Photo credit: Nando Harmsen

Impact Objectives

- Develop hexagonal crystal phase SiGe (Hex-SiGe) which features a direct bandgap and will add photonic capabilities to electronics
- Revolutionise the electronics industry by adding intra-chip and chip-to-chip communication at the speed of light, offering a significantly reduced energy consumption

A game-changing Hex-SiGe nanolaser

***Dr Jos Haverkort** and **Professor Dr Erik Bakkers**, based at the **Eindhoven University of Technology**, are involved in a project that seeks to establish a new technology platform in the electronics industry. Here, they introduce themselves, what their project hopes to build upon, and how they propose to translate their findings*

Dr Jos Haverkort (Photo credit: Nando Harmsen)

Prof Dr Erik Bakkers (Photo credit: Bart van Overbeeke)

What are your respective research backgrounds?

EB: I have 15 years of experience on nanowire growth and am presently focusing on several nanowire device applications, including silicon-based light emitters within the SiliconLaser (SiLAS) project. I also work on advanced nanowire quantum devices for observing Majorana fermions.

JH: I am the Project Leader of the SiLAS project and my research is dedicated to the optical properties of nanowires, with particular emphasis on the optical spectroscopy of hexagonal silicon-germanium (SiGe) nanowires. My team has developed a nanowire solar cell with 17.8 per cent efficiency and I am presently investigating the efficiency limits of nanowire solar cells.

Could you introduce the SiLAS project and its objectives?

JH: Silicon semiconductor material is extremely successful for the electronics industry and has provided the basis for electronic devices like personal computers and smartphones. However, silicon is not able to emit light, implying that one needs semiconductor materials, like gallium arsenide (GaAs), indium phosphide (InP), or gallium nitride (GaN), for fabricating light emitting diodes, or semiconductor lasers for optical communication.

EB: Traditionally, both silicon (Si) and silicon-germanium have a cubic crystal structure. The SiLAS project is aiming to fabricate Si and SiGe with a hexagonal crystal structure, known as Hex-SiGe. The hexagonal crystal structure is the keypoint to transform SiGe into a light-emitting semiconductor for germanium compositions above 70 per cent.

In what ways does SiLAS build upon prior research conducted by yourself and your project partners?

EB: The SiLAS project combines the expertise of my group on advanced nanowire growth with advanced theoretical expertise in Jena and high resolution X-ray diffraction in Linz. This group performs X-ray diffraction using synchrotron radiation (DESY) to accurately obtain the lattice constants of Hex-SiGe as input for accurate bandstructure calculations in Jena.

SiLAS has just entered the second year of its four-year duration. How are things progressing? Have you faced any particular challenges so far?

EB: Our first-generation Hex-SiGe nanowire shells already showed light emission as well as indications for optical gain. We are presently developing substantially higher quality Hex-SiGe nanowire shells. It is our objective that these second-generation samples show optical gain in a more reproducible way.

Is an interdisciplinary approach important to this project's success?

JH: The European dimension is of key importance for the SiLAS project as it allows us to combine the expertise of different research teams which are all leading in their respective fields of research.

EB: The development of hexagonal group IV semiconductors requires advanced characterisation tools in a multidisciplinary team, including strong industrial participation, such as that we have established with IBM.

Are there any recent developments or forthcoming publications that you would like to share?

EB: Presently, we have strong indications, but not yet a direct proof, that it will be possible to demonstrate laser action in Hex-SiGe. We will only present our data in public once we are completely sure that Hex-SiGe is an efficient light emitter.

Finally, how will you ensure that your findings translate into real-world applications? To what extent are you collaborating with the electronics industry?

JH: IBM is a strong partner within the SiLAS consortium. We will further expand our industrial network as soon as we obtain direct evidence for efficient light emission and laser emission in Hex-SiGe.

A paradigm shift for the global electronics industry

*The **SiliconLaser (SiLAS)** project has been established to develop a silicon-compatible light emitter. If the team achieves this, it is fair to say that the electronics industry will be revolutionised. Although the project is only one-third of the way through its duration, the team has already managed to grow hexagonal crystal phase silicon and silicon germanium*

Silicon (Si) has long been the basis for the majority of electronic devices because of its special properties. The fact that it is a semiconductor means that it is able to conduct electricity in some circumstances, whilst acting as an insulator in others. In addition, it is also an extremely abundant element which means it is easy to harvest and is also extremely cost-efficient.

