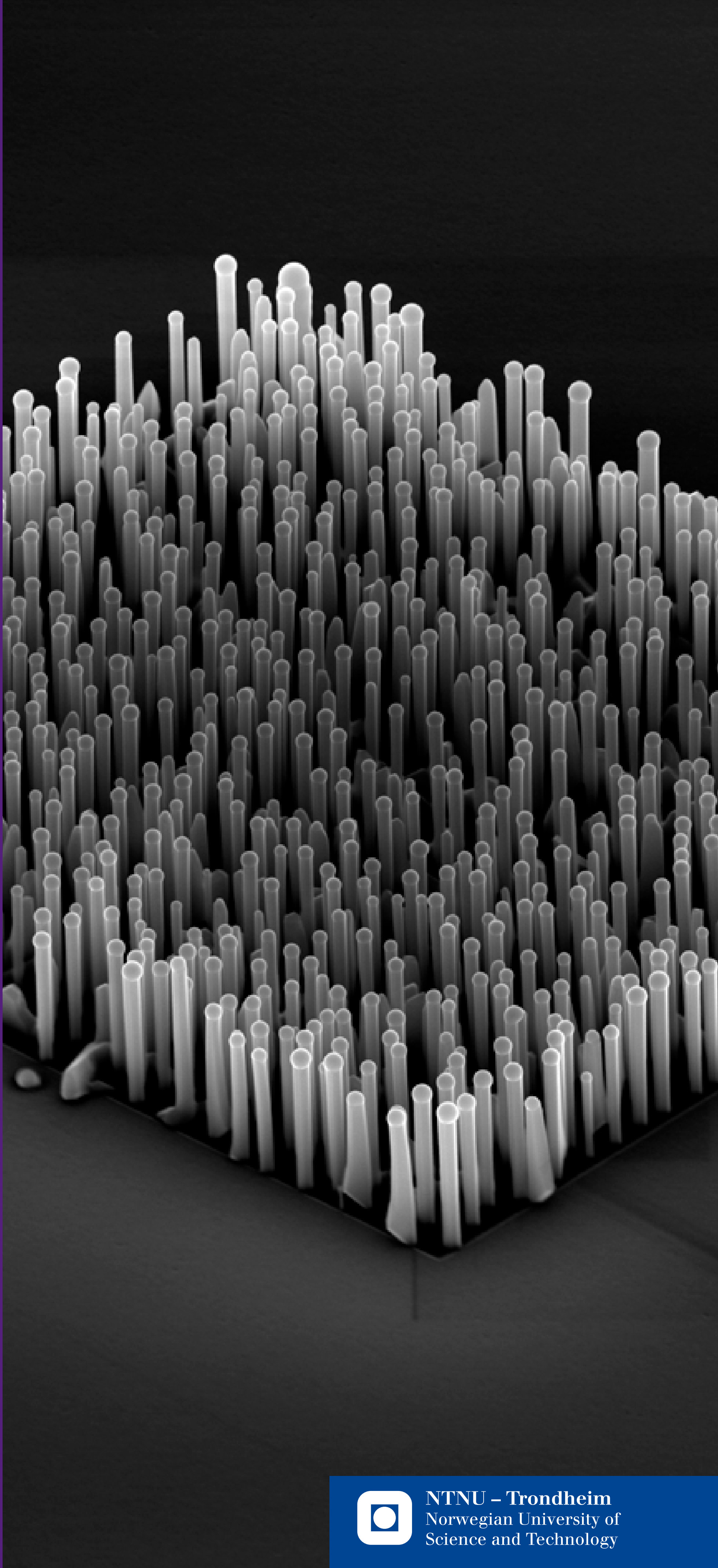
Annual Report Nano@NTNU 2015



NTNU – Trondheim
Norwegian University of
Science and Technology

Nano@NTNU 2015

The year 2015 will be remembered as the year NTNU merged with 3 university colleges and became the largest university in Norway. For the nano-community at NTNU, 2015 was marked by the establishment of a new name and mandate for the strategic initiative covering nanotechnology, nanoscience and functional materials. The role of Nano@NTNU is to promote and coordinate cross disciplinary activities within these fields of science at NTNU, as well as to operate and develop the NTNU NanoLab cleanroom.

