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Electrum Laboratory Strategy 2027 and beyond

The Electrum Laboratory provides a unique environment for innovation in nano- and microtechnology – bridging education, research, development, prototyping and small-scale production. During more than three decades, the Laboratory has delivered an unmatched combined output of research publications, technology, competence and new companies. This document outlines the strategy for continuous success beyond its 40´th anniversary.

The strategy has been approved by the Electrum Laboratory Board after thorough discussions in the user community of the Laboratory as detailed in a scenario analysis report, on the self-evaluation submitted to the KTH RAE 2021 and on a compilation of user visions for the Lab, attached as appendices 1 - 3, respectively.

Vision

The Electrum Laboratory will be an essential part of a thriving innovation ecosystem striving to meet scientific challenges and societal goals at both global and local levels. The excellent research carried out in the Laboratory will contribute cutting edge device technology with applications across a broad field of science and technology relevant to global sustainable development goals, as well as to local and KTH internal goals. Further, the Electrum Laboratory innovation ecosystem will generate many new deep-tech companies and attract many existing companies as users.

Mission

The Electrum Laboratory shall continue to be the most competitive lab in Northern Europe for research, education, innovation, industrial development and small-scale device production in the nano- and microtechnology field, thereby helping its users to be internationally competitive.

Window of opportunities

As the current pandemic situation has made clear to everyone: our modern society depends heavily on electronic and other devices manufactured with nano- and microfabrication techniques. An ever-growing part of the value creation across the board depends on these devices. The globalization of the economy over the past several decades have led to heavy concentration and geographical imbalances in the supply chains with great impact in many business segments. Consequently, many countries as well as the EU are now drastically increasing R&D spending in this area in order to help the establishment of more local manufacturing. The Electrum Laboratory could greatly contribute to this and should be able to become a major beneficiary of this imminent development.

The Digital and Green transitions are already huge political commitments. For their implementations, not only general-purpose electronic chips will be needed but also numerous specialized electronic and other similar devices e.g., efficient power devices for vehicle electrification; photonic and high frequency devices for communication systems; quantum devices for computing and communication, sensors and actuators for all kinds of Internet of Things applications, environmental monitoring or medical /health care applications; the list could be greatly extended. For all these types of devices and specialized circuits, the Electrum Laboratory offers an impressive infrastructure for R&D and even small-scale production facilitating eventual scale-up. Deep knowhow and control of such critical devices greatly enhances the opportunities for successful commercialization also at higher system levels. The Electrum Laboratory with its excellent track record of collaboration between academia and industry will be a key asset able to provide the needed support for the technological and societal transformations ahead.

Finally, there is currently a window of opportunity for internal renewal due to the fact that many of the leading staff members at KTH, RISE and other collaborators just have retired or will do so shortly. This opens for recruitment of new faculty and researchers bringing in new competences and application experiences, which will ensure that the all-important human resources are appropriately complemented and developed to address the scientific challenges of the next decade.

Competitive edge

The Electrum Laboratory Board of Directors has clearly stated that research should be the primary driver for the activities at the Laboratory.

However, in this context is necessary to analyze also the ecosystem competitiveness beyond a narrow focus of the Laboratory itself. In a couple of areas, the overall performance provides unique opportunities even at a global comparison:

- High power devices needed for the exploding electrification of the energy and automotive sectors. Together the stakeholders in the Electrum eco-system cover the entire supply chain for power devices in Silicon Carbide and other materials for the next generation, from materials and process technology via devices to systems. We believe that this fact is one of the main attractors to Electrum, KTH, and indeed Stockholm as a place to carry out R&D. Building on this base, new research opportunities on novel oxide-based materials and device concepts should be part of any research strategy.
- KTH has outstanding expertise in the fields of MEMS and photonic devices for e.g., communication and life science applications, sectors where the larger Stockholm environment undoubtedly has a globally leading position. In combination with the existence of an open experimental CMOS-line it provides unique opportunities for all kinds of “More than Moore” applications by integrating specialized sensors and other devices with sufficient intelligence to be useful at a system level.

Contributions to the vision and ambitions for these and other and viable research fields are highlighted in appendix 3.

When it comes to the Electrum Laboratory itself as an infrastructure, it is strongly competitive in fabrication of complex structures, devices and circuits with a significant degree of integration, requiring a technology readiness level far above the normal for a university laboratory, but still with a university laboratory level of flexibility. The reproducible processes in semi-automated tools, compatible with small-scale production and operating at industrial level yield under an ISO9001 certified quality management system, adds to this strength and meets the prerequisites for substantial support to start-ups and SME´s.

Scientific success often results in spin-off companies, welcome to stay and prosper within the technology incubator at the Laboratory. The commercial usage is about 50 %, and increasing. In average, one new company per year joins the Lab. In the past, most new companies were start-ups based on research and development at KTH and RISE, while recently also several companies have approached from outside, attracted by the Electrum ecosystem for innovation.

The real strength of the Electrum Lab is its proven track record of combining excellent research results and proofs of concepts with delivery of actual devices to outside partners for integration in real application specific systems and for allowing a smooth transfer of these high-tech results into commercial production. This combination has proven both cost efficient and technically competitive.

While the history and current status provide an excellent starting point for the future of the Electrum Lab it is very clear that a continued success will require significantly increased project funding and broader Electrum Laboratory user base at KTH. To achieve this will need

- aggressive action and broadening/renewal of content scope and a broader competitive success for applications to the various funding agencies. It will also require significant renewal of KTH faculty, in particular younger faculty with research interest in micro/nano-devices and the kind of infrastructure that the Electrum Lab can provide.

- a bold, united academic vision, encompassing all parts of KTH, to be competitive, especially at the national level. To this end, a better coordination between Electrum and Albanova will be necessary, accepting and enhancing the complementary aspects of the two locations. It will also require a better joint communication about the many past successes and future ambitions at the KTH level.

Market analysis

The key customers at Electrum Laboratory are the research and development groups at KTH and RISE, as well as start-ups and small and medium size companies using the facilities for prototyping or "small-scale" production. The research and development activities that these users carry out in the Lab, are based on advanced materials physics and device processing technology, aiming to support applications addressing the societal challenges in digitalization, health, energy and environment. Thereby the Electrum Laboratory will contribute to reaching several of the UN sustainable development goals (SDGs). Due to its enormous importance, these research fields have been well funded by Swedish national agencies and within EU Horizon Europe. This situation is expected to continue and even improve since motivated by the increasing interest to maintain a European semiconductor industry.

In addition to building on the existing strengths mentioned above new and emerging fields of science and technology should be developed to keep the Laboratory relevant also in the future. This development must clearly be led by the R&D projects pursued by the users of the Lab. As examples, we just point at a couple of complementary areas of potential expansion which could be of interest:

- Integrated quantum devices based on semiconductor-like processing technologies. This is a field where huge efforts are being launched at the European level and where the current activities would greatly benefit from the capabilities of the Electrum Laboratory to achieve needed breakthroughs in integration. In order to align with the national efforts financed by the Wallenberg foundation a tight collaboration with the quantum communication group at the Science School of KTH would be instrumental.
- Novel wide band gap materials, e.g., gallium oxide, as well as the more mature III-Nitrides, have great potential for devices with applications in power systems, telecom, sensors etc.

Materials know-how has a long tradition at the Electrum Lab and although the materials technology for Nitrides has matured in recent years, the potential for advanced devices and new applications is still very attractive and there would be lots of synergies with the existing III-V technology in the Lab.

- The use of polymers for flexible and/or biodegrade-able devices or simply substrates for electronics, is of great interest for wearables, health and other applications. With moderate investments in such technologies, new application areas with great potential societal impact and start-up opportunities would open.

As recommended below, these as well as other cases would greatly benefit from recruitment of additional faculty at KTH to enhance the knowledge base.

Naturally, only a limited number of companies demands access to an infrastructure with the capabilities of Electrum Lab. Still this unique ecosystem for innovation steadily fosters and attracts new start-ups and external companies at an increasing rate and increasing success. As long as the research and development activities flourish, there will be a need for an incubator, capable to accommodate and nurture novel technologies to commercial maturity.

As Electrum Lab operates in a field where the competition for scientific funding is extremely though, the environment will benefit from a focused effort to attract projects, designed to fully exploit the potential of the infrastructure, i.e., where design and fabrication of complex structures, devices and circuits at a high degree of integration is the unique selling argument.

Competitor analysis

Electrum Laboratory does not intend to compete with the large efforts at e.g., IMEC in Belgium or LETI in France, which focus on mainstream technologies and backed by the large equipment manufacturers.

Instead, the Electrum Lab aims to fill the gap between research and commercialization for more specialized devices and applications based industry. In this segment, there are a dozen of laboratories in Europe, operated by universities or, more often, by research institutes. These laboratories are primarily supporting their local industry and innovation environments, and have in some cases status as national infrastructures. Some of the most prominent laboratories in this category are Tyndall (Cork, Ireland), MESA+ (Twente, Netherlands), DTU Nanolab (Copenhagen, Denmark), Micronova (Helsinki, Finland), LAAS CNRS (Toulouse, France), Sintef MiNaLab (Oslo, Norway), and several Fraunhofer institutes in Germany. All with their own specialties and key processes.

In this context, Electrum Lab provides an extraordinary combination of quality and flexibility. The experimental open access CMOS line is unique in Europe and the availability of complete process lines for different materials systems in quality-controlled equipment, including silicon based MEMS, III-Vs for optoelectronics, and silicon carbide for high temperature and high power applications opens possibilities for integration, not available anywhere else.

In addition, Electrum Lab provides easy access to relevant expertise throughout the network of users and stakeholders, enabling a very fruitful cross-fertilization. This is also a basis for the successful Electrum innovation ecosystem, which supports Sweden with competence in nano- and micro technology and contributes to the Swedish semiconductor industry, as a whole.

Internally within Myfab and within KTH there is of course some competition with respect to infrastructure services to research projects. However, the technical capabilities of the various labs have over the past decades developed into rather complementary profiles. None of the other national labs can match the Electrum Lab with respect to broad semiconductor process technology nor can any other lab offer the quality assurance of ISO9000, essential factors behind the uniquely large industrial R&D activities at Electrum. As a technology incubator in its field, Electrum has no competition in Sweden, even if the still quite immature ProNano initiative, operated by RISE in Lund, is aiming to establish a similar activity to support business in southern Sweden.

Overarching SWOT

Strengths

- Broad technology offerings of industrial quality processes
- Unique innovation environment for scientists and entrepreneurs
- Combination of research, development, and small-scale production
- Long and successful track record

Weaknesses

- Need for renewal of scientific agenda and competence
- Few activities in flexible or polymer electronics
- Unclear long-term development of Kista Campus
- Low usage rate, especially in research and development

Opportunities

- Several viable research fields with increasing funding at national and EU level
- Electrification of society demands more power electronics
- Improved coordination between the Lab and the users and between the various user groups
- Growing attraction for companies

Threats

- Changing prioritizations in the Swedish research funding landscape
- Internal competition for resources within KTH
- Limited possibilities to attract funding directly to the Lab, both at the Myfab/national and at the European levels
- City development demands, which may restrict the type of operations carried out at the Lab

For a more detailed SWOT see the scenario analysis in Appendix 1.

Action plan with recommendations

Any sufficiently bold strategy will of course meet a number of challenges. The action plan presented here is organized to highlight the challenges and describe the proposed mitigation measures.

Sustainable development and increased usage

Electrum Laboratory and its stakeholders will secure a sustainable development of the infrastructure and the environment, by attracting new competence and funding, to build the next research and development platform in the fields of semiconductor-based materials science, and nano- and micro-technology. To implement this the following actions are crucial:

KTH EECS must initiate a faculty recruitment action for future research leaders in relevant topics and genuine interest in the development of the Electrum Lab. At least one of these should be an international recruitment for a professor position.

RISE must establish a significant portfolio of new industrial development projects using the facility.

Industrial renewal should be pursued by nurturing new companies attracted to the environment. Special focus should be on the opportunities offered by the R&D projects in the Lab.

A new scientific leadership must be appointed for the Electrum Lab, with closer ties between the KTH research agenda and the Lab. As a first, interim step we propose that KTH appointments a Scientific Director coupled to the Lab, with the task to elaborate a proposal for more detailed research program at KTH, recruit external partners in support of the program, and establish an action plan for its implementation, including a credible funding scheme. As a more long-term solution a position which combines a professorship (possibly newly recruited) with the position as Director of the Lab should be considered. This scientific leadership should then be complemented with a position as Director of Operations to assist in the daily operations and user interactions. (C.f. KTH/PDC where this model has been applied for a long time.)

Myfab KTH and beyond

KTH operates two infrastructures, Electrum Laboratory and Albanova Nanolab, within the field of nano- and micro-fabrication, however with different and largely complementary focus and user base. Both laboratories are part of the Myfab KTH node.

KTH Rector need to install a top-level committee responsible for the overall KTH joint strategic vision and marketing for the two labs, including the Myfab participation. The science and technology profiles, and the future development and investment plans will be formulated to form a basis for collaboration and to counteract internal competition. The committee will be comprised of professor-level individuals and the Lab directors, and will have a balanced composition with respect to the stakeholders at the two labs.

Electrum Lab and its stakeholders will also actively seek benefit from a closer collaboration with other KTH infrastructures, primarily Hultgren Laboratory and 2MILab.

Societal interaction agenda

Electrum Lab has a profound role and importance for KTH, far beyond education and research, and KTH management will bring this up in top-level discussions with strategic partners. Especially, it should be considered in discussions on the development strategy for Kista with City of Stockholm and other major stakeholders in Kista Science City.

KTH will give general support for inclusion of the nano- and micro-fabrication field as part of the Region´s Smart Specialization Strategy in the EU context, to be endorsed by the Stockholm Region.

Internal Organization

The user groups at Electrum Laboratory have main responsibility for operation and maintenance of tools, quality of processes and support to users. Together with the lab staff – with responsibility for the infrastructure and media supply – the Laboratory is fairly efficiently operated with clear distribution of tasks. However, the staff is limited and the spread at different organizations causes some inefficiencies, and lock-in effects.

A discussion with the user groups must be initiated on how to form a more efficient organization for improved user support, coordination and redundancy and on needs for securing the necessary competence development. The discussion should include the option to transfer staff between groups and the Lab.

Marketing Plan

Marketing of Electrum Laboratory and increasing the awareness of nano- and micro-technology is continuously made through seminars, participation at conferences, interaction with research groups, visits from companies and general public, as well as press releases and articles. The web pages of Myfab and of KTH draw new users and interest.

A more ambitious marketing plan for the laboratory will be elaborated, approaching different target groups, e.g., at KTH and other universities, and at companies in our network, and beyond. Myfab access – a program for attracting new users from Swedish academia and companies – has proven successful and should be further promoted to find new participants. The web pages are in need of renewal and improved visibility is anticipated through deepened collaboration with KTH Innovation and KTH Communication Support.

