LUND UNIVERSITY

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Skills, innovation and scale-up in Compound Semiconductors – A Swedish pilot line to boost European Sustainability and Resilience

Compound semiconductors are critically needed to enable the digital transformation, electrification and quantum revolution. Compound semiconductors are also an area where Europe already has worldwide leadership in science and technology, giving it a strong position, both to defend and to further develop. In light of this, lab-to-fab transfer and the capacity to innovate advanced chips should be consolidated and strengthened.

To achieve these aims, there is an urgent need for a skilled workforce of technicians, engineers, and scientists familiar with clean room techniques and with semiconductor characterization and production technology. Europe also needs to provide access to the equipment and the competence sought by various stakeholders – start-up companies, institutes as well as established firms – to develop innovations from idea to market, providing employment opportunities in Europe which will contribute to European sovereignty and resilience in this critical area.

Lund University has the capacity and ambition to host an integrated Research & Training Centre and Pilot line that addresses these needs within the specific area of Compound Semiconductors.

Compound semiconductor nanodevice technology makes it possible to harvest the superior performance of specific, highly optimized material combinations on established silicon (Si) platforms. State-of-the-art compound semiconductor device technology is presently deployed in transistor and solar technology in European projects and developed for optical display techniques, future communication and radar-technology, sensor implementation for drug delivery, reconfigurable RF-electronics, neuromorphics, and the next generation of AI technology. Wide bandgap materials and power devices are under development and supported by the already established Pilot Line 4. For compound devices, generic process modules are created, and Process Design Kits (PDKs) have been established for devices created from our understanding of compound nanotechnology and material properties.

Our aim is to establish a European Centre and Pilot line that **integrates leading-edge research with workforce education including hands-on training in state-of-the-art semiconductor technology as well as lab-to-fab transfer**. The Centre will make the technology available for European users through links to key innovation hubs in Europe as well as to the available Pan European network of competence centers and thus enable start-ups and SMEs to bring the information technology of the future to the market. The Centre will be located in the vicinity of the national Swedish Chips Competence Center (SCCC) to facilitate synergies and coordination. The effort will complement and support related activities in Pilot lines including APECS, WBG, and PIXE with a unique effort on innovation at lower TRLs and tech-transfer towards production.

The Pilot line will be embedded in the unique environment in Lund, Sweden, where the following elements for a link in the European semiconductor value chain are already in place:

- Lund University, ranked highly in Europe[1] with 46000 students, including 10 000 engineering students (ranked #1 worldwide in Sustainability and #3 worldwide in Innovation).
- NanoLund, one of the world's leading research environments for compound semiconductor nanotechnology located at Lund University (500 scientists and staff).
- A long tradition in circuit design using PDKs and commercial foundry services in advanced Si CMOS nodes, as well as the development of unique PDKs for compound nanodevices.
- Lund Nano Lab (LNL), an existing state-of-the-art cleanroom for academic research and education, provision of skills and staff training programs. The clean room already today provides hands-on training in clean room techniques to 100 students annually on leading-edge compound nanodevice technologies. LNL is an open facility available for industrial users from the Nordics countries and Europe facilitated through Myfab and NFFA.EU.
- Science Village, encompassing the ESS European Research Infrastructure Consortium (ERIC), the world's most powerful neutron source for advanced materials investigation (1.8 B€), as well as MAX IV, the world's brightest synchrotron, with unique capabilities to support nanomaterial and device development (400 M€).
- Location in one of Europe's most innovative regions. Sweden as a country is consistently ranked number 1 on the European innovation scoreboard.
- A European semiconductor industry network with the experience and competence to guide SME development and to integrate device innovations, ensuring deep-tech uptake.
- Coordination and participation in several national industry-academy collaboration centers including ACT, (Advanced Chip Technologies), Sentio, classIC, C3NiT, and SCCC. These centres form natural links to research and development within several international companies including Ericsson, SAAB, Volvo Cars, Tetra Pak, as well as a number of SMEs and start-ups with ambition to expand activities on the European markets and contributing to European resilience.
- A network of well-developed collaborations with key European institutions in the form of funded EU-projects, including IMEC, several Fraunhofer institutes, CEA/LETI, VTT, Tyndall national institute as well as a large number of European universities.

