Skill development programme for industry and manufacturing in India | Silicon Carbide semiconductor

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Educational concept description created by Mikael Syväjärvi, Alminica AB, May-July 2024.

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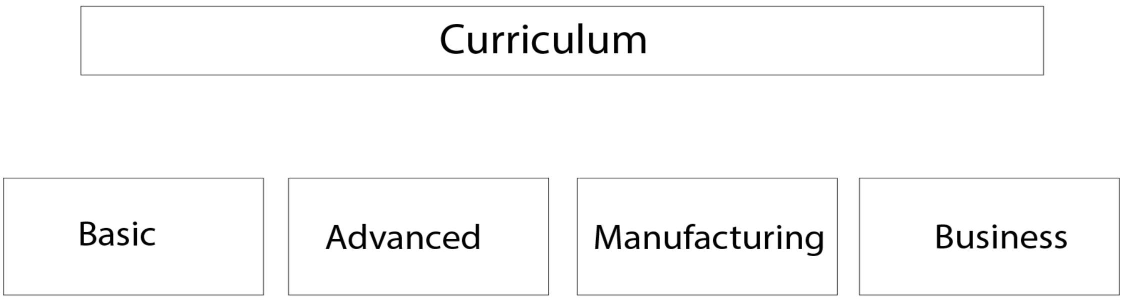
Visit the platforms: www.swedenindia.tech and www.euindia.tech

Summary

This concept description introduces a skill development in silicon carbide semiconductor. The educational content (curriculum) is based on courses in four stages: basic, advanced, manufacturing and business.

The **basic** is for everyone with interest in semiconductors, including those who will not be semiconductor professionals but want to have basic knowledge which can be added value in their particular profession.
The **advanced** includes expert areas combined with semiconductor. Expert areas are artificial intelligence and digitalization. Training includes virtual training to have experience of relevant manufacturing.
The **manufacturing** includes specifics in silicon carbide crystal growth and manufacturing. This includes hands on training to those who decide to go for semiconductor manufacturing career.
The **business** includes new business models in manufacturing.

The four stages jointly form a curriculum. It aims to provide skill development at high educational institutions in India.



About Sweden-India Technologies Platform

The Sweden-India Technologies Platform was founded to create transfer of knowledge in advanced materials (mainly third generation semiconductors) for emerging technologies, as well as semiconductor equipment and their processes, for manufacturing in India. The advanced materials and technologies can have more efficient uptake in India by partnership with knowledge ecosystem in Sweden and obtain synergies by using the Swedish network and activity in EU. There is a first pilot in silicon carbide equipment and processes to initiate and test the concept. Other materials and equipment will follow and it will be expanded to EU-India.

Flexible IP solutions

A benefit with aligning Sweden-India research is that in Swedish research system the IP created in a research outcome belongs to the individual researcher. Universities claim no right to IP outcome. This has the practical effect that researchers can decide what will be done with IP and enter any partnership worldwide as per own decision.

About Silicon Carbide

Silicon carbide (SiC) is a third generation semiconductor that is ideal for power electronics. These are critical components in electric vehicles, solar energy systems, data centers, and more where high power conversion is needed. The silicon carbide power electronics market is rapidly growing. There are now also a range of other applications besides power electronics based on silicon carbide which are emerging. Once those have higher technology readiness level, there will be new markets and business opportunities.

30 years of SiC crystal growth and equipment development in Sweden – available for India

Sweden has a long history in the silicon carbide crystal growth. The activities were initiated in the early 1990s at Swedish universities and involved industries such as ABB. At that time the silicon carbide was globally at R&D level and no applications were commercial. The Swedish activities established an ecosystem that has a wide range of experiences in SiC crystal growth processes and manufacture equipment for SiC crystal growth. The knowhow can match the SiC interests in India where there is strong focus by Make in India and India Semiconductor Mission. The overall aim is to create transfer of knowledge with open innovation character so more players can use the technology, both in academia as well as industry. By that the platform will also contribute to the India Atmanirbhar Bharat (Self-Reliant India) initiative. This offers a once in a lifetime opportunity to establish transfer of knowledge and initiate new joint developments in education, research and industry.

