2016

Annual Report

In accordance with the 'Partnerconvenant QuTech'

QUTech

Foreword

On behalf of all team members, Ronald Hanson (Scientific Director) and Kemo Agovic (Managing Director) are proud to present the 2016 annual report of QuTech.

In 2016, QuTech continued and intensified its research with more scientists, engineers and support staff, lab spaces were extended and collaborations are further intensified. Ronald Hanson: ‘Each visitor in 2016, be it from academia or from industry or from government, gave the same feedback: QuTech is a very special place with very special people! I am proud of the amazing quality of the people and the work done at QuTech, which reflects the way we work together.’

This annual report gives an overview of the QuTech activities in 2016. While the first chapter (Research) gives an overview per scientific roadmap, the highlights show the strength of the collaborations within and around QuTech. Hanson: ‘These highlights reflect the quality of our people, from students to engineers to support staff to professors. Over the years we build up an unique environment of openness and colla-boration between different disciplines as well as partnering with industry.’ Agovic adds: ‘At QuTech, we are working on high-quality research and engineering. We stay focussed and keep track. Besides that, our teams have an open attitude towards the outside world, they collaborate and compete at the same time.’ In the near future we expect even more exposure to the outside word, we expect more important results being achieved in QuTech. Agovic: ‘We strive to have a lean and mean, research-driven organisation which is will remain open for new collaborations.’

For quantum research in Europe the Quantum Manifesto, in which the Flagship was announced, kicks off new and intensified collaborations and opportunities. The IARPA grant resulting in the QuSurf consortium, Microsoft’s announcement of more quantum research in Delft and intensified collaborations with Intel reflect the mission-driven research at QuTech. Kemo Agovic: ‘The outside world recognises QuTech’s added value, we are joining forces. I believe there is a unique opportunity for QuTech to become the heart of a thriving "Quantum Campus”, with Microsoft being the first on-campus partner. In the next years, we expect that world-wide just a few major centres of quantum technologies will emerge, and we want QuTech to be one of these key players.’

In the coming years, science and technology will reach new levels. Hanson: ‘I see that much of the work of the last years, geared at making new collaborations work, is now starting to pay off both scientifically and on the technology development side, in all roadmaps. These are exciting times!’

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Executive Summary

QuTech is the advanced research centre for Quantum Computing and Quantum Internet, a collaboration founded in 2014 by Delft University of Technology (TU Delft) and The Netherlands Organization for Applied Scientific Research (TNO). Within TU Delft, the faculties that participate in QuTech are the Faculty of Applied Sciences (AS) and the Faculty of Electrical Engineering, Mathematics and Computer Sciences (EEMCS). This annual report presents the most important developments concerning QuTech in the year 2016.

Within each of QuTech's three scientific roadmaps, Fault-Tolerant Quantum Computing, Quantum Internet and Networked Computing and Topological Quantum Computing, scientists have been focussing on the scalability of the quantum systems. Advanced scalable architectures have been explored by combining theoretical and experimental expertise. Novel devices were developed with the support of experts of the roadmap Shared Development. Further details about the highlights of the scientific and technological roadmaps can be found in the "Research" section of this report.

To remain at the forefront of quantum information science and technology, QuTech has intensified its partnerships and collaborations. QuSurf, an international consortium consisting of QuTech, ETH Zurich and Zurich Instruments, won a IARPA grant (the US Intelligence Advanced Research Projects Activity) to develop a 'logical qubit' over the next 5 years. Besides, QuTech director Leo Kouwenhoven was hired by Microsoft, which announced that it will double its investments in quantum research. Kouwenhoven will lead the new quantum lab that Microsoft intends to set up on the campus of TU Delft.

One of the highlights of 2016 was the Conference Quantum Europe, which was organized by the EU Presidency in close cooperation with QuTech and the European Commission. On the 17th and 18th of May, leading scientists, industrial CEOs and investors from all over Europe and the world gathered in Amsterdam to deliberate on how to place and keep Europe at the front of developing quantum technologies. They discussed how Europe's capabilities in quantum technologies can create a lucrative knowledge-based industry, leading to economic, scientific and societal benefits. The conference paved the way for the European Flagship initiative.

Ronald Hanson won the Huibregtsen prize for research on 'safe surfing on the quantum internet' and was awarded a Vici grant for quantum internet. Our new PI, Menno Veldhorst was awarded a Vidi grant to start up his research in the roadmap Fault-Tolerant Quantum Computing.

On the Outreach and Communication side, QuTech participated in several public events. On the 19th of October, Leo Kouwenhoven gave a lecture on Quantum Computing that was broadcasted on Dutch television in the NPO3 programme Universiteit van Nederland. Also, QuTech hosted a visit for readers of The New Scientist. Furthermore, an enthusiastic team of PhD researchers launched the QuTech blog 'Bits of Quantum'.

QuTech Academy has set the goal to educate the world on quantum information science, both to bring about a generation of highly-educated quantum scientists and engineers as well as to involve the public and policy makers. Stephanie Wehner created an online learning MOOC with over 10.000 participants. Furthermore, 5 MSc courses were developed for campus and online education aimed at students of Applied Physics, Electrical Engineering, Computer Science and Mathematics.

The "Organization" section of this annual report offers insight into the governance of QuTech. It presents a number of graphs on staffing levels and structure. Over the year 2016, QuTech has not only achieved scientific successes in all scientific roadmaps and intensified collaborations, but has also grown, both in terms of excellent staff as well as in terms of equipment and space. The number of people working in QuTech has grown from 110 to 164. This number is expected to increase in the coming years to about 250 in 2020. The lab and office spaces were expanded from 2000 to 2700 m^2 and the number of experimental setups increased from 23 to 36, both of which will increase even further in the coming years.

The "Financial overview and expenses" section provides information on QuTech budgets within the framework of the "partner covenant". Finally, the appendices provide overviews of current QuTech projects as well as of all our peer-reviewed scientific publications in 2016 and our BSc and MSc students who graduated in 2016.

Research

ROADMAPS

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Pim Top

Fault-Tolerant Quantum Computing

> ROADMAP LEADERS: **LIEVEN VANDERSYPEN, LEO DICARLO**

Fault-Tolerant Quantum Computing (FT) — In the past year, the roadmap has focused on scalability of quantum information devices both on the fabrication level as well as on the architecture level.

A first breakthrough was the first all-electrical universal control and independent read-out of two electron spins in a Si/SiGe based two-qubit device. This device was programmed and tested for running simple quantum algorithms at the end of 2016 (manuscript in preparation).

In collaboration with Intel, we co-developed masks for quantum dot arrays that will be fully integrated in a 300mm cleanroom at Intel. We will receive the first devices in 2017, and we expect them to be superior to Delft-made devices in terms of yield and uniformity. In collaboration with Intel, QuTech/FT also took important steps in boosting yield and uniformity for devices made in Delft.

Following our long-term vision towards large-scale on-chip networks of qubit registers, we have taken further steps in spin control. We demonstrated spin shuttling, preserving not only the spin projection, as shown last year, but also the spin phase (under review). We realized coherent coupling between two spins via a quantum mediator, a separate quantum object (*Nature Nanotechnology* **12**, 26-30, 2017). Furthermore, we co-developed ideas with Intel to create a 1024-qubit array (32x32 qubits). Finally, we have established quantum dots as a credible platform for quantum simulation of Mott-Hubbard physics (under review).

>>

>> On the superconducting side, the effort to build a fault-tolerant quantum processor with circuit QED has been consolidated by the award of IARPA funding for team QuSurf, a TUD-led consortium comprising QuTech (TU Delft + TNO), Zurich Instruments and ETH Zurich. This team focuses on extensible software, room-temperature electronics, and cryogenic systems engineering, which is the perfect complement to our growing effort to develop quantum hardware in partnership with Intel.

In 2016, we produced a fully vertical interconnection to a 7-qubit quantum processor, which is key to the scalability of two-dimensional qubit arrays (patent). We demonstrated precision control of same-frequency qubits on a chip using a room-temperature vector-switch matrix (NPJ Quantum Info). We established the design of a scalable unit cell for surface coding by exploiting frequency reuse (patent and manuscript submitted). We performed state-of-the-art digital quantum simulation of light-matter dynamics at ultrastrong coupling, (manuscript submitted). Finally, we demonstrated a full quantum-computer stack (at the one-qubit level), from high-level programming language, through compiler and

New group leaders in 2016

Menno Veldhorst (Spin qubits)
Menno obtained his PhD at the University of Twente for his research on superconducting and topological hybrid systems. Based on his Rubicon grant, he carried out his postdoctoral research at CQC2T in Sydney. One of his main achievements was the demonstration of universal quantum logic in silicon, which Physics World announced as one of last year's top ten breakthroughs in physics. At QuTech, Menno will continue his research on silicon, with the ambition to transit silicon quantum computation from university-based research to industry. The focus will be on the realiza-

optimizer, to quantum hardware.
Key objectives for 2017 are the realization and control of a logical qubit in a 17-qubit quantum processor and a multi-qubit quantum-computer stack.

As an important step towards the design of cryogenic electronics, we clarified the connection between the specifications of the electronics and qubit performance. Furthermore, we designed a cryogenic CMOS RF-amplifier, which we are currently evaluating. We also cooled down and tested commercial FPGAs and found good performance at 4K. In order to ease the challenge of interfacing with large numbers of qubits, we designed and began implementing several multiplexing and floating-gate approaches.

For 2017, we aim to extend the demonstrator to larger numbers of qubits and to spin qubits. In 2018, the demonstrator will also encompass cryogenic control electronics and novel interconnect solutions.

tion of a scalable CMOS qubit platform. Many scientific hurdles will have to be cleared, which will provide even more opportunities for fundamental research.

Viatcheslav (Slava) Dobrovitski (Theory Fault-Tolerant Quantum Computing/Quantum Internet and Networked Computing). Slava got his PhD in physics at Moscow State University in 1997, and right away joined a national laboratory, the US DOE Ames Laboratory, as a visiting scientist. In a few years, he became a permanent staff member and stayed there for almost twenty years. Since 2008, he has collaborated quite a bit with Ronald Hanson and his group, and more recently he started working with Lieven Vandersypen and his group members.

During his career, Slava has studied various topics in the field of quantum and classical many-spin dynamics, from multiscale modelling of magnetic nanostructures to spin decoherence in quantum dots and coherence protection of quantum spin registers in diamonds.

Quantum Internet and Networked Computing

> ROADMAP LEADER: **RONALD HANSON**

Quantum Internet and Networked Computing (QINC) — The internet, a vast network that enables simultaneous long-range classical communication between any two points on earth, has had a revolutionary impact on our world. The long-term vision presented in the QINC roadmap is to build a matching quantum internet that will operate in parallel to the internet we have today.

The scientific highlights of 2016 continued the routes set by the breakthrough of 2015, the loophole-free Bell test. A second loophole-free Bell test with additional analysis was performed, which further consolidated this landmark result (*Scientific Reports* **6**, 30289, 2016). Furthermore, we demonstrated robust quantum memories based on nuclear spins in the diamond lattice (*Phys. Rev. X* **6**, 021040, 2016). This work showed that quantum states could be maintained over 1000 repetitions of the remote entangling protocol. This result paved the way for entanglement purification and quantum repeating, which are essential steps in further increasing the distance over which entanglement can be established.