As a key element of the envisioned new Pilot line, Lund University is in the process of designing Nanolab Science Village**,** a new 1500 m^2 clean room specifically designed for leading-edge research, workforce training and deep-tech innovation in compound semiconductor technology (TRL 1-6). **To fully realize the potential of Nanolab Science Village as a Pilot line for compound semiconductor nanodevices, European co-investment is required.**

The proposed integration of the pilot line with university-based research operations will enable us to provide **hands-on training in semiconductor technology and clean room techniques to a large number of engineering students**. University-based, lower-TRL research in, for example, neuromorphics, quantum technology, radar- and communication technology, and alternative computing technologies will be a **strong attractor for new, innovation-minded talent** to the semiconductor sector**.**

We further propose the expansion of the production pilot-line facilities, operated in Lund targeting the higher TRLs. Additional European investments into these facilities would provide the equipment and know-how to enable both up-scaling and production of compound semiconductors as a resource to European industry, institutes and start-ups, forming a complete deep-tech hub with connections to complimentary European efforts.

[1] https://www.timeshighereducation.com/student/best-universities/best-universities-europe

These investments and more leverage the European and national investments to date (exceeding 3 B€) for advanced materials infrastructures at ESS, MAX IV and Lund University in Science Village.

The total required investment for realizing the Lund node contribution to this vision is 50 - 100 M€ in capital investment and 5-10 M€ annually in running costs.

Annex 1: Specification of Pilot line for Compound semiconductor nanodevices

Annex 2: Description of the current host research environment NanoLund at Lund University

Annex 3: Illustration of the semiconductor innovation environment in Science Village

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Annex 1: Specification of Pilot line for Compound semiconductor nanodevices

Expected Outcome: The proposed Lund effort is expected to contribute to the following outcomes:

- Broadly accessible pilot line fostering the creation of electronic, photonic and sensing devices and systems (co-)integrating compound nanodevices starting at lower TRLs and bridging the transitions towards operational Pilot Lines, for instance related to heterogeneous integration.
- Innovation building on new technology for future radar and communication as well as neuromorphic implementation, leveraging technology development within European projects.
- Establish a strong link with European institutions in the form of a Pilot Line for compound semiconductors.
- Significant progress towards the adoption of the compound nanodevices in the silicon and semi-conductor arena by allowing the production of new (co-)integrated devices and systems in a quality-controlled way.
- Formation of innovative start-up companies (several annually) building on a strong track record on innovation to drive economic growth in Europe.
- Building on existing investments in ESS and Max IV to develop the innovative ecosystem in Lund Science Village.

Scope: We will use our strong experience in compound nanodevices and their integration on Si CMOS platforms and initially build on the IP developed, to establish a compound nanodevice pilot line(s), where European companies, research centres and academic institutions, can produce on a pilot scale novel electronic and/or photonic devices and systems integrating compound semiconductors.

The Lund effort will focus on the (co-)integration of compound nanodevices with established technologies such as CMOS[2] integration and heterogeneous integration. The focus will be on high-performance electronics, optoelectronics, power technology, and sensor technology and their integration on Si CMOS platforms.

The multidisciplinary research and innovation activities will address:

- Building the toolkit and design modules necessary for creating prototype devices and systems, characterise and assess their performance and their ability to cover the device requirements of the targeted applications.
- Process characterisation and monitoring to control and guarantee quality of relevant device parameters and to allow yield predictions of the integrated devices, in particular using *in-situ* and *operando* investigations at Max IV and ESS
- Integration with education, offering hands-on training at many levels: engineering students, PhD-students, and future clean room personnel.

[2] Complementary metal–oxide–semiconductor (CMOS)

- Adaptation of standard semiconductor technologies including passivation schemes, strategies to align devices over different technologies, modules to contact the compound nanodevices with the periphery, optimized planarization strategies and packaging services.
- Reliability and packaging requirements in collaboration with established technologies within the available pilot lines.
- Implementing multiple wafer runs or other offering to best cover business opportunities
- Defining a sustainable model of functioning beyond the project lifetime, and include activities preparing for the later transfer of the pilot line to an industrial production environment; examples of such activities include addressing relevant cost issues and market perspectives, potential business partners, etc.