Silicon carbide manufacturing

Central in silicon carbide manufacturing is the hot-zone (container in which the SiC is produced). The IPR is mainly in hot-zone design and this is why hot-zone geometries are not openly available. Industries develop their own hot-zone geometries. That together with crystal growth process are industry knowhow. New manufacturing requires to have skilled professionals with SiC crystal growth competence.

New manufacturing has two options for SiC crystal growth: develop own knowhow or start from a standard process. Develop own knowhow without support is a slow process. The standard process sets the starting point but needs to be tuned to have commercial grade material. The refining of process is where the industrial crystal growth professionals become important. As comparison, everyone can have training and get car driving license, but hundreds of hours own driving experience is necessary in order to be a good driver. The same is for SiC crystal growth. It takes long time to be full expert even with initial training. Therefore a long-term partnership that includes skill development, innovation development and transfer of knowledge is a strategic move.

Skill development

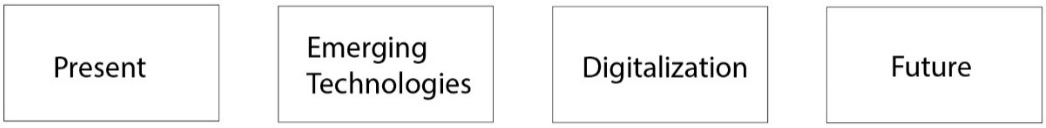
Increasingly there will be need of skilled professionals when the semiconductor industry grows. Some students are self-motivated in the semiconductor field from their personal interest. Other students will have their main interest in another area than semiconductors. There will be more outcomes if they will be applying their (other area) knowledge to the semiconductor world. Create an added level of competence. The semiconductors have wide effects in the society, either directly or indirectly. The direct semiconductor technical influence is clear. Indirect effect in other domains can be in AI, legal, cybersecurity, etc. There is an added value when the (other area) knowledge in the indirect domains is applied on top of semiconductors. In such way the transfer of knowledge in silicon carbide semiconductor by the skill development programme can have more effect on the society. The skill development in semiconductors to students will boost the future professionals both directly and indirectly. That is addressed by transfer of knowledge at basic and advanced level. In addition, there are (industrial) manufacturing and new business development.

Curriculum

For that the skill development has several modules. Each course in a module will have 16 hours of lectures corresponding to 1 credit point.

Basic

The basic educational module is semiconductors for non-experts. That training has a wide range, from introduction to semiconductors (explained for non-experts) to innovation and entrepreneurship and examples from silicon carbide. The aim is to combine new knowledge for new business. New business in addition to the direct semiconductor business. The skill development also includes aspects of research leadership and career development. The wider range of training provides a ground for the students who will make choices for their next career decisions, directly or indirectly in SiC.



Advanced

The advanced education is for those who are interested to go deeper into manufacturing of semiconductors. The training will be using virtual reality and digital twins. It will be applied on a virtual educational reactor for manufacturing of silicon carbide.

Manufacturing

This module includes two levels: crystal growth and industrial manufacturing with machines for experimental hands-on experience.