On the networked quantum computing side, the main breakthrough of 2016 was the successful realization of active quantum error correction on a logical qubit (*Nature Communications* **7**, 11526, 2016). In this work, we were the first to implement several key capabilities: measurements to detect errors, fast processing of the error syndrome and real-time correction of the errors. By

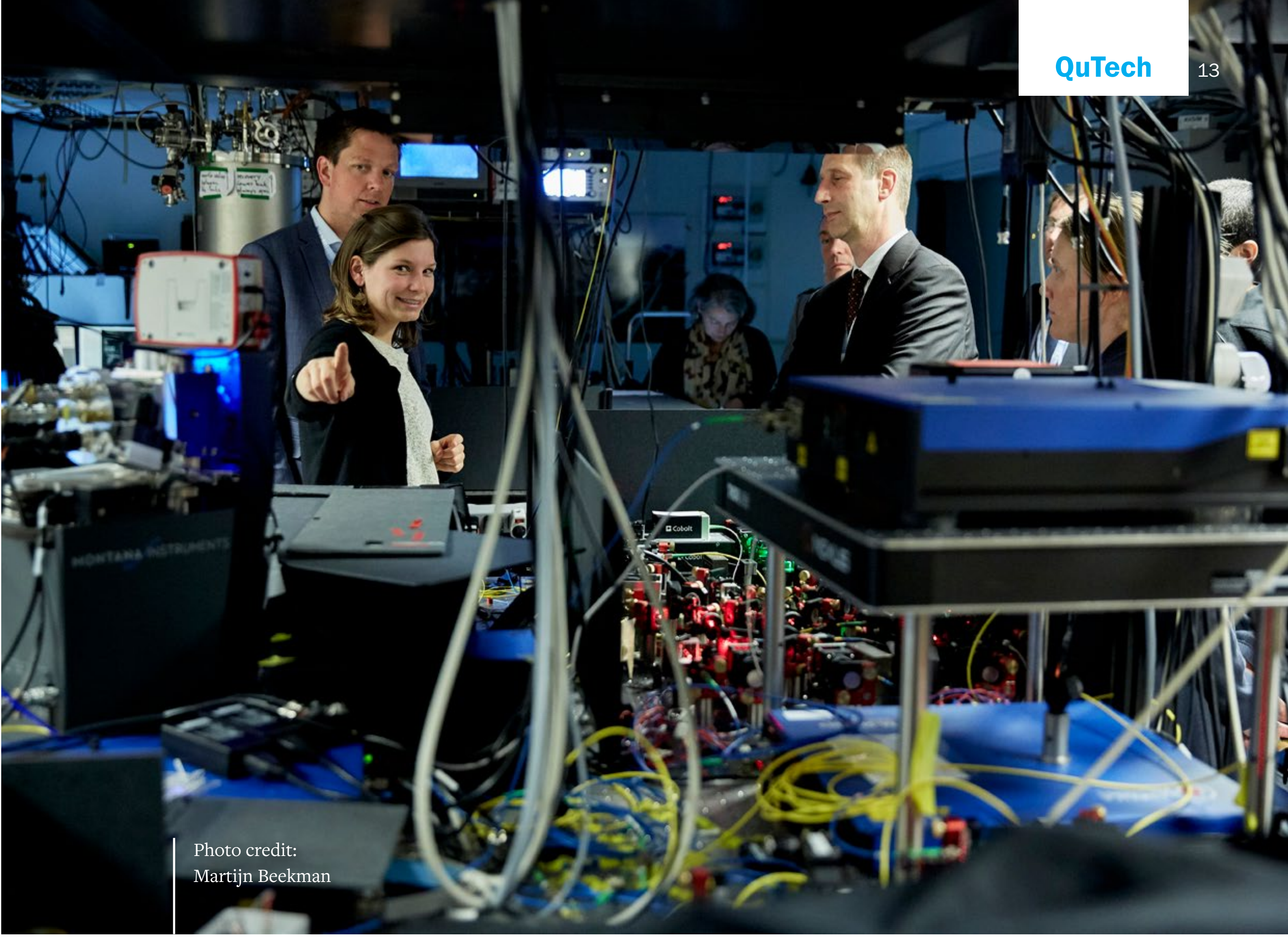


Photo credit:
Martijn Beekman

repeatedly detecting and correcting errors we could protect quantum superpositions for a longer time than without using error correction. Additionally, we characterized the interplay of repeated measurements for error correction with slowly varying experimental noise, an essential step for analysing error correction codes under realistic conditions (*Nature Communications* **7**, 13111, 2016).

Several theoretical breakthroughs have been achieved in 2016 that allow us to characterize experimental setups much more efficiently than before. We were the first to show that the fidelity of a quantum gate can be estimated through randomized benchmarking using a number of measurement sequences that are constant in the number of qubits, and several orders of magnitude better than any previous analysis. This theoretical demonstration brings rigorous randomized benchmarking for quantum computers with many qubits into the realm of experimental possibilities. Simultaneously, building on work done earlier this year to estimate decoherence (*Nature Communications*, 13022, 2016), we introduced a new method called capacity estimation. This method allows us to characterize quantum memories in the presence of arbitrarily correlated errors. As a special case, this >>

>> procedure can also be used to test quantum error correcting codes and to assess the performance of quantum repeaters.

The quantum internet will enable long-range quantum communication between connected quantum processors and achieve unparalleled capabilities that are probably impossible using only classical means. Achieving our goal poses formidable challenges, which demand unique solutions spanning physics, material science, computer science and engineering. To realize this vision, we aim to build a demonstrator in 2020 that connects three Dutch cities into a fully quantum internet. In parallel, we are exploring possible designs that will allow us to scale up our efforts to a large-scale fault-tolerant quantum network.

Topological Quantum Computing

> ROADMAP LEADER: **LEO KOUWENHOVEN**

Topological Quantum Computing (TOPO) — In 2016, the Topological Quantum Computation Roadmap developed novel device geometries and experimental methods tailored to create and control Majorana-based quantum bits.

The TOPO roadmap continued its efforts to achieve the first demonstration of topological quantum bits, a goal that requires the synergy of material science, sophisticated experimental methods, and theoretical modeling. Our cluster tool can now produce very clean semiconductor nanowires by means of Molecular Beam Epitaxy (MBE). The next challenge, which we will work on throughout 2017, is the integration of superconducting circuits.

Topological quantum bits require complex networks of semiconductor nanowires, such

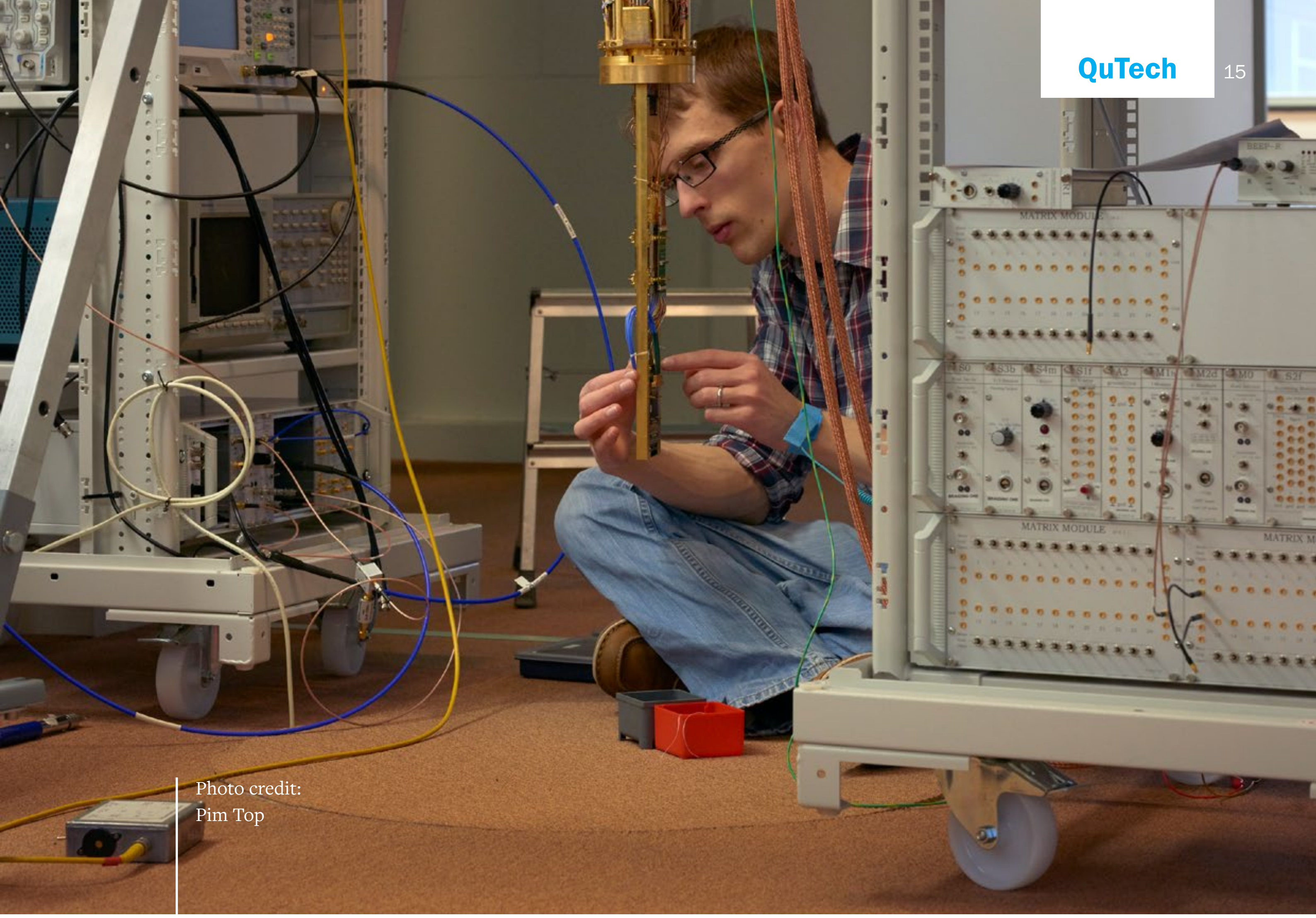
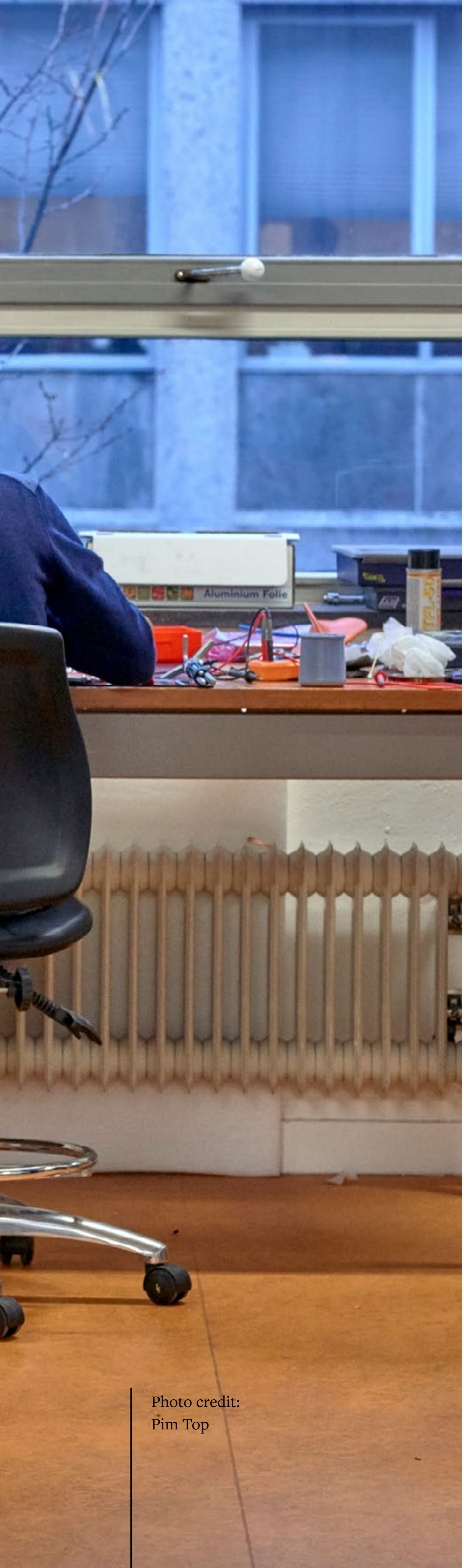


Photo credit:
Pim Top

as crosses (X) and hashtags (#). To this end, we developed a flexible method to create wire networks at will. This innovation, based on the three-dimensional design of the growth substrate, will be used to create prototype topological quantum bits in the near future. High-quality semiconductor structures are characterized by their ballistic nature, which allows the electrons to pass through without scattering on impurities. We have shown that our platform of InSb nanowires has this property (*Nano Letters*, **16**, 3482 (2016)) as well as suitably engineered metallic contacts and an electrostatic environment. Planar semiconductors with two-dimensional electron states can be a promising platform for topological quantum bits. We have demonstrated ballistic transport in InSb quantum wells (*Nano Letters*, **16**, 7509, (2016)) and showed that the Landé g-factor is well suited for Majorana states.

A long-standing challenge of two dimensional topological states is the unambiguous demonstration of the topologically protected edge modes. Together with our collaborators at the University of Copenhagen and at Purdue University, we have shown that this can be achieved by a circular geometry of the leads to the semiconductor. With this method, >>



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>> we performed a quantitative analysis of the edge and bulk conductance in InAs/GaSb structures (*Phys. Rev. Letters*, **117**, 077701 (2016)).

Experiments addressing the Majorana states rely on probing the electronic dispersion inside the semiconductor nanowire. In collaboration with TU Eindhoven, we demonstrated that this can be performed via a built-in tunneling probe by engineering the composition of the nanowire (*Nano Letters*, **17**, 721 (2017)).

We developed the first on-chip laser based on the AC Josephson effect of a superconducting tunnel junction embedded in a microwave cavity (*Science*, **355**, 939 (2017)). Embedded sources of coherent photons have the prospect of replacing external microwave generators and will improve the control of superconducting quantum circuits.

