Preface February 2018

The five highlights of January 2018

Tackling the challenges of 5G with hybrid III-V/Si technology

Engineering better batteries to drive the electrified future

What chip technology can do for cell therapy

“Metrology is not a cost factor, but a profit center”

Lost in information? ONTOFORCE’s search engine connects your data
“Our unique collaborative model is the rock on which imec’s success has been built”

When imec’s very first CEO – Roger Van Overstraeten – founded imec, he strongly believed that working together would be the key to success for our research center, which at the time was still a small operation. Initial responses from the industry and the world of research were somewhat skeptical: how could imec ever become a success in such a small country as Belgium without any infrastructure or industry specialized in semiconductor technology? Yet imec’s ambitions were brought to fruition. First by Roger Van Overstraeten, then by Gilbert Declerck. And since 2009 I have been at the helm of what is now a 3500-strong team of leading scientists from all around the world.

In January, I was awarded the ‘SEMI Sales and Marketing Excellence Award’ during the Industry Strategy Symposium held in Half Moon Bay, California. My first reaction was one of surprise that we were receiving this specific award. Normally, we receive recognition for our scientific excellence or technological expertise.

But I soon came to realize that this award was a wonderful appreciation from the industry for the way we join forces with our partners (our ‘customers’), as well as for the many years of effort we have put in to developing a unique collaborative model in which all of the parties in the supply chain may partake, whether they are big or small, whether they compete or not.
Our current ecosystem of companies originally consisted of the chip industry supply chain, ranging from the suppliers of devices and equipment makers, through to the chip and system manufacturers. But in recent years, it also increasingly includes companies that produce applications across a wide range of industries, from auto manufacturers right through to medical companies. It was a major challenge to keep our collaborative model intact along the way – especially during the period of consolidation in the chip industry – but we managed!

Our secret recipe? Listening! We visited our partners regularly and listened carefully to what they needed, what they were concerned with and what they expected from us. And then we pulled all that knowledge together, analyzed it, and tried to apply the conclusions to our own ideas and those of other partners. Sometimes we had to adjust or cancel some interesting research programs and start new ones. It was all about making the right choices. For each of our partners, our research has to be of at least equal value – or even greater value – than the research that they are able to carry out individually, within their own company.

In the February edition of our magazine, you will read about just such a new program that we embarked on recently: high-speed analog/RF, with the aim of developing 5G RF front-end technologies for mobile handsets. Also the article about 3D batteries demonstrates just how important collaboration is – across the whole supply chain – when it comes to producing a compact, stable and efficient battery. In the end, though, it is not awards (such as ‘SEMI Sales and Marketing Excellence Award’) that are the most satisfying accolade for our collaborative model, but the success of the technologies and products that we develop together with our partners.

Luc Van den hove,
President and CEO of imec
CES 2018: imec announces important next steps in stress, emotion and disease detection

As part of its imec.ichange research program (which aims to stimulate and encourage healthier lifestyles using wearable technology), imec announced at this year’s Consumer Electronics Show (CES) in Las Vegas that it has collected the largest multi-sensor dataset worldwide on stress detection. Imec’s ‘Stress in the Work Environment’ (SWEET) study captured data from more than 1,000 people and is the first large-scale study that used clinical-grade wearables to establish the link between mental stress and physiological symptoms in daily life.

Moreover, imec demonstrated a prototype of an electroencephalogram (EEG) headset that measures emotions and cognitive processes in the brain – representing a major breakthrough in emotion measurement for therapeutic, learning and gaming applications.

And did you miss out on Chris Van Hoof’s talk on how to fight chronic disease using micro-wearables for nanodiagnostics? Check out the 15-minute speech of imec’s Connected Health Solutions R&D Lead [here](#).
Imec introduces hyperspectral imaging breakthroughs at SPIE Photonics West

At SPIE Photonics West, imec demonstrated its very first shortwave infrared (SWIR) range hyperspectral imaging camera. Imec’s SWIR camera integrates CMOS-based spectral filters together with InGaAs-based imagers, thus combining the compact and low-cost capabilities of CMOS technology with the spectral range of InGaAs. As the SWIR range provides discriminatory information on all kinds of materials, this new camera paves the way to hyperspectral imaging applications in food sorting, waste management, machine vision, precision agriculture and medical diagnostics.

In the hyperspectral realm as well, imec presented its second-generation high-speed SNAPSCAN camera, a proprietary imec concept that combines a high signal-to-noise ratio and high spatial and spectral resolutions with the user-friendliness of a snapshot hyperspectral imaging camera. Imec’s second-generation hyperspectral camera uses an ultrasonic speed piezo motor stage and innovative software to enable the acquisition of high resolution hyperspectral images in less than 200ms. It will enable imec’s partners to develop consistent spectral libraries and customized solutions faster than ever, and this for a wide range of new (medical) applications.

First imec open.minds event rallies close to 1,000 imec colleagues in Brussels

At the very end of December, close to 1,000 imec colleagues from across the organization gathered in Brussels to get a roundup of how imec performed in 2017 and to get a good perspective on the technological challenges imec plans to tackle in the next couple of months.

But, first and foremost, the open.minds event aimed at putting the continuous commitment of the imec employees center stage – with 13 teams receiving a much-valued open.minds award in categories as diverse as “Operational Excellence”, “Scientific Recognition” and “National & International Media Coverage”.

Do you have what it takes to receive one of the 2018 open.minds awards? We’re constantly looking for the next generation of ‘Forward Thinkers’ to join our ranks! Check out imec’s job opportunities here.

Imec puts its cell therapy technology center stage at the Precision Medicine World Conference

At the Precision Medicine World Conference, Liesbet Lagae (Director Life Science Technologies at imec) gave a talk on how imec technologies help streamline immunotherapy workflows – using silicon chip technology to build fully integrated solutions that combine microfluidics, photonics based biosensors, PCR, and single cell manipulation.
Interested in learning more about the imec technologies that will function as the building blocks for bioprocessing and the delivery of future, personalized therapies? Download imec’s brand-new white paper on how nanoelectronics drives accuracy, improves turnaround times and increases yields in cell therapy workflows here. Or check out our totally revamped life sciences web pages.