Re-investments and infrastructure improvement

The infrastructure, with processing tools, media supply systems, ventilation, etc. has been continuously updated during more than 30 years of operation. It is possible – by comparatively minor means – to modernize and keep the systems up to date, and to further prolong the lifetime of the infrastructure with at least 10 years.

A strategic investment plan must be elaborated, including upgrading of tools to meet new processing demands, and the demands for e.g., increased media supply, energy efficient climate control, and limitation of emissions.

City development adaption

The development of Kista from an industrial area to a town with housing, schools and public buildings, served by a tramway, may in the future set limits for the transport and handling of gases and chemicals. Electrum Lab is collaborating with the Stockholm fire department and rescue service on the demands on gas and chemical handling, and on a common rescue plan.

A contingency plan for phasing out the most dangerous gases will be developed by Electrum Lab in collaboration with the relevant user groups, and possible limitations in use of other gases and chemicals need to be identified. KTH will implement the solutions as necessary, including e.g., stricter handling routines, decommission of potentially hazardous processes, new gas scrubbers, and re-location within the lab of tools using similar gases, for shared gas supply.

Appendices

1. Scenarios for the Electrum Laboratory, internal report spring 2021
2. Self-evaluation for the Electrum Lab submitted to the KTH Research Assessment Exercise2021
3. Market analysis for the research segment, including a compilation of user contributions

Appendix 1

Scenarios for the Future of the Electrum Laboratory

Purpose and status of this document

The purpose of this document is to present the current situation, including usage, financing and a SWOT analysis, and to initiate a serious discussion about potential future developments. To this end a few possible strategy scenarios are outlined as examples and a set of recommended actions is proposed. All stakeholders of the Electrum Laboratory have been invited to contribute to this discussion and to present alternative ideas and scenarios, and multiple meetings have taken place to this end. The document has been approved by the Electrum Laboratory Board. It is now distributed to Rector at KTH, the Electrum Laboratory management and to all participating stakeholders for further actions towards implementation of the recommendations presented below.

Introduction

Over the past 36 years the Electrum Laboratory has developed from an idea into a unique world-class facility for research, development and small-scale production of micro- and nano-devices for electronics, photonics, mechanics and sensing as well as for equipment and process development. It has over the decades been home to a mix of students, researchers, engineers, large companies and start-ups. The projects carried out in the Electrum Laboratory has not only generated excellent research, as verified e.g., through the multiple KTH Research Assessment Exercises, but also ***direct*** technology transfer to several very successful industrial activities in the local region, which today employ about 500 people and have more than 1 200 MSEK turnover with a healthy profit. In the past, most new companies were start-ups from KTH and RISE, while recently, several companies have approached from outside, attracted by the Electrum Lab ecosystem. Jointly, these companies have attracted very significant private foreign investments in Sweden over the past 20 years. In average one new company joins the Electrum Lab per year. The two most successful companies, both now established in Stockholm, are:

- Silex Microsystems (780 MSEK and 237 employees), world's leading "pure-play" microsystems foundry
- Finisar, part of II-VI (274 MSK and 153 employees), high frequency telecom devices incl. tunable lasers

Largest of those still primarily active at Electrum are:

- IR-nova (60 MSEK, 28 employees), imaging infra-red detectors and modules
- TranSiC - part of ONsemi (29 MSEK, 13 employees), SiC based power electronics
- Ascatron - part of II-VI (15 MSEK, 13 employees), - SiC process technology and devices
- KISAB (5 MSEK, 7 employees). low defect density SiC wafers

The students and PhDs emanating from the Laboratory are contributing to almost every relevant company in the region and beyond, adding a substantial competence provision to the regional businesses. Many employees of major device manufacturing and high-tech industries and start-ups in Sweden (e.g., Ericsson, ABB, FLIR, Tobii) are strongly associated with the lab. Outside Sweden, several former Ph.D. students are now at major industries like Intel, Osram, Bosch, IMEC etc.) and many are cleanroom managers or decision makers, also in the newly emerging economic powers, including China.

Several new technologies have been invented, imported or refined to usefulness in the Electrum Laboratory, in particularly with respect to semiconductor epitaxy and etching with ensuing applications to highly sophisticated electronic, optical and micromechanical devices supporting communication infrastructures, power systems, consumer electronics and technology for life science. The key distinguishing element of the activities at the Electrum Laboratory has been the focus on devices which could be delivered to outside users for realistic evaluation in their specific applications. The Laboratory has also paved the way towards higher quality standards including being the first ISO certified microfabrication R&D Laboratory in the country, and still one of the few in Europe.

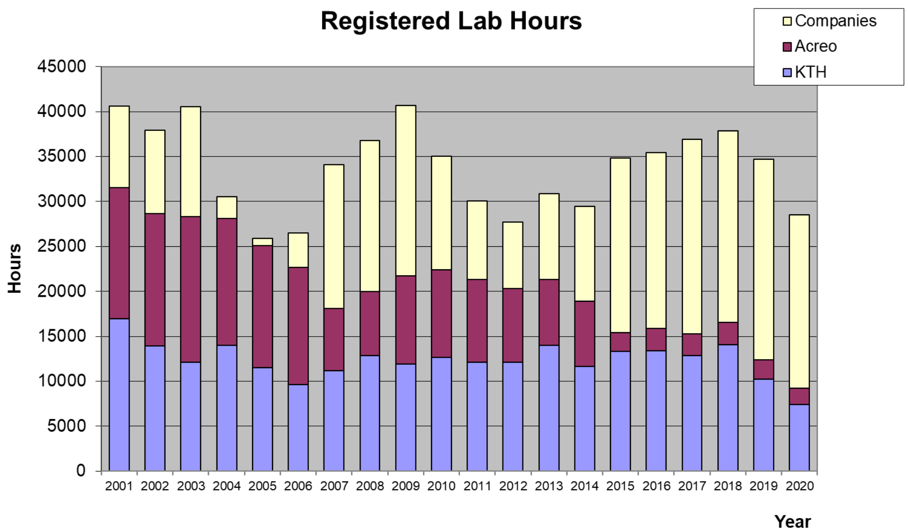
Challenges

Despite being at the heart of many great research, innovation and commercial successes in the past, its existing excellent world class technology and several strong current project developments, the Electrum Laboratory for the future needs to meet new developments and new requirements. In response to changing external factors, the strategy for long-term development of the Electrum Laboratory facilities continuously needs to be updated. Currently, some of the most important trends driving the development at KTH and in the local region are:

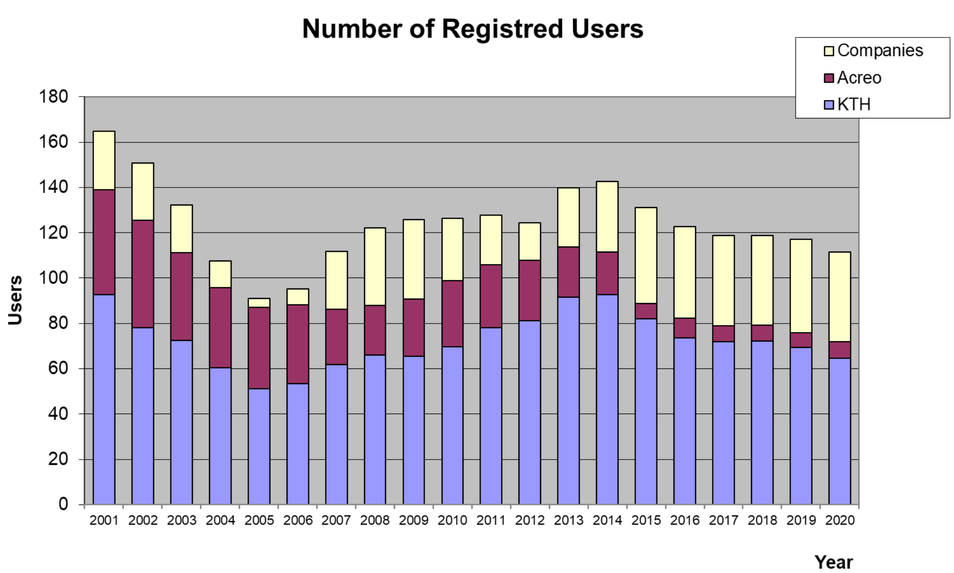
- A recent decision by the Rector of KTH to start an investigation regarding the status of all KTH satellite campuses.
- The tendency in the past two years of decline in the Laboratory use by KTH research projects, possibly in part related to the decreasing Swedish funding available in the relevant areas.
- The low-level usage of the Laboratory by RISE projects since several years.
- The fact that the Laboratory use has been dominated by commercial companies for several years.
- The constant challenges in keeping a balanced budget, reflecting the discrepancy between the needs perceived by the users at working level and the willingness/ability to financially support the common infrastructure at the project management level.
- The increasing age of the facility installations, tools and personnel, creating a demand for new recruitments and in-depth reinvestments in the coming 5-year period.
- The gradual transition over the past decades of Kista from an industrial area to a much more mixed city environment, including domestic housing, schools, trams, etc., in the immediate neighborhood of Electrum.

Current utilization of the Electrum Laboratory

The usage of the Electrum Laboratory is illustrated in the following two graphs. The first depicts the overall number of hours registered for work inside the cleanroom. It clearly shows that the commercial use has increased, both in hours and as a fraction. The variation depends both on the general economic activity in the region and on the singular effects of large company users moving out of the lab.



The second graph illustrates the number of users. In combination with the previous figure, the data reflects the well-known fact that the academic users spend less hours per person in the lab than do commercial users. Hence, the importance of the lab for the academic users is actually more significant than what is indicated just by the hours registered.



Current financial model and development

The financial model for the Electrum Laboratory operation is fully transparent to users and has been successfully used with only minor modifications for over two decades. It builds on the following elements:

KTH is the owner of the Electrum Laboratory but has a long-term collaboration agreement with RISE about joint operation and responsibility for the facility. Furthermore, the Electrum Laboratory is through KTH part of the national distributed research infrastructure Myfab financed by the Swedish Research Council.

A user ownership model is applied, where the Electrum Laboratory is responsible for the infrastructure, some specified common processes and equipment and for the overall coordination and handling of specific support and projects directed at the infrastructure at large. Each user group may place an equipment in the Electrum Laboratory based on the general principle that it is open for others to use, subject to approval of technical operation skills. The equipment owner is allowed to charge user projects for running costs according to the Myfab tariff. The Electrum Laboratory monitors usage and acts as a clearing house for these fees. For historical and other reasons, the Electrum Lab itself is also responsible for a limited number of machines. This operational model ensures that the technical expertise among the users is actually engaged in maintaining a well-functioning lab and minimizes the central costs and incentivizes a dynamic technical development. As history shows, the Electrum Laboratory has been well served by this model which is very appropriate for an R&D facility and in contrast to a foundry model. Never-the-less the model has proven to be very useful in allowing also for pilot and small-scale production by combining sufficient yield and uptime with great flexibility.

The financing model for the general infrastructure is based on full cost and equal sharing of these based on usage (hours and clean-room area) and is fully transparent to the users.

Users are represented in the Steering board and agree on an annual basis on a cost budget based on their project needs, available resources and cost predictions from historical data over several decades.

External general support or support for specific projects undertaken by the Electrum Laboratory itself are then deducted from the operational costs.

As mentioned above, users are subject to the Myfab approved list of fees per hour and machine type, respecting the full cost model. In our model, the organization (research group) responsible for a machine will receive this fee for covering their running, maintenance and lab area rental costs. The Electrum Laboratory is only acting as a clearing house for these machine fees which amount to about 15-20 MSEK /year. Therefore, these costs neither add to the cost nor to the user fees of the Lab as such.

In addition, external users may get specific full control of a specific area or machine in return for full cost payment. The total income from external users is also subtracted from the cost.

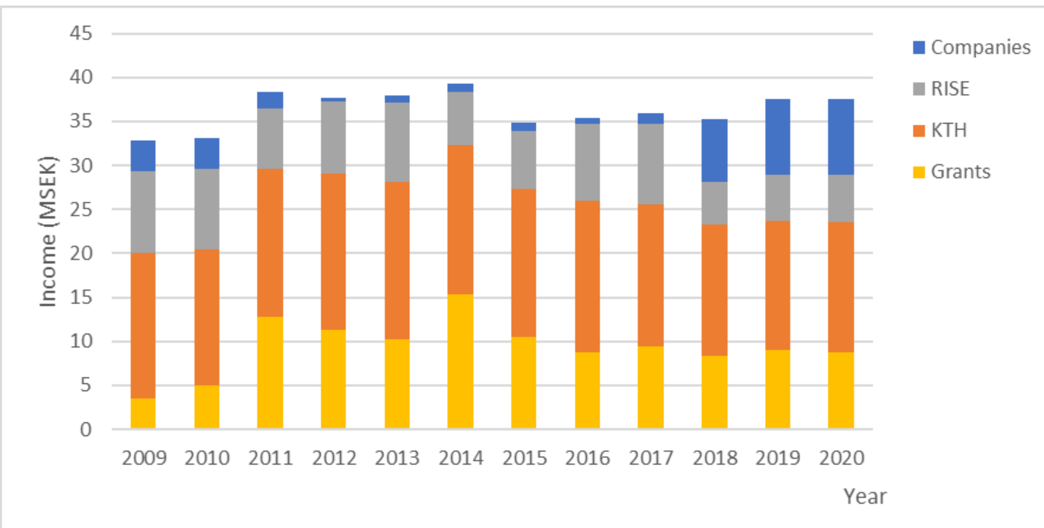
At the end, the remaining cost is distributed between KTH and RISE based on hours and clean-room area. For each organization, internal support is deducted before the user fees are distributed to the individual groups and projects. Importantly, these costs are then fixed for the coming year in order to ensure that the fixed costs of the infrastructure will be covered.

It should be noted that the user fees are substantial in comparison to most research infrastructures, many of which are completely free and based on a system for allocation timeslots. We firmly believe that our model has helped to keep up the long-term quality and renewal of the equipment and processes to the benefit of the users.