On-chip microwave sources can also probe the Andreev levels of the superconducting weak links, which are the atomic building blocks of topological quantum bits. We designed and built a circuit utilizing a superconducting tunnel junction as a broadband microwave spectrometer up to 90 GHz in frequency. Utilizing this device, we measured the Andreev level structure in a semiconductor nanowire (arXiv:1609.00333).

Shared Development

> ROADMAP LEADER: **GARRELT ALBERTS**

Shared Development (SD) — In the Shared Development (SD) roadmap, technology developments are managed for the 3 scientific roadmaps of QuTech. Furthermore, the SD roadmap facilitates taking quantum technology to market (technology push) and constitutes a portal to QuTech for third parties who want to get access to state-of-the-art Quantum Technology (technology pull).

Topological Quantum Computing roadmap

Technologies have been developed to create a Majorana Device, which can act as a very stable and scalable qubit. Nanowires are a critical component of quantum computers based on Majorana quasi particles. In 2015, a new and very advanced system for material deposition was installed in the cleanroom in Delft. This unique MBE/ALD setup for the growth of semiconductor nanowires has been installed and tested in the Van Leeuwenhoek Laboratory (VLL). In 2016, as first proof-of-concept, the MBE was successfully used to grow InAs nanowires.
We developed Proto-Majorana Devices with perfectly flat (<1nm rms) dielectrics with conductive gates underneath. Nanowires were laid on top of these devices. We also developed nanowire characterization and process control for extremely well defined thin layers of superconductive material (NbTiN), in which the crack problem was tackled. 3D lithography techniques were developed to enable the growth of nanowire crosses.

Fault-Tolerant Quantum Computing roadmap

We developed technologies to measure and control 17 or 49 superconducting transmon qubit devices; the next generation of the successful vector switch matrix will be designed and built to be used for qubit control by frequency re-use. The FPGA-based feedback loop electronics, which were designed and built in 2015, were tested, implemented, and applied in quantum measurements in 2016. To support the full use of this system, the functional architecture for the first small-size demonstrator of the quantum computer has been defined. This functional architecture includes error correction functionality and automated control of simple qubit algorithms. We also provided technical support in the development of a quantum emulator, aimed at emulating small scale quantum systems at a very detailed level of up to 40 qubits.

We participated in the development of a cryogen CMOS control system for spin qubits. This system is essential to allow upscaling of quantum computers to larger numbers of qubits (>50 qubits). The successful computer-assisted tuning of double spin qubits will be extended for tuning devices with larger numbers of qubits.

Quantum Internet and Network Computing roadmap

We demonstrated the feasibility of technology that converts the frequency of single photons from an NV-center to telecommunication wavelength. A difference frequency generation (DFG) setup was upgraded with a new crystal and an ultranarrow-frequency pump laser, and overall conversion efficiency was improved.

Our engineers designed and assembled an interferometer, which is a crucial component for the planned experimental demonstration of spin-photon entanglement. This interferometer features an extremely stable unbalanced (with large Optical Path Difference) fiber interferometer system for the telecom (1588nm) wavelength, with an option of active piezo-stretcher assisted stabilization of the Optical Path Difference (OPD). Also an unbalanced interferometer for the visible (637nm) wavelength was created, which achieved better than 2% phase stabilization.

Bringing quantum technology to society

Quantum Technology development support for the Intel project continued in 2016, while the QuSurf project started-up. The QuSurf project consists of a consortium of TU Delft, TNO, ETH, and ZI and is granted a funding from IARPA for the development of the first logical qubit. For the Dutch Defense department, several consultancy activities related to Quantum Computing, Communication and (post-) Quantum Cryptography were performed. Furthermore, together with TU Delft, Leiden University, and satellite manufacturer OHB, we submitted a proposal to ESA for a scientific experiment on quantum technologies at weak gravitational fields.

QuTech Academy

> ROADMAP LEADER: **STEPHANIE WEHNER**

Worldwide, QuTech is the frontrunner in Quantum Computing and Quantum Communication. Therefore, we are in a unique position to "Educate the World". To build the first Quantum Computer and Quantum Internet, we need a workforce that has in-depth knowledge in the areas of both quantum physics and computer science & engineering. In addition, we need to supply the nascent quantum industry with the necessary human capital possessing an excellent training in quantum technologies.

Therefore, the goal of our QuTech Academy is 'Educating the world in Quantum': involving different audiences, stimulating a process of thought and inspiring more and more students to choose the field of Quantum, informing companies on future developments and showing policy-makers that this field is ever evolving and extremely important for the competitive advantage of this country and of Europe.

Under the leadership of Stephanie Wehner, the QuTech Academy has made significant steps forward in 2016 to becoming the first in mainland Europe to offer a targeted programme in the area of Quantum Technology and Quantum Information. In 2016 QuTech Academy offered four courses at MSc level, organised numerous lectures and colloquia for both MSc and PhD students year-round and launched a second MOOC on the EdX platform.

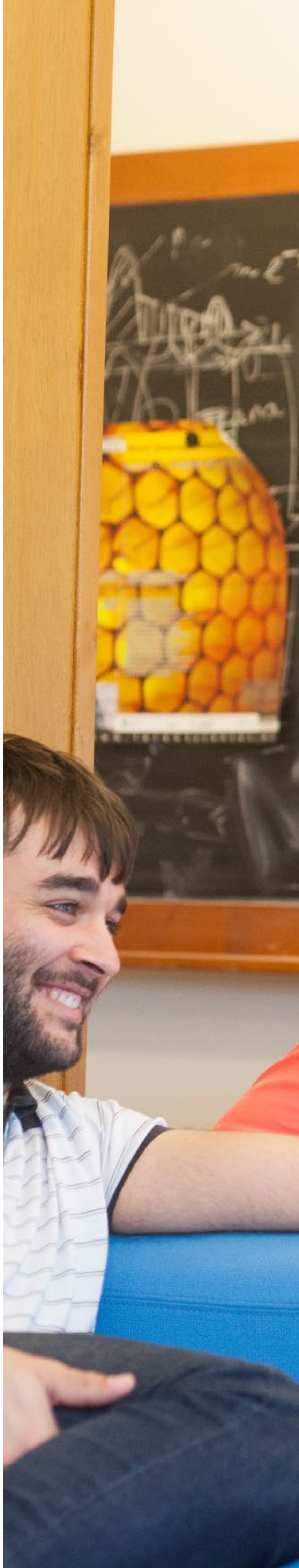
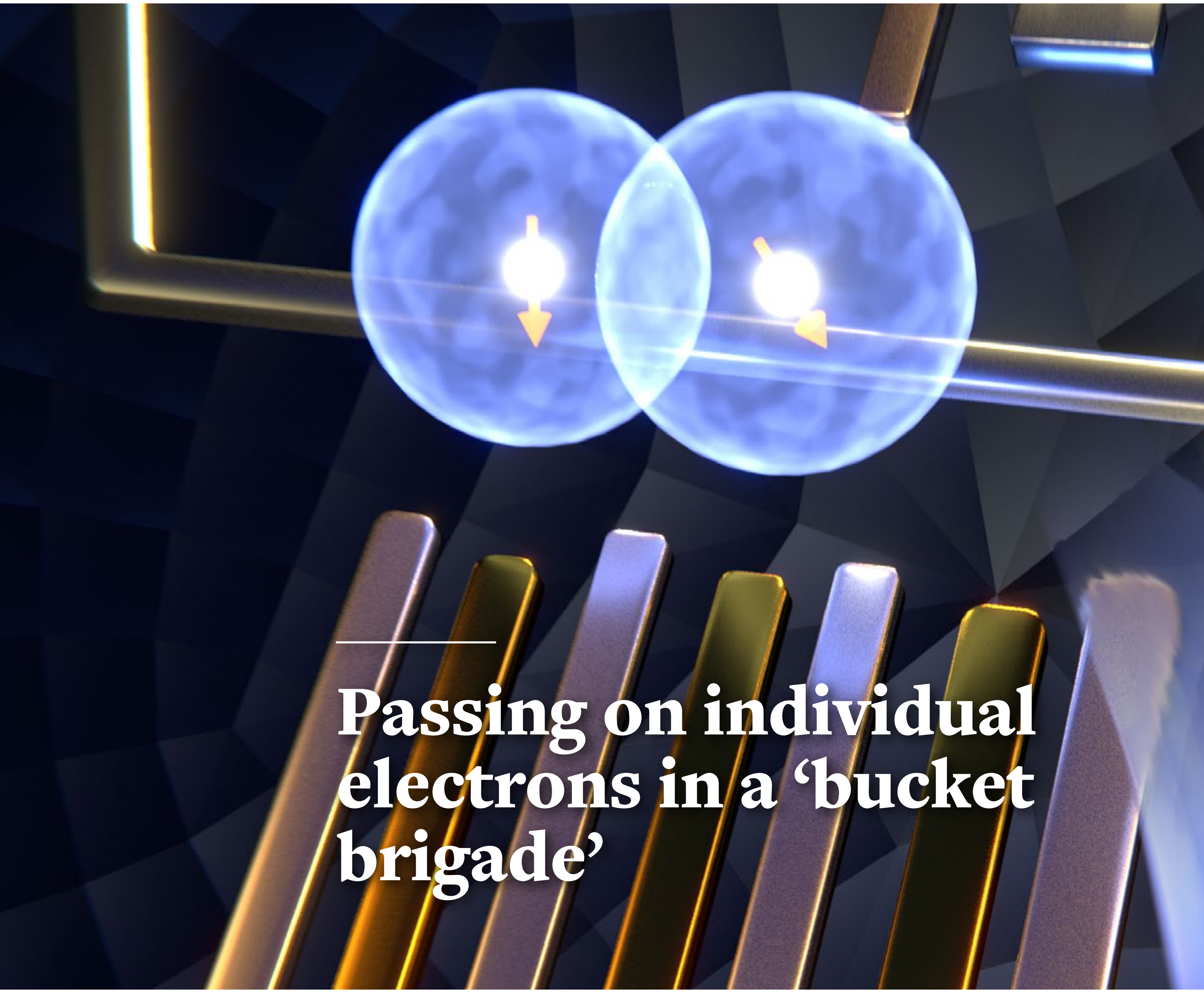


Photo credit:
Kim van Dam

Research

> HIGHLIGHTED PUBLICATIONS



Passing on individual electrons in a ‘bucket brigade’

Single-Spin CCD, T. A. Baart, M. Shafiei, T. Fujita, C. Reichl, W. Wegscheider, L. M. K. Vandersypen, *Nature Nanotechnology* **11**, 330-334 (2016)

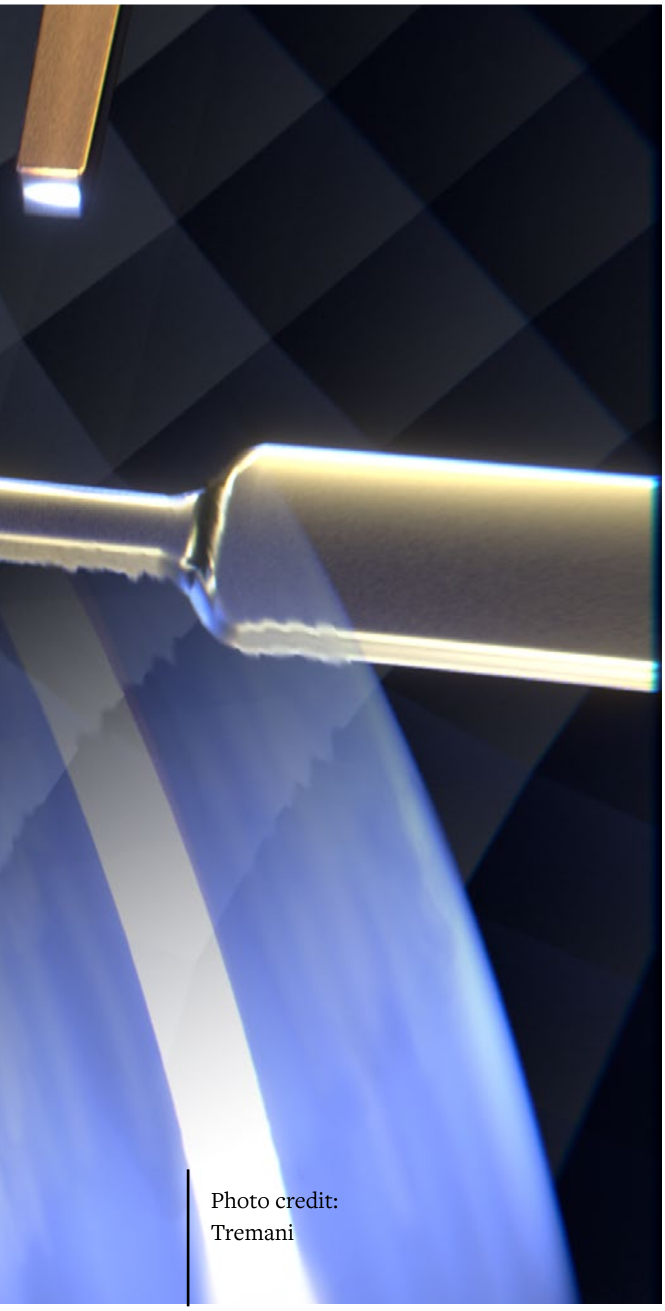


Photo credit: Tremani

Lieven Vandersypen and his team succeeded in shuttling electrons one by one through a chain and reading them out at the end of that chain, without disturbing their state during the process. This represents an important step in the development of a quantum computer. QuTech PhD Tim Baart: “This field, spintronics, is all about being able to store, transport and manipulate electrons and their spin with great precision.” The spin of an individual electron can be used to store quantum information. The spin state then represents a digital ‘0’ or ‘1’. Until now, no-one succeeded in transporting single electrons over large distances while preserving their spin.