**New imec.digimeter comes with a tool to map your mobile DNA**

Did you know six in ten Flemish smartphone users impose rules on themselves to keep their smartphone usage under control? That is one of the conclusions of the new imec.digimeter report that inquired more than 2,300 Flemings about their digital habits. The latest survey shows that smartphones and computers have become an indispensable part of our lives, that the use of digital services continues to boom, and that digital dependency is rising – especially among those in their 20s and 30s. In other words: the end of the ‘digibesity’ phenomenon is not yet in sight. Hence, the imec.digimeter researchers have now expanded their yearly study with a ‘Mobile DNA’ app that allows anyone to map – and get a better understanding of – his or her media usage. More about the imec.digimeter here.
Intro

Although the standards for 5G have not been finalized yet, general expectations for this fifth generation of mobile networks are high. 5G is expected to enable extreme mobile broadband with data rates up to 10Gbps, in order to meet, for example, the future demand for video streaming. It also promises to enable machine-to-machine communication in support of the Internet-of-Things Platform. And it is expected to allow for critical machine communication – such as driverless cars communicating with each other and with neighboring base stations. These applications typically require extremely high reliability, and low latencies, below 1ms.

To allow for this almost unlimited experience, innovations are required in the overall network infrastructure (including base stations and small cells) as well as in the technologies for mobile devices.
In the first phase of the 5G deployment, wireless communication radios will most probably operate in the sub-6GHz radio frequency (RF) bands. But to cope with the upcoming spectrum scarcity within these bands, bandwidth is being sought at millimeter-wave (mm-wave) bands – more specifically the RF bands within the 24 to 100GHz range. The introduction of these mm-wave frequencies will have a significant impact on the overall 5G network infrastructure. For mobile handsets such as smartphones, this translates into an increasing complexity of the RF front-end modules – that contain e.g. the transmitter/receiver, bandpass filters, power amplifiers and local oscillators. Both sub-6GHz bands and mm-wave bands will now need to be enabled in one common architecture, and devices will probably need to access several bands simultaneously. Therefore, higher speed front-end devices than currently used in 4G-LTE are needed. Also, the mm-wave functionality will have to be implemented in battery powered mobile devices, which will put severe restrictions on the power consumption of the mm-wave circuits. To meet all these challenges, we will need high-speed devices that have both a high output power and a high power efficiency.

Schematic representation of the increased RF-front-end-module complexity with every generation of mobile communication.
State-of-the-art high-speed devices

Today, several device technologies are being used for RF applications, including for example RF SOI and SiGe technologies. Of particular interest is the use of III-V circuits. III-V high electron mobility transistors (HEMTs, GaAs or InP based) are already in standard use for high-frequency applications. The RF performance of these devices significantly outperforms that of standard Si CMOS devices, especially when considering FinFETs which suffer from intrinsically higher parasitics. Next to that, III-V heterojunction bipolar transistors (HBTs) have also shown great potential when high speed requirements need to be fulfilled. And, although originally designed for high-power applications, III-N devices (such as GaN-based HEMT devices) have demonstrated high-frequency performance exceeding 400GHz.

So far, Si and III-V (or III-N) circuits have been fabricated and packaged separately, and then later assembled on the same carrier substrate. This approach however does not really allow for the optimization of the performance, the reduction of power, cost and form factor, and the increase in the complexity of the circuits. Reducing the form factor will however be essential, as many different dies will be needed to fabricate the RF front-end module, and space within the mobile handset is limited. The fabrication of III-V-based devices presents other challenges. In general, (lab-like) fabrication processes and materials are being used that are not compatible with cost-effective high-volume Si manufacturing. In addition, these III-V HEMT and HBT devices are mostly fabricated on smaller size (2 to 3 inch) non-Si substrates.

High-speed analog/RF: addressing the 5G performance needs for mobile devices

To enable RF front-end modules for future 5G mobile handsets, imec has launched the Industrial Affiliation Program ‘High-speed analog/RF’ – starting as from January 2018.

Within this program, imec and its partners will jointly explore hybrid Si/III-V to enable highly performant RF devices with high output power and high power efficiency.

On the III-V side, imec will explore several device architectures, including III-V (GaAs and InP) and III-N HEMT devices, III-V HBT devices, as well as III-V and III-N MOSFET devices.
In a first phase, the program will focus on integrating III-V and III-N standalone devices on a 200mm and 300mm Si platform. This will require the development of specific process steps and modules that have been identified as critical for the integration. Examples are modules that reduce the parasitics in these non-Si devices; the epitaxial growth of RF-compatible III-V and III-N buffer layers (which are needed to compensate for the lattice mismatch between the III-V and III-N materials and Si); modules for gate stack optimization; and defectivity assessment. Also, the use of CMOS-compatible Cu or W based back-end-of-line processes will be investigated, to replace the Au-based interconnect schemes typically used for the non-Si devices. During this first phase, the program partners will also look into the scalability of the III-V and III-N devices. Making smaller III-V/III-N devices is currently challenged by the current-driven operation mode of the devices, and by the patterning technologies that are being used.

In a second phase, the program will target the co-integration of the specialized high-speed III-V/III-N devices (used for the RF transceiver) with standard Si CMOS (used for the digital signal processing). This way, a higher degree of integration will be achieved for all building blocks of the RF front-end module. Imec sees two advantages of this co-integration. First, it will further reduce the overall form factor of the front-end module. And second, with the help of digitally assisted RF circuit design, hybrid Si/III-V technology can be seen as a way forward to improve the energy efficiency of the overall circuit. Several approaches for the co-integration will be explored, such as monolithic or 2D integration (with the Si devices and III-V/III-N devices in the same plane) or 3D integration (via either 3D stacking, or sequential 3D through the sequential processing of different device layers).

**Leveraging existing technology solutions**

*Imec houses several key technologies under one roof and is therefore uniquely placed to develop hybrid Si/III-V RF front-end technologies for 5G applications.*

For example, the program partners will make use of imec’s expertise on III-V-on-300mm Si technologies — developed in the context of CMOS scaling. More specifically, imec will bring in extensive knowledge of III-V technologies, including III-V epitaxial growth on Si, gate-stack and contact optimization, and reliability assessment. Imec can also rely on an extended CMOS toolset, such as 193nm (immersion) lithography and CMOS compatible back-end-of-line modules.

The analog/RF program will also leverage imec’s expertise in III-N technology, such as our GaN-on-200mm Si technology platform. Originally developed for power electronics applications, it will be investigated how these GaN-on-Si devices can be tuned towards RF applications. For example, the buffer layers will have to be made RF compatible, and the devices will have to be re-designed for lower operating voltages.
And we will use our expertise on sub-6GHz and mm-wave wireless communication technologies. Close collaboration with the modelling and circuit design teams will be essential to define the required device targets for 5G applications. Their work will be supported by the use of advanced circuit design techniques such as RF design and technology co-optimization (RF DTCO).