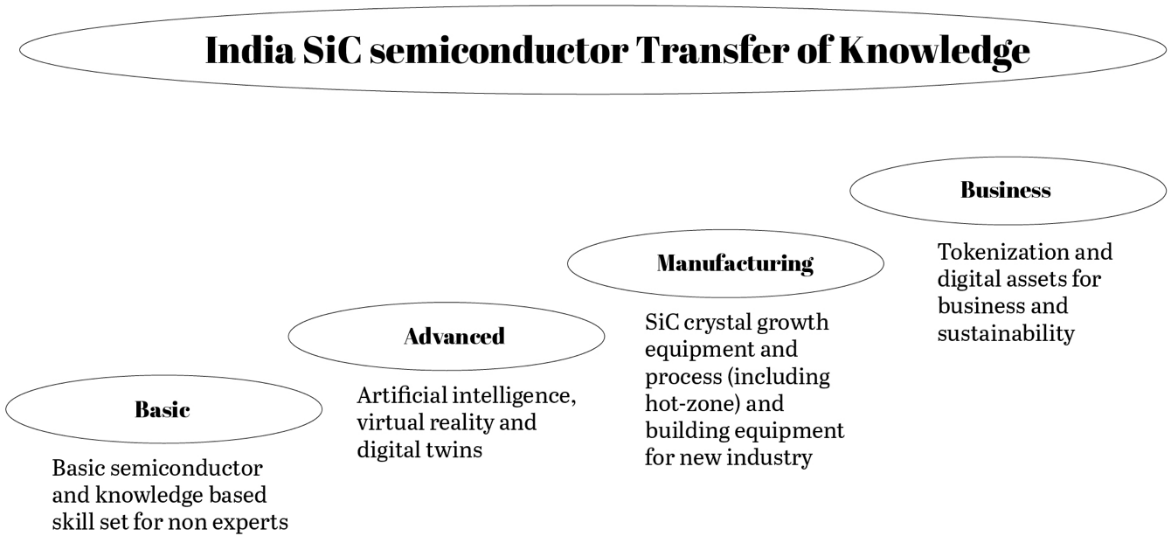
The training in crystal growth will use an educational and research reactor for growth of silicon carbide. It will be applied in a simplified version of the main silicon carbide method (PVT – Physical Vapor Transport). The educational EDUR-PVT has an open source approach for hot-zone and process that is available to all. In such way more students can be trained, and researchers can freely explore SiC growth. The EDUR-PVT can be used in normal lab environment. There is no need for cleanroom facilities.

The training in industrial manufacturing has sensitive knowledge that is not open to all. This transfer of knowledge is in collaboration with Swedish industrial manufacturing experts.

This module can also include training on how to build a PVT reactor.

Business

Digitalization and shared data for values in future business and sustainability. This is about the new business models which use tokenization and climate impact accounting.



Introductory workshop

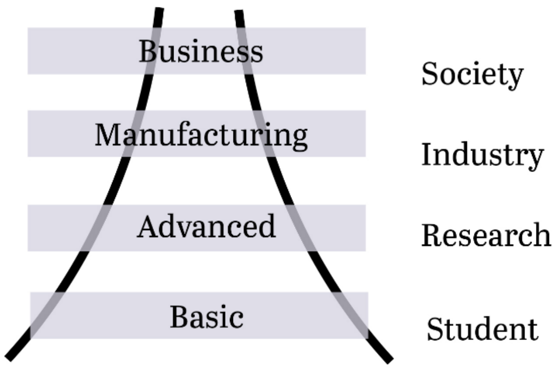
Organizations with interest in the skill development programme can have an introductory workshop.

Certificate

The courses will have certificates.

Benefits for India

There are benefits for the students, researchers and industry to align with Sweden-India concept in silicon carbide. The evolution from basic and advanced skill development will facilitate industry and society development. There are more than 55000 higher education institutions (>1100 universities, >43000 colleges and >11000 stand-alone institutions) in India. Semiconductor training would have several attractive motivations both for students and universities/colleges, such as access to advanced knowledge and technology, career opportunities and improved employment outcomes, etc. The benefits create a synergistic relationship, enhancing the students educational experience and the institutional capabilities in the field of semiconductors.



Students and educational institutions

By participating in this training program, students can significantly enhance their technical skills, industry knowledge, and career prospects in the semiconductor field, particularly in the high-demand area of silicon carbide technology.

