Activity Report

Albanova Nanofabrication Facility

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Prof. David Haviland
haviland@kth.se

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Summary:

This document contains a report of the activity carried out in the Albanova Nano-Fabrication Facility, located in Albanova University Center, Stockholm. This lab is a joint facility for nanometer scale fabrication and metrology which is used by several research groups in the Stockholm area. The laboratory was established through three large equipment grants in 1998, 2001 and 2006 from the Knut and Alice Wallenberg Foundation. Together with smaller grants from VR, Gustaffson foundation and KTH start-up, there is about 30 M SEK of investment in equipment in the nanolab.

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Background

The KTH Nano-Fabrication Laboratory (Nano-Fab Lab) started with an 9 M Sek equipment grant from the K A Wallenberg foundation, granted in March 1998 (PI Haviland). This provided a foundation for establishing electron beam lithography at KTH. Today we are the sole provider to the academic research community in the Stockholm area of this very versatile nano fabrication technique. The initial grant allowed the purchase and installation of a Raith 150 electron beam lithography system and support equipment including a reactive ion etching (RIE) apparatus. A second equipment grant for 10 M SEK (PI Haviland) was granted in May 2001 when the laboratory was moved to Albanova University Center. This grant allowed for expansion of our equipment base to include Scanning Probe Microscopy, contact printing photo lithography, vacuum deposition equipment, and an additional RIE. A third large equipment grant of 7 M SEK was granted in 2006 (PI Krasnov), which has allowed for a new high resolution SEM, and multi-target sputtering system. In addition to these major purchases, several smaller grants from individual investigators totaling about 4 M SEK have provided equipment which is in the lab and open for joint use.

Laboratory Focus and Philosophy of Lab Operation

The Nano-Fab lab is focused on controlled fabrication at micrometer nanometer length scales, and on metrology or accurate measurement at these length scales. Our specialty is not bulk composite "nano-structured" materials, but rather nano-scale *fabrication* with a high degree of control over the pattern and arrangement of the resulting structure. The groups using the lab are engaged in research on fundamental and applied device physics with superconducting and spin-electronic circuits, Si quantum dots, photonic crystals, X-ray diffractive optics, non-linear optics and laser physics, and Bio- nanotechnology.

The users of the lab work with a variety of materials, many of which are non-standard to established semiconducting process lines. These include Ferro magnetic metals, Ni , Co , Fe, Superconductors such as Al and Nb and High Tc materials, Non-linear optical crystals such as KTP, electroplated Cr, and proteins or self assembled monolayers used in bio technology. This variety of materials and processes affects the philosophy of the lab and choice of equipment considerably. Our process are generally not standard and already programmed in to machines that were designed for a production environment with highly automated design to accommodate only a specific wafer size. We often work with chips and small batch processes, and large wafer handling machines are not practical for our purpose. We often need to fine tune our process parameters and our instruments may need modification, so users need to be knowledgeable with the inside workings of the apparatus. Our environment is well suited to graduate education and exploratory research, were the focus is not on scaling up production, but rather on proof of concept.

Our vision is to provide a practical and cost-efficient shared lab space which is well adapted to exploratory research, so that we can rationally share the cost of purchase and maintenance for expensive equipment, when it is possible to share. We have strived to keep the overhead cost low and bureaucracy minimal, so that exploratory research can thrive, and new ideas can be quickly tried without the need of a large funding base or

formal project. The Nano-Fab Lab is not only guided by rational economic considerations, but also by the conviction that through the shared laboratory environment, increased interaction between different research groups will lead to innovation and more rapid progress, while at the same time enhancing the educational process of graduate students.

Graduate students, post docs, and undergraduate thesis project students constitute the main users of the lab, but the lab also serves as a demonstration platform for advanced undergraduate students, and as a small scale production facility for start-up companies. Thus far the lab has been instrumental to the PhD projects of many graduate students, and many are currently in progress with their degrees. A list of past and present PhD and Diploma projects is given in Appendix 1. The graduate students and Diploma students are trained in courses offered by faculty involved with the lab. Some of these students then become licensed users of the equipment.