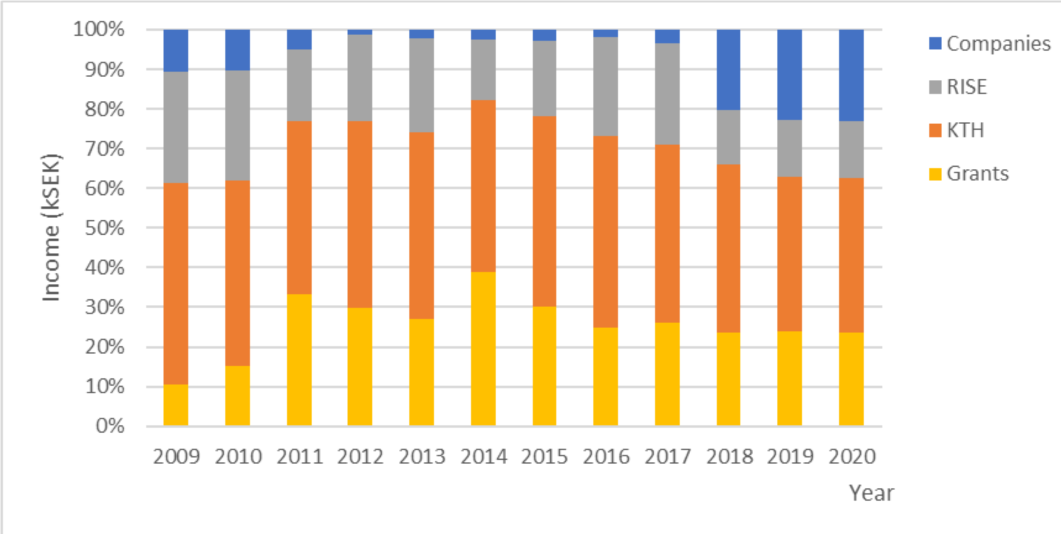
A final important note on the balance sheet: Electrum Laboratory has made a point to always keep reserves ("myndighetskapital") amounting to at least future depreciations. Hence, there is no hidden debt or overspending. Currently, the accumulated free reserves are about 4 MSEK to be used as a buffer for emergency investments or other unforeseen events.

The development of the finances over the past ten years is depicted in the following two graphs. The first shows the contributions from different categories of stakeholders in real terms and the second as fractions. We can make some clear observations:

The financial volume has been comparatively stable around 35 +-4 MSEK per year. This amount does not include the cross-transfer of equipment user fees between the various user groups, which amounts to an additional 15-20 MSEK per year.



A second observation is that the company use has increased significantly over the past two years. Historically we have experienced this before and it may be a sign that one or more of the companies may need/want to move out of the Electrum Laboratory, which should it happen, would of course leave a gap in both content and financing which will take some years to regain.



However, a few more insights can be gained when considering the changing nature of some user contributions. One is that original RISE projects have essentially disappeared, and the RISE activity is now largely about support to some of the companies. One ought therefore to look at the current combined company and RISE contribution as having commercial origin, further enhancing the exposure to commercial realities and developments. Second, the nature of the "Grants" has changed from mostly support for generally useful new equipment to projects based on direct staff work, hence adding to the task-list and not directly supporting the infrastructure as such. Finally, one should note that the overall KTH contribution has remained fairly constant, the direct KTH-user fees have been shrinking, primarily as a consequence of decreased hours worked.

Although the financial model of the Electrum Laboratory is basically sound, the analysis above indicates it will be necessary to enter into a discussion on the balance of costs and risks between different categories of users. What was acceptable for marginal users may not be fully applicable once the usage becomes large. The current Myfab tariff does not take this into account. Also, the long-term robustness of the operation requires a clear ownership with sufficient self-interest to operate the shared infrastructure.

Questions for the future

The combined effect of all the factors mentioned above raises some basic questions which the Electrum Laboratory will have to answer convincingly during the next few years.

- Can today´s activities be continued in view of expected increased external safety concerns? Which activities would then be acceptable?
- What does various parts of KTH need to do in order to increase the number of academic users, thus ensuring continued to support the Laboratory as part of a National research infrastructure?
- How is the innovation culture maintained to continuously nurture new deep tech successes?
- How to strike the balance between "stability" in terms of reproducibility and uptime and experimental process and technology renewal driven by the needs of emerging science?

- How can the increasing need from commercial companies for private lab areas be made compatible with the ambition to provide an open lab environment?
- How to increase the interest of both industrial collaborators and research funders in the need for a facility which permits realization of devices based on semiconductor and similar technologies with possibilities to scale to production?
- How do we in a long-term perspective ensure a balance between user fees and operation costs?
- How do we finance 10 – 30 MSEK investment in infrastructure upgrades, to give the Laboratory another >20 years of lifetime?
- How to finance tool investments to satisfy both commercial and academic needs, baseline as well as cutting edge research equipment?
- How do we secure that a new generation of key personnel can be recruited and educated, for the next decades of operation, despite increased costs in the short perspective?

SWOT-analysis

To proactively meet these and other challenges and to underpin the scenarios for future development strategies which are briefly described in the next section, we will here try to analyze the situation for the Electrum Laboratory using a SWOT analysis. The lists of bullet points under each category are not exhaustive and new additions and/or alternative suggestions are welcome to keep the SWOT analysis continuously updated.

Strengths

- Excellent facilities, also in a European comparison
- Working CMOS line
- Stable demand for state-of-the art silicon micromechanics
- Significant expertise in compound semiconductors, III-V, SiC, SiGe
- Professional management resulting in high process stability and excellent quality management.
- Mostly production-style equipment with higher capacity and more stable processes and higher up-time than normally found at university infrastructures
- Very close and fruitful collaboration with several companies as users of the lab, driving both technology and quality for the benefit of both research and industry
- ISO certified process environment
- Excellent quality of research output
- Excellent spin-off track record
- Strong interest from a number of start-ups and SME´s, of both in-house and external origin. Generally, these companies need the shared facilities offered in the Electrum environment, at least for a long time.

Weaknesses

- Research funding to the area has decreased in recent years.
- Despite substantial machine and process additions in recent years (CMP, micro transfer printing, currently procured DRIE etc.) a demand for renewal of the processing tools remains.
- No in-house e-beam lithography.
- Limited renewal of younger faculty at KTH using the Laboratory.
- Relatively few students nearby.
- Applied physics research at KTH has largely moved out and can be expected to focus on work at the Albanova Nanolab facility.
- RISE is establishing a new facility for innovation support in Lund (ProNano) which may dilute interest in Electrum Laboratory.
- Need for continuous replacement of ageing infrastructure and personnel.
- Somewhat raised user fees can be expected due to the fact that lab specific project funding is coming to an end.
- Difficult to integrate in the local innovation support system, which is more focused on software and digital applications than hardware.
- Some adjustments and/or limitations with respect to use of process gases may become necessary due to external safety requirements. Similarly, available media supply may become a limitation, depending on future processes and equipment and on future company requests.

Opportunities

- Support for tool investments is to some extent available from VR, Myfab and KTH infrastructure grants.
- Relatively little in-house research on fundamental process or equipment technology which opens for new R&D in this direction.
- Quantum computing is advancing but no real integrated technology exists. This could be exploited by the combination of silicon technology, micromechanics and AFM expertise at KTH, particularly when considering also KTH competence in theoretical physics and computer science.
- KTH has a strong position in quantum communication which also includes activities in the Electrum Lab.
- Terahertz devices for future communication systems based on silicon and silicon micromechanics. May become essential for 6G.
- Life science applications- although difficult to pursue from the Laboratory alone the area is a priority in the regional context.
- New materials: 2D (graphene etc.), Gallium oxide for power devices, ...
- Continued development of the 3D integration, enabled by the recently acquired processes, e.g., CMP, Vapor HF, and Micro transfer printing, allowing integration of CMOS circuits and functional devices for telecom, sensing, etc. At least some of the research projects (current and future) could be developed towards spin-off and commercialization e.g., with support from RISE or KTH innovation.
- There is obviously a need for an incubator of the Electrum Laboratory type. This could be further expanded and obtain support in its own right as an incubator.

- The small-scale production process lines may be used as a basis for foundry services and prototyping for commercial customers.

Threats

- The overall usage seems to be decreasing, which if not reversed might result in an increasing short-term deficit.
- One or more of the major companies may move out of Electrum (for good or bad reasons)
- RISE may decide to focus on other segments than those addressed by the Electrum Laboratory.
- Reduced commitment to Electrum Laboratory and/or to Kista campus in general by KTH
- KTH-internal fights over internal and/or national subsidies.
- Reduced commitment to and/or changed requirements regarding the development of Kista by the City of Stockholm.
- The future development of Kista as a city neighborhood might in the future not allow the handling of types and/or volumes of gases and chemicals needed for the Electrum Laboratory.
- The demand from commercial users on private lab areas reduces the benefit from shared tools.
- The possible lack of commitment to the field of both Electronics and Micro-and Nanofabrication in the regional Smart Specialization Strategy in the context of EU.

Scenarios

Clearly, the future will need a broad set of intelligent calculating, sensing, actuating, communicating and power handling devices to fuel the digital and AI revolution. Most of them will be based on technologies like those available at the Electrum Lab. Nevertheless, identifying and supporting specific, locally anchored profiles of scientific and technical excellence will, of course, be crucial. Equally important is a well communicated, overarching vision and mission for the Lab.

Due to excellent, often unique technology and proven capabilities one could imagine several strategic pathways towards a strong and dynamic Electrum Laboratory also a decade ahead. However, these pathways may result in different basic profiles of the Laboratory, each with its benefits and challenges. They have all in common that they will take long time to fully implement.

Apart from the scenarios discussed below, a few others have been discussed but have been dropped for various reasons, such as being judged not to be in the interest of the stakeholders or unlikely to gather sufficient political and/or financial support. A few brief comments on such scenarios are listed at the end of the Scenario B discussion below.

A. Research as the driver

Clearly, the importance of micro- and nanofabrication for the future of both science and industry is undisputable. Almost every large university of science and technology worldwide has a dedicated facility in this area to support their efforts. Science in this field has been awarded several Nobel Prizes over the past decades and continues to produce excellent results in both basic and applied science. Advanced fabrication facilities are a prerequisite for competitive research also in the future. These facilities usually also become prime enablers for deep-tech start-ups and innovations picked up by existing companies and thus serves to create disruptive, societal impact directly based on the research and technology developed. This is the main argument for pursuing this scenario.

This scenario recognizes that the main missions of KTH are education, research and collaboration with society. Although not official, in practice these missions normally also come in this priority order. Since the educational activities at Electrum Laboratory always have been rather limited, it follows that a substantial research user base, utilizing a large fraction of the resources, is needed to motivate continued, large KTH central support to Electrum Laboratory as an infrastructure.

For historical reasons, KTH has developed two micro/nano-fabrication labs, at Electrum and at Albanova. The two facilities were built up largely with support from different funders and with different aims (Industry, Vinnova, SSF and KAW as opposed to largely VR and KAW). This has led to a largely complementary profile in terms of equipment, processes, mode of operation and external collaboration. Nevertheless, they work in the same general area, particularly when viewed from outside KTH. However, the geographical split prohibits potential synergies regarding e.g., lab supply infrastructure, but also hampers synergies in the intellectual environment. As a result, KTH stands weaker in the national and international competition in this important field.

To remedy the two above issues would require:

- Significantly increased project funding and broader Electrum Laboratory user base at KTH. This will need aggressive action and broadening/renewal of content scope and a broader competitive success for applications to the various funding agencies. It will also require significant renewal of KTH faculty, in particular younger faculty with research interest in micro/nano-devices and the kind of infrastructure that the Electrum Lab can provide.
- It would also require a bold, united academic vision encompassing all of KTH to be competitive, especially at the national level. To this end, a better coordination between Electrum and Albanova will be necessary, accepting and enhancing the complementary aspects of the two locations. It will also require a better joint communication about the many past successes and future ambitions at the KTH level. A first step towards such an alignment could be the establishment at the KTH level of a joint strategic planning group encompassing senior representatives from both users and current lab management at the two locations. In addition, more attention should be paid to the (already agreed) mutual participation in board and management meetings of the two labs.

Complementary contributions to the academic use should also be possible through increased collaboration with external user communities, in particular at Uppsala University.

Any contributions from research or development projects at RISE would potentially also contribute. Unfortunately, the probability of significant increase of the RISE contribution in the near term is judged to be small. There seems also to be some doubt regarding the engagement from RISE management, an uncertainty which should be clarified.

The non-academic partners would be able to continue to use the facility on similar conditions as today. They would not have to take the full responsibility for the short to medium term financial situation, but they would also have to adapt to the changing needs of KTH, which may limit their physical and/or technical expansion plans. In the longer term, they would, as currently, face the risk should KTH fail to succeed in its ambition.

B. Consolidation of KTH Kista activities to the KTH Central Campus

Although there are no concrete plans, it is conceivable that KTH at some point in the future may decide to consolidate its Kista activities to the KTH central campus. The motivation for such a move may be largely political, driven by a city development perspective, and unrelated to the scientific-technical performance of the Electrum Lab as such. Already now mere existence of the Lab has raised questions regarding the development of some neighborhood properties. However, a consolidation could also be the result of a strategic KTH decision to co-locate the Electrum Lab and the Albanova Nanolab in order to enhance internal synergies.

In this scenario and in order to keep continuity of successful KTH research, it would clearly be necessary to retain at least a minimum of basic silicon processing for micromechanics and electronics. How much of the processes relying on the use of toxic, corrosive and flammable gases that can be maintained is questionable considering the location in a densely built-up area somewhere at the main campus, with mixed other activities and lot of uncoordinated people moving around in the vicinity.

Even relocating only the most essential of the research facilities at the Electrum Laboratory, given its current size and project volume, would clearly require construction of new facility, possibly even a new building. Further, to actually achieve the synergies both in facility management and operation and intellectual environment, it would have to be co-located and coordinated with at least the Albanova lab but possibly also with some other similar activities like e.g., the Hultgren lab (material sciences) or Greenhouse Labs (chemistry). Hence, most likely this would become a large several hundred MSEK operation involving several departments and requiring several years of planning time.

For reasons of physical space, environmental considerations or due to age, some equipment may not be relocated, and its users may have to either change topic or find other labs where their projects could be continued.

It is a unanimous comment from both academic and industrial users at the current Electrum Lab that a joint facility is one of the most attractive features of the Electrum Lab and that it would be highly desirable also in the future. However, it is an open issue if it there would be sufficient capacity (lab area and process portfolio) and a long-term KTH interest to continue to host also significant commercial activities in such a new setting at the main campus. Given KTH´s ambition to support start-ups and SMEs in the local innovation eco-system it might seem natural but there will of course be a certain risk associated with investing in a facility depending also on external, commercial customers.

Activities and users with requirements (lab area and/or processes) different from those of KTH would have to solve their long-term needs for clean-room capacity on their own. An option could be that another actor, such as one of the current commercial companies using Electrum, takes the long-term responsibility to develop the Electrum environment. Another option could be to investigate the need for a completely new facility at another location, "Electrum 2.0". Of course, KTH could still be a minor part in such developments and participate with those resources that would require a larger clean-room environment. However, at the present time, it does not seem realistic that KTH would re-locate major operations except to its main campus, nor that KTH would take the lead in such a development.

C. Electrum Laboratory as a combined R&D-lab service provider and incubator.

Several of the current users, both academic and commercial, have emphasized that they would like to see an even more "professionalized" Electrum lab, taking care of both the common facility and equipment maintenance and, in addition, providing more user support and increased process service offerings. Note that the profile should still be research and development, so not a conventional production foundry. The reason for this request is the ever-increasing complexity of equipment and processes which many users do not have, or even doesn´t want to have, sufficient competence or sufficient resources to master. Some users proposing this model have claimed that they would be willing to pay more for such a service, without specifying any amount, though.