Students

The students will have:
- access to advanced knowledge and technology
- hands-on experience
- career opportunities in emerging semiconductor markets
- a unique network with Sweden and EU
- demonstrated skill development in third generation semiconductors for future competitiveness
- exposure to leading-edge research, innovation and entrepreneurship

Students will gain exposure to third-generation semiconductor technology, particularly in SiC which is crucial for power electronics in electric vehicles, solar energy systems, and data centers. This advanced knowledge can set them apart in the job market. The advanced training involves practical experience with crystal growth and industrial manufacturing processes using educational and research reactors. This hands-on experience is invaluable and aligns with industry needs, making students job-ready. As the SiC market is rapidly growing, students trained in this technology will be well-positioned in this expanding field. They can become leading in new developments and innovations in SiC applications and new industry. By acquiring skills gap in the semiconductor industry early, the trained students can meet the future demands of the industry, making them more competitive and employable. The program includes modules on innovation and entrepreneurship, encouraging students to explore new business opportunities in addition to technical expertize. Contributing to national initiatives like Make in India and India Semiconductor Mission, as well as Atmanirbhar Bharat (Self-Reliant India) can provide students with a sense of purpose and national pride, potentially opening doors to government-supported projects and funding. The modules cover various aspects of semiconductors, including digitalization and AI applications. This interdisciplinary approach can broaden the expertise and applicability of the students' skills across different sectors. The comprehensive training and exposure to cutting-edge technology and industry practices ensure that students are not only ready for immediate employment but are also equipped for long-term career growth and adaptability in the growing semiconductor industry.

Universities and colleges

Indian universities and colleges can significantly enhance their academic offerings, research capabilities, and overall institutional standing, while also contributing to the broader goals of national development and technological advancement.

The universities and colleges can have:

- enhanced academic reputation
- cutting-edge curriculum
- research and development opportunities
- industry collaboration and funding
- improved employment outcomes for graduates
- faculty development
- infrastructure development
- alignment with national initiative
- attraction of international students and faculty

Universities and colleges can attract more students interested in cutting-edge technology and advanced materials research. Integrating advanced SiC technology and manufacturing processes into the curriculum ensures that the academic offerings are up-to-date with the latest semiconductor industry standards, making the programs more relevant and attractive to prospective students. Access to Swedish and EU research collaborations and advanced SiC technology allows institutions to engage in high-impact research projects, potentially leading to significant academic contributions and publications. It will also open up to be associated partner of direct partner in Horizon Europe that is EU's framework program for research and innovation 2021-2027. The program can facilitate partnerships with industry leaders, leading to funding opportunities, sponsored research projects, and potential commercialization of new technologies developed within the university. By providing students with skills that are highly valued in the semiconductor industry, institutions can enhance their graduates' employability and success in securing high-quality jobs, thereby improving the university's job placement statistics. The program offers training for faculty members, allowing them to upgrade their skills and knowledge in SiC technology, which can lead to more effective teaching and mentorship for students. Given the growing semiconductor field, it opens up opportunities to upgrade laboratory facilities and acquire advanced equipment, enhancing the overall infrastructure of the institution. Supporting national initiatives such as Make in India, India Semiconductor Mission, and Atmanirbhar Bharat aligns the institution with the country's strategic goals, potentially attracting government support and funding. Since the silicon carbide training is not available in same extent anywhere in the world to include basic, advanced, manufacturing and business package, offering unique and advanced courses can attract international students and faculty, fostering a diverse and enriched academic environment. The innovation and entrepreneurship can stimulate a culture of innovation within the institution, encouraging students and faculty to develop new technologies and start-ups. By contributing to the creation of a skilled workforce in SiC technology, institutions help address the industry's talent gap, ensuring a steady supply of professionals ready to meet the demands of the semiconductor sector. The programme facilitates Sweden and EU collaborations, knowledge exchange, and the possibility of joint degree programs with foreign universities.

Industry organizations

Indian industries can significantly enhance their technological capabilities, competitiveness, and market position, while also contributing to broader economic and technological advancements in the country.

