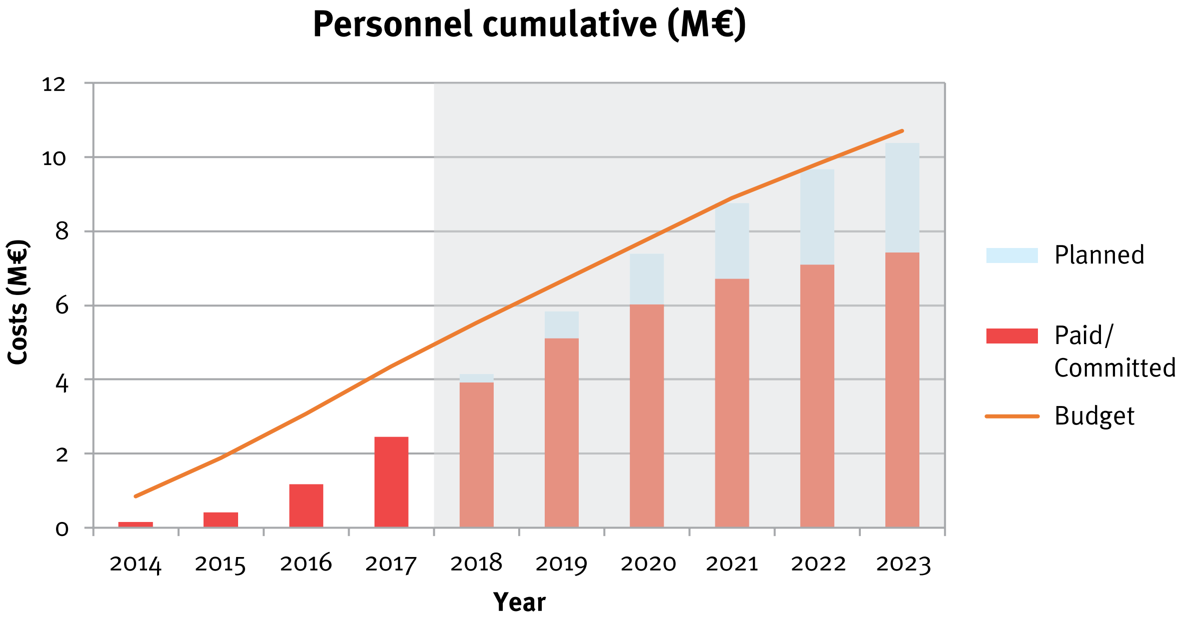

Figure 24
Cumulative personnel budget: realization and planning.

Institutional embedding and organisational structure

Organisational and Management Structure

Figure 25 shows the management structure of the project, which was described in more detail in the 2014/15 year report, see the website of the Gravitation Program[1].
In 2017, the chair of Erik Bakkers in the PSN group has become a separate group: Advanced Nanomaterials and Devices (AND). The group will remain fully committed to the Gravitation program.

By the end of 2017, Huug de Waardt, who already is Graduate School Program Director of the department of Electrical Engineering, was appointed director of the NWO graduate school on Photonics and become responsible for the educational activities in the Gravitation project.