In contrast to the current governance model a larger role for the Lab itself would mean that the Electrum Lab should be responsible for most of the tools and processes and thereby also have a larger pool of technical lab staff with the prime task to keep all tools and processes up to specifications. Such a model would be closer to the current organization of MC2 at Chalmers and to the initial mode of operation of Electrum Lab during the 90´s. Hence, it would be entirely possible to change the operational model in such a direction. Indeed, there should be some direct synergies from a maintenance point of view of organizing the staff currently spread out over several groups (Electrum Lab, RISE, EKT) in a coherent group. However, the main objective of improving up-time and process reliability could only be realized if users agree in substantial detail on the priorities, expected service levels and financial arrangements. In the past, the technical and project requirements have not been sufficiently aligned to realize the potential synergies within the resources committed by the users. In the future, improved service levels will mean larger costs, just as today. In addition, one should remember that many problems can only be solved through external support from equipment manufacturers, regardless of organization or ownership of the lab. It would be somewhat naïve to think that absolute service guarantees would be possible.

To be feasible it seems that such a more service-delivering lab organization would need a certain amount of freedom to operate, to make minor profits to be able reinvest in strategic resources, equipment and skilled staff. One would need to carefully consider the legal format and long-term ownership of such an organization. The ownership must be sufficiently financially robust and have at least a decade-long commitment to avoid short term cash-flow issues and to attract users, who de facto will need to have at least a three-to-five-year perspective.

As KTH key missions are likely to continue to be education and research, and since KTH as a public authority has some difficulties hosting commercial activities, keeping KTH as the owner and operator would still require that the main use would need to be academic, albeit with an added innovation-oriented mission. Should this not be the foreseen case, another owner may be more appropriate. RISE could perhaps take the responsibility for running the infrastructure. With a key focus on innovation and support to start-ups and SMEs and based on the currently active companies it could become an attractive asset. Being an institute, the possibility to engage commercially would be larger than if KTH remains the owner. It is also worth to note that RISE of today is a large organization with the financial standing to be a credible owner, as opposed to the situation for Acreo in 1993 when KTH assumed ownership of the Electrum Lab. Nevertheless, RISE may need earmarked financial support from the government or its agencies to become credible as a long-term sustainable action. In principle, one could also think of a purely private/commercial owner and operator. However, the requirements of financial robustness and long-term commitment would remain and thus likely exclude smaller organizations.

An important consideration will be the possibility to fund future investments in new equipment, both for replacement and introduction of new capabilities. During the past decades, the tools open to all Electrum Lab users have been possible in part due to dedicated equipment grants for research and in part from investments made by user groups based on their project funds and/or the income from user tool-fees according to the Myfab tariffs. The amounts invested have been of the order of 10-20 Mkr/year over the past decade and need to be continued at that level for the Lab to remain competitive. In the long run one could anticipate that the research-oriented equipment grants would diminish if KTH is no longer the legal owner and operator of the Lab. Should the investments be transposed into user fees, it would mean a 30% increase of the overall costs but also more importantly, roughly a doubling of the direct user fees (which are about 15 Mkr/yr). It may be questioned if this would be realistic.

A final reflection regarding the incubator role of the Electrum Lab. In an incubator focus is normally on the flow of new companies, rather than on providing ever-lasting support to the existing ones. This is somewhat contradictory to our experiences in the past. The type of start-ups that need the lab facilities are typically early in the value chain, work with technology which must be verified in outside system trials and require substantial upfront investment in hardware. Hence, the start-ups typically need many years of sheltered support before they take off. In addition, some of the very advanced devices developed have such a small potential world market in terms of wafers processed, that they may forever have to rely on co-utilization of the chip manufacturing equipment. Hence, there will always be a need for a very long-term strategy for supporting start-ups in this field combined with a readiness to support SME´s also in the production stage.

Conclusions and recommendations

As mentioned at the beginning of this document, the status description and the scenarios described above have been discussed in multiple meetings with the stakeholders, including the various groups at KTH, RISE the larger current companies using the lab and with relevant user groups at Uppsala University. The entire document and its recommendations have been thoroughly discussed and finally approved by the Board of the Electrum Laboratory.

During the discussions, it became apparent that a large majority of the users very much appreciate the current mode of operation and the overarching concept of a shared environment between academic and industrial R&D projects. The close proximity brings about mutual benefits which go beyond visible collaboration in joint projects and includes joint problem solving in the lab, more reproducible and efficient processes, recruitment of students, access to a larger intellectual environment with seminars. In short, the Electrum Laboratory is the locus of a great eco-system for academics, start-ups and SMEs alike. It is this spirit that the Lab stakeholders want to preserve also for the future.

The Electrum Laboratory Board and Management are convinced that the Electrum Laboratory is a unique resource that will continue to enable:

- excellent, internationally competitive research in fields extremely relevant for the future,
- provide a steady flow of competence in terms of engineers, Ph.D. and project collaboration,
- a thriving collaborative ecosystem of academics, start-ups and SMEs with essential contributions to the business sector in Kista, Stockholm and beyond.

Therefore, the Electrum Laboratory Board and a clear majority of the Lab users favor a development along the lines presented in Scenario A. However, it is simultaneously recognized that there are significant challenges also in this scenario, primarily relating to academic usage and city development. These challenges can and must be addressed jointly by KTH and all other stakeholders. Recommendations for actions to this end are presented below.

Scenarios B is judged not to preserve the Laboratory´s most valuable asset, i.e., the collaborative academy-industry spirit, and to significantly reduce the long-term impact of the Laboratory. In our view, this disadvantage would not be offset by an increased academic interaction. Moving the part of the Laboratory, discussed as an option in Scenario B would significantly reduce the capability of the Lab to maintain its focus on the cross-section between science and industrially relevant device research. Moving the Laboratory would, in addition to the direct moving expenses, also significantly increase the rental costs well beyond what the current activities would be able to absorb without additional direct support.

Scenario C is not judged to be feasible due to lack of a sufficiently willing and financially strong partner who could accept the ownership as well as a sustainable model for the necessary continuous reinvestments in infrastructure, equipment and staff. Further, also in this scenario, the interface academy – industry collaboration is deemed likely to diminish in favor of a development towards a more dedicated commercial foundry /incubator.

In summary, in order to ensure a successful implementation of scenario A, “Research as the driver”, we conclude with the following recommendations, all of which can and should be pursued in the short term:

1) KTH Rector should install a top-level committee responsible for the overall KTH joint strategic vision and marketing for the Electrum Lab and the Albanova Nano Lab, including a coherent participation in the Myfab collaboration. The remit should include a joint, long-term investment plan which respects and enhances the complementarity of the two Labs. It should be comprised of professor-level individuals with a broad overview of the relevant research field and the funding landscape. The committee should have a balanced composition with respect to stakeholders at the two labs. The directors of the two labs should also be part of the committee to ensure sufficient technical anchorage and smooth implementation of decisions.

2) KTH should bring up the role and importance of the Electrum Lab at the top-level discussions with its strategic partners to clarify their views on both short and long-term issues. Especially the following points should be discussed:
    - the strategic commitment of RISE to the Electrum Laboratory,
    - the development strategy for Kista with City of Stockholm
    - the inclusion of general support for the Micro- and Nanofabrication field as part of the Region´s Smart Specialization Strategy in the EU context, to be endorsed by the Stockholm Region.

3) The Department of Electronics and the EECS School at KTH should initiate a faculty recruitment action aimed at strengthening the utilization of the Electrum Lab by KTH researchers.

4) RISE management should take new initiatives to establish a significant portfolio of new industrial R&D projects of interest to the Electrum Lab demonstrating its unique characteristics and thus bring in new customers to the Lab.

5) The Electrum Lab should install a position Scientific / Technical Director to enhance the strategic liaison between the Laboratory and the senior researchers in the current and future research groups at KTH and at collaborating partners.

6) The Electrum Lab management should discuss with RISE, key industrial users and relevant KTH research groups to identify and propose potential ***modifications*** of the current governance, financial and operational models with the aim for improved efficiency and better service provision. Such a plan must address both the service level agreement and the long-term financial issues to ensure that potential benefits will be realistic and sustainable.

7) The Electrum Lab management should investigate and make preliminary plans for adapting the lab activities to potential future restrictions with respect to hazardous gases and materials. Such preliminary plans should aim at mitigation enabling continued operation and should include cost estimates.

Appendix 2

Electrum Laboratory

1. Research profile and quality

The Electrum building in Kista, with offices and vast laboratories, was inaugurated in 1987. The idea was already at that time to build an environment for innovation – bridging education, research, development, prototyping and small-scale production in nano- and micro-technology. Today the Electrum Lab hosts leading research groups, producing ground breaking scientific results and new products, and innovators forming new companies growing in our production incubator. The lab includes a 1300 m^2 cleanroom with process lines for device research and manufacturing, and in addition 1000 m^2 of state-of-the-art laboratories for nanomaterials synthesis and processing, and for advanced characterization of materials and devices. Most activities fulfil Technology Readiness Level TRL 2 - 6, but all TRLs 1 - 9 are supported.

Electrum Laboratory is owned by KTH and operated in close collaboration with RISE, the Swedish industrial research institute. Electrum Lab constitutes – together with Albanova Nanolab – the KTH node of Myfab, i.e., the national research infrastructure for cleanroom based nano- and micro-fabrication, and characterization, partly funded by the Swedish Research Council.

i. Central research area, main activities, service offered

Electrum Lab supports device oriented research requiring advanced nano- and micro-fabrication, and characterization techniques, especially semiconductor based processing for electronic, photonic and mechanical devices and circuits. The infrastructure provides a broad set of tools and well controlled processes to yield efficient and reproducible results at high flexibility for research as well as small scale production. Complete process lines are maintained, for various applications:

- Fully CMOS compatible electronics including circuits and heterogeneous integration options in silicon, Si
- High power and high temperature devices and circuits in silicon carbide, SiC
- Nano- and micro- electro-mechanical systems (NEMS/MEMS) technology in silicon
- Optoelectronics and photonics in the indium phosphide, InP and gallium arsenide, GaAs materials systems

Substrate sizes from small pieces up to 200 mm diameter are handled, and the tools are primarily of industrial standard, facilitating the transfer from research results into industrial development and production. Further access to specialty or back-up processes is available through the close collaboration with the Myfab labs, as well as Nordic and European partners. Electrum Lab offers open access, primarily through introduction of the users to the cleanroom environment, and to handle the tools on their own. Process and characterization services are also offered. Lab area may be rented by academic or commercial user groups for proprietary tools, or for tools and processes shared with others.

ii. Contributions to the advancement of the state-of-the-art

Silicon Electronics – Electrum Lab is one of few academic institutions worldwide that has an advanced SOI CMOS platform available. It is combined with a high performance planarization process – also unique, thanks to a large SSF Research Infrastructure Fellow grant – allowing heterogeneous integration of non-conventional devices and formation of 3D integrated circuits. This enables almost any Internet of Things (IoT) application, e.g. DNA-detection, silicon optics, or energy harvests. Emerging technologies such as 2D-materials (graphene) and spintronic devices are also pursued in this context.

Power Electronics – A strong competence area is SiC based discrete devices and integrated circuits, ICs, for power, high temperature, and harsh environment applications, also including space. Recent IC demonstrators are state-of-the-art, in terms of operating temperature 500-600 °C and complexity, where both analog and digital demonstrators, with thousands of integrated transistors, have been realized. This work builds on the know-how in SiC device fabrication technology accumulated at Electrum Lab since more than 25 years, which has also resulted in several of start-up companies.

Micro system technology – MST for life science applications bridges the gap between academic research and commercial products. This includes lab-on-chip technology for virus detection in breath, digital biosensors needing small sample volumes in the range of tens of microliters with related micro-needles for blood sampling, and aerosol nozzles for lung disease treatments. With organ-on-chip technology the blood-brain-barrier has been modelled to mimic the effect of intravascular administration of psychoactive drugs, and to identify a previously unknown metabolic coupling between the blood and neurons. Organ-on-chip has also been used to mimic administration and response of a heart drug.

In the field of MST based terahertz devices and systems several breakthroughs have been achieved, including the world's lowest loss waveguide technology, several filter demonstrators in frequency bands from 100 to 700 GHz with unprecedented Q-factors, large-scale highly integrated antenna arrays, beam steering demonstrators, and several devices such as ortho-mode transducers, MEMS waveguide switches and phase shifters, which were for the first time demonstrated at sub-THz frequencies, as well as investigation of 2D materials for THz applications. The vision is to construct complete THz systems on single microchips, based on micro machined waveguides with integrated THz components. This approach will revolutionize the exploitation of the THz frequency spectrum for, e.g. 6G mobile networks.

Opto Electronics – Quantum cascade lasers for high speed free space communication in the mid-infrared range provide high scattering tolerance in mist or fog. By employing buried structures, improved beam quality is achieved and high power surface emitting photonic crystal quantum cascade lasers are obtained. For quantum well based infrared imaging detectors, both research and commercial production is carried out. Vertical cavity telecom lasers, and new concepts for solar cells are developed.

iii. Quality and quantity of contributions to the body of scientific knowledge, engagement in national and international collaborations and its outcomes

Electrum Lab supports externally funded research projects at KTH with a total yearly turnaround of about 70 MSEK. Major funding agencies, making a primary quality evaluation before project approval, are Swedish Foundation for Strategic Research, Swedish Research Council, European Union (ERC, Horizon 2020), Knut & Alice Wallenberg Foundation, and Vinnova - Swedish Innovation Agency.

For the years 2018-2020 there are in total more than 500 publications, in journals and proceedings, published by the active users within Myfab KTH. Ten of these were in Nature. 37 PhD theses were produced and three patents approved.

Electrum Lab is active in a range of national and European infrastructure networks and collaborations. On the national level, the Myfab distributed infrastructure organizes the cleanroom labs at Chalmers, KTH, Uppsala and Lund Universities in a firm network for close collaboration on lab operation and administration, competence development, investments, etc. Myfab also handles the Swedish partnership in networks of national infrastructures. The NNN - Nordic Nanolab Network, represents the five Nordic national nodes, with in total twelve individual labs. NNN hosts regular meetings for lab managers, technology experts, and users (with major user meetings every two years). Myfab also represents Sweden in the EuroNanoLab distributed infrastructure, with in total 44 labs in 14 European countries. EuroNanolab aims for inclusion in the ESFRI roadmap for research infrastructures, implements the ”Go Nanofab IN” standard for data handling at nano labs according to FAIR-principles, and biannually holds ENRIS, the European Nanofabrication Research Infrastructure Symposium.

Electrum Lab is founding partner in the European Cleanroom Platform, active since mid-1990. This informal network of managers at leading nano- and micro-fabrication laboratories is invaluable for competence sharing, and only open for invited participants.