They can have:
- access to advanced technology from Swedish ecosystem and network with EU
- Access to a skilled workforce
- faster time to market
- enhanced competitiveness
- cost savings
- innovation and R&D collaboration
- intellectual property development

There are cost and IP benefits by the pooling effect and open innovation hot-zone and process. The pooling effect, where several industries share basic manufacturing resources and infrastructure, leads to cost savings in source materials, equipment, and services, reducing overall production costs. Industries can develop their own intellectual property (IP) in hot-zone design and crystal growth processes, creating proprietary technologies that can be leveraged for competitive advantage.

Certificates

There will be certificates for participants at courses.

EU-India

This concept is planned to broaden to EU-India in semiconductors and leading-edge technologies from advanced materials.

Silicon carbide crystal growth and manufacturing for industrial alignment

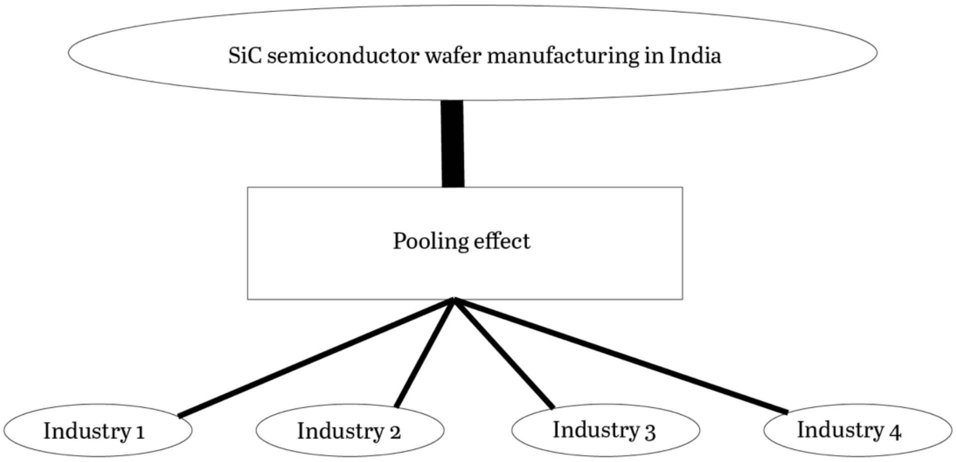
Having experienced team is essential. It is well known in SiC that the window parameter might shift slightly due to various reasons. That lowers the wafer yield. It is critical to have crystal growth knowledge with team to adapt to any shift in crystal growth. The team is also the one which develops the hot-zone further to have own IPR. Experienced SiC crystal growers who are open to recruitment to new manufacturing are difficult to find. To systematically attract skilled professionals to the manufacturing, it is necessary to have training already from basic level to educate the next generation and address the competence need early. This is where the transfer of knowledge in crystal growth technology together with training and skill development is a strong combination for the future competitiveness in SiC manufacturing.

Partnerships and Transfer of Knowledge (some examples)

- PVT reactor and 6 inch manufacturing process including hot-zone and process.
- Training: basic for non-experts
- Training: advanced for academic (student and PhD) with EDUR-PVT reactor
- Training: manufacturing (industrial) with commercial PVT reactor
- Development in 8-inch wafer, increase wafer yield, etc (innovation pipeline)
- Industrial production PVT reactors (6 inch and 8 inch)
- Pilot line: from raw materials for source to epiready wafer

Pooling effect

The silicon carbide manufacturing will be more efficiently established in India by applying a pooling effect. In this several industries share the basic (standard) level manufacturing. The manufacturing to commercial level is made by each manufacturing industry. Thus the business for each industry is in their own respective development and there is no competition. By pooling there is lower cost of source material, graphite material for hot-zone and seeds, as well as lower cost and more efficient service chain. The use of PVT reactors from same manufacturer in a pooling process will make available more data for process development.