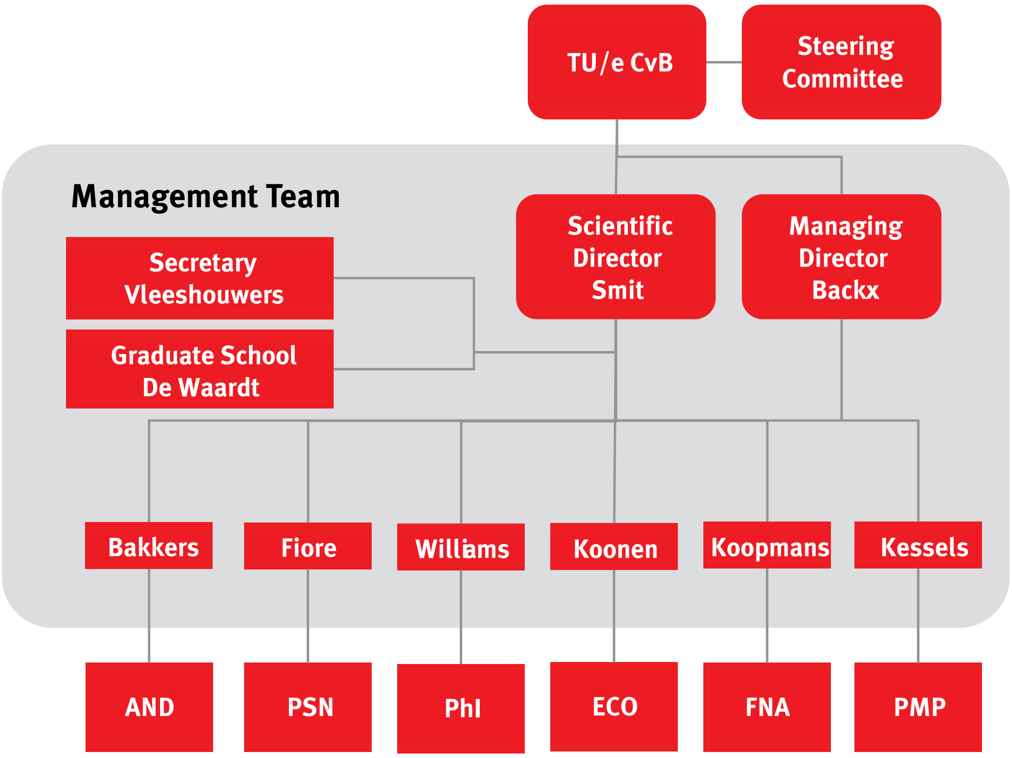

Figure 25
Management Structure of the Research Centre for Integrated Nanophotonics.

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[1] URL: https://www.tue.nl/onderzoek/research-centers/institute-for-photonic-integration/over-het-institute-for-photonic-integration/nwo-gravitation/

Organisational Embedding and Cooperation

The Gravitation project is the largest project of IPI, the TU/e Institute for Photonic Integration. 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 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 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 26). To this end, IPI and PhotonDelta have set up a Research Center based on industrial and public co-funding. This *Photonics Integration Technology Center* (PITC) is the intermediary between the IPI research at low *technology readiness* (TR) levels and the applications envisioned by the companies represented in PhotonDelta, which require high TR-levels. Companies participate in Photon Delta through membership of a Cooperative, which gives them privileged access to IPI and PITC research. The JePPIX activities are part of PITC. The PITC offers an effective channel for using knowledge generated within the Gravitation Project in commercial applications.

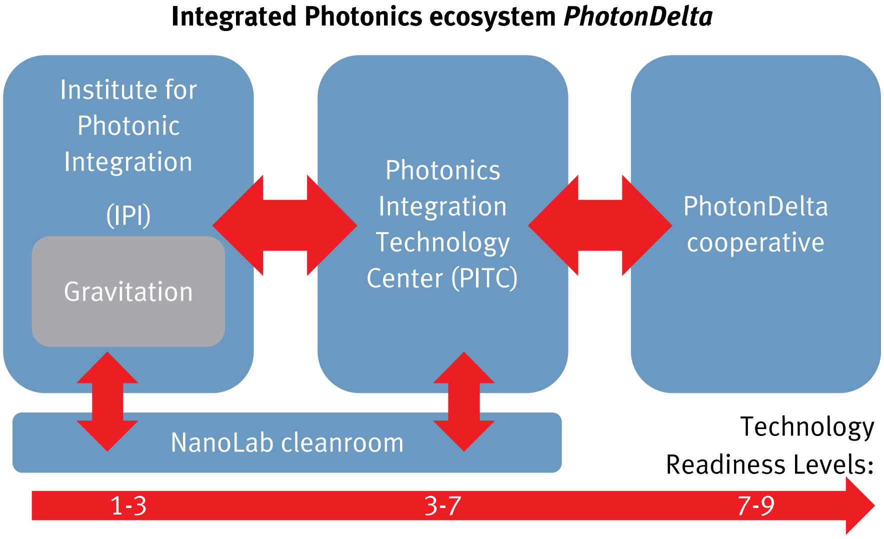


Figure 26
Integrated Photonics ecosystem PhotonDelta.