Bringing together expertise in III-V and III-N technology, CMOS technology, wireless communication technologies, and in modelling and circuit design technologies will be crucial to the development of true RF front-end technology solutions for 5G – from device to circuit level.

**Example: reliable III-V gate stacks – a key module for III-V MOSFET integration**

Besides HEMT and HBT devices, imec will explore III-V-based MOSFET devices for RF front-end applications. Interest in these devices comes from their lower gate leakage and favorable scalability.

The development of reliable III-V-based MOSFETs is however challenged by the formation of gate stacks with low interface and gate dielectric defects. Devices that have e.g. InGaAs as a channel material, most commonly use Al₂O₃ as a dielectric material within the gate stack. But the excessive interaction of channel charge carriers with oxide defects (present within the dielectric material or at the semiconductor-oxide interfaces) significantly impacts the overall device reliability. This interaction translates into trapping/de-trapping of the charge carriers by the oxide defects, and causes, for example, instability of the device threshold voltage, or frequency dispersion in the C-V characteristics.

![Various manifestations of oxide traps in the electrical characteristics of InGaAs devices with high-k gate stacks: (a) frequency dispersion of MOS C-V characteristics; (b) $V_{th}$ and SS instability; (c) $g_{m}$ instability in planar MOSFETs; (d) hysteresis of the $I_D-V_G$ characteristic of a FinFET.](image-url)

At the 2017 IEDM conference, imec gave an invited talk, reviewing recent studies on oxide defects in InGaAs gate stacks for MOSFETs. An overview was given on the recent understanding of charge trapping, and guidelines were presented for developing reliable III-V gate stacks. These insights will highly contribute to solving one of the major integration challenges of III-V MOSFET devices on a Si platform.
Within the study, various trap characterization techniques, such as positive bias temperature instability (PBTI) and defect capture-emission-time maps, were performed on a variety of InGaAs device test vehicles (including planar MOSFETs, FinFETs and nanowires). With these techniques, we can determine, for example, the shift in threshold voltage induced by charge trapping, the time-to-failure, the device ageing, and the accessible defect density in an oxide. We observed that the PBTI signatures are common for all device architectures, while scaling introduces additional challenges. It was also found that device aging is dominated by the slow traps (slow capture/emission times), while the shift in threshold voltage is mainly caused by fast traps (fast capture/emission times).

Alternative characterization techniques such as multifrequency C-V dispersion and hysteresis were used to determine the distribution of the oxide defect levels (above and below the conduction band of the InGaAs channel). This distribution of energy levels dictates the charge trapping transients in the Al₂O₃-based InGaAs gate stacks. From these measurements, we found a more favorable distribution of defect levels when using alternative dielectrics such as HfO₂.

The presented characterization of oxide traps is a crucial step towards the demonstration of reliable III-V gate stacks.

As an example, we propose an alternative, sufficiently reliable gate stack by replacing Al₂O₃ with a novel inter-dielectric layer (developed by ASM), capped by a thin LaSiOₓ layer and HfO₂.

Conclusion

The advent of 5G will not only bring great new opportunities but also new challenges for the technologies enabling this next-generation of mobile communications. Not only innovations in the overall network infrastructure will be needed, but also in the technologies for the mobile devices themselves. Imec’s program on High-speed analog/RF aims at providing the required RF front-end module technologies for mobile handsets operating at sub-6GHz and mm-wave frequencies. In a first phase, focus will be on integrating high-speed III-V and III-N standalone devices on a 200mm and 300mm Si platform. In a second phase, the program partners will jointly explore the co-integration of these device architectures with standard Si CMOS. The program leverages imec’s broad expertise in III-V-on-300mm Si technologies, III-N technology, CMOS technologies, wireless communication technologies, and in modelling and circuit design technologies. Imec invites companies – material and equipment suppliers, IDMs, foundries and system companies – to become partner of the program.
Biography Nadine Collaert

Nadine Collaert received an M.S. and Ph.D. degree in electrical engineering from the ESAT Department, KU Leuven, Belgium, in 1995 and 2000, respectively. Since then, she has been involved in the theory, design and technology of FinFET devices, emerging memory devices, transducers for biomedical applications and the integration and characterization of biocompatible materials (e.g. carbon-based materials). From 2012 until April 2016 she was program manager of the imec LOGIC program, focusing on high mobility channels, TFET and nanowires. Since April 2016 she has been a distinguished member of technical staff, responsible for the research on novel CMOS scaling approaches based on heterogeneous integration of new materials with Si and new material-enabled device and system approaches to increase functionality. She has authored or co-authored more than 300 papers in international journals and conference proceedings, and she holds more than 10 patents in the field of device design and process technology. She has been a member of the CDT committee of the IEDM conference and she is still a member of the Program Committees of the international conferences ESSDERC, ULIS/EUROSOI and VLSI Technology Symposium.
Recently, imec announced a major breakthrough in solid-state battery technology. The research center engineered a new solid electrolyte that has an exceptionally high conductivity of up to 10 mS/cm. According to imec’s Dr. Philippe Vereecken, there is even potential to reach 100 mS/cm, paving the way for a whole new generation of batteries for applications covering the spectrum from small portable electronics to electric vehicles and stationary grid storage. To create optimal solutions for these applications, with a higher energy density, faster charging time, longer lifetime, and an improved safety, imec’s researchers are now looking to further improve the innovative electrolytes and integrate them with thick-layered nanoparticle electrodes with innovative functional coatings.

Since the introduction of the rechargeable Li-ion battery in 1991, it has become the technology of choice for portable energy storage. With its available high energy density, it could store enough energy in a small volume to power the surge of portable electronic devices. But more and more, Li-ion technology is also chosen as the preferred solution to drive larger systems such as electric vehicles or stationary home batteries that store renewable energy and balance the smart electricity grid. These applications, however, place new demands on the battery technology that Li-ion cannot always fulfill.

For electric vehicles, e.g. a key consideration is to have batteries with as low a weight and volume as possible. That calls for an even higher energy density than is possible today. Also, the maximum current flow becomes more of an issue: the time to recharge critically depend on how fast energy can flow in and out of the battery. And as we consider economically critical applications such as grid storage and grid balancing, the cost and related high lifetime also become a key consideration.
Today's Li-ion technology has some room to improve, but not enough to sustain the future requirements for all these applications. So we need innovation: new cathode and anode architectures with higher energy densities and new electrolytes that can deliver the necessary conductivity and that are safer.