For these reasons, the electronics industry incorporates silicon into many of the products it produces, such as laptops, personal computers and smartphones. However, despite the numerous advantages associated with silicon, it is not without its faults. Dr Jos Haverkort, a leading scientist on nanowire growth based at the Eindhoven University of Technology, says that for instance: 'It is incapable of emitting light which means that developing a silicon-compatible light emitter has, for years, been something of a "holy grail" for researchers the world over'. Scientists are acutely aware of the fact that silicon is not able to emit light. The way around it is to use other semiconductor materials for light emission, such as gallium arsenide (GaAs), indium phosphide (InP) or gallium nitride (GaN).

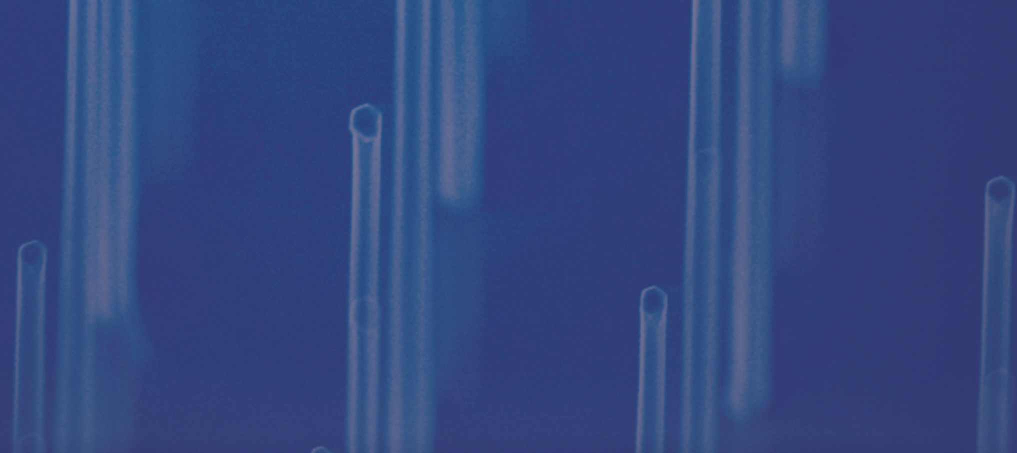
AN ABUNDANCE OF POTENTIAL APPLICATIONS

With this in mind, the SiliconLaser (SiLAS) project has been established. This four-year Horizon 2020 project is led by a team of researchers based at the Eindhoven University of Technology. Dr Jos Haverkort and Professor Dr Erik Bakkers are working towards developing a silicon-compatible light emitter with a hexagonal crystal structure. More specifically, they hope to fabricate Si and SiGe with a hexagonal crystal structure (Hex-SiGe). If achieved, it will transform SiGe into a light-emitting semiconductor for germanium compositions above 70 per cent.

There are a wide variety of potential applications for Hex-SiGe. 'Hexagonal SiGe could ultimately enable the monolithic integration of both light emitting devices and existing silicon photonics components with electronic circuitry, enabling us to fabricate truly optoelectronic integrated circuits,' explains Haverkort. 'Monolithic integration of a silicon-compatible light emitter will offer tremendous manufacturing advantages.' By integrating these components into existing complementary metal–oxide–semiconductor (CMOS) foundries, the team will significantly reduce the costs associated with developing materials which has obvious benefits; the functionality will be expanded, as will the potential applications.

If all of this was not reason enough for the team to be embarking on its quest, there are other related benefits that could genuinely transform the electronics industry and, more complexly, human experience. 'Silicon photonics is nowadays used in data centres to transmit data from rack to rack. It is expected that silicon photonics will penetrate towards board to board, chip to chip and finally to intra-chip communication,' highlights Bakkers. 'The closer photonics is approaching the chip level, the more urgent the demand for a silicon-compatible light source.' In addition, this would facilitate the replacing of copper wiring with optical fibre links that are powered by integrated Hex-SiGe emitters, something that would likely significantly reduce energy consumption in present day hyperscale data centres.