Capability and Equipment

The Nano- Lab has been extremely successful in establishing cost-effective nano-scale lithography for academic users in Stockholm. EBL is a versatile nano-fabrication tool well suited to prototype and proof of concept experiments that are typical of the university research environment. EBL allows for effective writing of both small (20 nm) and large (100 μm) structures quickly and efficiently in one process step. Our system experiences a heavy booking load at times, when it can be booked two weeks in advance, and on weekends and in the evenings.

In the Nanolab we fabricate small series of samples with thin film and nano lithography techniques from a wide variety of materials with minimum feature sizes down to 20 nm. We often ‘mix and match’ combining photo lithography and e-beam lithography. For many tasks, photo lithography is sufficient, which can achieve about 1.5μm minimum feature size in our lab. We order photo lithography masks externally from industrial vendors in Europe, which is much more cost effective than making them ourselves with our EBL system.

Our new SEM/FIB system will allow for more rapid imaging of samples, and thereby not load down our EBL system for imaging. The FIB is a very versatile technique for cutting and sculpting material at the nano scale. We anticipate rapid increase of usage of this system in 2008 as it becomes more well know to users. With 4 deposition systems and three reactive ion etchers, and an Ion gun, we have the capability to deposit and etch a wide variety of thin film structures.

Our major equipment includes:

E-beam lithography, Raith 150, 6 inch Laser stage
Dual beam system, High res. SEM + FIB
Scanning Probe Microscope, Veeco Multi Mode
Profilometer, KLA Tencor
RIE, Ar, O2, Oxford Plasma Lab 80+
RIE, BCl3, Cl2, Oxford Plasma Lab 80+
Mask aligner , contact, 4 inch Karl Suss
Mask aligner, projection Cannon
UHV E-gun sputtering, loadlock, Eurovac/homemade
HV E-gun deposition, Edwards, door system
UHV E-gun / Ion gun, loadlock, homemade
Carbon coater
Bonder, Wedge, Kulik and Soffa
Laminar flow benches, 3 ventilated, 1 unventilated
Optical microscope, DIC, DF, Viedo camera Cannon
Optical microscope, DIC, DF, 5 Mpix camera Cannon
Fluoresence. microscope. with cooled CCD, Olympus
Stereoscope, Nicon
Resist spinner
Hotplates 2,
Ovens, 2 standard, 1 Evacuated
Ultra Clean water
Ultrasound, variable power

A complete listing including specifications and instructions can be found at:
http://www.nanophys.kth.se/nanolab/index.html

Cost Sharing, Administration and Usage

The full cost for running the lab is 2.1MSEK in 2008. KTH Applied Physics and SU Physics subsidize the lab, 0.9 MSEK in 2008, and the remaining costs are distributed to the users. Users pay a base fee (5000 SEK/quarter in 2008) and hourly charges are made for EBL, Photo lithography, SPM and SEM usage. There are typically 25-30 users paying the base fee.

The lab is directed by Prof. David Haviland, and oversight is conducted by a board consisting representatives of the main user groups: Prof. Hans Hertz, Prof. Vladimir Krasnov, Prof. Fredrik Laurell, and Prof. Jan Linros. The technical staff is one lab manager, Dr. Anders Liljeborg, who is paid half time by Lab's budget. Some maintenance is done by service contract or hired service personal. Other service and repair is done by the lab manager. Many pieces of equipment have one or a group of principle users who use the equipment heavily and these users collectively take responsibility for maintaining and repairing the equipment. The Nanolab budget covers costs of standard maintenance and repairs for joint use equipment in the lab.

The EBL system is now 9 years old, and we are experiencing some problems with the laser stage. While we predict that the system will be useful for many years to come, we do need to either raise money for a major overhaul, or evaluate if a newer system with improved technology is a better option. Our new SEM and FIB system is a very versatile imaging and fabrication tool, and we should see increased usage as the system becomes better known and more users are trained. The Scanning Probe Microscope and AFM are experiencing increased usage. For both of these systems, good training courses are a vital part of effective usage of the equipment.