KTH is, together with RISE, partner in the EU financed Horizon 2020 Widespread project CAMART², with the goal to develop the infrastructure, science, education and innovation at Institute of Solid State Physics, University of Latvia in Riga (project coordinator). One goal is to build networks of industry and academia within the fields of materials science and nanotechnology in the Baltic Sea region. This will strengthen the collaboration and eventually attract new user groups to Electrum Lab.

SiNano Institute is a researcher's association in form of a distributed center of excellence in nano-electronics, participating in structuring of EU research programs and calls, organizing workshops and promoting collaboration between members, academy and industry. Aeneas – Association for European Nano Electronics Activities has 305 members and the status as Joint Undertaking, with the goal to strengthen European competiveness in electronic devices and systems.

iv. International comparisons regarding facility´s tools and the state-of-the-art

Over the more than 30 years of lab operation, the tools have continuously been renewed. The typical tool lifetime is 10 - 20 years, and investments in the range of 10 - 20 MSEK/year are covered by the user groups, by lab fees for tool deprecations, or by grants from research funding agencies. The tools chosen are a mix of research tools, primarily bought new and fulfilling specific research demands, and refurbished semiconductor industry production tools for wafer sizes 100 - 200 mm diameter. The latter tools make up the major processing lines, are robust, well maintained and provide extremely predicable, uniform, and reproducible processes with high throughput. The combination makes the infrastructure unique in a university context and may rather be compared to well-equipped institutes, including Fraunhofer, Sintef and VTT. This range of tools and processes makes it possible to seamlessly, in the same tools, transfer the research results into production. However, the lab lacks e-beam lithography, which is an important process for most nanofabrication, but it is available at the Myfab partners.

2. Viability and research environment

i. Internal and external funding; current status and strategies for the future

Electrum Lab implements a full cost coverage model, where the income is set to balance the cost to operate the infrastructure, at a quality agreed by the users. The cost is calculated based on historic actual costs and is fairly stable at around 54 MSEK/year. The major income is the user fees, in two categories:

1) The fees paid directly to Electrum Lab, to cover the infrastructure and media, premises, operation, coordination, some depreciations, etc. These fees are based on the number of users, their time spent in the lab, and lab surface for users' tools. Total income in this category is 26 MSEK/year, 12 MSEK of which is related to industrial and 14 MSEK to academic usage. This academic usage is to 25% covered directly by the academic user groups (projects) and to 75% (10.5 MSEK) by support from KTH FOFU.

2) Fees paid to Electrum Lab and reimbursed to the tool responsible groups for maintaining the tools, including tool consumables and chemicals, etc., and for services to users. These fees are based on logged tool and person time, and add up to about 18 MSEK/year, where 60% is industrial and 40% academic.

Electrum Lab is during the period 2020-24 supported by Swedish Research Council, through Myfab, with 3 MSEK/year for operation and an additional 5 MSEK/year for investments.

Two major external projects are run by Electrum Lab, i.e., CMPLab (SSF Research Infrastructure Fellow, 2016-20) and CAMART² (EU H2020 Widespread, 2017-23), both contribute with about 3.5 MSEK/year each, mainly for person time and related overhead.

Also in the future the primary funding is expected to be through user fees, including the KTH FOFU contribution. Additional external funding for infrastructure development will be actively sought for.

ii. Pricing structure and booking system

The fee system is based on cost categories and follows the Myfab guidelines: a monthly fee per registered cleanroom user, hourly fees for time spent in the cleanroom and for tool usage, and rent for lab space for tools of an academic group or a company. There are five tool rate categories, A - E, with the rate increasing with tool complexity and running cost. The user fees are categorized in three levels: *LOW* for Swedish academic users and for RISE as part of the collaboration agreement, *MEDIUM* for non-Swedish academia, micro-enterprises, and for long term collaboration partners, *HIGH* for large companies and at single use services.

All tools and users are registered in the Myfab LIMS (Laboratory Information Management System) database, developed jointly by the Myfab labs and today regarded a European standard, in use at several laboratories is six countries. The web based software is a key in lab management, with modules for, e.g., tool and user data, tool booking and logging, lab access, invoicing, user communication, and statistics.

iii. User group description and user group´s training services

The users represent academia, research institutes, and industry, with in overall 50% academic usage. Electrum Lab as a whole has about 200 registered users, with 50% as regular cleanroom users. More than 500 persons rely on the outcome from the lab, as materials, structures, and devices are deliverables from research, or used in commercial products. And they are often integrated parts in complex systems.

The main academic users are from KTH schools of EECS (i.e., MST with a lab related project volume in the period 2018-20 of in total 120 MSEK, and EES, 42 MSEK), SCI (Applied physics, 19 MSEK), and also CBH. Users from other Swedish universities are primarily from the Myfab nodes, KI and SU.

RISE is a core user group, also bringing projects with industrial partners and customers. Many industrial users are from companies emanating from or attracted by the Electrum Lab innovation environment, relying on the lab for production and/or development. These include IR-nova (detector arrays for IR imaging), Ascatron – part of II-VI, TranSiC – part of OnSemi, and KISAB (all three in SiC technology), Nanosized (pure water nanocharacterization) and BrightDay (graphene production). Another 20 companies use specific tools or services to a minor extent.

The major user groups rent lab space for tools, which are available to all lab users with driving license or by offering processing services. Training and processing is provided by the user groups.

3. Strategies and organization

i. Goals for development 5–10 years ahead

Electrum Lab has the goal to continue to develop as a key infrastructure and maintaining a thriving collaborative ecosystem of academics and entrepreneurs, enabling essential contributions to science and business in the field of nano- and micro technology. Hence, Electrum Lab will actively work to have KTH installing new faculty positions in fields of interest for the environment. Meanwhile, Kista gradually develops from an industrial area towards a more town like setting, putting a demand on the lab to reduce the use of potentially hazardous gases and chemicals. Hence, some renewal of the lab infrastructure will be is needed in the coming years; and it will be undertaken in close collaboration with the user groups.

ii. Congruence with university-level goals, as in KTH Development Plan 2018-23

A leading KTH – Electrum Lab is a first-class infrastructure regarding tools, processes, and results, with an operation model in many respects cited as an example for other infrastructures, e.g., the full cost coverage model, the Myfab LIMS management software, and the ISO9001 quality system.
An integrated KTH – Electrum Lab is a robust infrastructure, supporting several KTH groups from three schools in the roles of education, research and innovation. The organization deeply involves users in the lab operation and strategic planning of, e.g., premises and investments.
A visible KTH – Electrum Lab contributes to the high tech profile of KTH and attracts visitors from within KTH and academia, as well as from the society: pupils and teachers, industrialists, international delegations, e.g. from industry parks, embassies and ministries, with interest in the research programs and the innovation system. The Kista location gives KTH visibility outside central Stockholm.

An open KTH – The open access model makes Electrum Lab an innovative melting pot of students, researchers, technicians and entrepreneurs from all over the world. The open atmosphere is highly appreciated by all involved and is a basis for the high-quality results in research and innovation.
A KTH for a more digitalized and sustainable world – Electrum Lab is the center for development of semiconductors in Kista Science City, the leading ICT cluster in Europe, and contributes to world-class solutions in electronic devices supporting digitalization and reduced emissions for a sustainable society.
A KTH in a global world – Electrum Lab maintains a broad international network, both as an infrastructure and as part of users' projects, and the users represent a wide range of nationalities.

iii. Leadership structure and collegial structure

Electrum Lab is organized as a KTH Center at the EECS School, and is headed by a Board of Directors and a Director, both appointed by the president of KTH. Operation is in close collaboration with RISE, supported by a long term agreement.

The Director leads an operations group of six persons with responsibility for administration, operation and maintenance of the facility, user information, coordination of lab usage and development, safety and work environment, authority contacts, quality management, sales and marketing, etc.

User Groups at KTH or RISE are the main responsible for the tools, with respect to quality, maintenance and processes. User group representatives form a Management Group, planning the operation and usage of the facility, with the mandate to take decisions in current matters within budget. Through this organization the users' needs and competence are utilized to benefit the operation of the facility.

iv. Strategies for high quality

Electrum Lab is the first university lab in Sweden implementing an ISO9001 quality management system, yearly reviewed by an external auditor. KPIs and quality objectives for continuous improvement are defined by the Management Group based on the user groups' demands, partly identified in a user survey. The system is based on documented tool instructions, scheduled preventive maintenance, standard process recipes with recurring performance control, and calibrated characterization tools. Hence, the Myfab LIMS software has a central role for documentation, and information to users. Thanks to the high quality standards – reached by close interaction between academic and industrial users, sharing the common goal of complex device fabrication – Electrum Lab enables scientific excellence in a broad range of research areas, as well as high impact industry development in very competitive sectors.

4. Interaction between research and teaching

i. Interaction between research and teaching at all three levels of education

Electrum Lab is unique in combining education, research and innovation and is used as a platform for education at all levels. Already high school students may visit the lab for a brief introduction to the research field and technologies used. Undergraduate students get tutorials on process technology, characterization, and on the possibilities given by nano- and micro-technology. Master students are offered courses where lab exercises are an integrated part and may also write their master's thesis based on achievements in the lab. PhD students use the facilities for their research and thesis work, almost entirely based on their own experimental work in the laboratories.

KTH courses where access to Electrum Lab is essential:

- IH2652 – Methods and Instruments of Analysis 7,5 hp, EECS EES
- IH2659 – Nanofabrication Technologies 7.5 hp, EECS EES
- FIH3606 – Material Characterization for Electronics and Photonics 10.5 hp, EECS EES
- EK2350 – Microsystem Technology 7,5 hp, EECS MST
- EK2360 – Hands-On Microelectromechanical Systems Engineering 7.5 hp, EECS MST
- SK2822 – Compound semiconductors and Photonic Devices 7.5 hp, SCI Applied Physics

Electrum Lab is also active in lifelong learning, as technicians, researchers, and innovators active in the lab bring and spread their knowledge in the environment, and further to society and to be implemented in industry. The lab staff has a special role in introducing new users to fields of lab infrastructure and media supply, cleanroom behavior, chemical handling, and safety.

5. Impact and engagement in society

i. Relevance, scale and impact of the RI´s engagements with society and industry

Electrum Lab has a long track record of creating and supporting innovation and entrepreneurs, where the production incubator, operated with RISE, STING and KTH Innovation, is instrumental. The main contribution is to provide the means for a smooth transition from research and development into small scale production, including access to state-of-the art equipment and lab infrastructure, and by support and transfer of knowledge. In the past, most new companies were start-ups from KTH and RISE, while recently, several companies have approached from outside, attracted by the Electrum Lab ecosystem.

In average one new company per year joins the lab. Total turnaround for the companies coming directly out of Electrum Lab was 1200 MSEK, with 500 employees in 2019. Jointly, these companies have attracted very significant private foreign investments in Sweden during the past 20 years.

The two most successful, both now established in Stockholm with own production facilities:

- Silex Microsystems (780 MSEK, 237 employees) world's leading "pure-play" MEMS foundry
- Finisar, part of II-VI (274 MSK, 153 employees) high frequency telecom opto devices, incl. tunable lasers

Largest of those with primary production or development activities at Electrum Lab:

- IR-nova (60 MSEK, 28 employees) imaging infrared photo detectors and modules
- TranSiC - part of ONsemi (29 MSEK, 13 employees) silicon carbide based power devices
- Ascatron - part of II-VI (15 MSEK, 13 employees) silicon carbide process technology and devices
- Kiselkarbid i Stockholm, KISAB (5 MSEK, 7 employees) low defect density silicon carbide wafers

Ph.D. students educated at Electrum Lab are now academic leaders or managers in national and international institutions and industries. Many are employees of major device manufacturing and high tech industries in Sweden, e.g., Ericsson, ABB, FLIR, Tobii, and at the companies which have emanated from the Electrum innovation ecosystem. Outside Sweden, several former Ph.D. students are at major industries like Intel, Osram, Bosch, IMEC etc., and also many are found as faculty, cleanroom managers or decision makers in the newly emerging economic powers, including China.

ii. Dissemination beyond academia

The CAMART[2] project and the collaboration with RISE are currently the main platforms for industry contacts, through site visits, thematic seminars and tours of the Electrum Lab. The Myfab web page is a primary contact point and, together with "ambassadors" at our partners, attract most new users. Within Myfab news articles and press releases are produced, and the Nordic Nanolab User Meeting is an event bringing together academic and industrial users from the Nordic countries.

iii. Relation to sustainability and the UN Sustainable Development Goals (SDGs)

The devices developed are based on advanced materials physics and processing technology, aiming to form the "Things" in IoT, supporting 4th Industrial Revolution to reach the SDGs. Here some examples.

SDG 2 Zero Hunger – Drone carried sensors for monitoring of forests and agriculture areas. Radiometers for future miniaturized weather satellites.
SDG 3 Health – Organ-on-chip to model organs and tissue. Painless drug administration. DNA and RNA decoding. Implantable sensors for diabetic and pre-diabetic monitoring. Lab-on-chip sensing for point of care analysis, e.g., test platforms for infectious diseases, or health status.
SDG 7 Energy – High efficiency light sources, i.e., lasers and LEDs. Increasing solar cell efficiency by multi-junction solutions or nano layer surface coatings. Low loss SiC based power devices for smart grids, power systems, and electric vehicles.
SDG 9 Industry – Sensors, actuators, and accelerometers. THz devices for industrial radar and beyond 5G telecom high data networks. High efficiency photon detectors. Integrated quantum photonics. Free space optical communication. SiC high temperature devices and circuits. IR gas sensors.
SDG 11 Cities – Equipping urban plants with AI for smart sensing of environment and physiology. Road safety by THz frequency car radar, and in-cabin monitoring. Lasers for optical communication.

SDG 13 Climate – Photonic CO_2 sensors for environmental sensing and monitoring. Devices for telecom, virtual reality or virtual presence, reducing the need for physical travel. SiC power electronics essential for the electrification of society, e.g., for road transports, and smart grids.

iv. Plans and structure for increased impact

Marketing of Electrum Lab and increasing the awareness of nano- and micro-technology is made through seminars, participation at conferences, visits from companies, research groups and general public, as well as press releases and articles. Activities in all these fields need to be intensified. Myfab access – a program for attracting new users from Swedish academia and companies – has proven successful and should be further promoted to find new participants. The web page draws new users and interest and is in need of renewal. Improved visibility is anticipated through collaboration with KTH Innovation and KTH Communication Support.

6. Recommendations to strengthen the RI and its future potential

To secure a sustainable development of Electrum Lab, future research leaders in the fields of semiconductor based materials science, and nano- and micro-technology must be attracted to the environment to engage in building the next research platform. Hence, KTH should establish new faculty positions in relevant topics. Also a renewal of industrial development projects at RISE, using the infrastructure, is desired. Industrial renewal should be further pursued by nurturing new start-ups attracted to the environment. To strengthen the links between the lab and the users, a Scientific Director should be appointed, to assist the Director in responding to the user needs and scientific developments.