Other potential applications of interest include autonomous cars and autonomous systems which would be able to continuously map their environment using different sensors, including a Light Detection and Ranging (LIDAR) system, which is a remote sensing method that can measure distances to a target using a pulsed laser light. 'Silicon photonics allows a LIDAR system with solid-state beam steering combined with simultaneous distance and velocity measurements to scan the environment,' expounds Haverkort. 'An integrated Hex-SiGe laser would allow electronics



> *The fact that the team can successfully grow Hex-Si and Hex-SiGe is certainly significant and, given that the project has only been going for one-third of its total duration, there is an abundance of promise*

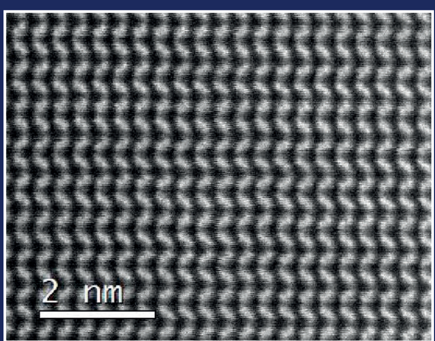
industries to produce the complete solid-state LIDAR system at high volume in silicon foundries.'

NOTHING IS WORTH DOING WITHOUT EFFORT

Given this plethora of potential applications, it is little wonder that the team has established this project. The wealth of expertise required to realise the ambitions of the initiative has necessitated working alongside other academic institutions and industries, such as the University of Oxford (Professor Michael Johnston), Friedrich Schiller University Jena (Professor Silvana Botti), Johannes Kepler University Linz (Dr Julian Stangl), IBM Research (Heinz Schmid) and the Technical University of Munich (Professor Jonathan Finley).

The former US President Theodore Roosevelt was once quoted as saying: 'Nothing in the world is worth having or worth doing unless it means effort, pain, difficulty'. It is fair to say that the team behind the SiLAS project agrees with this sentiment. The multitude of benefits associated with achieving the aims of the project serve as powerful motivation to overcome the barriers to developing a silicon-compatible light emitter. For instance, while many different theoretical groups have suggested that developing Hex-SiGe was expected to be a direct bandgap semiconductor, fabricating it is a major challenge as both Si and Ge naturally crystallise in a cubic lattice.

The team was therefore understandably delighted at transferring the hexagonal crystal structure from the nanowire core towards the nanowire shell. This signalled a major breakthrough and one the researchers could then build on. 'Although a direct bandgap has been predicted theoretically, it was not clear whether Hex-SiGe could ever become an efficient light emitter. During the initial phase of the SiLAS project, Jonathan Finley's group at the Walter Schottky Institute in Munich has observed initial indications for amplified spontaneous emission in Hex-Ge,' shares Haverkort. 'Professor Johnston's group at the University of Oxford performed the first conductivity lifetime measurements on Hex-SiGe and observed lifetimes close to a nanosecond, which is similar as for direct bandgap III/V materials.'



Electron microscopy image of hexagonal Ge

At Haverkort and Bakker's university, they have observed room temperature emission from the very first Hex-Ge sample they prepared and they are optimistic that they can convert what are highly promising initial results into a major piece of evidence for direct bandgap emission in the near future.

FABRICATING HEX-SIGE IN A CMOS-COMPATIBLE WAY

The researchers are acutely aware that their present fabrication route is not yet CMOS-compatible, but their first priority is demonstrating laser action in Hex-SiGe. 'The fact that the team can successfully grow Hex-Si and Hex-SiGe is certainly significant and, given that the project has only been going for one-third of its total duration, there is an abundance of promise,' says Haverkort. They expect that publishing their findings will have significant impact on the scientific community and they have already identified two actions that could enable them to fabricate Hex-SiGe in a CMOS-compatible way.

Ultimately, they have ascertained that Hex-SiGe is an extremely promising material for fabricating light-emitting diodes or lasers. While it is well known that the physical properties of a material can be completely different when changing the crystal structure, the key point of hexagonal crystal phase SiGe it its ability to efficiently emit light. If, when the project has been completed, the team has achieved what it initially set out to, the electronics industry will go through a paradigm shift.

Project Insights

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BIOS

Professor Dr Erik Bakkers received his PhD in 2000. He started as a research staff member in 2000 at Philips Research Laboratories in Eindhoven. In 2010 he joined the Eindhoven University of Technology, and later the Kavli Institute of Nanoscience at the Delft Technical University as full professor. His research interests cover the fabrication of nanowires with a special focus on III-V materials.

Dr Jos Haverkort received his PhD in 1987 (Cum Laude). He is an associate professor at Eindhoven University of Technology. His current research is focusing on the optical properties of hexagonal GaP and SiGe nanowires as well as on the enhancement of the open circuit voltage in nanowire solar cells.