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 2019. 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 IPI and 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 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 from proof-of-concept to prototyping, including 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.

The PITC is 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.

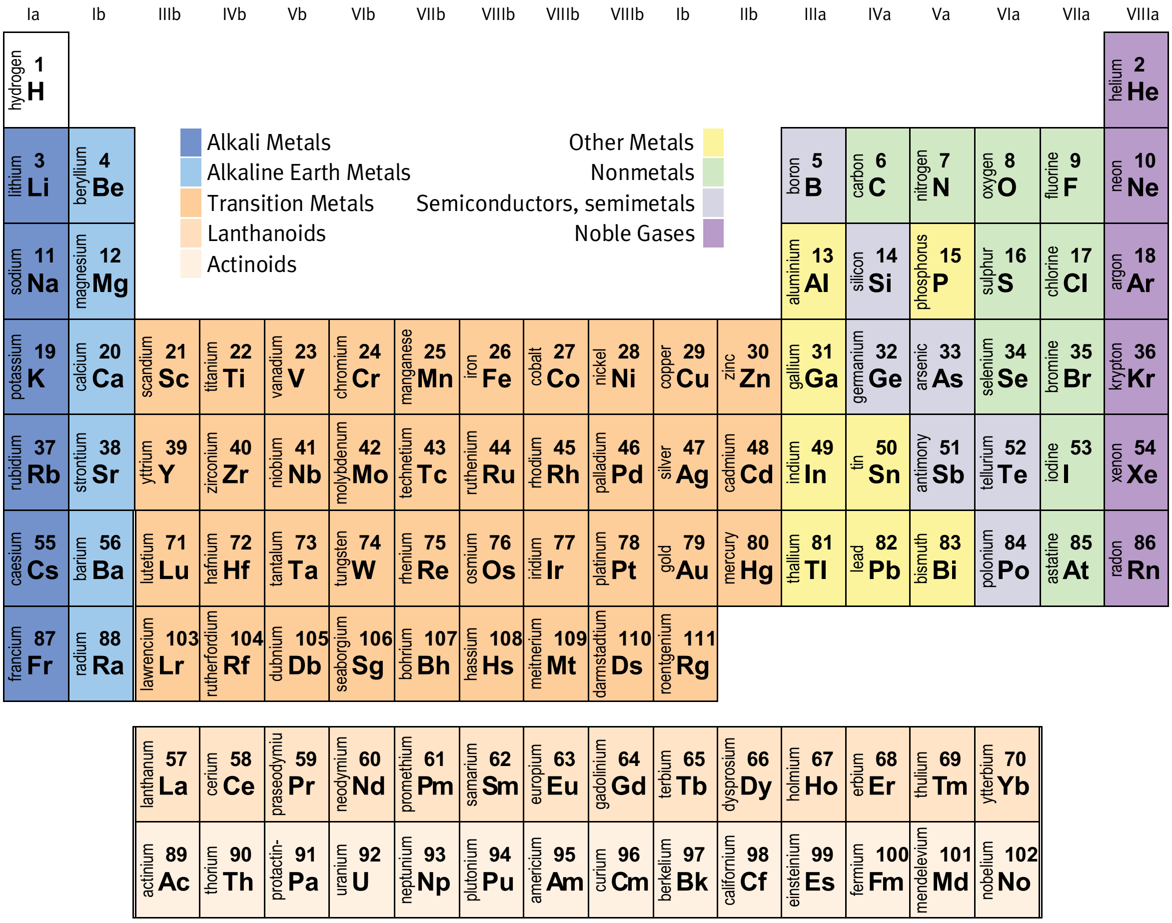
In 2017, there were over 80 companies and institutions active in the Netherlands in the field of integrated photonics. That number is growing steadily. PhotonDelta will strengthen a collaborative approach to valorization; 6 companies have become member of PhotonDelta. The initiative is supported by Eindhoven 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.