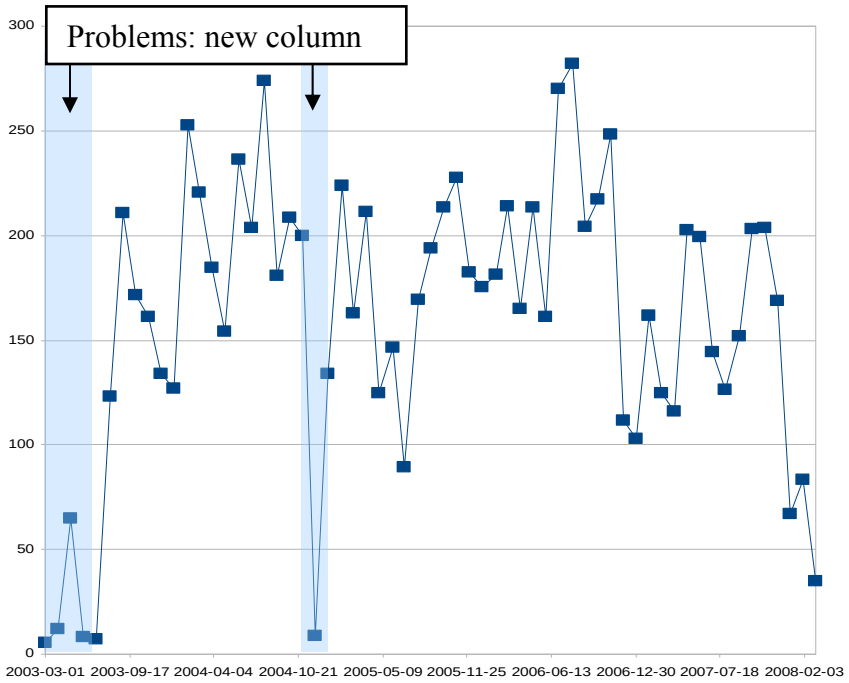

Fig. 1 Historical perspective of e-beam usage in the Nano-Fab Lab, plotted as percent of a 40 hour work week.

Future Equipment and New Space

We recently received delivery on a new multi-target sputtering system which is now being brought in to operation. And as this report is written, we are installing a 3rd RIE system. We are presently applying for money for a new AFM, and an upgrade of our EBL system with continuous path mode. The lab is presently at capacity, and if any major new equipment is to be installed, we will need to expand with an additional room. There is a free room next door which could easily be modified for our purposes, but some investment will have to be made to upgrade the lab space.

Courses and Training

The location of this facility at Albanova is ideal for interdisciplinary research. With easy access to KTH campus, Karolinska Institute and Stockholm University, we have a unique opportunity to bring nanotechnology and nanofabrication methods and techniques to a wider audience of researchers. We have been doing this with our courses in AFM and

EBL, and a general Nano Lab course. These courses offer a primer for graduate students, allowing them to see if the techniques and capabilities of the Nano Lab can be applied in their work. Experience shows that some fraction of the students will continue to learn and achieve the necessary skill level to be a regular user of the lab.

Three courses that we currently offer which are centered on the Nanolab are:

Introduction to Scanning Probe Microscopy – this course is a joint course with KTH surface chemistry (Prof. Mark Rutland), KTH applied Physics (Prof. David Haviland) and a frequent guest, Prof. Jan Hoh, Department of Physiology, Johns Hopkins School of Medicine. It is aimed at graduate students and researchers.

Introduction to Electron Beam Lithography – is an introductory course covering the technique of EBL. It is taken by graduates students and undergraduate thesis project workers who use the EBL system.

Clean Room Processes and Procedures – an overview course for graduate students and post docs, given by senior graduate students and post docs, which covers the capabilities and proper usage of equipment in the lab.

In the near future we will have two new courses:

Nanoscale Technology – joint SU, KTH course giving a broad overview. Designed for advanced undergraduate and masters students. Demonstrations will be done in the Nanolab. The course is a good starting point for an undergraduate thesis project in the lab.