EDUR-PVT

PVT

The most common and industrially applied silicon carbide crystal growth process is the PVT (physical vapor transport) method. In this silicon and carbon bearing species are transported from a source to a seed. The source is a polycrystalline silicon carbide powder. The distance of source to seed is 5-15 millimeter. The transport of vapor species is controlled by having an inert gas (typically argon, 5-50 mbar) as growth ambient. The temperature is typically 2100-2300^{o}C. The preparation and process steps are complex. Much of industrial knowhow is included in those steps, as well as geometry of growth container in which source and seed are placed. An academic training using standard (industrial) PVT tool would then be using steps which actually are not relevant in manufacturing. From training point of view the PVT is too complex, and it is also costly due to high reactor cost and high costs for consumables (often parts can only be used 1-3 times).

Close space PVT

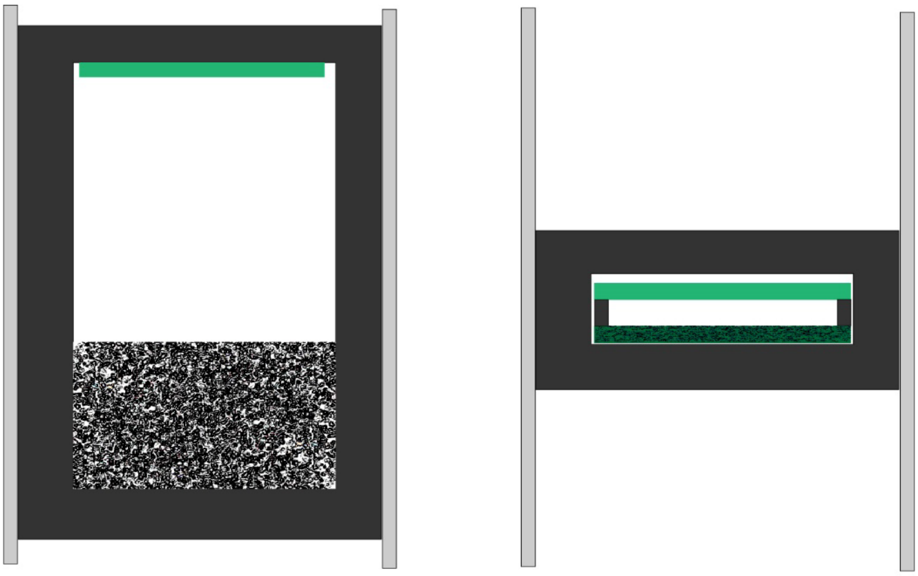
The close space PVT is a simplified version of PVT. It has some differences. The distance is shorter, typically 1 mm. The growth temperature is lower, typically 1800-2000^{o}C. The source is a dense ceramic silicon carbide wafer. The growth ambient is often vacuum, or low pressure of inert gas (typically argon, less than 5 mbar).

These differences make that PVT is better suitable for growing boules (which are cut and prepared to wafers), while close space PVT is for epitaxy (film on a substrate).
The close space arrangement has been used in SiC research for fluorescent SiC for a new type of white LED, cubic silicon carbide, epitaxial graphene, aluminium nitride.

EDUR-PVT

The close space PVT is more suitable for transfer of knowledge and new knowledge creation purposes. The process can be applied in same equipment that is used for the standard PVT. The preparation, growth container and process are more simple than the standard PVT. The container parts can be reused more than 10 times and have lower cost since size is smaller.

In addition, the close space method can be applied for new research directions both for epitaxy on SiC wafers, as well as surface engineering of wafer surfaces. That research can create new knowledge, and new technologies for added value silicon carbide markets. For the Sweden-India skill development there is developed an Education and Research (EDUR) PVT reactor that will be available for academic purposes (students and researchers).