The financial management model is poorly adapted to the potentially large variations in the income from user fees, e.g., when a major customer leaves the lab (for god or bad reasons). Electrum Lab will work for a greater acceptance for accumulating capital for future needs, contributing to sustainability.

KTH operates two infrastructures, Electrum Lab and Albanova Nanolab, within the field of nano- and micro-fabrication, however with different and largely complementary focus and user base. Both are part of the Myfab KTH node. The science and technology profiles of the two laboratories should be more clearly formulated to form a basis for collaboration, and for joint future development and investment plans. Electrum Lab and its stakeholders would also benefit from a closer collaboration with other KTH infrastructures, primarily Hultgren Laboratory and 2MILab.

The user groups have main responsibility for operation and maintenance of tools, quality of processes and support to users. Together with the lab staff – with responsibility for the infrastructure and media supply – the lab is efficiently operated with clear distribution of tasks. However, the limited staff is spread at different organizations. The environment as a whole would benefit from increased technical staff, improved coordination, and development of competences for greater redundancy. A discussion with the users on how this best could be pursued should be initiated.

The infrastructure of processing tools, media supply systems, ventilation, etc. has been continuously updated during the 30 years of operation. It is possible to, by comparatively minor means, modernize and keep the systems up to date, and to further prolong the lifetime of the infrastructure with at least 5 - 10 years. However, the demands for e.g., increased media supply, energy efficient climate control, and limited emissions will demand some investments in near future.

The development of Kista from an industrial area to a town with housing, schools and public buildings will set limits for the transport and handling of gases and chemicals. A plan for phasing out the most dangerous gases will be demanded, and limitations in use of other gases and chemicals might be needed. Possible solutions are e.g., stricter handling routines, decommission of potentially hazardous processes, new gas scrubbers, and re-location within the lab of tools using similar gases, for shared gas supply.

Electrum Lab has a profound role and importance for KTH, far beyond education and research, and KTH should bring up this in top-level discussions with strategic partners. Especially it should be regarded in discussions on the development strategy for Kista with City of Stockholm, and KTH is also encouraged to give general support for inclusion of the nano- and micro-fabrication field as part of the Region´s Smart Specialization Strategy in the EU context, to be endorsed by the Stockholm Region.

Appendix 3

Market analysis for research and innovation at Electrum Lab

1. Background

The customers at Electrum Laboratory are the research and development groups at KTH and RISE, as well as start-ups and medium sized companies using the facilities for prototyping and production. Currently, the academic usage and the institute/commercial usage represent about 50% each.

In recent years the commercial usage has increased significantly, with companies both using the common tools in the laboratory for their processing, and renting larger proprietary lab areas. Not only spin-off companies emanating from Electrum, but also external companies are attracted by the innovation ecosystem. Even though prosperous companies are expected to leave after some time, this is compensated by in average one new company joining the laboratory every year to grow in the environment. Hence, the commercial laboratory usage is expected to slightly increase, or at least stay at current volume of around 40 individual users and well above 20.000 cleanroom hours per year.

Nevertheless, the primary driver for Electrum Laboratory is research and innovation at KTH and RISE. This includes both the research and innovation projects per se, and their contribution to future spin-off companies using the lab resources. Hence, this market analysis is based on the visions and estimations from most of the research groups using Electrum Lab, as the principal investigators at the Lab were invited to contribute with their views, in order to find out about their planned activities for the next decade, and to offer a possibility to influence the development of the laboratory infrastructure and organization. All contributions are found in the following pages and a brief summary is given below.

A crucial point to note – which has emerged from our discussions – is that a large incentive for the companies and for RISE to work in the Electrum Lab is the presence of a dynamic research environment. Without a strong research driven agenda supported by KTH, it is unlikely that the strong company interest could be sustained.

In general, the contributing research leaders have been reluctant to give estimates of the volume of their future lab activities, in terms of personnel or project funding, and no major change in volume has been anticipated. As a best estimation, given these conditions, the total research volume at Electrum Lab will stay at a level close to current, i.e., about 60 individual users, spending altogether up to 10.000 hours in the cleanroom per year.

2. Research fields

2.1 Silicon technology

The silicon based CMOS activity (***Per-Erik Hellström and Mikael Östling***) at Electrum Lab has always been strong and has recently experienced a major break-through by the establishment of a high yielding in-house CMOS line, together with a design environment, as a baseline for future research. Hence, two major directions are identified, i.e., 3D manufacturing of integrated circuits for increased device density to continue Moore's law in the long term, and heterogeneous material/device integration, targeting various application areas, for example, high-temperature electronics for space, low temperature electronics for quantum computing, transparent electronics and sensors for bio and medical technologies.

The CMOS integration capability will also be exploited by adding spintronic device functionality, e.g., for hardware security, energy efficient in-memory computing, or microwave devices, including system level demonstrators (***Gunnar Malm***).

The silicon based MEMS activities (***Frank Niklaus***) are aiming to support the development of sensors and actuators and other devices, especially for the development of IoT in a broad sense. Current development is in the field is integration, fabrication and packaging of novel 3D micro and nanodevices. For the future, his includes wafer level packaging of photonic devices and for 2D material transfer.

2.2 Wide bandgap materials and devices

Electrum Laboratory has an impressive track record since 1992 for wide bandgap materials, and specially SiC based devices for high temperature and high voltage applications (***Carl-Mikael Zetterling and Mikael Östling***). The combination of high voltage or high temperature devices and integrated circuits in SiC seems to be a possible way forward.

Even though SiC devices, e.g., Schottky diodes and MOSFETs, are already commercially available, research tasks remain in solving the issues of reliability of unipolar devices and in the possibility to fabricate bipolar SiC devices for extreme voltages, far beyond what is possible with existing Si technology (***Anders Hallén***).

Novel wide bandgap materials, currently attracting increasing interest for both electronic and opto-electronic applications are metal oxide semiconductors. Relevant material systems are based on ZnO, Al_2O_3, Ga_2O_3, SnO_2 and TiO_2, etc. However, an investment of 10-30 MSEK for a novel HVPE/MOVPE reactor for crystal growth is needed to fully explore the possibilities of these materials (***Anders Hallén***).

RISE has ongoing R&D projects on III-N based devices for power/RF and life-science applications, which eventually will establish novel concepts and new device architectures to create groundbreaking technology for RF, power electronic systems, and bio sensors in terms of efficiency, compactness and cost-efficiency (***Qin Wang***).

2.3 Photonic materials and devices

The activities on photonic materials and devices have been instrumental as a basis for many startup companies from the environment and the research contributes to all fields of computing, communication and sensing. Photonics is a Key Digital Technology, radically transforming industry, and powering Industry 4.0, and is fundamental to address the enormous global societal and environmental challenges of our times.

Next development steps include a large degree of integration, e.g., of photonic functions with silicon technology. Hence, the silicon based CMOS platform will be a fundamental part of a silicon photonics activity, together with a new setup for transfer-printing to allow the integration of III-V-based materials/device membranes (***Mattias Hammar***). In the up-coming field of quantum communication, notable contributions have already been made regarding single-photon sources, which will be further exploited towards the system level.

A wide range of high-performance photonic devices will be further developed, based on advanced and to some extent unique, technologies (i.e., HVPE and epitaxial lateral overgrowth) available at Electrum Lab (***Yanting Sun***). This includes quantum cascade lasers for mid-IR wavelengths operating at THz frequencies for spectroscopy and free space communication, photovoltaic and photo electrochemical devices for solar cells and solar fuel production at low cost and high efficiency.

RISE has long term experience on photonics and optoelectronic devices. Especially large format and wide aperture electroabsorption modulators for free space optical communication has gained unique impact in the related application areas worldwide (***Qin Wang***).

2.4 Novel research areas and soft materials

Stretchable electronics, i.e., electronic devices made of materials, which can accommodate mechanical deformations during operation, are promising for a wide range of bio-electronic applications, including wearables and implanted electronics (***Jiantong Li***). A major challenge in fabrication of these devices is the patterning process, usually met by inkjet printing and 3D printing techniques. In order to support this growing research field, novel techniques should be added to the Electrum Lab offer.

Bioengineering of organ-on-chip and body-on-chip systems for understanding of physiological mechanisms, of pharmaceuticals and toxins, or of tissue replacement need to some extent access to Electrum Lab for fabrication of electrodes and microfluidic systems (***Anna Herland***). This field is growing to address increasingly complex aspects, including disease modelling for brain and metabolic diseases. Hence, fully biodegradable and bioresorbable electronics will be developed for health and environmental monitoring.

Microfluidics and lab-on-a-chip-systems for biosensors and biomedical microdevices require the possibility to work on hard and soft materials in parallel in the lab environment. Hence, tools for 3D printing and soft lithography would be beneficial (***Wouter van der Wijngaart***).

Microwave and millimeter wave (THz) waveguides and switches on polymer based materials has a high potential, but would need access to roll-to-roll high-aspect ratio polymer fabrication with micrometer resolution (***Sjoerd Haasl***).

3. Electrum Laboratory infrastructure and organization development

In addition to investment suggestions for novel tools, enabling higher performance of the laboratory as a whole, or for tools instrumental for the development of specific research fields, some research leaders also wish for a more supportive laboratory organization, able to provide processing services and advice on specific processes. Reduced resources for department-employed research and processing engineers would make service and processing support from Electrum Lab extremely valuable for the user groups.

The drawbacks with the current system – where tools must have an appointed tool-responsible group to be supported by the laboratory – were identified, as it leads to a laboratory only supporting the currently active users and their activities. Some users argue in favor of a policy to maintain a fully equipped laboratory, which also maintains less used processes in benefit of minor user groups and higher flexibility.

Several research leaders highlight the very fruitful eco-system of academics, institutes and companies operating at Electrum Laboratory. These interactions enable novel as well as improved processes to the benefit of all partners and this should be developed as a basis for the lab in the future. Hence, a vision for he Electrum Laboratory should be to become a world-leading infrastructure by strengthening its ability to deliver high quality processes, serving the changing needs from its users from academy, institutes, and industry.

4. Conclusion

It is clear that the Electrum Laboratory is well recognized for providing an environment with an extraordinary combination of quality and flexibility with a competitive edge in fabrication of complex structures, devices and circuits at a high degree of integration, requiring a technology readiness level above the normal for a university laboratory, but still with a university laboratory level of flexibility. Particularly appreciated by the start-ups and industrial users is the access to reproducible processes in semi-automated tools, compatible with small-scale production and operating at industrial level yield under an ISO9001 certified quality management system.

The market analysis shows that a broad range of state-of-the-art research activities is covered by the groups active at Electrum Laboratory. In a global perspective, all research fields are highly relevant, and are in line with the United Nations Sustainable Development goals. Hence, in general the application fields are well funded by Swedish and European agencies. Nevertheless, it is perception that there is a lack of funding at the hardware level as compared to both the needs and the capacity of Electrum Lab. Simultaneously, many of the research activities are only to a limited degree utilizing the full potential of the infrastructure.

Furthermore, it seems that even though the laboratory masters a unique mix of materials systems and device technologies, few projects seem to benefit from the exploitation of the borderland between the established technologies to create novel device solutions. Such an intensified cross utilization of the technologies and a deepened collaboration between the research groups should be beneficial for the whole environment.

Based on these observations, a suggestion is to further strengthen the faculty using the Electrum Laboratory with new members in order to broaden the user base and the scientific scope.

Principal Investigator: ***Per-Erik Hellström*** and ***Mikael Östling***, with research leaders at EECS
Research Field: **CMOS process technology for devices and integrated circuits**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

The PI's research on advanced devices for future electronics has always had a fundamental experimental component. Historically, this research focused on new materials and advanced device concepts to enable high performance devices and continued scaling according Moore's law. The research has been very successful with large projects on high-frequency CMOS, scaled CMOS devices, integration of 2D materials and recently process technologies and device architectures for future sequential 3D manufacturing of integrated circuits. In recent years, a high yielding in-house CMOS technology, together with a design environment, has been developed as a baseline for future research.

2. Electrum Lab interaction

The Electrum Laboratory has been absolutely instrumental to perform the research on advance devices for electronics. All devices/circuits have been fabricated in the Electrum Laboratory and it is the access to the processes in the Electrum Laboratory that enables the research and makes it stand out in an international perspective. There has been a very fruitful interaction between the research projects and the Electrum Laboratory guiding the constant renewal and development of new process technologies.

3. Research vision

The PI current research vision consists of two major directions.

<u>Process technologies for sequential 3D manufacturing of Integrated Circuits</u>
In current manufacturing of integrated circuits, the transistors are made on the Si wafers and fabricated beside each other over the whole die (chip). High performance is achieved by scaling down the size of the transistors and the interconnects between them. The manufacturing is split between transistor fabrication first (demanding high process temperatures) and secondly the fabrication of the interconnections. In order to continue Moore's law in the long term, the third dimension needs to be exploited by stacking transistors on top of each other. There are many obstacles to achieve this, most of stems from the fact that transistors needs to be build when interconnects are already present on the wafer. We will continue our research (in the last 5 years we have developed solutions for sequential 3D integration using Ge device) to solve the many challenges to enable sequential 3D integrated circuits.

<u>Heterogeneous material/device integration with CMOS technology</u>
The successful realization of a high yielding CMOS technology, fabricated in Electrum Laboratory, within the SSF funded project "CMOS Technologies and Circuits for heterogeneous integration, 2018-2022) will be the basis for a new research direction. Access and full control of a CMOS design and process technology in a University is a world unique capability that will enable research on expanding CMOS technology beyond the conventional realm of electronics. The research is cross-disciplinary in nature targeting various application areas, for example, high-temperature electronics for space, low temperature electronics for quantum computing, transparent electronics and sensors for bio and medical technologies. Key aspect of the research is the ability to perform on-die integration of novel materials and devices that traditionally has not been used in CMOS electronics, with the purpose of enhancing the technologies/applications with the computation and data manipulation enabled by CMOS electronics.

4. Vision for Electrum Lab

There is a very fruitful eco-system of academics, institutes and companies operating in the Electrum Laboratory. The interaction between these partners delivers a very dynamic and result oriented infrastructure that I believe is very important to protect and foster further. Often these interactions enable novel as well as improved processes to the benefit of all partners. The Electrum laboratory has historically excelled in its ability to change and develop with the needs of both academic research and industry. I believe the vision for the Electrum Laboratory should be to become a world-leading infrastructure by strengthen its ability to deliver high quality processes serving the changing needs from its users, academic, institutes and industry.

Principal Investigator: ***Gunnar Malm***, professor in Integrated Devices and Circuits
Research field: **Semiconductor and Spintronic Device Physics**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

My currently VR funded research has a focus on simulations approaches that are useful for predictive modelling of emerging device technologies, including realistic material properties and variability. I combine experimental studies at Electrum Laboratory with an eScience approach, using resources at the Swedish National Infrastructure for Computing (SNIC) and other scientific clusters.