In addition, the Lund pilot line will develop a business case and exploitation strategy, in line with strategies commonly used in RIAs.

Research should build on existing standards or contribute to standardisation whenever suitable. Interoperability for data sharing should be addressed.

We will build on or seek collaboration with existing projects and develop synergies with other relevant European, national, or regional initiatives, funding programmes and platforms. Projects are expected to develop synergies and relate to activities and outcomes of the projects selected under the other topics.

We will cover the contribution to the governance and overall coordination of within the European Chips Act initiative.

To host the Pilot line, Lund University plans to construct Nanolab Science Village, scheduled for completion by 2029/2030.

Annex 2: Description of the current host research environment NanoLund at Lund University

NanoLund is a strategic research area funded by the Swedish Government and encompasses more than 50 research groups with more than 150 graduate students. It has a strong foundation in advanced semiconductor materials and component development with a highly interdisciplinary application program within areas such as energy, electrification, information technologies and personalized medicine. Having doubled in size during the last 10 years (through organic growth via competitive grants) it is Sweden's largest research environment in its field.

NanoLund at a glance

- Founded in 1989
- A profile area of the top-100 Lund University
- Strategic Research Area funded by the Swedish Government

- 400 staff, including
  - >50 PIs (13 ERC award winners)
  - 150 PhD students
  - 80 postdocs
- 100 undergraduate students annually trained in nanofabrication
- 1500 m^2 nanofabrication space
- 30 M€ turn-over

- Core competence in group III -V semiconductor nanostructures
- 15 spin-out companies in operation, including 2 EIC Accelerator winners
- Gateway to world-unique infrastructures MAX IV and ESS

NanoLund Excellence: NanoLund is recognized as one of Lund university's flagship research environments, based on: scientific excellence, clear interdisciplinarity and diffusion of technology to society; 30 years of continuous, external centre funding; leadership in undergraduate and graduate education integrated with research; a high degree of innovation and interaction with the business sector and society; and making substantial infrastructure available to the university and external users. NanoLund and the ongoing research has been rated excellent and outstanding in both individual and group context, e.g., it includes 14 recipients of ERC awards, 7 holders of major Swedish distinguished Scholars and Professor awards, 16 on-going major EU projects and 11 ongoing +2MEURO national collaborative projects.

NanoLund in Society: NanoLund aim to apply cutting edge nanotechnology to address societal needs with industrial collaboration and innovation as central enablers. We aim for collaborations within innovation and development areas where our stakeholders face common challenges and where research can be part of a solution. Established collaborations with large multi-billion turnover companies include Ericsson, Alfa Laval, IBM, Volvo Cars and Tetra Pak. We are systematically creating networking and competence exchanges with both large companies and smaller ones, including start-ups. Another growing collaboration area is characterisation of materials and functional devices, including gateway activities for international leading facilities MAX IV and ESS. This includes both working directly on semiconductor technology as well as with industrial users of semiconductor technology (such as the production industries). We support innovation activities and researchers have been successful in pushing tailored nanostructures to the market through spin-off companies. In recent years, the number of active spin-off companies has averaged around 15 at any given time. These companies are important collaboration partners, users of the open infrastructures and offer career opportunities for students and post-docs. Companies have also already successfully attracted prestigious funding from the European Innovation Council (EIC).