Left: PVT with SiC powder as source and larger size for bulk growth
Right: EDU-PVT with SiC ceramic as source and smaller size for epitaxial (thin film) growth

	PVT	**EDUR-PVT**
Source	Powder (porous)	Ceramic (dense)
Substrate	Attachment to lid necessary	No seed attachment
Distance source to substrate	5-15 mm	1-5 mm
Ambient pressure	5-50 mbar	Vacuum or max 5 mbar
Growth temperature	2100-2300°C	1800-2000°C

Laboratory environment

Environment: the EDUR-PVT can be used in normal lab environment. There is no need for cleanroom facilities. The close space method can be applied in any PVT reactor independently of manufacturer.

About Mikael Syväjärvi

Dr Mikael Syväjärvi, Alminica AB, Sweden, is a researcher, innovator and entrepreneur active to develop innovation ecosystems and create global partnerships in advanced materials and emerging technologies. He is active in skill development and training by transfer of knowledge to the young generation.

He has experience from building platforms and broader contexts for research to market, such as avenues in European research and innovation strategy for smart specialisation by European Commission for regional economic growth using the entrepreneurial discovery process when he was procured expert for Region of Östergötland in the focus area advanced materials. The work by the working group led to the formation of the platform Innovative Materials Arena. He has experience from strategic national innovation programmes when he was in the board (2014-218) in the national innovation programme for graphene. He has seen the birth and initiation of the graphene flagship programme. He was awarded scholarships to study the graphene to market. He has built the SiC platform IW-SiC and initiated the Sweden-India SiC and semiconductor platform (www.swedenindia.tech). All these experiences were useful for initiating the concept note.

Dr Mikael Syväjärvi has worked in SiC since 1994 when he made his master thesis in electrochemical etching of silicon and silicon carbide. He has more than 200 publications in SiC. He started with SiC crystal growth in 1995 and explored the physical vapor transport (PVT) growth, liquid phase epitaxy (LPE), and sublimation epitaxy. He was laboratory implementation responsible for LPE development for the worlds first SiC microgravity growth in 1997 on the sounding rocket MASER7. Since 2005 he is also active in graphene on SiC growth and co-founder of Graphensic AB (2011). He is inventor of Fast Sublimation Growth Process (FSGP) and was responsible for the technology transfer of FSGP to El Seed Corporation, Ltd (Jp). The process was further developed to have basal plane defect free SiC in KISAB company. He founded Alminica AB in 2016 that is a company active in innovation services for research to business, impact from reseach and training young generation researchers. In 2021 he quit his position at Linköping University and founded ICM Research Institute as department for research.

He is active in global partnerships for promoting impact from research, educating next generation research leaders, and establishing supply chains and value chains using sustainable manufacturing. He is supporting several start-ups in deeptech (mentor, adviser, board, etc). He is a visiting Professor of Advanced Industrial Materials Innovation at University of Lincoln (UK).

Links
www.alminica.se
www.nitton07.tech
www.icmresearchinstitute.se

Research in SiC and teaching:

Education
The curriculum is based on experience from courses at Linköping University:

- ETE266 Semiconductors in our daily life (2005, 2006, 2007, 2008) - initiated and developed the course

- ETE310 Physics and the environment (2008, 2009, 2010, 2011, 2014, 2015) - initiated and developed the course
- ETE331 Environmental Technologies for the Future (2016, 2017, 2018, 2019) - initiated and developed the course.
- Lectures in seminar series for undergraduate and graduate students: “SiC: properties, growth and applications” (1999; 2000); “New Materials” (2001; 2002; 2003; 2006); “Growth of semiconductor materials” (2002; 2003).
- Course responsible: TFYY51 Engineering project in Applied Physics and Electrical Engineering programme (2006, 2007, 2008).