The researchers at QuTech achieved this by exploiting the mechanism of a CCD, short for a charge-coupled device. In a CCD, pockets of electrical charge are passed along a capacitor array in much the same way as buckets in a bucket brigade – a line of people passing along buckets of water to extinguish a fire. The pockets of electrical charge arrive sequentially at the end of the array, where they are detected by a charge amplifier. This simple concept works excellently for CCD cameras with millions of pixels, and QuTech discovered that it also works n spintronics. “We call our version of this concept a ‘single-spin CCD’,” says Baart. “This device can shuttle electrons one by one along a chain without disturbing their spin state and then read out the state at the end of the chain.”

Researchers demonstrate error-corrected building block of a quantum computer

Repeated quantum error correction on a continuously encoded qubit by real-time feedback, J. Cramer, N. Kalb, M.A. Rol, B. Hensen, M. S. Blok, M. Markham, D. J. Twitchen, R. Hanson, T. H. Taminiau, *Nature Communications* **7**, 11526 (2016)

Quantum computers are based on qubits, which can take the values 0 or 1 but, unlike classical bits, they can also be 0 and 1 at the same time. Unfortunately, this quantum information is very fragile and thus gets lost easily. A team of scientists led by Tim Taminiau at QuTech were the first to demonstrate that errors in quantum computations can be detected and actively corrected without losing the delicate quantum information. The correction of errors in quantum computations is a crucial step towards a working quantum computer. The work was published in Nature Communications.

The scientists used electronic and nuclear spins in diamond to implement a complete error-correction process for the first time. These spins can be used to process quantum information with high fidelity and to store it long enough to process and actively correct the errors using classical electronics. The QuTech team managed to extend the time that quantum information could be protected. This demonstration of active quantum error correction is an important milestone towards more complex error correction systems, which are essential for the scalability of quantum information technology.

Tiny batteries for superconductivity

Josephson ϕ_0-junction in nanowire quantum dots
D.B. Szombati, S. Nadj-Perge, D. Car, S.R. Plissard, E.P.A.M. Bakkers & L.P. Kouwenhoven
Nature Physics **12**, 568–572 (2016) doi:10.1038/nphys3742

The current in any lightbulb flows due to a difference in voltage, which is necessary to overcome the electrical resistance. But not in superconductors, where the current doesn't experience any resistance. Superconductive currents flow if there is a phase difference, which so far could only be created by using energy. Scientists in Professor Leo Kouwenhoven's group built a so-called ϕ_0-Josephson Junction, which has a phase difference at default. It can therefore function as a tiny battery to store superconducting currents.

Scientists have known since the 1960s that superconducting currents can be manipulated by means of Josephson Junctions. "A Josephson Junction consists of two superconductors that are connected by a bridge, for instance a nanowire made of a non-superconducting material, such as a semiconductor", PhD student Daniel Szombati explains. "These junctions have the special property that they can adjust the phase drop that controls the current flow in a superconducting material. Just like a dam in a hydro plant, which controls the water level drop, or a galvanic battery, which has a potential difference between its electrodes, the Josephson Junction serves as a barrier for superconducting phase. This phase at either end of the junction can be manipulated with strong magnetic fields, but this requires a lot of energy."

QuTech's new ϕ_0-Josephson Junction is special because it has a default phase difference. "In this junction, an electric field is required to make the current stop," says Daniel Szombati. "Effectively, we have created a small superconducting battery that can store a tiny amount of superconductive current. Just like for a hydro plant where the dam controls the water level drop, the Josephson junction serves as a barrier for superconducting phase.

ϕ_0-Josephon Junctions are also a step towards quantum bits based on Majorana fermions. Signs of this elusive particle, which was predicted in the 1930s by Ettore Majorana, where first seen in the lab of Leo Kouwenhoven. Research is now focusing on creating Majorana fermions and performing operations with them that can only be explained with so-called 'non-Abelian statistics'. "A read-out of such a quantum memory would be the firm and definitive proof that Majorana fermions do not only exist, but could also be used as quantum bits", Kouwenhoven explains.

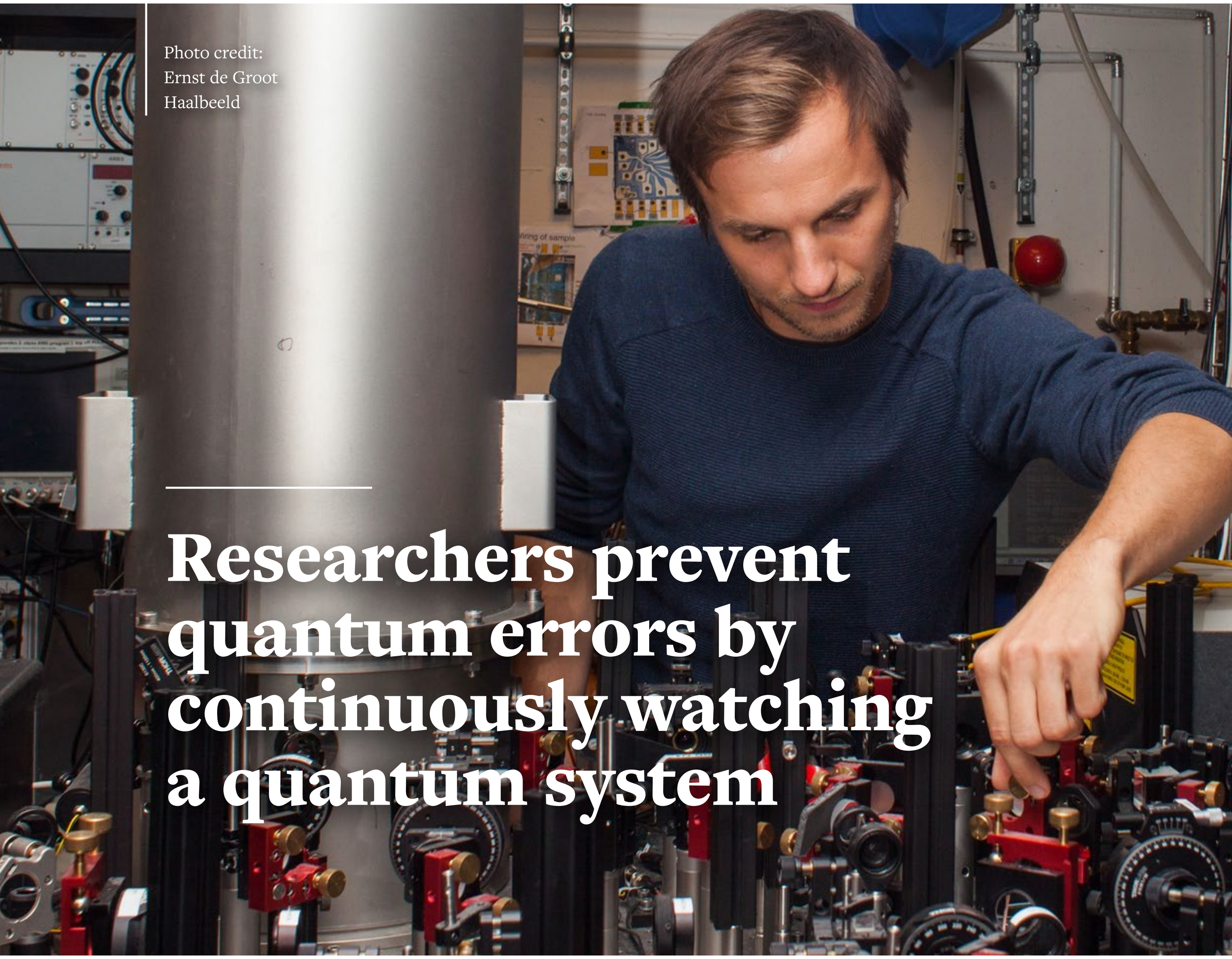


Photo credit:
Ernst de Groot
Haalbeeld

Researchers prevent quantum errors by continuously watching a quantum system

A team of scientists led by Tim Taminiau at QuTech experimentally demonstrated that errors in quantum computations can be suppressed by repeated observations of quantum bits encoded in spins in diamond. Via this technique, unwanted transformations of these qubits are suppressed. The presented work provides direct insight into the physics of measuring quantum states and is relevant for quantum error detection and correction, which are both crucial for a working quantum computer.

As the Greek philosopher Zeno of Elea stated in his ‘arrow paradox’, a flying arrow is standing still when constantly observed.

Experimental creation of quantum Zeno subspaces by repeated multi-spin projections in diamond
N. Kalb, J. Cramer, D. J. Twitchen, M. Markham, R. Hanson & T. H. Taminiau
Nature Communications **7**, 13111 (2016)

In classical mechanics, which is applicable to flying arrows, this paradox was solved by differential calculus. In quantum mechanics, however, observations really do restrict the evolution of quantum systems; this is called the quantum Zeno effect. If an observable of a quantum state is measured, the system is projected into an eigenstate of this observable. For example, if a qubit in a superposition of '0' and '1' is observed, the qubit is projected into either '0' or '1' and will remain frozen in that state under repeated further observations.

While just freezing a quantum state by projecting a single qubit does not allow for computations, new opportunities arise when observing the joint properties of multi-qubit systems. The projection of joint observables in multi-qubit systems generates quantum subspaces. In this way, unwanted evolution between different subspaces can be blocked, while the complex quantum states within one subspace allow for quantum computations.

The scientists at QuTech experimentally generated quantum Zeno subspaces in up to three nuclear spins in diamond. Joint observables on these nuclear spins are projected via a nearby electronic spin, generating protected quantum states in Zeno subspaces. The researchers showed that an increasing number of projections enhanced the time that quantum information is protected, and they derived a scaling law that is independent of the number of spins. The presented work allows for the investigation of the interplay between frequent observations and various noise environments. Furthermore, the projection of joint observables is the basis of most quantum error correction protocols, which are essential for useful quantum computations.

More stable qubits in perfectly normal silicon

Gate fidelity and coherence of an electron spin in a Si/SiGe quantum dot with magnet, E. Kawakami, T. Jullien, P. Scarlino, D.R. Ward, D.E. Savage, M.g. Lagaly, V.V. Dobrovitski, Mark Friesen, S.N. Coppersmith, M.A. Eriksson and L.M.K. Vandersypen, *Proceedings of the National Academy of Science,* **113**, 11738–11743 (2016)

Qubits based on electron spins are looking more and more promising. It was thought that these could only be produced in the expensive semiconductor material gallium arsenide, but researchers in Delft, at the University of Wisconsin and at Ames Laboratory, led by Prof. Lieven Vandersypen of QuTech, discovered that the stability of qubits could be maintained 100 times more effectively in silicon than in gallium arsenide. Their research is published in PNAS.

“The length of time the superposition can be maintained before it spontaneously reverts to 1 or 0 is critical for an effectively functioning quantum computer,” VanderSypen explains. “In gallium arsenide, this is about 10 nanoseconds, but in silicon we achieved a time period that was 100 times longer. Using smart technologies, we were able to stretch this to 0.4 milliseconds. Although a coherence time of 0.4 milliseconds may not sound very long, for a computer it is nearly an eternity. Moreover, the gate fidelity in silicon is 10 to 100 times better. The gate fidelity is the measure of whether an operation performed on a qubit will actually work.’

The researchers used ‘standard’ silicon, an extremely cheap material of which there is an almost infinite supply: it is the main ingredient of sand. Earlier research by the University of New South Wales in Australia demonstrated that isotopically purified silicon-28 can produce even better results. Researchers believe that replacing gallium arsenide with silicon will be extremely important for the design of the quantum computer. The required technology for fabricating nanostructures in silicon has already reached an advanced stage in chip technology, and now, as the researchers hoped, silicon also proved to be a better qubit material.