Nanofabrication with Focused Ion and Electron beams – an expanded version of our EBL course to include SEM techniques and FIB techniques, first run planned for January 2009.

In addition to these courses KTH Applied Physics and SU Physics offer many other courses such as Mesoscopic Physics, Spin Electronics, Superconductivity, Condensed Matter Physics, Laser Physics, X-ray Physics, Experimental Technology, and others which touch on many aspects of work in the Nanolab. These courses occasionally use the Nanolab for demonstration.

Appendix 1: Nano-Lab projects

Below is a list of Ph.D. projects where the Nano-Lab was a key laboratory in carrying out the project. These students were *active users* of the nano-lab, meaning that they worked in the facility, and paid for usage. In addition to these students, roughly the same number of thesis have been generated where essential components (Zone plates, polled crystals, qubit samples, photonic crystals, etc.) for the experiments were generated in the Nano Lab.

The following PhD thesis have been defended:

1. Impedance of Soft Magnetic Multilayers: Application to GHz Thin Film Inductors, Andrey Gromov, Advisor: Vladislav Korenivski
2. Coulomb blockade of Cooper pair tunneling in one dimensional Josephson junction arrays, Karin Andersson, Advisor: David Haviland
3. Charging effects in small capacitance Josephson junction circuits, Peter Ågren, Advisor: David Haviland
4. Single Charge and Spin Transport in Nanostructures, Jan Johansson, Advisor: Vladislav Korenivski.
5. Two-Dimensional Photonic Crystals in InP-based Materials, Mikaël Mulot, Advisor: Anan Srinivasan
6. Plasma assisted technology for Si-based photonic integrated circuits Fotonik, Matteo Dainese, Advisor: Lech Woczenski
7. Spin Dependent Transport in Co Nano-Scale Tunnel Junctions, Mattias Urech, Advisor: Vladislav Korenivski
8. Nanometer Scale Protein Templates for Bionanotechnology Applications, Jonas Rundqvist, Advisor: David Haviland
9. Quantum effects in nanoscale Josephson junction circuits, Silvia Corlevi, Advisor: David Haviland
10. Sample and hold measurement for binary detection of a quantum state. Jochen Walter, Advisor: David Haviland
11. Si Nanowires, Nanopillars and Quantum Dots: Fabrication and Characterization. Robert Johaz, Advisor: Jan Linros
12. Nanofabrication of Zone Plate Optics for Compact Soft X-Ray Microscopy, Anders Holmberg, Advisor: Hans Hertz
13. Fabrication and characterization of nano-domain structures in KTP, Carlota Canalias, Advisor Fredrik Laurell
14. Optical Parametric Amplification iwht Periodically Poled $KTiOPO_4$, Anna Fragemann, Advisor: Fredrik Laurell
15. Ferroelectric Domain Engineering and Characterization for Photonic Applications, Simonetta Grilli, Advisor: Fredrik Laurell
16. Fabrication and Characterization of Periodically-polled KTP and Rb-doped KTP for application sin the visible and UV, Shunhua Wang, Advisor: Fredrik Laurell
17. Spin transport in normal and superconducting nanowires, Ninos Poli, Advisor: Vladislav Korenivski.

18. Photonic Crystals and Optical filters, Audrey Berrier Advisor: Anand Srinivasan
19. Characterization of domain switching and optical damage properties in ferroelectrics, Junji Hirohashi, Advisor Fredrik Laurell.
20. Synthesis and properties of single luminescent silicon quantum dots, Ilya Sychugov, Advisor: Jan Linros.
21. Design, Fabrication, and Characterization of Nano-Photonic Components Based on Silicon and Plasmonic Material. Liu Liu, Advisor: Lech Wosinski

The following PhD students are in progress.