**Why use solid-state electrolytes?**

An essential component of the battery is the electrolyte, the medium through which the Li-ions migrate between the anode and cathode. In today's batteries, that electrolyte is a liquid. It fills the open spaces inside the porous membrane that is placed between the anode and the cathode. And it also soaks the powder electrodes, completely filling all pores and spaces and providing as much contact as possible between the electrodes and the electrolyte. Crucial for a battery's properties is a high ion conductivity, i.e. the speed by which the ions can move about the electrolyte (expressed in mS/cm or milli-Siemens per centimeter). The higher that ion conductivity, the faster a battery can charge. And conversely the more power it can release.

Replacing the liquid electrolyte with a solid would allow removing the membrane and placing the electrodes much closer together, making the battery more compact and thus delivering a greater energy density. Until recently, however, the solid-state electrolytes didn't have the required conductivity. One such electrolyte is LiPON (lithium-phosphate-salt doped with nitrogen), which has an intrinsic conductivity of only $10^{-7}$-$10^{-6}$ S/cm. But that means the electrolyte layer can be no thicker than one micrometer. The only practical application of such solid-state electrolytes is therefore in planar thin-film batteries in which the ions have to travel only a short distance. Such batteries are great for micro-storage, e.g. in combination with energy scavenging for autonomous sensors, but for other applications their capacity is inadequate.

**A breakthrough electrolyte**

To engineer new solid electrolytes with an ion conductivity that is high enough to drive large-capacity cells, imec's scientists have been looking towards composite materials. In November last year, a first result was announced: a new way to engineer nanocomposite materials that amplifies the ion conductivity to exceed that of liquid electrolytes.
A distinguishing feature of the new solid nanocomposite electrolyte (SCE) is that it is applied as a liquid – via wet chemical coating – and only afterwards is converted into a solid. That way it is perfectly suited to be casted into dense powder electrodes where it fills all cavities and makes maximum contact, just as a liquid electrolyte does. In addition the material retains some elasticity even after solidification, which is critical for batteries as the electrodes expand and contract during charging and discharging. The possibility of wet application of the SCE precursor makes this technology also compatible with current Li-ion battery fabrication processes. This will make it easier for the industry to adopt it compared to materials for which disruptive fabrication processes would have to be put in place.

Imec’s solid electrolyte is a composite of a nanoporous oxide matrix with selected ionic compounds and additives. Unique is that the ionic conductivity of the final nanoengineered product is higher than that of the Li-salt electrolyte without the oxide matrix. That effect is attributed to an enhanced mobility of the Li-ions along the oxide surface. As the material has an extremely large surface area of about 500m²/mL – comparable to an Olympic swimming pool folded into a shot glass – the result is a Li-ion conductivity exceeding 10 mS/cm at room temperature.

With this new material, imec’s engineers have already built a cell prototype using standard available technology for the electrodes: LFP (LiFePO₄) for the cathode and LTO for the anode. Compared to a similar cell made with liquid electrolyte, the new cell reached 80% of the capacity at a charging rate of 1 C (h⁻¹). And there is reason to hope for even better results: computations show that the new SCE can in theory be engineered to sustain conductivities of up to 100 mS/cm, which is a target set by imec in its open innovation research program.
Smaller particles, higher energy density

To get at the energy densities required for e.g. electric vehicles with long driving range, more will be needed than new electrolytes. We will also have to engineer the electrodes to contain more active material. The solution seems straightforward: use smaller electrode particles, which can be packed even more densely in the electrodes. As these will have a higher surface contact per volume, this should also improve the power and charging rate of the cell.

But here the issues for improvement are the same as with liquid electrolytes: a greater contact surface also greatly promotes surface reactions and thus material degradation. Therefore, to extend the stability window, imec’s experts work on a solution applying an ultrathin buffer layer to the particles through ALD (atomic layer deposition), another core expertise of imec. These layers should of course be chemically inert and highly conductive, lest they behave as insulators and neutralize the enhanced surface again.

With such a surface passivation, it will become possible to apply smaller particles in the electrode. And because the solid-state electrolyte allows applying thicker electrodes, this also opens the potential for batteries with a higher energy density, considerably exceeding 800 Wh/l (at a charging rate of 2C or more; i.e. a battery is charged in less than 30 minutes).
To extend the energy density even more, towards 1,000 Wh/L and beyond, imec is working on lithium metal anodes. Lithium metal has the highest energy density possible for the anode and is the Holy Grail for rechargeable lithium batteries. But currently it can only be used in primary or non-rechargeable Li-batteries. For rechargeable batteries, the use of metallic lithium may affect the lifetime and reliability of the batteries, as recharging promotes the formation of metal needles that may short the cell. Imec researchers believe they can overcome these issues through a combination of a rigid solid-electrolyte component and thin buffer layers at the interfaces.

**Joining research efforts**

The previous decade progress in battery development has concentrated on electrode materials and improvements in the existing Li-ion technology. More disruptive improvements, such as the move to solid-state electrolytes, require a concerted and sustained research effort. And they also demand looking at the challenge with new eyes and from new angles.

At imec we can leverage our unique expertise in nanomaterials, thin-films and interfaces, expertise gained from decades of semiconductor processing research. An example is the know-how on mesoporous materials for low-k dielectrics in chips. This experience has contributed to the development and testing of the novel nanocomposite electrolyte. Likewise, the extended know-how in thin-film deposition in high-aspect ratios is now used to create innovative coating of battery powder electrodes.

When this endeavor can now be combined with the concerted effort of material and battery suppliers, the road is open to better, safer batteries that will drive the electrified future.

*Imec’s development of next-generation batteries is embedded in an open innovation program, in which Panasonic is one of the partners. The research is part of EnergyVille, a research initiative that brings together the expertise of imec, KU Leuven, VITO, and Hasselt University to develop sustainable energy and intelligent energy systems. A next step is to upscale the current innovations in the new state-of-the-art battery lab (including dry room) on the EnergyVille campus.*
Biography Philippe Vereecken

Philippe Vereecken obtained a PhD in physical chemistry in 1998 from Ghent University. After a stay at The Johns Hopkins University as a postdoctoral researcher, he worked at IBM Research (New York) as research staff member (RSM) for several years. In 2005, he joined imec, first in the nanomaterials group. In 2009, he was appointed Associate Professor at the Center for Surface Chemistry and Catalysis, Faculty of Bioscience Engineering, KU Leuven. In 2010, Philippe Vereecken started the energy storage activities at imec. Currently, his work is focused on the development of solid-state Li-ion batteries.
A new era of cancer treatment

Immunotherapy is considered to be the next big thing after the development of chemotherapy 40 years ago. Other than chemo and radiotherapy, immunotherapy holds the promise to achieve complete, long-lasting remissions and cures for all types of cancer.