Grants and projects in silicon carbide

- RePowerSiC, EIC Pathfinder, 2024-2028 (starts Oct 1, 2024) on high power laser transmission (HPLT) in SiC based on the transmission of power via laser onto a photovoltaic receiver. The transmission could be through optic fiber, replacing conventional copper wires, or through free space, suitable for aerospace environments. There are many applications of this technology, such as the simultaneous transfer of power and data or optically powering remote antennas, aerial vehicles or even satellites. The current HPLT technology faces two major limitations: the intrinsic entropic losses associated to low bandgap materials (such as GaAs) and the series resistance losses that degrade the device performance at high power densities. To overcome these limitations, RePowerSiC aims to develop a new breakthrough LPC technology based on two key elements, the use of silicon carbide (SiC) and the development of new device architectures. Partner is SiC crystal growth.
- SiComb, H2020 EU-FET Open (FET – Future emerging technology in the EU program RIA – Research and Innovation action) ”CMOS compatible and ultra broadband on-chip SiC frequency comb” 2020-2024. Partner in Transfer of Knowledge and impact creation.
- Carl Tryggers Stiftelse “High quality SiC films for high frequency devices”, 2006-2007.
- Ångpanneföreningen Research Foundation “Cubic SiC for energy efficient power and optoelectronics” 2008-2012.
- Ångpanneföreningen Research Foundation “A new white LED for general lighting” 2009-2012.
- Richerts Foundation “A new white LED for general lighting” 2009-2012.
- Swedish Energy Agency “Cubic SiC for white LEDs” 2009-2011.
- Nordic Energy Research: “Northern Light Emitting Diode Initiative” 2010-2012, 7000 kSEK; NORLED (www.ifm.liu.se/norled) funded by Nordic Energy Research. Initiated the network and Coordinator of the project with 11 partners from four countries. The project was selected as one of four from 51 applications.
- Swedish Research Council “Flourescent Silicon Carbide for white light emitting diodes” 2010-2012.
- Swedish Energy Agency “Cubic silicon carbide as a new photovoltaic and light emitting material”, 2014-2016.
- Swedish Governmental Agency for Innovation Systems (Vinnova) ”Cubic silicon carbide as a new solar cell material”, 2013-2015.
- Swedish Research Council “Bulk growth of 3C-SiC” 2015-2018.
- Swedish Research Council “Cubic silicon carbide for solar driven applications”, Swedish Research Links 2016-2018.
- Swedish Research Council "Cubic Silicon Carbide as Photoelectrode for Hydrogen Generation from Solar-driven Water Splitting" 2015-2018 (Co-PI in growth of 3C-SiC)
- Swedish research council for sustainable development (FORMAS) "Innovative photoelectrode for conversion of CO2 and water into fuels using solar energy" 2017-2019 (Co-PI in growth of 3C-SiC)
- Swedish Research Council Strong Research Environments Area “Stimuli-enabled energy materials for smart bioelectronic devices” 2017-2022; Co-PI in growth; 24 MSEK.

- Swedish Governmental Agency for Innovation Systems (Vinnova) “Non-poisonous substitute for hard chrome in volume applications” 2017-2018.
- European Regional Development fund - ACCESS project (East Sweden regional partnership) to strengthen innovation capacity in small and medium sized companies in collaboration with research “Silicon carbide membrane for pressure sensors in fuel engines” 10-11/2018.
- Swedish Energy Agency “Silicon carbide membrane and new light source for a robust high temperature automotive pressure sensor” 2018-2019.
- New-Energy and Industrial Technology Development Organization, Japan, “Development of white LED by substrate technology” 2010-2011. Coordinator Satoshi Kamiyama, El Seed Corp. Co-PI in growth of fluorescent SiC.
- Japan Society for the Promotion of Science, Meijo University (Japan), Linköping University (Sweden), Rensselaer Polytechnic Institute (USA). Co-PI in growth of fluorescent SiC
- Research Council of Norway, EnergyX programme, “Efficient Exploitation of the Sun with Intermediate Band Silicon Carbide (SunSiC)” 2014-2017. Co-PI in growth of cubic SiC
- Innovation Fund Denmark, “A new type of white light-emitting diode using fluorescent silicon carbide (LEDSiC)“ 2015-2018. Co-PI in growth of fluorescent SiC.