NanoLund Infrastructure: NanoLund is heavily involved in both running, developing, and using a wide range of infrastructures. NanoLund has a key responsibility for Lund Nano Lab (LNL). LNL constitutes one node of Myfab, the national research infrastructure for micro and nanofabrication. Myfab was 2020 rated outstanding (and best) in the overarching national infrastructure evaluation. LNL is an open research facility (e.g. part of LTH OpenDoor) available to academic research groups, start-ups and company users. Another important task for LNL is to educate students enrolled at Lund

University. The user base of the LNL, which was designed originally for 40-50 users, has tripled to 140 users since 2007 and Lund University has decided to establish a new Nanolab in Science Village. The new Nanolab Science Village will be the third major research facility at Science Village alongside MAX IV and ESS. Whereas MAX IV and ESS focus on materials analysis, Nanolab Science Village will become the first infrastructure in Science Village to create new advanced materials and promote device technology at higher TRLs. The planning and preparations for Nanolab Science Village will be a major exciting and important task in the coming years with a total investment of ~60MEURO.

NanoLund researchers possess an extensive range of cutting-edge characterisation instruments and techniques ranging from microscopes capable of e.g. single-atom imaging, single cell manipulation and advanced imaging, milliKelvin electrical/magnetic measures and ultrafast spectroscopy to the femto/attosecond timescale. These characterisation laboratories are coordinated by Lund Nano Characterisation Labs (LNCL) and are distributed across LU. The nCHREM facility (part of the national ARTEMIS infrastructure network) has state-of-the-art tools for electron microscopy, including a Environmental transmission electron microscopy for in-situ experiments uniquely suited for studying compound semiconductors. The community develop and use major cutting-edge characterisation tools at synchrotron facilities, such as MAX IV. This includes the strong engagement in beamline and strategy development starting with the initial conception of MAX IV and continuing today. Members also develop and use neutron facilities worldwide and collaborate with the ESS.

NanoLund at the new campus: NanoLund will play a central role in the efforts to establish a new campus area at Science Village and integrate research with the MAX IV and ESS facilities. This includes both strategic developments and real implementation. Most of the activities in the area will in the next 5-10 years be co-localized in an interconnected building complex. The integration of this large truly interdisciplinary gathering of competences and infrastructures in one place has a significant development potential also driving forward other parts of Lund University. We are highly committed to strengthening the integration between research and education, for example through undergraduate student memberships and many activities in undergraduate education programs. We have made it a specific point to address the implementation of technology in companies, including addressing the safety and recycling aspects. We have a broad academic age distribution and established procedures for recruiting new members for further development. NanoLund has a basic strength in the low TRLs, but given the technologies and methods we are moving towards higher TRLs reaching 4-6 in semiconductor tech.

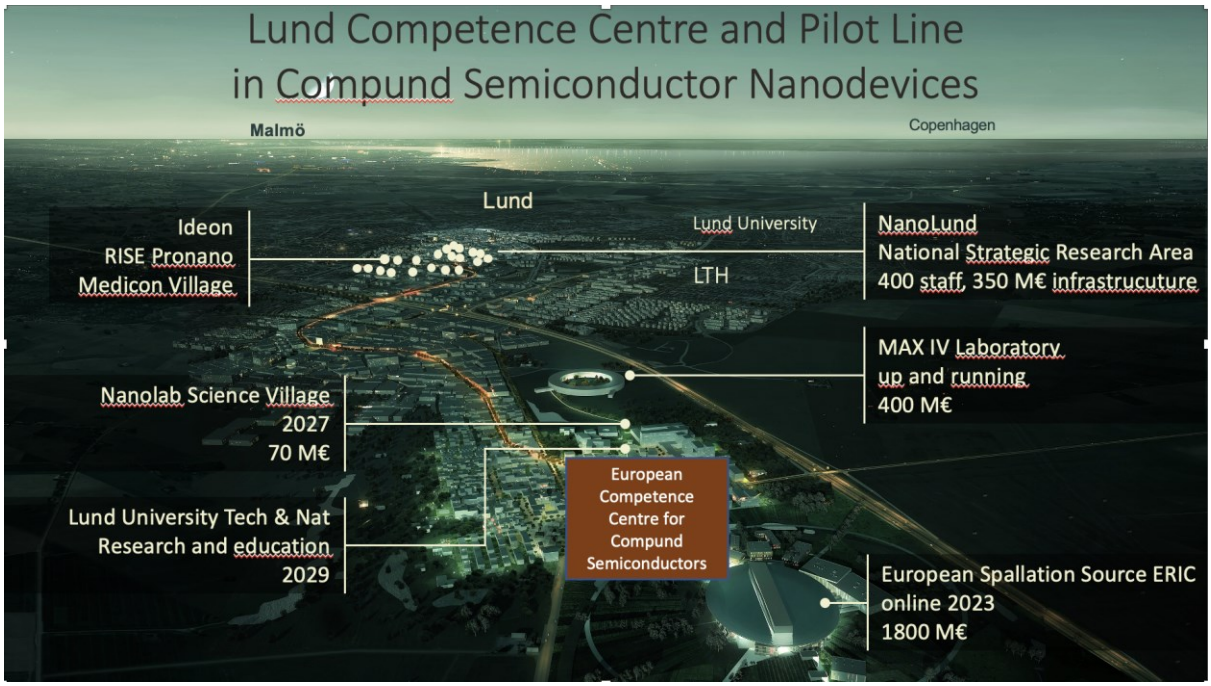
NanoLund visions for the future: In the future, heterogeneous integration of device technologies will increasingly shape emerging ICT applications beyond 2030 and it is the aim to be an important player in this area. New technology is vital for future communication systems, electrification, energy efficient electronics, and to improve renewable energy sources and autonomous systems. The center constitutes a critical mass with strong scientific and technical positions in **semiconductor material science** as well as **device and circuit technology** connecting both to local and international industry, and into **unique infrastructure** in Lund. We will drive a strategy for **functional integration of III-V and III-N technology on Si and Si CMOS.** We will focus on identified process modules that can be applied to several technologies and create a common process platform centered **around PhD education**. We will support new application driven material research and enable processing at higher Technical Readiness Levels (TRLs 4-6). We will continue to take a leading role in Europe in selected key areas of semiconductor technology.