One type of immunotherapy is cell-based immunotherapy, using the patient’s own immune (T-)cells, adapted in a way to better fight cancer. The latter is done by engineering the T cells with a specific T-cell receptor that specifically binds the cancer cells. Of these, the so-called CAR T cells, with a chimeric antigen receptor (CAR) on the cell surface, holds the most promise. Whereas CAR T cell therapy was first restricted to small and often experimental clinical trials in patients with blood cancer, it now resulted in the first FDA-approved therapies for two types of blood cancer.

The cost of these therapies is enormous: a few 100,000 dollar. This is related to the cumbersome workflows and regulatory requirements to proof high quality, reproducibility and effectiveness.
The cell therapy workflow

CAR T cell therapy is based on a patient’s own immune system. For this reason, the workflow starts with taking blood from the patient, typically in a hospital, selecting the white blood cells, and from this the T cells. Next, the isolated patient T cells are transported from the collection site, to a manufacturing facility. Here, the T cells are re-engineered to produce receptors on their surface that allows the cells to now recognize and destroy cancer cells. The code for the new receptor is inserted into the T cells through viral vectors or electroporation. These re-engineered T cells are then cultured in bioreactors for expansion into numbers ordering in the hundreds of millions. Finally, the re-engineered cells are re-introduced in the patient, where they have the ability to further multiply and kill cancer cells.

Schematic of the CAR T cell therapy workflow

Next to the biological issues (side effects, efficacy for solid tumors, new tumor targets, ...), a key challenge is related to the manufacturing process. In patient-specific cell therapy, the complexity of the end product – living cells with a specific product profile – and the variability of the starting material (the patient’s own cells) make it challenging to ensure a cell therapy product that is comparable in quality and in terms of both safety and efficacy. Also, there is the complex logistics chain with blood being taken from a patient at a hospital or center, being cryopreserved, shipped to a facility where it is reprogrammed and manufactured in the lab, and then shipped back for infusion into the patient. And, there is the need for a short turn-around time due to the patient’s situation and evolution of his disease. And the therapy should be affordable by keeping cost of goods (CoGs) down and more importantly have a scalable sustainable manufacturing process.

How nanoelectronics can innovate the cell therapy workflow

The complexity, cycle time and cost of the CAR T cell therapy workflow is a major challenge to overcome in order to achieve clinical implementation of this revolutionary new cancer treatment. Chip technology can help to achieve this.
Over the last few decades, the semiconductor industry has grown exponentially, poised to increase value to the end-user while driving down costs by scaling. The result is the world’s highest standard in precision and high-volume production of nanoelectronics chip-based solutions.

Imec has used its semiconductor process expertise and infrastructure to make significant innovations in single-use silicon biochip and microfluidic technology, creating toolboxes of on-chip functions spanning cell sorting, single cell electroporation, integrated biosensors, and enzymatic assays key to addressing the challenges in CAR T therapy. These existing demonstrations on chip could enable to provide smarter solutions for discrete unit operations for complete CAR T workflow integration from T cell isolation from the patient all the way to reintroduction of therapeutically modified cells to the patient. Solving these challenges would enable more patients to access and benefit from the next most anticipated class of life changing therapies.

Examples of relevant chip-based technology that imec develops are:

**A bubble-based jet flow sorting technique**

Imec developed an alternative sorting technique – a microfluidic FACS technique – based on the use of micro vapor bubbles generating a jet flow for high speed, but gentle, cell sorting in microfluidic channels. The technique combines high throughput, high precision, flexibility, assured biosafety and affordability. The sorting speed is 5,000 cells/sec per single microfluidic channel, with a > 90% cell sorting yield, > 99% purity and well preserved cell viability. Compared with other microfluidic cell sorting techniques, the bubble jet sorter is a generic cell sorting technique which is independent of any cell physical characteristics such as size or compressibility. This cell sorter technology has many advantages over the current cell therapy standard for selection, IMS: multi-marker support; more compact and automated; low disposable cost; no post-sorting step needed.
A micro-electrode array for single-cell electroporation

Imec develops very large scale microelectrode arrays (MEA) for single-cell electroporation. These are silicon chips with thousands of small electrodes, covered with surface chemistry to make it compatible with cell cultures. When a small voltage is applied to the cell (via the electrode underneath), the cell membrane opens up and molecules in solution enter the cell. In this way, one is sure that every cell is transfected. The voltage used in these electrodes is so small that it has no negative effect on the cell. A second advantage (next to the low voltage) of the MEA-based single-cell electroporation is that there is a very precise control on the electroporation parameters for each individual cell, that can be verified one by one. This will most likely enhance the precision of the technique, resulting in more transfected cells, which are in good condition too. This will increase the yield and reproducibility, minimize the potential toxic effect and increase the ultimate efficacy of the cell therapy in the patient.

Ion sensors

After gene transfer, the CAR T cells have to be multiplied to millions of viable cells. This happens in bioreactors. It is key to carefully monitor and control what happens inside these bioreactors in order to achieve a cost-effective, robust and uniform commercial product. Measurement of parameters such as pH and dissolved O2 and CO2 provide information on the micro-environment of the cells. Imec develops multi-ion sensors for fluid monitoring, which can measure e.g. pH, Cl, Na, K, Ca, and NO3. It is a generic platform which can be tailored towards specific applications: by changing the selective membranes on the electrodes, the sensor can be adopted to detect other ions. The sensors outperform current systems in terms of performance and are easy to mass-produce, have a wireless connection, are energy optimized and extremely miniaturized.