Researchers at QuTech achieved this result in intensive collaboration with other researchers, including scientists of Intel Corporation, who joined a partnership with QuTech last year. The greatest challenge for quantum technologists now is to scale up the various qubits for use in circuits of multiple interplaying qubits. “At least hundreds of qubits – and preferably many more – will need to work together to make a working quantum computer,” says Vandersypen.

Electron spins talk to each other via a ‘quantum mediator’

Photo credit: Tremani

Coherent spin-exchange via a quantum mediator, T.A. Baart, T. Fujita, C. Reichl, W. Wegscheider, L.M.K. Vandersypen
Nature Nanotechnology, **12**, 26-30 (2016)

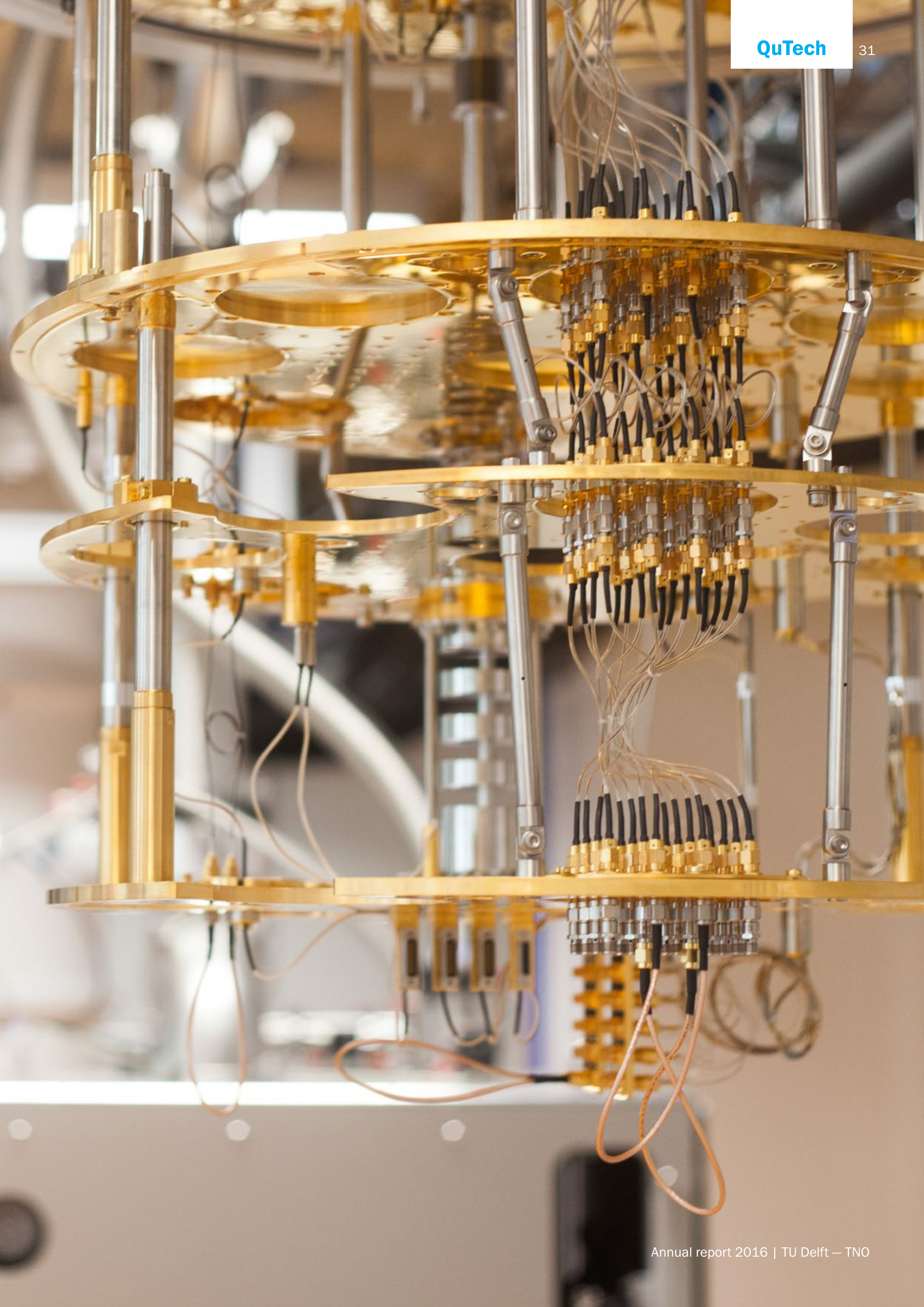
The unparalleled possibilities of quantum computers are currently still limited because information exchange between the bits in such computers is difficult, especially over larger distances. The QuTech research group of Lieven Vandersypen was the first to succeed in enabling communication between two non-neighbouring quantum bits in the form of electron spins in semiconductors. >>

>> Information exchange is something we hardly think about these days. “However, for the quantum computer – which is potentially much faster than the current computers –information exchange between quantum bits is very complex, especially over long distances,” explains Vandersypen.

“Previous research has shown that two neighbouring electron spins can interact with each other, but if the distance between them increases, this interaction sharply decreases,” says PhD student Tim Baart. “We have now managed to make two non-neighbouring electrons communicate with each other. To achieve this, we used a quantum mediator: an object that can exchange the information between the two spins over a larger distance.”

The research of Vandersypen and Baart forms an important step in the construction of a larger quantum computer, in which the communication between quantum bits over large distances is essential. Now that the concept of this quantum mediator has been demonstrated in practice, the researchers intend to increase the distance between electron spins and place other types of ‘mediators’ between the quantum bits as well.

Photo credit:
Kim van Dam



Partnerships

Photo credit:
Martijn Beekman

Scientists and Engineers from Delft and Zurich earn Major IARPA Grant for Qubit Development

An international consortium consisting of QuTech in Delft, ETH Zurich and Zurich Instruments has been granted 11 million dollars by IARPA (the US Intelligence Advanced Research Projects Activity) to develop a ‘logical qubit’ over the next 5 years. Under the name of QuSurf, this consortium will develop a cluster of physical quantum bits that can work together to reliably generate a logical quantum bit whose quantum data is protected from errors. In total, IARPA selected four international consortia for the endeavour, two which focused on trapped ions and two on superconducting quantum circuits, one of which was QuSurf.

QuSurf is being managed by associate professor Leo DiCarlo of QuTech. QuSurf is part of IARPA’s LogiQ programme, which is “seeking creative technical solutions to the challenge of encoding imperfect physical qubits into a logical qubit”.
Quantum computers offer huge potential to solve problems that are too challenging for modern computers, such as searching, factoring, and simulating physical and chemical systems in nature. Quantum computers can do this by exploiting a unique feature of quantum mechanics, a phenomenon called superposition: the possibility for a qubit to be in 0 and 1 at the same time. As DiCarlo explains, “Superposition opens the door to parallelization of computation, resulting in polynomial and even exponential speedups in certain problems. However, superposition is vulnerable to disturbance (noise) from the surrounding environment, and thus very fragile.”

Therefore, scientists worldwide are working on creating clusters of qubits that can be used to preserve quantum data robustly from such disturbances. “In our approach, ‘17’ is a magic number”, says DiCarlo. “That’s the number of physical qubits we need to get to work together to produce a logical qubit with 99.9% reliability, implying less than 1 error per 1000 operations. The IARPA funding provides us with the means to engage in the quantum science and engineering needed to get there.”

IARPA is a U.S. government agency dedicated to funding high-risk, high-payoff research. Results from QuSurf will be amply disseminated via peer-reviewed journals and conferences.

Microsoft intensifies quantum cooperation with QuTech

Microsoft announced that it is doubling its investments in quantum research. It is already an important private partner of QuTech and will be extending its cooperation with the Delft quantum institute. In addition, Microsoft will set up its own lab on the campus at TU Delft. The lab will be led by Leo Kouwenhoven, who was hired for this position by Microsoft. At the same time, he will remain a professor at TU Delft and continue to supervise PhD candidates and students.

Hanson is pleased with the increased cooperation with Microsoft. “TU Delft and Microsoft have been working together intensively since 2010, on the basis of annual contracts that were renewed each year. Microsoft has now expressed its ambition to engage in a more long-term collaboration with QuTech and to set up its own lab. This is very much in line with QuTech's own ambition to seek out intensive collaborations with technology companies.”
In this latest move, Microsoft is increasing its investment in the development of topological qubits, one of the five roadmaps of QuTech in Delft. Microsoft established its own quantum lab in Santa Barbara, on the campus of the University of California, in 2005. Besides a dedicated lab in Delft, Microsoft is also looking to set up a lab at the University of Copenhagen.

Quantum Europe

To fully reap the benefits of the quantum revolution, a European effort is required. Academia, industry and institutions need to join forces to set ambitious unifying goals. In this context, the EU Presidency organized the Conference Quantum Europe 2016 in close cooperation with QuTech and the European Commission.

On 17 and 18 May 2016, leading scientists, industrial CEOs and investors from all over Europe and the world gathered in Amsterdam to deliberate on how to place and keep Europe at the front of developing quantum technologies. They discussed how Europe’s capabilities in quantum technologies can create a lucrative knowledge-based industry,

Photo credit:
Martijn Beekman

leading to economic, scientific and societal benefits. The conference ‘Quantum Europe 2016’ paved the way for the European Flagship initiative.

The following notions were highlighted at the Conference:

- A European Flagship initiative is both timely and needed. Technologies are at a tipping point and global investments are rising.
- Ambitious unifying goals and roadmaps need to be established. The preparation and set-up should be efficient, open and flexible to ensure a quick start and a solid base.
- Partnerships with the private sector are key for commercialization and for the involvement of industries.
- High risk, high gain technologies should be at the core of the Flagship programme.
- Training and education at all levels is vital to attain a future workforce for quantum industries.
- International cooperation is necessary to meet the scientific and technological challenges ahead.

To organize the preparations of a European Flagship initiative, a High Level Group (HLG) will be established with a broad European representation of academia, industries and institutions. We are grateful for the full endorsement by policy makers, industry and academia, the support of Commissioner Günther Oettinger, and the willingness to form good partnerships.

Outreach

Photo credit:
Judith de Keijzer

Ronald Hanson has been awarded a Vici grant

Quantum internet: making interception impossible
According to quantum theory, particles such as electrons can be in two places at the same time, and they can be intertwined in such a way that they loose their identity. Hanson will explore this schizophrenic behavior over massive distances using lots of particles simultaneously, answering fundamental questions and investigating applications such as communications that cannot be intercepted.

> RONALD HANSON

Menno Veldhorst has been awarded a Vidi Grant

Despite major advances, a practical quantum computer is yet to become a reality. Physicists are currently attempting to make the building blocks of a quantum computer more reliable. Menno Veldhorst will do this by tackling damaging noise at the source, reducing the need for cooling, and upscaling to an initial quantum architecture.

Ronald Hanson wins Huibregtsen prize 2016

The Huibregtsen prize 2016 was won by Professor Ronald Hanson for his research on ‘Safe surfing on the quantum internet’. State Secretary Sander Dekker announced the winner during the annual Avond van Wetenschap en Maatschappij (Science and Society evening). The prize, which consists of €25,000 and a sculpture of ‘The Thinker’, is awarded each year for a research project that is scientifically innovative and likely to lead to beneficial practical applications.

Visit of New Scientist readers

The New Scientist invited their readers to visit QuTech. This was the second time in two years that QuTech and New Scientist organized an event like this for the public. Ronald Hanson gave a lecture and the visitors were given several lab tours. The visit was so popular that we had to set a maximum number of people for the event.

Launch QuTech blog | Bits of Quantum

In 2016, we launched our own blog. The idea for a blog came from our PhD Students.

Editorial team member Jonas Helsen: ‘We present fun bits about life as an academic but also posts that explain science in a correct but entertaining way. In the future, I would like some more special blog posts, including interviews, series about a specific topic and posts written by a PI. Since we wanted to make a blog for the whole institute, it seemed a good idea to involve as many groups as possible. We have a large group of enthusiastic co-writers. The things we do in our work are inherently difficult to understand. The world of the scientist is often unknown to others, so I think that "outreach" via science communication works best if scientists participate as often as they can.

QuTech’s Communication department arranged a workshop ‘Writing a blog’ for the editorial team and helps to support the main goal of the blog: ‘a view of the scientist’s world, both at the personal and at the academic level.’