I publish in high impact journals such Phys. Rev. B, Nanoscale, Nature Communications and in various IEEE journals. My research has resulted in one US patent. I teach four courses in device physics at first, second and third level (connected to my Electrum Lab external lab, see below).

2. Electrum Lab interaction

My research output over the last five years (2016-2021) was partly based on SiC, Ge and graphene sample fabrication at Electrum Lab. In total 11 original journal articles included some fabrication at Electrum Lab. For the spintronic part researchers affiliated with other parts of Myfab contributed with the actual fabrication. At present, I have limited funding for dedicated experimental work within Electrum Lab. Over the previous five period a few large grants, to several (2-3) co-PIs at EES, from e.g. the KAW foundation, VR and SSF enabled such activities.

My electrical characterization lab has been organized as an external lab within the Electrum Lab LIMS booking system since at least 2008. All KTH researchers and other parts of the Myfab network have full access to the measurement equipment (at a relatively low hourly fee). In this period most of the equipment has been upgraded or refurbished at regular intervals, using the EES divisions FOFU allocation or similar. The main users outside EES come from the division of Micro and Nanosystems (MST) also at the school of EECS, KTH.

3. Research vision

I will focus on emerging device functionality that can be integrated with CMOS at the end of the scaling roadmap. This functionality could include hardware security, energy efficient in-memory computing or microwave devices based on spintronics. Regarding these topics, my research would most likely focus on device physics and receive 'fundamental research' funding from VR, ERC or similar. Sample fabrication and material deposition would be joint with several groups, many of them outside KTH and Myfab. I work with TU Vienna and look actively for industrial cooperation (e.g. Ericsson).

In addition, I would pursue funding for system level demonstrators together with co-PIs such as Assoc. Prof. Hellström who drives the KTH CMOS platform. I could possibly continue the very successful work on SiC extreme environment electronics with Prof. Zetterling. However, I have not submitted any such funding proposals recently.

4. Vision for Electrum Lab

It could possibly be strategic to maintain a versatile CMOS platform at Electrum Lab. The needs of a CMOS platform indicate which tools at Electrum Lab that could be considered as a necessary baseline.

Some EES division FOFU allocation could be suggested as local co-funding for a CMOS platform. However, the risk-reward balance is not clear to me since a majority of senior PIs at EES has other research profiles and our resources would be limited (maybe 500 kSEK /year).

I do not have a clear proposal for additions of new tools for purely academic purposes. I have no personal plans to suggest any such tools.

My personal goal for the Electrum Lab support would be to merge the current support staff groupings at Electrum Lab, EES and RISE. The current distributed organization exists mainly for historical reasons, going back over 25 years, and is not relevant today.

In my opinion, RISE should have very limited input on the future Electrum Lab directions. They are not contributing to the research agenda.

Principal Investigator: Prof. ***Frank Niklaus***
Research Field: **Micro and Nanosystem Integration**
Group/Department: EECS, Division of Micro and Nanosystems

1. Current status

There is a continuous need for ever smaller sensors & MEMS components for the IoT and society, but fabricating and packaging of miniaturized 3D components still is difficult, elaborate and expensive. In the Micro and Nanosystem Integration Group at KTH, we explore and develop novel 3D manufacturing, integration and packaging technologies and employ them to realize new types of sensors and 3D micro and nanodevices.

Device applications that we target include low-cost optical gas sensors for environmental monitoring of gasses such as CO_2, single bio-molecule sensors for medical and diagnostic applications and nanoelectromechanical switches for low power and harsh environment non-volatile memory that have applications in IoT devices. We are educating highly skilled experts in micro and nanotechnologies on various levels, including master students (through master-level courses and project work) as well as on PhD level by educating a significant number of PhD students in our group (currently > 10).

2. Electrum Lab interaction

The Electrum Lab is a critical pillar for our research in the sense that it provides industrial-grade tools and processes for 4-8 inch wafers, which is a critical capability that sets us apart from many other university groups and that has been a door opener for us to participate in a number of international and national collaborative EU funded projects. At the same time, a critical feature of the Electrum Lab is the possibility to develop experimental processes on the existing tools, which have resulted in the development of unique capabilities that are also accessible to other users in the Electrum Lab. As a result of the various ongoing projects, we have a number of PhD students working in the Electrum Lab that also intensely interact with researchers of other groups, thus fostering exchange of knowledge.

3. Research vision

We foresee that our research will continue to critically rely on standard wafer-level Si and polymer fabrication technologies, including lithography, deposition and etching processes. In particular, several of our ongoing and anticipated projects depend on aligned wafer bonding for both, wafer level packaging of photonic devices and for 2D material transfer. The funding sources that we typically target are EU project funding and funding from Vinnova, SSF and VR. Predicting the number of persons involved in activities in Electrum Lab in the future is difficult and entirely depends on our success in attracting research project funding. However, the goal would be to continuously have at least 4-5 PhD students and researchers in our group that are using the Electrum Lab.

4. Vision for Electrum Lab

Generally, we would like to see an operation of the Lab in a similar way as has been in the past years. This includes continuous upgrading and updating of tools and processes, and maintaining the flexibility of developing the tools and the processes in the lab, as well as the possibility to introduce new processes and materials into the lab. Thereby it is important to maintain a full selection of critical processes, even if not every process/tool may be 100% economic for the lab. Cutting down on certain critical process for economic reasons, such as standard back-side lithography or bond alignment, would have detrimental effects on the competitive advantage of the lab. I feel that it is generally important to also offer nanofabrication processes and tools (e.g. e-beam lithography) in the future. This may be achieved to closely coordinate and work together with the Albanova lab. I believe that, ultimately it would be highly desirable to physically co-locate all the key KTH labs in a "Micro and Nanotechnology Center" that is run in a similar fashion as the Electrum Lab at/near KTH campus. I understand that this will require substantial efforts and compromises at some level (e.g. limitations for certain gasses?), however such an approach would ensure the long-term future of the excellent and unique lab facilities at KTH.

Principal Investigator: ***Carl-Mikael Zetterling and Mikael Östling***
Research Field: **Silicon carbide for extreme environment electronics**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

Research in the field of silicon carbide (SiC) processing, device technology and integrated circuits has been part of Electrum Laboratory for 30 years and resulted in about 50 PhD theses and several start-up companies. Today, Electrum Laboratory and the Kista research environment holds one of the world's leading SiC establishments and continues to deliver unique competence and infrastructure for future industrial applications. SiC unipolar devices already have a positive impact on the transition to electric vehicles, leading to a reduced use of fossil fuels and the market is expected to grow rapidly. A niche area open for university research is extreme environment electronics. This encompasses high temperature, high voltages, and radiation hardness, in integrated circuits.

2. Electrum Laboratory interaction

The lab infrastructure has been a key ingredient to the prominent position of KTH SiC research and the establishment of several SiC start-up companies in Kista. In the first 10 years, KTH investigated basic process technologies like gate oxidation and ohmic contacts. In the next 10 years, KTH developed basic bipolar transistors, first to 1200 V (and spun out as TranSiC, now ONsemi, still with research in Electrum Lab) and later demonstrated up to 15 kV by KTH. The latest 10 years, KTH developed full bipolar and CMOS integrated circuit technologies, and demonstrated integrated circuits working at 600 °C, and in radiation hard environments.

The process capabilities of Electrum Laboratory involves all major SiC process steps needed for fabrication of high temperature electronic circuits as well as power devices with one exception: ion implantation. However, KTH have made all devices and integrated circuits with and without ion implantation. Nowadays, ion implantation can be procured as a service, and is not necessary to maintain these expensive machines in Electrum.

3. Research vision

After demonstrating some radiation hardness in off-line tests of integrated circuits, a larger undertaking was started with funding from the Swedish National Space Agency (SNSA), to investigate the operating limits of SiC in space. All integrated circuits were made in Electrum Lab, and now involving multi project wafer runs (MPW) with the University of Arkansas. SNSA also funds a new project to investigate very high voltage integrated circuits in SiC (approaching kV-level amplifiers) for electric propulsion of small satellites.

The area of high temperature integrated circuits in SiC came out of the KAW project Working on Venus, where all electronics needed for a Venus lander (surface temperature of 460 °C) were demonstrated using electronics made in Electrum Laboratory. Currently this area lacks funding, but there is industrial interest in high temperature motor circuits and future projects have been proposed.

4. Vision for Electrum Lab

Both KTH and RISE have been involved in the SiC research and device development at Electrum Laboratory and, generally, it is more effective to consolidate and strengthen activities that have already proven their value. The companies utilizing the lab have need for extending the capabilities for handling increasing wafer diameters and this should also be considered for university research, as small diameter wafers are harder to procure. It is a strength that SiC material growth is available in Electrum Laboratory through II-VI (formerly Ascatron) and KISAB. Since the Electrum Laboratory has complete integrated circuit lines (with ion implantation outsourced), a pilot line for SiC integrated circuits for extreme environment electronics would be possible.

Principal Investigator: ***Anders Hallén***
Research Field: **Silicon carbide device development**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

Research in the field of silicon carbide (SiC) material, processing and device technology has been part of Electrum Lab for 25 years and resulted in about 50 PhD theses and several start-up companies. Today, Electrum Laboratory and the Kista research environment holds one of the world's leading SiC establishments and continues to deliver unique competence and infrastructure for future industrial applications. SiC unipolar devices are already have a positive impact on the transition to electric vehicles, leading to a reduced use of fossil fuels and the market is expected to grow rapidly.

2. Electrum Lab interaction

The lab infrastructure has been a key ingredient to the prominent position of KTH SiC research and the establishment of several SiC upstart companies in Kista. The process capabilities involves all major SiC process steps needed for fabrication of power devices as well as high temperature electronic circuits with one important exception: ion implantation.

3. Research vision

Unipolar SiC devices, such as Schottky diodes and MOSFETs for voltages up to around 2 kV are already commercially available; however, there are several crucial issues where substantial research is needed for further advancement of the SiC field. Many of these issues are process related and are highly suitable for the available infrastructure and expertise available around the Kista cleanroom. Two examples of very relevant issues are reliability problems with SiC MOSFETs due to bipolar degradation and also the poor interface between SiC and the gate oxide layer. Reliability is a matter of growing concern, as novel wide bandgap materials are replacing the existing Si-based power technologies and this is a field that is already engaging other KTH divisions, for instance Power Electronics within the EECS School.

A second area for future research is the possibility to fabricate bipolar SiC devices for extreme voltages, far beyond what is possible with existing Si technology. This is a new research field where device design, process technology, and packaging and testing all needs to be involved in order to be able to optimize the benefits with SiC and possibly also other wide bandgap semiconductors.

4. Vision for Electrum Lab

Both KTH and RISE have been involved in the SiC research and device development at Electrum Lab and, generally, it is more effective to consolidate and strengthen activities that have already proven their value. The companies utilizing the lab have need for extending the capabilities for handling increasing wafer diameters and this should be supported. To make the SiC process line complete, one suggestion is also to invest in ion implantation facilities, both for industrial needs, but also to contribute to research needs and development of implantation technologies for SiC and other upcoming wide bandgap semiconductors, such as GaN and Ga_2O_3.

Principal Investigator: ***Anders Hallén***
Research Field: **Flexible epitaxial system for metal oxide semiconductors**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

Metal oxide semiconductors are finding increasing usage in a number of electronic and opto-electronic applications, for instance, transparent conductive oxides for smart screens, thin film transistors for flat panel displays, sensors, photovoltaic and power devices. The reasons for the current popularity of these materials are the possibility to manufacture thin films with wide and tunable bandgaps, high carrier mobilities, and controlled doping using abundant and environmental-friendly sources.

2. Electrum Lab interaction

Within the Swedish Myfab consortium, there is presently no focused activities on the development of metal oxide thin films growth, although a number of research groups are investigating novel device applications for material systems based on ZnO, Al_2O_3, Ga_2O_3, SnO_2, TiO_2, etc. Therefore, we would like to point out the opportunity for the Electrum Laboratory to engage in this field by investing in a modern and flexible HVPE/MOVPE reactor system. HVPE will enable thick layers and MOVPE quantum structures.

3. Research vision

This would be a visionary investment in the range of 10-30 MSEK (depending on ambition and pending a more detailed market survey) which, in combination with the existing infrastructure and competence, could make a substantial boost to national (and international) R&D in this rapidly growing field. In combination with the strong device fabrication tradition and in-house process expertise, including substantial industrial engagement and spin-off success stories, such an investment should be seen as a strategic reinforcement with good potential for novel device research and application spin-offs that involves several research groups throughout KTH and RISE.

4. Vision for Electrum Lab

This proposal involves a novel direction of the research at KTH and Electrum Laboratory. We have an extensive experience and infrastructure for development of other wide bandgap materials, most noteworthy being SiC, but also GaN. Investing in a new epi-reactor at Electrum Lab also follows a long tradition in the field of epitaxial growth and semiconductor processing and applications at the lab, but the specific research area is new and it is therefore suggested to complement this investment with announcing a tenure track in the direction of oxide semiconductors.

Principal Investigator: ***Qin Wang***
Research Field: **III-N electronic/photonic devices/components**
Group/Department: Nano technology Unit, Smart Hardware Department, Digital Systems Division, RISE Research Institutes of Sweden.

1. Current status

Nano Unit at RISE has ongoing R&D projects on III-N based HEMTs and UVC LED for power/RF and life-science applications, these activities are financed by national and international funds such as Vinnova, EC and USA Navy.

2. Electrum Lab interaction

All designed devices are fabricated in Electrum lab in wafer scale, which has potential to scale up for future commercialization.

3. Research vision

Outcome of these research projects would hopefully initiate novel concepts and new device architectures to create groundbreaking technology for RF, power electronic systems and bio sensors in terms of efficiency, compactness and cost-efficiency.

4. Vision for Electrum Lab

Micro/nano fabrication facilities at Electrum are needed to process and characterize the devices, especially large area nano fabrication tool in 100 nm range is preferred. In addition, RTA would be needed to form ohmic contacts onto these III-N devices. Currently we need to carry out this process step at MC2 Chalmers.

Principal Investigator: ***Mattias Hammar*** and research leaders at EECS and Appl. Phys., KTH
Research Field: **Photonic materials and devices**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

The Electrum Laboratory has a long tradition in photonic materials and devices. Based on major infrastructure investments, this has resulted in a multifold of national and international projects as well as bilateral collaborations with Swedish industry. The research results have also been instrumental in establishing a range of startups in the Stockholm region and resulted in approximately 50 PhD and licentiate theses. More recently there have been important investments in the upgrading of two epitaxial growth systems as well as dedicated processing equipment and there are several ongoing projects in the photonics area, including silicon photonics, quantum communication, solar cells, non-linear optics, and quantum cascade lasers for communication and sensing.

2. Electrum Lab interaction

The Electrum Laboratory have had and has an enormous importance in this development since it provides full capabilities for all steps in the development from materials synthesis through advanced process technologies to device and system-level characterization and analysis. As stated, this has been a key ingredient in the realization of several start-up companies, some being major success stories.