A miniaturized lens-free microscope

Also in the bioreactor, a visual inspection of the cells is indispensable to get direct feedback on the viability and overall condition of the cells. Normally this is performed by a process operator by taking a sample out of the bioreactor and inspecting it with a microscope. Imec has been developing a lens-free imaging cytometer technology that could be integrated on top of microfluidic channels, enabling in-flow cell imaging in microfluidic channels, or into bioreactor walls. The lens-free holographic-imaging based system uses a LED or LASER light source and a CMOS imager to capture the light that is diffracted off small objects. The captured diffraction pattern (called a hologram) resembles the ripple effect pattern caused by an object landing on a water surface. Custom software algorithms are required to reconstruct the hologram into an in-focus image that resembles the object that is being imaged. It is a compact solution, which enables a large field of view and very good resolution, at an affordable price. A machine-learning based image analysis and classification pipeline is also being developed to evaluate the images and differentiate between specific cell types using powerful classification algorithms.

Waveguide-based biosensor assays
Again in the bioreactor step of the workflow, it is important to analyze by-products of cell metabolism—proteins and enzymes. Current technologies e.g. based on immunoassays (mostly ELISA), mass spectrometry, chromatography or spectroscopy are not yet available in on-line setups, require large efforts in sample preparation and often lack specificity in complex culture media with a high protein background. As an alternative, imec develops photonics-based immunoassays. Photonics is a well-known technology used in e.g. glass fibers to transport data in a more efficient way. But photonic waveguides and other components can also be used for life science applications. To enable this, imec—together with partners in the European PIX4life project—has set up a silicon nitride—for visible light—photonics pilot line. A full library of photonic components is available for life science companies to build the next generation of photonic biochips. With this photonics platform—and more specifically with the use of photonic waveguides—imec has built a fluorescent immunoassay and an enzymatic colorimetric assay which could be used for online monitoring of relevant cytokines in bioreactors for CAR T cell expansion.

**Save time and lives with a chip-centered workflow**

With a microfluidic-based and chip-centered approach, it is expected to have a much shorter turnaround time (from T cell selection to infusion), for several reasons: (1) all process steps (selection, electroporation) are performed very accurately resulting in a higher yield of CAR T cells from the same amount of blood; moreover, this would eliminate the differences in efficacy and toxicity as seen today in clinical trials; (2) by using microfluidics, processes occur much faster (e.g. cellular reprogramming with microfluidics occurs 50 times faster than traditional reprogramming); (3) chip processing enables a high level of parallelization, speeding up the process enormously.

It is the unique partnership between chip technology and pharma that can lead to innovative results, also in the field of cell therapy.

**Want to know more?**

- For more details on the chip-based technology that imec develops for cell therapy, [download the whitepaper](#) on this topic.
- Read [the article](#) on the PIX4life project to learn more about the silicon nitride photonics platform for life science applications.
Biography Liesbet Lagae

Liesbet Lagae is co-founder and Program Director of the Life Science Technologies in imec. In this role, she oversees the emerging R&D, the public funded activities and early business creation. She holds a PhD degree from the KU Leuven, Belgium for her work on Magnetic Random Access Memories obtained under an IWT grant. As a young group leader, she has initiated the field of molecular and cellular biochips leveraging silicon technologies at imec, Belgium. The life science program has grown from emerging activities to a mature business line that provides smart silicon chip solutions to the life science industry. Applications include medical diagnostics, point-of-care solutions, DNA sequencing, cytometry, bioreactors, neuroprobes, implants. She holds a prestigious ERC consolidator grant for developing a platform on single cell analysis and sorting. She has (co-) authored 125 peer-reviewed papers in international journals and holds 15 patents in the field. She is also part-time professor in nanobiotechnology at KU Leuven/Physics department.
Metrology can be considered a collection of subdomains, each subdomain representing a specific analysis technique. Think about secondary ion mass spectroscopy (SIMS), a technique for determining the composition of a material (surface) – with applications for organic and inorganic structures. Another subdomain is scanning probes, comprising several concepts for measuring, e.g., topography, adhesion, material hardness and chemical properties, and we have our own scanning spreading resistance microscopy (SSRM) technique, allowing to determine carrier profiles in a semiconductor. In recent years, many of these techniques have largely evolved and have become mature enough to be used in research or production of semiconductor applications. Lab-to-fab transition, and an increasing focus on volume, automation and throughput time are seen as important trends.
Orbi-trap SIMS: a revolutionary improvement in mass resolution

In recent years, progress in SIMS has been remarkable. SIMS allows studying the composition of a material surface by sputtering the surface with a beam of energetic ions. As a result, secondary ions are released and analyzed by means of a mass spectrometer. In 2017, the introduction of a new concept for mass spectrometry, the Orbi-trap, has enabled a significant improvement (10-50x) in mass resolution (>250,000), and in accuracy of mass determination (<2ppm). This way, complex molecules can be uniquely identified. Originally developed for applications in biological and medical research (single cell proteomics), these properties represent a quantum leap for the analysis accuracy and interpretation of SIMS data in semiconductor technology. With Orbi-trap SIMS, it is now possible to analyze, for example, photoresists and self-assembled monolayers, or to make a distinction between two elements with very similar mass (such as arsenic and germanium). The technique can also be used to support the self-focusing SIMS concept, which was developed at imec for analyzing extremely small structures.

Hybrid metrology: 1+ 1 =3

Over the last years, the concept of hybrid metrology has become increasingly important. Following this concept, different metrology techniques are used to measure one and the same structure.

This allows either correlating complementary information (such as structure and functional properties), or eliminating specific uncertainties of the individual techniques. An illustration is the combination of transmission electron microscopy (TEM, an imaging technique) with scanning probes (SPM, functional analysis). Combining TEM information (structure and composition) with the observation of functional properties at the nanometer scale via SPM (or, via SRRM for carriers, or via piezo-force for ferro-electrical properties,...) on the same structure provides a unique approach for generating insight in the functioning of new structures. Last year, imec played a pioneering role in the development of the SPM/TEM hybrid metrology – which was also presented at the IEDM conference.
In addition, our team made a major breakthrough towards more accurate 3D analysis, by combining the atom probe technique (APT, atom probe tomography) with atomic force microscopy (AFM). Prior to an atom probe measurement, a sample is prepared in the form of a sharp tip. From this tip, ions are evaporated, captured by a position sensitive detector and individually analyzed according to their mass. The tip acts as an ion-optical component, and creates an image magnification of $\times 10^6$. The result is a 3D analysis of the sample with a (theoretical) spatial resolution < 0.2nm. In practice, the exact value of the magnification (resolution) is unknown, because the detailed shape of the tip changes continuously and cannot be determined in-situ, until recently. Most of the labs and manufacturers explore the integration of TEM in an APT system as an expensive and complex solution to this problem. By showing that the APT tip can be imaged with AFM, imec demonstrated a promising, simpler, more quantitative and cost effective alternative. The further exploration of this concept will be complemented with new complex data algorithms that will be developed in collaboration with Vision Lab, an imec research group at the University of Antwerp.