The editorial team of the blog consists of four members:

- Jonas Helsen (Wehner Group)
- James Kroll (Kouwenhoven Lab)
- Adriaan Rol (DiCarlo Lab)
- Suzanne van Dam (Hanson Lab)

Visit the blog at:
http://www.blog.qutech.nl

Fysica Young Speakers Contest

Every year the Young Speakers Contest is a roaring success at FYSICA, the annual physics conference of the Netherlands' Physical Society (NNV). It's a contest for the best oral presentation of a young scientist. QuTech's PhD student Julia Cramer was runner-up at the contest of 2016 with her talk on 'Quantum error correction with spins in diamond'.

Media: In the Spotlight

Portrait of Ronald Hanson in *De Ingenieur* (December 2016)

Ronald Hanson in *MINDF*CK* (December 2016)

NPO3 Lecture Leo Kouwenhoven

In 2016, several lectures of the University of the Netherlands (Universiteit van Nederland) were broadcast on Dutch national television. The University of the Netherlands is an initiative of internet entrepreneur Alexander Klöpping, who also hosted the unique series of television lectures. Leo Kouwenhoven had the honour of giving one of these lectures. Kouwenhoven's lecture about the upcoming revolution of quantum computers was broadcast on Thursday October 19, 2016.

> LEO KOUWENHOVEN

Education

Photo credit:
Martijn Beekman

NEW: Quantum Cryptography, online learning on EdX

Stephanie Wehner created this interdisciplinary course together with Thomas Vidick, Assistant Professor of Computing and Mathematical Sciences at the California Institute of Technology, as an introduction to the exciting field of quantum cryptography. The course answers the question “How can you tell a secret when everyone is able to listen in?” Participants of the course learn how to use quantum effects, such as quantum entanglement and uncertainty, to implement cryptographic tasks with levels of security that are impossible to achieve by classical computations. The course is still open on the EdX platform.

Academy Courses: Towards a programme in Quantum Technologies

QuTech Academy offers the following campus and online programme for students of Applied Physics, Electrical Engineering, Computer Science and Mathematics.

MSc course “Fundamentals of Quantum Information” by Leo DiCarlo
Students learn to apply basic techniques used in quantum algorithms and examine basic examples of such algorithms.

MSc course “Electronics for Quantum Computation” by Edoardo Charbon and Koen Bertels
Students learn about the concepts of quantum computing while practicing to interface with a quantum computer in real life.

MSc course “Quantum Cryptography” by Stephanie Wehner
Students learn the fundamentals of quantum information theory and quantum cryptography.

MSc course “Quantum Hardware” by Ronald Hanson and Lieven Vandersypen
Students learn to understand and appreciate the key challenges in realizing quantum hardware and technology.

Online Course “Condensed Matter: Tying Quantum Knots” by Anton Ahkmerov in collaboration with Maryland University.
This course offers a simple and hands-on overview of topological insulators, Majoranas and other topological phenomena. The course is available year-round on the EdX platform.

Organization

Photo credit:
Frank van der Burg

Governance

The governance model of QuTech is shown in figure 1. The colours of the arrows and boxes indicate supervision, ownership, performance, justification, steering, advice and executive power.

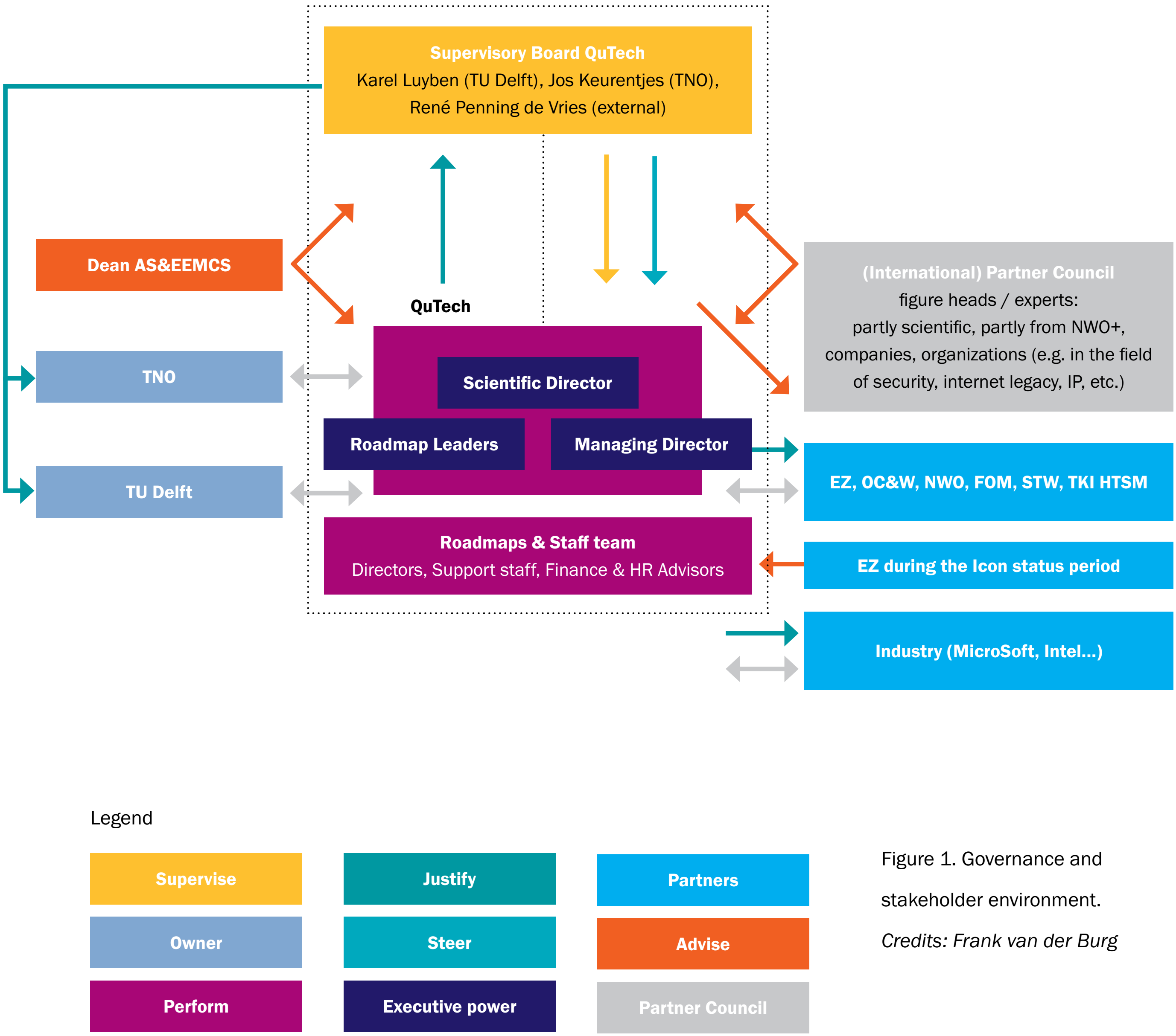
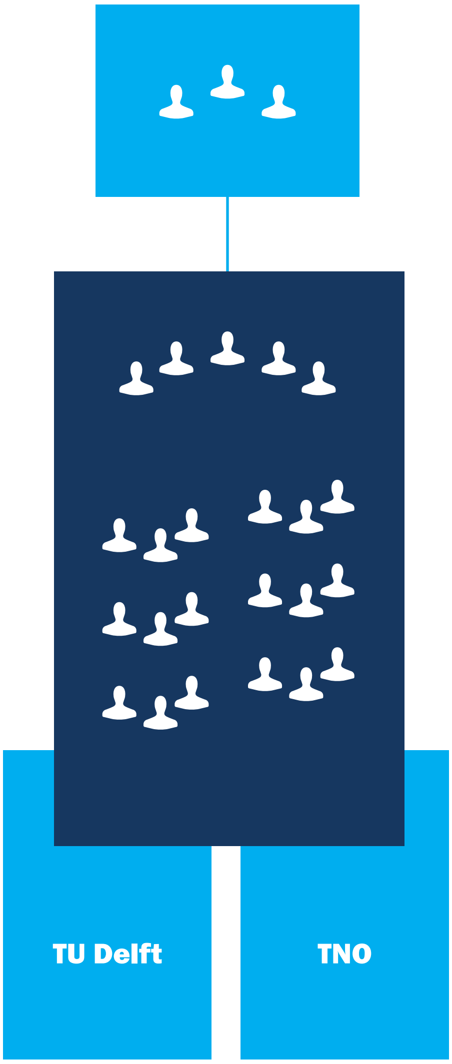


Figure 1. Governance and stakeholder environment.

Credits: Frank van der Burg

QuTech is organized along Roadmaps, as shown in figure 3. A large part of the activities take place within these Roadmaps. General support is organized centrally. Each Roadmap has a Roadmap Leader (RL), who is responsible for the principal investigators (PIs, both from TNW and EWI), postdocs, PhD candidates, MSc students, engineers and roadmap-dedicated technicians.



Supervisory Board: Karel Luyben, chair (Rector Magnificus TU Delft), Jos Keurentjes (Chief Scientific Officer TNO), René Penning de Vries (Figure Head ICT of the Ministry of Economic Affairs)

Roadmap Leaders: Leo DiCarlo, Leo Kouwenhoven, Lieven Vandersypen, Garrelt Alberts, Ronald Hanson, Stephanie Wehner

QuTech Faculty: about ~30 members (scientists)

Management and staff:

- Interim Scientific Director: Ronald Hanson
- Managing Director: Kemo Agovic
- Management Support staff: ~15
- Technical staff: ~20

Figure 2. QuTech governance, roadmap leaders, staff

Roadmaps are organized as shown for example in figure 3, where the roadmap consists of a number (n) of clusters led by a principal investigator (PI). There are two categories of senior scientists: team leaders and group leaders. Group leaders have wider supervision responsibilities.

In practice, a person can work in several roadmaps. The colored dots show the current contributions across the boundaries of the roadmaps.

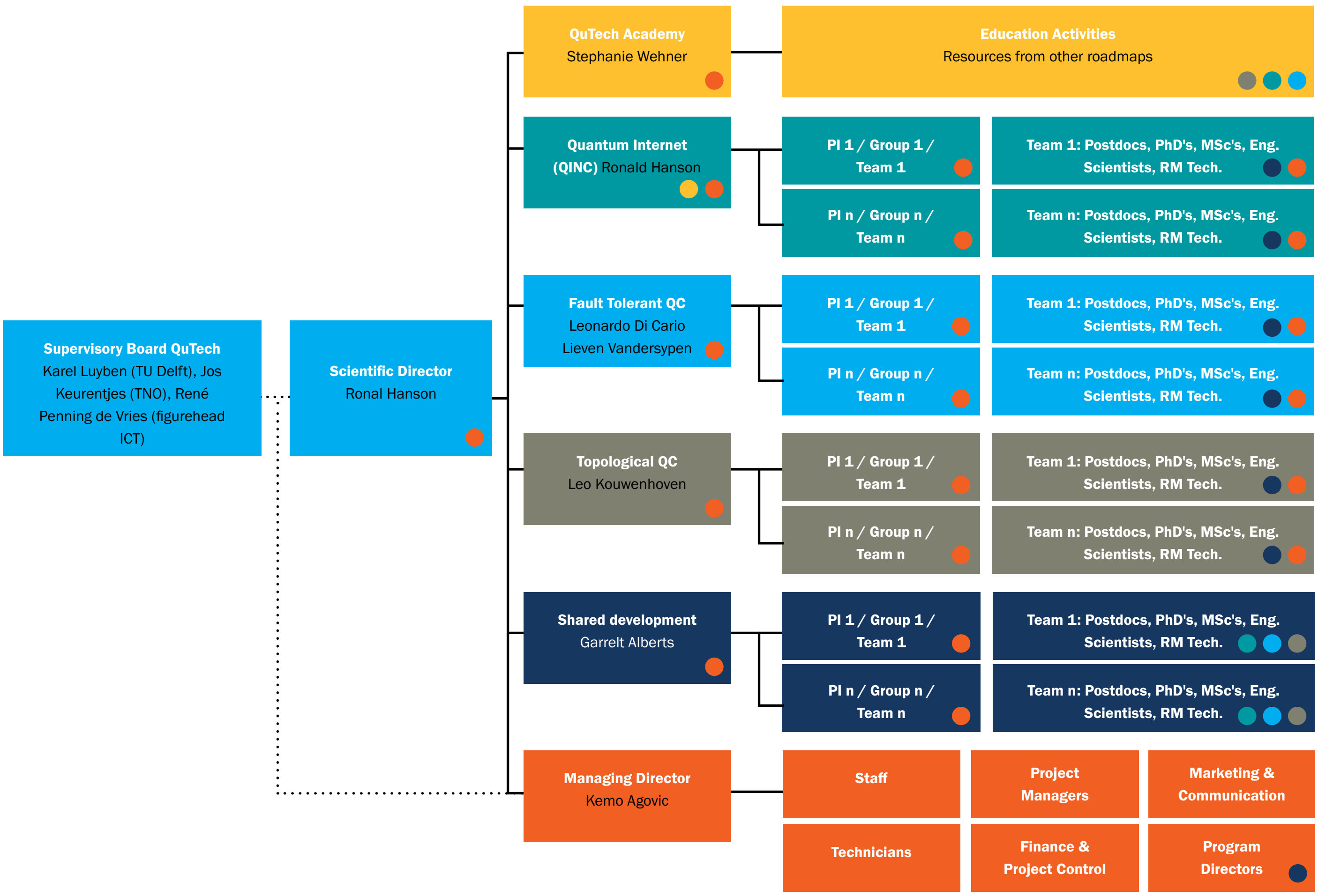
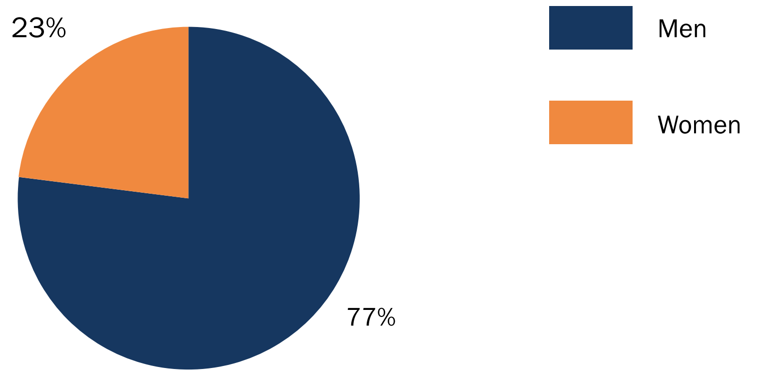