3. Research vision

The field of photonics has a steadily increasing application domain, with offsets in all fields of computing, communication and sensing. Of importance is thereby the integration aspect, e.g. to directly include photonics functions in CMOS circuitry or to provide advanced photonic components for various integrated systems. We see three research directions:

<u>Silicon Photonics</u>
This regards photonics-electronics integration on the chip, e.g. for on- or off-chip data communication but also for integrated lab-on-a-chip sensor systems. Of particular importance for the development is the in house availability at Electrum of a high-performance CMOS processing line, including design environment as well as a new setup for transfer-printing to allow the integration of III-V-based materials/device membranes.

<u>Quantum Communication</u>
While the theoretical foundation for quantum communication by now is well-established and supported by ample proof-of-concept experiments, the development of the corresponding enabling technologies, is lagging behind. This provides significant scope for innovative approaches in a field that is well aligned to the KTH/EECS research tradition in integrated electronics and photonics, including a well-adapted infrastructure at the Electrum Laboratory. It also corresponds to an expected blooming research area, not at least reflected by the launch of a one-billion-EUR quantum technology flagship by the European Commission, which together with the recently announced Wallenberg Quantum Technology Center (WACQT) will provide excellent opportunities for sustainable funding during the coming decade. We are part of the KTH Center Quantum Technology Hub established in 2019 and we have made notable contributions regarding single-photon sources, which can be further exploited towards the system level.

<u>High-performance photonics devices</u>
Using advanced concepts such as photonic-crystal guiding, membrane technologies, heteroepitaxy, materials pooling, and surface nanostructuring various device implementations are examined. This includes high-speed and high-power lasers for fiber-based telecommunication, free-space communication and Lidar applications as well as high-efficiency light-emitting diodes and solar cells. This is a lab-intensive activity and should involve around 10-15 cleanroom users, out of which approximately half are from the EECS domain.

4. Vision for Electrum Lab

The activities rely on full processing capabilities for both silicon and III-V based materials. A progression to 4”-wafer capability is of importance although the epitaxy presently is limited to smaller wafer sizes. If possible we would like to see a larger engagement from Electrum Lab. Less resources for department-employed research and processing engineers would make service and potentially also processing support from Electrum Lab extremely valuable. The multi-user character of Electrum Lab, involving both RISE and industrial partners, will remain to be of importance to all these activities.

Principal Investigator: ***Yanting Sun***
Research Field: **III-V semiconductors and photonic devices**
Group/Department: Photonics/Applied Physics

1. Current status

III-V compound semiconductors are the key materials for realizing high frequency and photonic devices because of their direct bandgap and high electron mobility. Epitaxy technologies play critical role in the research and fabrication of III-V semiconductor based electronic and photonic devices. Our group conducts research on epitaxial growth of InP, GaAs, and GaP based III-V semiconductors by hydride vapor phase epitaxy (HVPE) technology for photonic device applications. We collaborated with Thales, III-V Lab and other European partners on high power mid-infrared buried heterostructure quantum cascade laser (BH-QCL) operating at room temperature in continuous wave (CW) mode enabled by semi-insulating InP regrowth by HVPE. Mir-QCL has broad application in spectroscopy and is promising for high speed free space communication, which is investigated in collaborate with FOI in a Horizon 2020 project. Epitaxial lateral overgrowth (ELOG) technology has been developed in HVPE for III-V/Si integration, which was implemented to fabricate III-V/Si based LED in collaboration with Tyndall National Institute in Ireland. III-V/Si technology was investigated for Si based multi-junction solar cell (SiMJSC) to absorb photons with different energy by III-V semiconductor and Si separately to enhance conversion efficiency. The research was supported by Energimyndigeheten. With support from VINNOVA and EIT KIC InnoEnergy a spin-off company, Tandem Sun AB was created to commercialize III-V/Si technology for SiMJSC application. By exploiting the high growth rate up to 100 μm/hour by HVPE, quasi-phase matched (QPM) orientation-patterned GaP (OP-GaP) has been developed in KAW project for the application of quantum photonic information. We are collaborating with III-V Lab, Thales and US Air Force Laboratory to use QPM OP-GaP for compact, high-power, tunable laser sources in the mid and long-wave infrared (MLWIR) region.

2. Electrum Lab interaction

As complementary to MOVPE and MBE technologies, HVPE is unique epitaxy technology for III-V semiconductors because of its high growth rate and inherent growth selectivity arising from near equilibrium growth behavior. However, there are only handful HVPE reactors in the world used for III-V semiconductors growth and Electrum Lab has one of them. As shown by the track record of our group in participating international, European, and national projects, our expertise on HVPE and the availability of HVPE reactor in Electrum lab are essential to realize innovative photonic devices requiring thick layer and buried heterostructures of high purity and semi-insulating III-V semiconductors. Other groups in KTH, such as Laser Physics group in Department of Applied Physics, recognized the advantage of HVPE to develop III-V based nonlinear optical crystal technology and we are collaborating in the development of OP-GaP for parametric frequency conversion. With the infrastructure of Electrum Lab, we will be able to attract new users to Electrum Lab and foster new collaborative research projects.

3. Research vision

Electrum lab is fully equipped for complete process flow of functional III-V semiconductor based photonic devices. The research results developed in Electrum Lab can be transferred and scaled up in industrial semiconductor facilities for commercialization, which is an asset for innovation oriented applied research. In next 5-10 years, we will focus on research of QCL in mid-infrared and THz, and applications of III-V/Si technology for photonic integration, photovoltaic, and photoelectrochemical solar fuel production. By using advanced buried heterostructure for efficient heat dissipation in QCL, high power and high temperature operation of mid-IR and THz QCL can be expected. Such QCL devices can be used for spectroscopy and free space communication. By using III-V/Si technology, electricity and green fuels of hydrogen and methanol, etc. can be produced by solar driven photovoltaics and photoelectrochemical processes at low cost and high efficiency. The access to Electrum Lab with unique HVPE reactor will facilitate our funding application to VR, Formas, Energimyndigheten, Olle Engkvist Foundation, KAW Foundation, etc. in Sweden and collaboration with leading groups in European universities and industry to apply funding from Horizon Europe program.

4. Vision for Electrum Lab

With skilled engineering staff, maintenance of equipment for high uptime, consistency and reproducibility of process, development of new process in equipment and new equipment for innovative processes in Electrum Lab will be essential for achieving research goals in next 5-10 years.

Principal Investigator: ***Qin Wang***
Research Field: **Components/systems for free space photonic applications**
Group/Department: Nano technology Unit, Smart Hardware Department, Digital Systems Division, RISE Research Institutes of Sweden.

1. Current status

Nano Unit at RISE has long term experience on photonics and optoelectronic devices such as LEDs, lasers, photodetectors, and modulators, especially large format and wide aperture electroabsorption modulators (EAM) for free space optical communication has gained unique impact in the related application areas worldwide. Now we are involved in EU photonHub project and offer components/systems technology for free space photonic applications to the project partners, especially to SMEs for developing new photonic products.

2. Electrum Lab interaction

The Electrum lab facilities are the base platform to carry out the work described above.

3. Research vision

Photonics is a Key Digital Technology that is radically transforming the traditional industrial base. Photonics is essential to the functioning of new applications which are powering Industry 4.0 and which are also critical to our ability to fundamentally address the enormous global societal and environmental challenges of our times, https://www.photonhub.eu/.

4. Vision for Electrum Lab

The tools for fabrication of the photonic devices and related integration/packaging at Electrum are the key factors to ensure the work that we could offer.

Principal Investigator: ***Jiantong Li***
Research Field: **Miniaturized Self-Charging Power Systems for Stretchable Electronics**
Group/Department: EECS, Division of Electronics and Embedded Systems (EES)

1. Current status

Stretchable electronics is a kind of emerging electronics that can accommodate mechanical deformations of the electronic devices during their operation. They are thereby very promising for a wide range of bio-electronics applications where mechanical deformation is necessary, such as personalized healthcare systems, wearable smart displays, and implantable prosthetic devices. For such applications, todays' batteries are too bulky, rigid and in need of frequent replacement. With this regards, the concept of self-charging power systems (SCPSs) is envisioned as a promising candidate to replace batteries. They directly convert mechanical energy from human body to electricity and store it in energy storage units to power various wearable or implantable electronics. However, the present prototypes of SCPSs are still bulky and rigid. In the coming years, one of our research focus is to fabricate miniaturized stretchable SCPS systems as "long-term and maintenance-free" power sources for future wearable and implantable electronics. The entire system, consisting of energy harvesting component, energy storage component, and rectifying circuits, will be fabricated in a "monolithic" manner through integration with inkjet/3D printing of emerging materials (2D materials, conducting and semiconducting polymers) and lithography-based stretchable interconnects on stretchable substrates to miniaturize the form factor of the systems and optimize their efficiency. The monolithically fabricated small-scale (footprint $< 3\ cm^2$) stretchable autonomous power sources will push the state of the art in the scientific society. More importantly, they will expedite the development of various bio-electronics applications to greatly contribute to healthcare and well-being (SDG3).

The fabrication techniques, materials, and stretchable self-charging power systems are all emerging topics. They have great potential to contribute to the existing courses (such as FIL3014 Microscale 3D patterning techniques) or be developed into a new PhD course.

2. Electrum Lab interaction

We will use the Electrum Lab to fabricate stretchable interconnects (photolithography + metal deposition). Meanwhile, our printing processes for 2D materials and conducting/semiconducting polymers, and printed energy harvesters and storage devices (e.g., supercapacitors) could be useful for other users when they want to develop flexible/stretchable electronics, organic electronics, and 2D materials-based electronics, or integration with non-silicon devices. We have initialized the collaboration with Per-Erik for monolithic 3D integration.

3. Research vision

The major challenge is to develop patterning techniques compatible with the new materials and substrates which should be both stretchable and biocompatible. As the conventional lithography processes typically cannot prove efficiency here, in the coming years we will still focus on direct patterning (mask-free) process, such as inkjet printing and 3D printing, for the materials and substrates. The printing processes of emerging materials on biocompatible stretchable substrates are expected to play an important role in stretchable electronics and bio-electronics. The end users of our research could be healthcare companies and hospitals.

In this field, our primary funding sources are VR and Vinnova. 3-5 students could be involved in the next 5-10 years and 1-2 need the lab access (more students could work in the lab after more tools are developed in Electrum Lab, as detailed below).

4. Vision for Electrum Lab

The present lab environment (photolithography and metal deposition) has been sufficient for our recent research. However, in order to further enhance our research, we hope for transfer printing tools/processes that could transfer devices from silicon wafers to flexible substrates with good alignment, and advanced inkjet/3D printing tools with high resolution, high reliability, and high integration of various processes (printing, drying, sintering and monitoring).

Principal Investigator: ***Anna Herland***
Research Field: **Bioengineering**
Group/Department: MST / IS. / EECS / KTH and AIMES Center for the advancement of integrated medical and engineering sciences, Department of Neuroscience, Karolinska Institutet

1. Current status

I work in the field of bioengineering. We design systems of living cells and engineered devices and biomaterials to recreate physiological functions for studies in vitro and in vivo. These systems can be used to understand physiological mechanisms in health and disease as well as to study actions of pharmaceuticals and toxins. We also use then for tissue replacement or tissue monitoring. I have made some of the world-leading studies in microfluidic based organ-on-chip and body-on-chip systems. We collaborate world-wide on this topic with academic and industrial partners. I have been running PhD and master level education on these topics.

2. Electrum Lab interaction

We fabricate electrodes and microfluidic systems in the clean room.

3. Research vision

Increased device fabrication for bioengineered systems. We will address disease modelling for brain and metabolic diseases. We will develop fully biodegradable and bioresorbable electronics for health and environmental monitoring.
Funding: VR, KAW, SSF
Challenge for us: scaling up production of or microfluidic systems with integrated sensing to a reasonable price
Personell: 2 cleanroom users

4. Vision for Electrum Lab

The most important for the future is that Electrum can offer pay-for-service alternatives. Many users in Life Science and Chemistry cannot have a clean room fab expert but would like to order certain structures, electrodes etc. It would be interesting if Electrum could also offer advice for scaling up production of certain systems.

Most important tools are standard clean room fab processes, metal and insultation deposition tool.

Principal Investigator: ***Wouter van der Wijngaart***
Research Field: **Micro/nanostructured soft matter for biomedical microdevices**
Group/Department: EECS / IS / MST

1. Current status

Micro and nanosystems with a research focus on microfluidic and lab-on-a-chip systems, micro/nanostructured soft matter, biosensors and biomedical microdevices.

2. Electrum Lab interaction

I use the lab mainly for micro and nanostructuring of HARD materials.

3. Research vision

My research focuses on the micro and nanostructuring of SOFT matter (fluids, polymers, living cells/tissue, biomolecules).

I will use the lab if I need to make TOOLS to structure soft matter, or for BIOHYBRID structures (combinations of living/biomaterial and synthetic materials) if such hybrids include hard materials.

4. Vision for Electrum Lab

A lot of future development in my area will depend on work with/integration of living and dead material.

Electrum Lab focuses on HARD materials, and these are currently not in the “roadmap” of most bio or medical techniques.

We see a lot of microstructuring now moving to 3D printing or soft litography facilities within research labs all over KTH, KI and SU.

The value of Electrum Lab is in its offer to industrial partners. I think it is of utmost importance that Electrum Lab understands its industrial partners, their needs, and why these companies seek Electrum Lab (rather than own or other facilities). I believe that is where you need to look for the future.

Principal Investigator: ***Sjoerd Haasl***
Research Field: **Microwave and millimeter-wave waveguides and switches**
Group/Department: Sensors and Materials Unit, Smart Hardware Department, Digital Systems Division, RISE Research Institutes of Sweden.

5. Current status

My current research is in the area of microwave and millimeter-wave (THz) waveguides and switches based on the gap waveguide technology. These allow the development of electronically steerable antennas with applications in the areas of automotive (radars for autonomous driving), 5G communication and defense (radar). The technology is relatively new and unexploited and has a great potential if cost-efficient fabrication can be obtained.

6. Electrum Lab interaction

The Electrum lab provides the possibility to quickly iterate prototypes in house. The cost-efficient technologies that are under development can be used in other fields as well such as microfluidics, lab-on-a-chip and applications that require millimeter-scale cost-efficient high aspect ratio microstructures in general.

7. Research vision

The major challenges will be to develop roll-to-roll high-aspect ratio polymer fabrication with micrometer resolution. Should this be possible, a

8. Vision for Electrum Lab

I would like to see tools for cost-efficient polymer fabrication to be available. Simple tools such a laminator may already be available, but roll-to-roll equipment (given the need arises) would open up an entire field that may benefit many. Further support in the development of equipment to fabricate and process graphene may also benefit many Electrum lab researchers.