Glossary

5G	5th 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



Ia	Ib	IIIb	IVb	Vb	VIb	VIIb	VIIIb	VIIIb	VIIIb	Ib	IIb	IIIa	IVa	Va	VIa	VIIa	VIIIa
hydrogen 1 **H**																	helium 2 **He**
lithium 3 **Li**	beryllium 4 **Be**											boron 5 **B**	carbon 6 **C**	nitrogen 7 **N**	oxygen 8 **O**	fluorine 9 **F**	neon 10 **Ne**
sodium 11 **Na**	magnesium 12 **Mg**											aluminium 13 **Al**	silicon 14 **Si**	phosphorus 15 **P**	sulphur 16 **S**	chlorine 17 **Cl**	argon 18 **Ar**
potassium 19 **K**	calcium 20 **Ca**	scandium 21 **Sc**	titanium 22 **Ti**	vanadium 23 **V**	chromium 24 **Cr**	manganese 25 **Mn**	iron 26 **Fe**	cobalt 27 **Co**	nickel 28 **Ni**	copper 29 **Cu**	zinc 30 **Zn**	gallium 31 **Ga**	germanium 32 **Ge**	arsenic 33 **As**	selenium 34 **Se**	bromine 35 **Br**	krypton 36 **Kr**
rubidium 37 **Rb**	strontium 38 **Sr**	yttrium 39 **Y**	zirconium 40 **Zr**	niobium 41 **Nb**	molybdenum 42 **Mo**	technetium 43 **Tc**	ruthenium 44 **Ru**	rhodium 45 **Rh**	palladium 46 **Pd**	silver 47 **Ag**	cadmium 48 **Cd**	indium 49 **In**	tin 50 **Sn**	antimony 51 **Sb**	tellurium 52 **Te**	iodine 53 **I**	xenon 54 **Xe**
caesium 55 **Cs**	barium 56 **Ba**	lutetium 71 **Lu**	hafnium 72 **Hf**	tantalum 73 **Ta**	tungsten 74 **W**	rhenium 75 **Re**	osmium 76 **Os**	iridium 77 **Ir**	platinum 78 **Pt**	gold 79 **Au**	mercury 80 **Hg**	thallium 81 **Tl**	lead 82 **Pb**	bismuth 83 **Bi**	polonium 84 **Po**	astatine 85 **At**	radon 86 **Rn**
francium 87 **Fr**	radium 88 **Ra**	lawrencium 103 **Lr**	rutherfordium 104 **Rf**	dubnium 105 **Db**	seaborgium 106 **Sg**	bohrium 107 **Bh**	hassium 108 **Hs**	meitnerium 109 **Mt**	darmstadtium 110 **Ds**	roentgenium 111 **Rg**							

🟦 Alkali Metals
🟦 Alkaline Earth Metals
🟧 Transition Metals
🟧 Lanthanoids
⬜ Actinoids

Other Metals 🟨
Nonmetals 🟩
Semiconductors, semimetals ⬜
Noble Gases 🟪

lanthanum 57 **La**	cerium 58 **Ce**	praseodymiu 59 **Pr**	neodymium 60 **Nd**	promethium 61 **Pm**	samarium 62 **Sm**	europium 63 **Eu**	gadolinium 64 **Gd**	terbium 65 **Tb**	dysprosium 66 **Dy**	holmium 67 **Ho**	erbium 68 **Er**	thulium 69 **Tm**	ytterbium 70 **Yb**
actinium 89 **Ac**	thorium 90 **Th**	protactin- 91 **Pa**	uranium 92 **U**	neptunium 93 **Np**	plutonium 94 **Pu**	americium 95 **Am**	curium 96 **Cm**	berkelium 97 **Bk**	californium 98 **Cf**	einsteinium 99 **Es**	fermium 100 **Fm**	mendelevium 101 **Md**	nobelium 102 **No**