Figure 3: Organogram QuTech

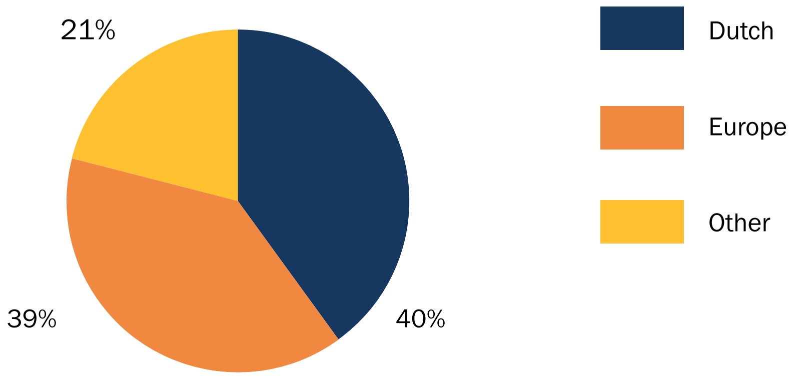
Statistics/graphics

At the end of 2016, 164 people were working for QuTech. This number is expected to increase in the coming years to about 250 in 2020.

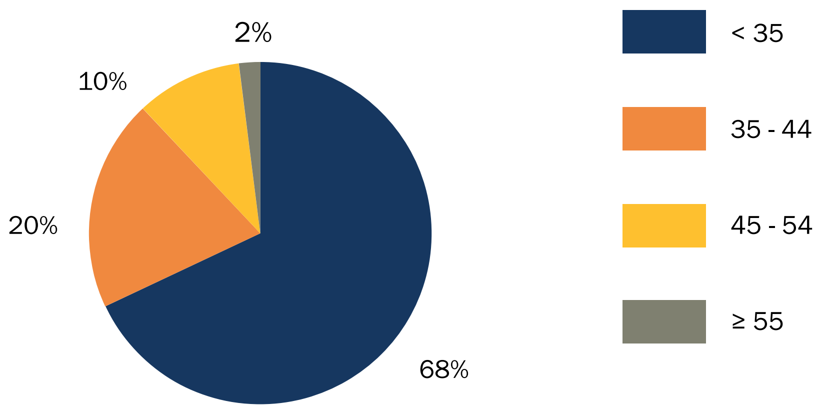
Gender



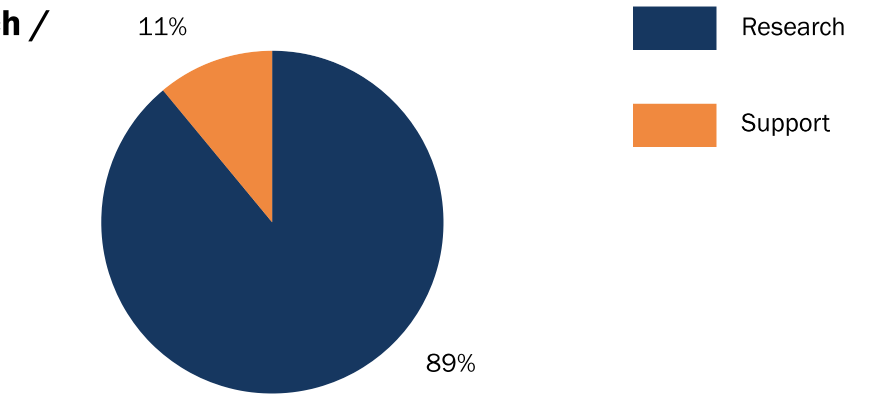
Nationality



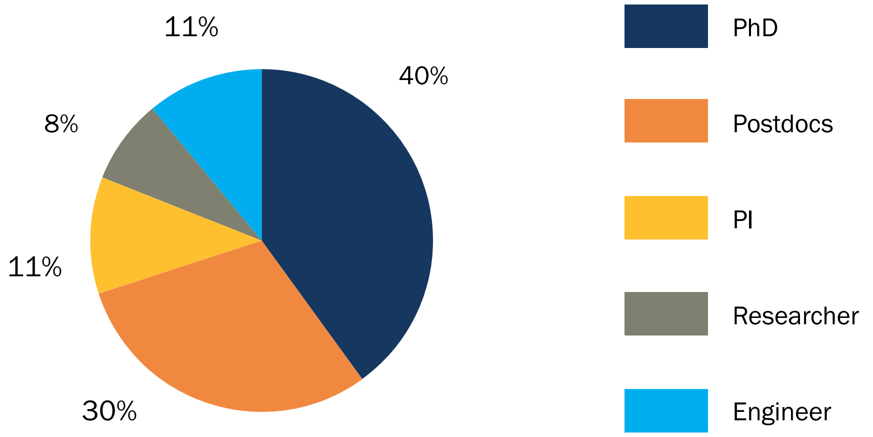
Age structure



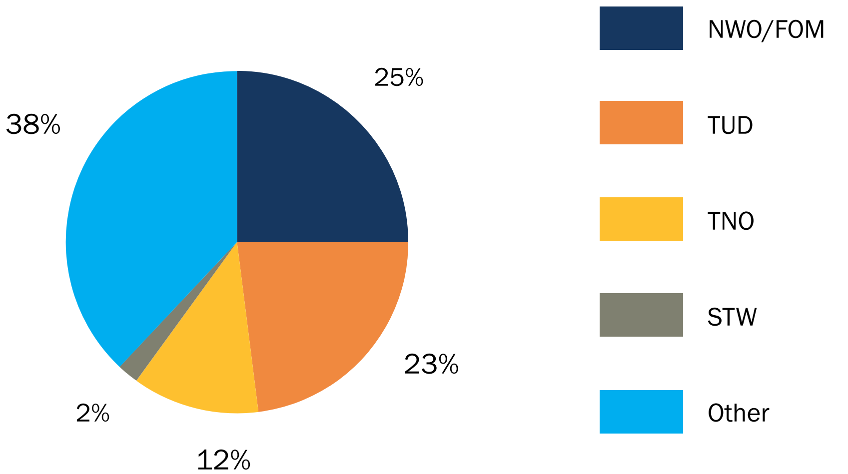
Ratio Research / Support staff



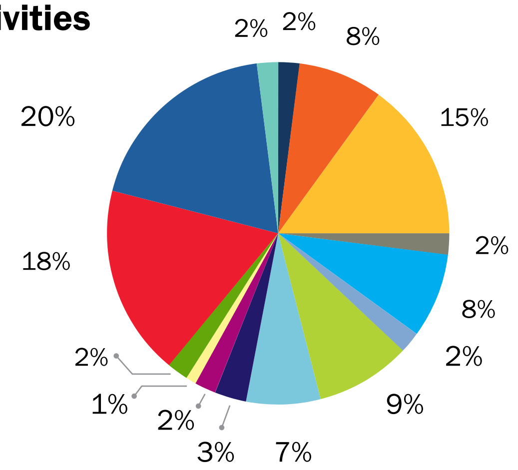
Research activities



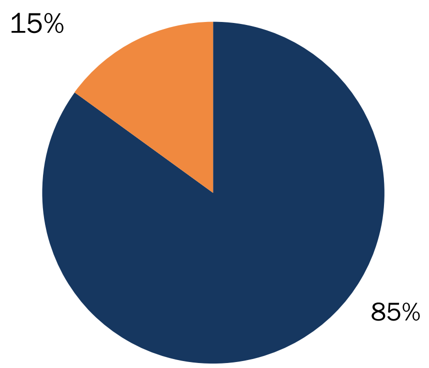
Funding source



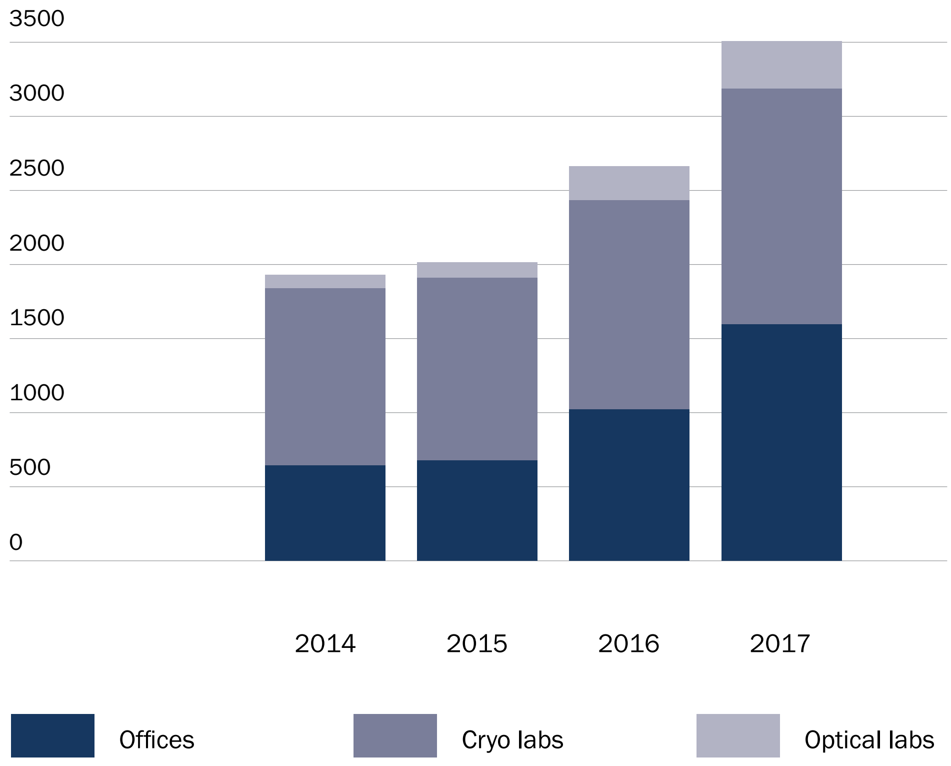
Research activities per funding source



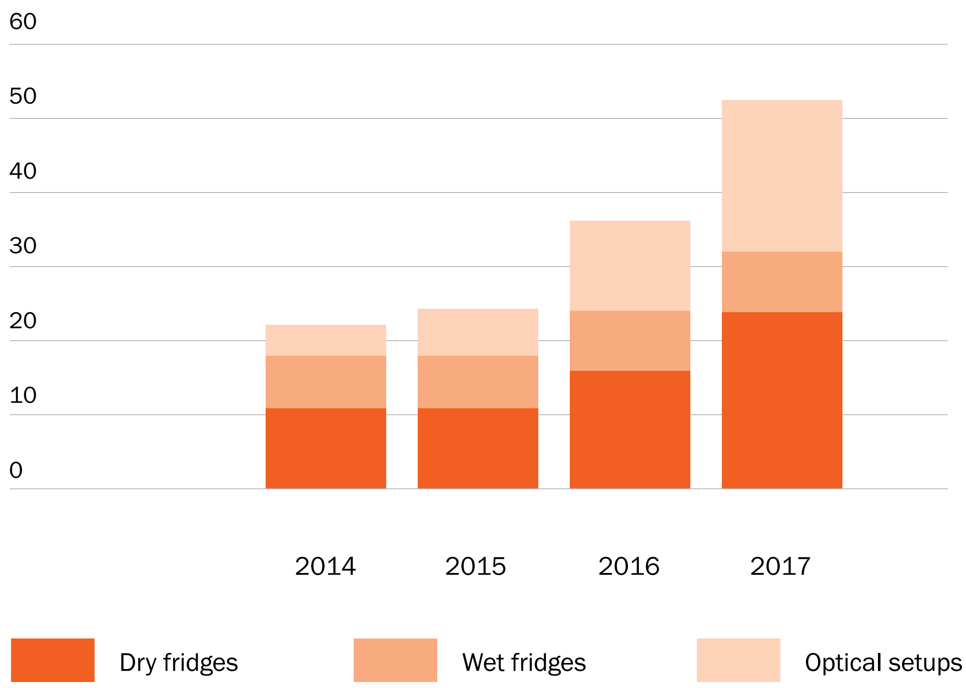
Temporary/ Permanent contract



Growth (m²) in lab and office spaces



Number of experimental setups



Financial overview

FUNDING AND EXPENSES

Photo credit:
Kim van Dam

QuTech started in 2014 with scientific staff and engineering and support staff. Both types of staff as well as the operating budget and the investments are funded by four main contribution sources: 1) TU Delft, 2) TNO, 3) industry funding and 4) public funding (EZ, HTSM TKI, NWO/FOM and STW).