Research goals with 5-10 years perspective:

- *Communication and computing technology:* The implementation of key aspects within the evolution of 6G and development of 7G technology is expected to be hardware-centric based on heterogeneous technology integration. Such device technology requiring above 100 GHz is a multidisciplinary challenge and area of strong potential in Lund. Algorithms for AI and machine learning consume unsustainable amounts of energy and add to latency, calling for new neuromorphic (brain-inspired) hardware, for efficient connectivity and integrating memory and computation via new materials and concepts.

- *Electrification, energy-saving, and clean energy:* The efficiency of power converters is critical in the electrification of industry and society. We have excellent strength in wide-band gap semiconductors that show a strong promise combining high breakdown voltages and drive currents. The technical development within energy harvesting by solar technology will continue to be vital for a fossil-free society. Increasing efficiency over a wide spectral range requires the integration of multiple materials and complex nano architectures. Optical interconnects to Si chips is one key technology for power-efficient data transfer.
- *Sensor technology and autonomous systems:* New sensor technology will assist in climate monitoring, industrial automation, healthcare, and presence detection. An example is radar sensors exploring technology within the D-band (>100 GHz). Integration of improved thin film materials on lab-on-a-chip devices is a natural next step towards an autonomous system. New technology such as integration of solar technology with Si CMOS and dedicated sensors opens for self-powered autonomous small systems in addition to the further development of established technologies.

Annex 3: Illustration of the semiconductor innovation environment in Science Village



The proposed European Competence Centre and Pilot Line for Compound Semiconductor Nanodevices will be centered in Science Village, the site of three major materials science infrastructures:

- The ESS European Research Infrastructure Consortium (ERIC), the world's most powerful neutron source for advanced materials investigation
- MAX IV, the world's brightest synchrotron, with unique capabilities to support semiconductor nanomaterial and device development
- Nanolab Science Village, Lund University's new clean room facility and pilot line with a focus on compound semiconductor nanodevices

Additionally, Lund University is planning to establish a research and education campus in Science Village, including large parts of NanoLund, a Strategic Research Area in nanoscience and -technology.

In total these investments exceed 3 billion Euros.

A proposed European co-investment in the Pilot Line (TRL 1-6), as well as a potential additional investment into production facility (TRL 6-8) would leverage these investments to strengthen Europe's technology leadership in compound semiconductor technology.