As a final example of the increasing importance of hybrid metrology, I would like to mention a project in which imec combined a SIMS instrument with in-situ SPM: a world first. This will allow determining composition (SIMS) as well as functional properties (electrical SPM). In the future, the exploration and demonstration of this approach will be a main focus point of our research efforts.

**Probing small confined volumes: a challenge for metrology**

Another important milestone is the commercialization of the Fourier Transform-scanning spreading resistance microscopy (FFT-SSRM) technique. This novel technique is based on SSRM, an analysis technique that was invented at imec years ago. SSRM is among the few techniques that allows to determine carrier profiles in a semiconductor. But the standard SSRM technology (and its underlying approaches) cannot be applied to small volumes, such as FinFETs and nanowires, due to signal distortion by parasitic resistances. Imec's FFT-SSRM concept overcomes this issue. In 2017, it was translated into a commercial product and installed at several partners of imec.
Analyzing extremely small structures (such as nanowires, 3 to 4nm in diameter), 3D geometries and confined volumes (small structures embedded in a complex environment such as tungsten or oxide) presents one of the main challenges for metrology in the years to come.

Even for high-resolution techniques such as TEM, a complex sample preparation (into lamella, < 10nm) and special measurement procedures (TEM tomography) are required to access the area that is relevant (e.g., the channel underneath the metal gate in a gate-all-around device). In this context, imec continues the development of its scalpel AFM technique. In scalpel AFM, the tip of the AFM probe is also used to slice layers on an atomic scale, after which a local functional measurement is performed.

Conceptually, metrology on nanostructures remains a major challenge. A nanowire device, for example, contains about 500 dopant atoms at most. In the source/drain extension, maybe three are left. What is the statistical relevance of measuring such a single device (i.e., counting three atoms)? What is the meaning of ‘concentration’ at the nanometer scale? If we want to continue performing quantitative analyses, we will have to introduce novel metrics, such as the average distance to the next atom. In addition, we will have to take into account the stochastic variability in the properties of the structures (e.g. dopant fluctuations).

**Trend: array-based metrology, sensitivity and statistical relevance**

As a result of these statistical limitations, the development of array-based metrology is emerging as a major trend. Instead of deploying expensive tools (with very high resolution) for measuring e.g. single devices, we start doing measurements on arrays of devices, with relative small resolution (by using broad beams).
Because of the underlying physics of the measurement technique, the information can be restricted to the structure of relevance, and the signal coming from the environment can be suppressed. By simultaneously measuring multiple devices in parallel, the quality of the signal can be improved, and statistically relevant data are obtained. For techniques such as Raman spectroscopy, micro-four point probe, RBS (Rutherford backscattering spectroscopy) and SIMS, imec has developed solutions that allow to measure and interpret effects such as CD variation, strain and composition variations in array structures.

On the longer term, I expect metrology to further evolve into this direction. A large number of techniques that are now being developed, such as Orbi-trap SIMS, TEM tomography or atom probe/AFM, will be massively deployed in the research and production of semiconductor applications. TEM and AFM, for example, which today are still perceived as single device analysis concepts, are expected to evolve into array based metrology as well. These analysis techniques will increasingly be used in-line; inline TEM, inline SIMS, inline XPS (x-ray photoelectron spectroscopy) will become a commodity.

**Metrology as a profit center**

On the downside, funding all these developments remains a difficult issue for the semiconductor industry. On the one hand, costs increase dramatically because of the growing complexity of semiconductor developments and because of the need for ever higher resolution. For example, enhancing the resolution from 1nm to 0.5nm is a huge step for the metrology developer. On the other hand, since a few years, the market for metrology tends towards monopolization. For techniques such as SIMS or atom probe, there is only one market player. Hence, by lack of competition, progress is slow and expensive. Nevertheless, it is important that the industry continues to invest in metrology.

Metrology is not a cost factor, but a profit center for industry. Some years ago, VLSI Research published a study showing that, for each dollar invested in metrology, there was a return of 10 dollar. Being able to quickly and accurately analyze semiconductor devices can accelerate technology development and yield enhancement. Advanced equipment and gathering fundamental metrology knowledge are cornerstones of successful technology development and high-volume production. For imec, gaining fundamental insight is key to the added value we bring to our partners. Therefore, we continuously invest in a high-performing metrology group with strong scientific foundations. Also, special attention must be paid to design for testability. In the coming years, providing test arrays needed for measuring array structures, and test structures that are metrology friendly will be key for metrology to achieving optimum results.
Biography Wilfried Vandervorst

Wilfried Vandervorst received his M.Sc. degree (electronic engineering) in 1977 from the KU Leuven, Belgium and the PhD degree in Applied Physics in 1983 from the same University. In 1983-1984 he worked at Bell Northern Research, Ottawa, Canada as a consultant in the field of materials characterization. In 1984 he joined imec where he became Director of the department dealing with materials characterization. Since 1990 he is also holding an appointment as a Professor at the KU Leuven (Physics Department) where he is teaching a course on materials characterization and supervising PhD students. In 2001, after an international peer review, he was elected as an imec Fellow for his outstanding scientific achievements related to semiconductor metrology, and in 2013 as Senior imec Fellow. He is engaged in advanced research on metrology and material (interactions) for semiconductor technology. He has co-authored more than 600 papers in peer-reviewed journals, gave more than 150 invited presentations and is co-inventor of more than 60 patents.
From start-up to scale-up

The product behind ONTOFORCE is the semantic search platform DISQOVER, which is currently mainly used in pharmaceutical and biotech companies. The company was founded in 2011 and was one of the first start-ups to join the imec.istart program. Since then, ONTOFORCE – which still continues its collaboration with imec – has spread its wings. The company recently completed a new investment round of 4.3 million euros and has already established a foothold on the US market. This year, they have big plans to further expand their sales in the US, i.e. by participating in the Flanders New York Accelerator.