This paragraph provides more information on QuTech's financials, which are based on a "partner covenant", the partners being the Ministry of Economic Affairs (EZ) and the Ministry of Education, Culture and Science (OCW), the Dutch Organization for Applied Scientific Research (TNO), Delft University of Technology (TU Delft), the Dutch Organization for Scientific Research (NWO), technology foundation STW and the Foundation TKI High Tech Systems and Materials (HTSM). All these partners agreed to financially support QuTech, as a strategic partnership, for the period from June 2015 to June 2025. (Allocation of the 2020-2025 budgets takes places after a positive evaluation in 2018). Other partners include Microsoft, Intel, IARPA and the European Union (H2020, FP7), their budgets are not taken into account in this financial overview.

The goal is to develop the knowledge and the technology for quantum computers and quantum internet and to build up a multiform ecosystem in the Netherlands in collaboration with national and international partners.

The budget includes both in-kind and in-cash contribution by the partners:

TU Delft in-kind	29	M€
TU Delft in-cash	20	M€
TNO in-cash*	50.75	M€
NWO/FOM*	36.18	M€
STW in-cash	9.6	M€
Total	**145.53**	**M€**

*The HTSM TKI allowance is included in the budgets of TNO and NWO/FOM.

TU Delft budget

The 10-year commitment of TU Delft includes the following contributions:

- In-kind contribution (29 M€)
  - Provided for housing, energy, clean-room, infrastructure and the profes-sors/ researchers/ personnel of the faculties TNW and EWI.
- In-cash contribution (20M€)
  - Provided from the TU Delft strategy funds.

The budgeted in-cash contribution of TU Delft for 2016 (2 million Euro) was fully spent for QuTech purposes (scientific and support staff, equipment). The in-kind contribution turned out to be higher than forecasted (8.9 million Euro per year) and is foreseen to grow in the coming years.

TNO budget

The 10-year TNO budget comprises the follow-ing contributions:

- TNO strategic funds (29.75 million Euro)
  - SMO (Samenwerking Middelen Onderzoek) of the High Tech Systems and Materials roadmap and the ICT roadmap
  - Early Research Programme
- TNO in-kind contribution (up to 4.68 million Euro)
  - 10% reduction on TNO hourly rates for TNO employees that work at Qu-Tech (almost) full time
- EZ via TNO (11.75 million Euro)
  - This is the EZ fund allocated to TNO for QuTech purposes
- TKI-allowance via TNO (9.25 million Euro)
  - This is based on the contribution of 1 million Euro per year made by private companies.

The budgeted contribution of TNO for 2016 was fully spent for QuTech purposes within the roadmap Shared Development, whereas TNO personnel mainly contributed to the other roadmaps' goals.

NWO/FOM budget

The 10-year NWO/FOM budget comprises the following contributions:

- NWO FOM (3.75 million Euro + 3.75 million euro intended)
    - Two QuTech senior researcher startup positions filled
    - One open senior researcher startup position
    - The material budget for 2016 was fully spent
- NWO FOM IPP (3.75 million Euro + 3.75 million euro intended)
    - Industrial Partnership Programme with Microsoft; this IPP was explicitly included in the partner covenant in accordance with the request of EZ and HTSM partners for private contributions exceeding 2 million Euro per year to participate in QuTech.
    - One senior researcher position filled, one open
    - One OIO position filled per 1-1-2017
    - Two postdoc positions filled, two open
    - 1 technician position filled, one open
    - The material budget has partially been spent
- Private contribution
    - 8 PhD positions filled
    - 7 post doc positions filled, one open
    - 2 technician positions filled, one open
    - one senior researcher position partially filled
    - a large part of the budget for equipment and materials is spent
- TKI-allowance via NWO/FOM
    - TKI-allowance generated by collaboration between Microsoft-TU Delft-FOM

TKIs explained

The Top Consortium for Knowledge and Innovation (TKI) facilitates the collaboration of ‘Holland High Tech’ (formerly ‘High Tech Systems and Materials’), knowledge institutions and industrial organisations on a multi annual TKI programme based on public and private funding. A TKI programme includes fundamental research, industrial research, and experimental development, or a combination of these types of research. The Dutch Ministry of Economic Affairs stimulates the private-public collaboration between research organizations and industrial companies with TKI allowances. The basic principle is simple: for every euro that a private company invests in R&D at a knowledge institution, the Top Consortium for Knowledge and Innovation receives € 0.25 from the ministry. The TKI uses these revenues for new public-private research.

The contribution of the FOM budget (NWO FOM, TKI-allowance via NWO/FOM, NWO/FOM IPP, Private Contribution) for 2016 has not been fully spent yet.

In order to facilitate the research and development and the growth of the QuTech organization (250 FTE in 2020, labs, facilities etc.) in the upcoming years, QuTech dedicated a budget for new initiatives, attracting new scientists, new labs (equipment) and personnel.
Therefore the contribution of the FOM budget (NWO FOM, TKI-allowance via NWO/FOM, NWO/FOM IPP, Private Contribution) for 2016 is not fully spent yet. QuTech and FOM have made budget adjustments for the coming year in order to facilitate the QuTech ambitions.

QuTech and NWO/FOM agreed that TKI-allowance should go directly to QuTech (via TU Delft). Agreement from HTSM TKI is provided by the HTSM TKI board.

The private contribution budget is allocated for research in the roadmap Topological quantum computing (scientific staff, postdocs, PhD’s, technicians, equipment).

NWO/FOM funding 3750 k€	total planned (k€)	spent until end of 2016 (k€)
Salary SR	394	starting 1-3-2017
Startup SR	670	455
Salary SR	223	17
Startup SR	467	open
Future hire startup	1496	open
CVD machine for QINC	500	546 (ordered in 2017)
Total	3750	472

NWO/FOM IPP funding 3750 k€	total planned (k€)	spent until end of 2016 (k€)
Salary SR	425	80
Salary SR	354	open
Salary oio	216	starting 01-02-17
Salary postdoc	142	59
Salary postdoc	142	starting 01-01-17
Salary postdoc	142	open
Salary postdoc	178	open
Salary technician	290	115
Salary technician	290	open
Material budget	1571	189
Ordered in 2016		571
Total	3750	443

STW budget

For the period 2014-2019 STW has granted 2.6 million Euro. The budgeted costs (PhD's, materials, equipment, cleanroom, engineers) are partially spent. The remaining budget will be spent according the plan on three open research positions (PhD/PostDoc).

STW budget 2600 k€	total planned (k€)	spent until end of 2016 (k€)
QINC roadmap - 2 PhDs (2x 48 months)	339	95
QINC roadmap - 1 PD (2x24 months)	250	113
QINC roadmap - 1 PD (24 months)	124	starting in 2017
QINC roadmap - 1 PD (12 months)	62	10
QINC roadmap - Equipment project 'Golflengte-conversie voor aansluiting op bestaande telefominfrastructuur'	100	91
QINC roadmap - equipment and demonstrator, materials, travel costs	260	221
FT roadmap - partial PhDs (26 months in total)	101	85
FT roadmap - 1 PhD (1x 48 months)	152	10
FT roadmap - partial PhD group (2,5 years)	117	open
FT roadmap - 1 PD group (24 months)	124	open
FT roadmap - 1 PD group (24 months)	124	starting in 2017
FT roadmap - programmer hire	550	333
FT roadmap - cleanroom	100	25
FT roadmap - materials, consumables, travel	197	7
Total	2600	990

Photo credit:
Pim Top

Appendices

CONFERENCES HELD IN DELFT

Photo credit:
Ernst de Groot | Haalbeeld

ScaleQIT

The ScaleQIT project is specifically designed to develop a conceptual platform for potentially disruptive technologies, to advance their scope and breadth and to speed up the process of taking them from the lab to the real world.

Facts & figures:

- 3 days
- 95 participants
- 10+ countries
- 25 talks
- 25 posters

Silicon Quantum Electronics Workshop

The Silicon Quantum Electronics Workshop focuses on silicon-based approaches to realizing quantum electronics circuitry, such as quantum computers. The purpose of the workshop is to unite the leading researchers, students, and postdocs in the field to discuss advances in silicon quantum device fabrication, measurement, modeling, and theory.

Facts & figures:

- 2 days
- 195 participants
- 15+ countries
- 34 talks
- 40 posters

LIST OF PEER-REVIEWED PUBLICATIONS 2016

Single-Spin CCD
T. A. Baart, M. Shafiei, T. Fujita, C. Reichl, W. Wegscheider, L. M. K. Vandersypen
Nature Nanotechnology **11**, 330-334 (2016); doi:10.1038/nnano.2015.291

Asynchronous reference frame agreement in a quantum network
Tanvirul Islam and Stephanie Wehner
New Journal of Physics, Volume **18**, 2016; doi: 10.1088/1367-2630/18/3/033018

To see the world in a grain of spins
Stephanie Wehner
Science **351**, 6278, 2016; doi: 10.1126/science.aaf0748

High Kinetic Inductance Superconducting Nanowire Resonators for Circuit QED in a Magnetic Field
N. Samkharadze, A. Bruno, P. Scarlino, G. Zheng, D. P. DiVincenzo, L. DiCarlo, and L. M. K. Vandersypen
Phys. Rev, Applied **5**, 044004 (2016); doi: 10.1103/PhysRevApplied.5.044004

Sifting attacks in finite-size quantum key distribution
Corsin Pfister, Norbert Lütkenhaus, Stephanie Wehner and Patrick J Coles
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PhD defenses

We congratulate the following researchers on successfully defending their PhD research at QuTech.

Date	PhD defense
January 7	Maaike Bouwes Bavinck – Engineering the properties of nanowire quantum dots
February 1	Pasquale Scarlino – Spin and valley physics in a Si/SiGe quantum dot
February 19	Arjan Beukman – Topology in two-dimensional systems
February 26	Kun Zao & Vincent Mourik – Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices
April 29	Bas Hensen – Quantum nonlocality with spins in diamond
May 23	Tim Baart – CCD operations and long-range coupling of spins in quantum dot arrays
September 13	Erika Kawakami – Characterization of an electron spin-qubit in Si/SiGe quantum dot
September 30	Iman Esmaeil Zadeh - Integrated quantum photonics, from modular to monolithic integration
December 2	Julia Cramer – Quantum error correction with spins in diamond

Students

We congratulate the following students with obtaining their BSc or MSc degree at QuTech!

MSc	
Lisanne Coenen	Tom Timmerman
Zubin Ramlakhab	Abou el Mahdaoui
Jeroen Busz	Arian Stolk
Daniel Bouman	Thijs Stavenga
Jaco Morits	Sarwan Peiter
Olmo Kortenbosch	Marius van Eck
Willem Hekman	Sten Kamerling
Nick van Loo	Gautham Rangasamy
Luka Bavdaz	Rosario M. Incandela
Yoram Vos	Bahador ValizadehPasha
Hans Keur	Leon Riesebos
Laurens Janssen	

BSc	
Rick Koster	Remco van der Meer
Gijs van Hoogstraten	Benjamin Vervliet
Thomas Schiet	Christiaan Meijer
Marianne Teng	Sjoerd de Jong
Sander Blom	Peter Vinke
Tobias Bonsen	Steven de Rooij

QUTech