1. Spin torque in point contacts ,Alexander Konovalenko, Advisor: Vladislav Korenivski,
2. Spintronics, Sebastian Andersson, Advisor: Vladislav Korenivski,
3. Nonlinear dynamics of Microresonators, Erik Tholén, Advisor: David Haviland
4. X-Ray Diffractive Optics, Magnus Lindbloom Advisor: Hans Hertz
5. Fabrication of High Q superconducting microwave cavities. Adem Ergül, Advisor: David Haviland
6. Spintronics, Arndt-von Bieren, Advisor Vladislav Korenivski
7. Photonic Crystals, Ziyang Zhang, Advisor, Min Qiu
8. Photonic Crystals, Ning Zhu, Advisor, Lech Wosinski
9. Photonic Crystals, Yaocheng Shi, Advisor, Anand Srinivasan
10. Photonic Crystals, Jin Wang, Advisor, Min Qiu
11. Photonic Crystals, Naeem Shahid, Advisor, Anand Srinivasan
12. Si quantum dots, Benjamin Bruhn, Advisor, Jan Linros
13. Spin Torque Oscillators, Stefano Bonetti, Advisor Johan Åkerman
14. X-ray Optics, Julia Reinspach, Advisor: Hans Hertz,
15. Laser Physics, Gustav Stömkvist, Advisor Fredrik Laurell
16. Laser Physics, Katia Gallo, Advisor Fredrik Laurell
17. Laser Physics, Mårten Stjernström, Advisor Fredrik Laurell
18. Experimental Condensed Matter Physics, Daniel Öjerholm Ström, Advisor Vladimir Krasnov
19. Experimental Condensed Matter Physics, Sven Katterwe, Advisor Vladimir Krasnov
20. Experimental Condensed Matter Physics, Daniel Öjerholm Ström, Advisor Vladimir Krasnov
21. Experimental Condensed Matter Physics, Raras Golod, Advisor Vladimir Krasnov
22. Experimental Condensed Matter Physics, Stella Tagliati, Advisor Andreas Rhyd.
23. Quantum Optics, Hatim Azzouz, Advisor Mohamed Bourennane
24. Waveguide Sensors, Kristinn Gylfason, Advisor Göran Stemme

The following students have completed a Masters Thesis using the Nano-Lab but have not continued to the PhD.

1. Fabrication of 2D photonic crystals in InP membranes, M. Hede (2001) Advisor: Anan Srinivasan.

2. Investigation of inductively coupled plasma reactive ion etching for photonic crystal fabrication in GaAs-based materials, H. Johansson (2005), Advisor, Anan Srinivasan.
3. Fabrication and test of ferromagnetic single electron transistors. Katrin Pappert (2005) Advisor: Vladislav Korenivski,.
4. Fabrication and Measurements of One-dimensional Strip-Line Resonators, Evelyn Doherty, (2006), Advisor: David Haviland.
5. One Dimensional Resonators for Enhanced Quantum Bit Control, Frank Weber (2006) Advisor: David Haviland.
6. Protein Templates Manufactured with Electron Beam Lithography for Bionanotechnology Applications. Beatriz Mendoza Sanches (2006) Advisor: David Haviland
7. Quantum Fluctuations in One1Dimensional SQUID Arrays Susanne Dröscher (2007), Advisor David Haviland
8. Intermodulation Atomic Force Microscopy Daniel Platz (2007) Advisor David Haviland

The following Post Docs have also been actively using the Nano-Fab Lab:

1. Nano-scale patterned bio-functional surfaces, Devrim Pesen, Nanostructure Physics, 2006-2008
2. Magnetic resonant tunneling structures and spin injection, Adrian Iovan, Nanostructue Physics, 2004 – present
3. Bloch Oscillations and High Impedance bias in Josephson quantum circuits, Wiebke Guichard, Nanostructure Physcis, 2003-2004
4. X-ray diffractive elements for compact sources. Stefan Rehbein, Biomedical and X-Ray physics, 2002-2004
5. High Impedance bias for Josephson quantum circuits, Micho Watanabe, Nanostructure Physics, 1999-2001
6. Josephson qubits and quantum circuits, Volker Schollman, Nanostructure Physics 1998-2000

The following companies use the Nanolab:

1. Cobolt AB, 2001 – present
2. KIMAB, 2007 - present
3. LingVeta AB, under negotiation 2008
4. Spintronix, under negotiation 2008