DISQOVER: a new generation search engine

In this day and age, there is so much data that it is becoming increasingly difficult to find an efficient and relevant answer to our search queries. Hans Constandt (CEO and founder of ONTOFORCE) first experienced this when he was searching the web to find relevant, scientific studies that could help his son – who struggled with a learning disorder. From this experience, the idea for DISQOVER originated. Essentially, DISQOVER is an optimized search engine which draws on semantic technology to find links between data across databases faster and more efficiently. Although the platform was originally intended as a B2C offering, it is currently mainly used within the pharmaceutical and biotech industries.
Hans Constandt explains: “There are thousands of health research databases, clinical trials, literature reviews, patient studies, etc. available. Before setting up a new study, scientists first need to check what kind of research has already been done – both internally and externally – on, for instance, growth hormone applications for a particular disease. In many companies, even internal information resides in hundreds of different databases, each with their own interface and search logic. As a consequence, just finding this kind of background information is a very time-consuming process. This is where DISQOVER comes in.

Our platform brings together all these databases – both internal and public ones – and integrates the data, identifying links and visualizing the search path.

One of the assets is that we use semantic technology to find logical but often hidden connections between internal and external data, allowing you to easily combine information from a multitude of different sources. As such, pharma and biotech companies can save valuable time and money that they can now invest in developing new medicines or treatments.”

In just three days, the ONTOFORCE team can set up a working platform customized to a specific client’s needs, containing not just public databases but also connecting many internal sources, and bringing all knowledge together in one user-friendly hub. After a two-month trial, companies get the option to pay for a license per user per year.

ONTOFORCE has already convinced numerous pharma and biotech companies of the benefits of its technology. At the Bio-IT World Conference in Boston in 2017, multinational Amgen US even gave a talk explaining the benefits DISQOVER brought to them. They were excited about the fact that the platform brings both internal and commercial data within employees’ reach, enabling them to easily find related research themselves without having to consult internal experts on the subject matter. Hans Constandt: “This talk was a big milestone for us. Their support opened many doors and generated lots of new sales leads. In the end, there is still no better marketing tool than word-of-mouth.”

Although ONTOFORCE’s main focus is on the biotech and pharma industries, the basic, underlying DISQOVER platform is open access, allowing anyone to explore this new kind of search experience. For instance, patients or their relatives can use it to find more specific, scientific information on their condition or to search for alternative treatments.
Flanders New York Accelerator: if you can make it there, you can make it anywhere...

ONTOFORCE was one of the first start-ups to join the imec.istart program in 2011. Hans Constandt: “Even after our imec.istart track ended, we have continued to collaborate with imec and with IDLab, an imec research group at Ghent University, through a number of different projects. I’m especially grateful for the networking opportunities that the imec.istart team created for us, not just in Belgium, but internationally as well. When we were first thinking of launching our software in the US (Boston), imec helped us find the contacts we needed. And today they are supporting us again, now that we are part of the Flanders New York Accelerator. The program has just started a couple of days ago, but I can already feel that we have come to the right place to expand our foothold in the US.”

The Flanders New York Accelerator (FN YA) is a joint initiative of the Flemish Ministry of Innovation, ERA (Entrepreneurs Roundtable Accelerator), Flanders Investment & Trade and imec. The aim of the program is to help promising Flemish start-ups scale more quickly by helping them make a successful US market entry. ONTOFORCE is one of the six companies which were selected to join the first coaching track, which runs from January 22 to April 13, 2018.

Lies Boghaert (imec.istart internationalization coordinator): “The best thing about this program is that our Flemish start-ups are completely embedded in an American network of mentors and partners. They also get to work in an inspiring co-working space – together with other international start-ups – in ERA’s offices in Midtown Manhattan. As part of the three-month program, they attend highly specialized workshops and networking events. ERA also provides each start-up with a US mentor who coaches them and introduces them to the right contacts in their field.”

Hans Constandt: “A while back, I got a call from a father who wanted to thank us because – just when they had lost hope – he had discovered a clinical trial for his child through our platform. There is no money for us in this, but stories like this do give me lots of positive energy.”
Through the FNYA, ONTOFORCE hopes to further expand their sales in the US. They are not new to the US market though: they already have one US investor and 80% of their 1.3 million euro turnover in 2017 was generated overseas. In 2018, they plan to double their overall turnover, amongst others by significantly expanding their US sales. They also have concrete plans to set up a sales office in New York and to extend their Data Science team in Boston, and they have just hired their first US employee.

Although ONTOFORCE is looking for opportunities in the US, they are firmly rooted in Belgium. Hans Constandt: “We will definitely set up a sales office in the US, but we also need the local expertise and know-how that we can find here in Belgium, so our development team will definitely remain here. We’ve recently completed a new investment round of 4.3 million euros, bringing in two more Belgian investors, i.e. Korys and biotech pioneer Annie Vereecken. Our current shareholders, PMV and LRM, also decided to participate in this investment round.”

**Getting started: advice for other first-time entrepreneurs**

When asked what advice he would give other start-ups, Hans Constandt says: “As a start-up, you don’t get a second chance. There is very little room for failure. You have to make sure that you have a working product as quickly as possible – it doesn’t need to be perfect – but it needs to show your added value. As soon as you have a couple of paying customers – by preference big players – it becomes a lot easier to convince others. Of course, you also have to make sure that you have a good product-market fit. In our case, DISQOVER addresses a real problem that companies in the pharma and biotech industries are struggling with.”

As for the key to their own success, Hans Constandt’s first, intuitive response is ‘people’. Hans Constandt: “Human capital is essential. Over the years, we’ve recruited a passionate and complementary team.

*I believe that it’s very important to know what your own limitations are and to then surround yourself with people who excel at precisely these things.*

You cannot do everything on your own. Our success is the result of the hard work of the people who joined our team, from our amazing HR and finance experts to our office manager, top developers, and data scientists. That is also why we have recently attracted Dirk Pollet as our new co-CEO. We are upscaling at a fast pace now, so it’s good to have an experienced person next to me who can support us through this process.”
Biography Hans Constandt

Hans Constandt holds a bachelor in medicine, a master in biotechnology and a master in information sciences. After his studies, he filled a number of different positions, from postgraduate researcher in bioinformatics at Ghent University, to senior IT analyst and data architect, and consultant. In 2002, he started his 11-year career at Eli Lilly, first as a bioinformatics account manager, then as a senior business leader and eventually as the global lead for large-scale knowledge management projects. In the meantime, he obtained a master in innovation and entrepreneurship from Vlerick Management School and later he also became an MIT alumnus (via a business accelerator program that ONTOFORCE participated in). As an entrepreneur and innovator, he is on a mission to digitally transform and disrupt the industry, advocating the benefits of smarter, open data. In this context, he received the 2017 EIT Venture Award and ONTOFORCE was also selected as one of the Gartner Cool Vendors in 2014.