At the scientific level, a major highlight in 2015 was the ERC Advanced Grant awarded to Prof. Arne Brataas in the area of spintronics. We congratulate Arne with this impressive achievement and we look forward to the results to come. Arne's research activity is introduced in more detail in a special feature of this annual report.

The initiative at NTNU within nano-related research as a total has also grown significantly, both in number of projects and "new" groups. In particular, the nano-related activities at the Faculty of Engineering Science and Technology have grown in 2015.

Furthermore, the success of the NorFab II grant application to the Research Council of Norway was a major highlight. Thus, NorFab is the first national infrastructure to receive long-term financing for operational costs. Through this grant, the NorFab partners receive 140 MNOK to cover part of the operational costs and investments over the next five years. NTNU has led this national cleanroom infrastructure project since 2010 and will continue doing so in the coming years.

NTNU NanoLab exceeded 20.000 user hours in 2015, and the number of publications based on cleanroom work is continues to increase. The installation of a new, state-of-the-art Electron Beam Lithography instrument in the cleanroom was another highlight in 2015. The investment was made possible through a long-term financial commitment of NTNU, as well as the NorFab II grant. With this new EBL, NTNU NanoLab now offers a high-resolution nanostructuring process line capable of competing at the cutting edge.

The future for research in nanotechnology, nanoscience and functional materials is now looking bright, not only at NTNU as Norway's largest university but also on a national level.

Kay Gastinger, *Director Nano@NTNU*

NORWEGIAN MICRO- AND NANOFABRICATION FACILITY NorFab

The Norwegian Micro- and Nanofabrication Facility, NorFab was established in 2010 by The Research Council of Norway (RCN) as a national infrastructure with four partners; NTNU, University of Oslo, SINTEF ICT and University College of Southeast Norway. The initial funding for NorFab covered 2010-2014. To be able to continue the operation of NorFab and our support system in 2015, NorFab received partial funding from the NANO2021 program until The RCN granted a new project period (NorFabII) running from 2015 until 2019.

In 2015, NorFab has undertaken several networking initiatives. The Nordic NanoLab Network (NNN) now includes Myfab (Sweden), DTU Danchip (Denmark), VTT Micronova (Finland) and NorFab. The NNN leader group had two meetings to exchange best practice experiences. In addition, a common Myfab/NorFab User Meeting was organized by NNN in Lund in April. The Nordic NanoLab Expert Network (NNEN) constitutes a forum for exchange of experiences within micro- and nanofabrication among engineers. In 2015, NNEN organized three workshops in thin film, characterization and facility operation. A EuroNanoLab Network has also been initiated with seven national cleanroom infrastructures from seven European countries.

On the national level, NorFab organized a Matchmaking Seminar for academic staff and industry representatives in Trondheim in June.

Website: www.norfab.no

NanoNetwork

The Norwegian PhD Network on Nano-technology for Microsystems was established in 2009, with the objective to coordinate, integrate, and strengthen PhD programs in the field of nanotechnology and microsystems in Norway. The partner institutions are NTNU, University of Oslo, University of Bergen, Southeast Norway University College, and SINTEF ICT Microsystems and Nanotechnology. The funding from NANO2021 ended in 2013, but the network activities continued on funding from the Division of Science, RCN, Program for National Graduate Schools, from January 2014.

In 2015, the Network offered 8 PhD courses on compact format and provided travel support for the candidates to attend these courses. The network has allocated funding for laboratory and processing expenses to 19 PhD candidates and travel support to 13 candidates to present their work at international conferences. Our 2015 annual workshop was held in Oslo from June 15-17, gathering 97 participants from the network partnership research communities.

Website: www.nano-network.net

Front page: GaAsSb nanowires grown on a focused ion beam patterned Si/SiOx substrate. Imaging with the ion beam causes damage and removes the mask layer, resulting in nanowire growth in the scanned area. Nanowires at the edges are observed to grow higher and thicker than those in the center, as Ga atoms hitting the nearby mask surface migrate and become trapped in the droplets.

Insulatronics

Conventional electronics- and spintronics-based logic and memory devices, interconnects, and microwave oscillators function via (spin-polarized) charge transport, which inherently dissipates power due to ohmic losses. Insulatronics is profoundly different because there are no moving charges involved, so the power reduction is significant.

In our ERC Advanced Grant Insulatronics, we seek to determine the extents to which spin-waves and coherent magnons in antiferromagnetic insulators and ferromagnetic insulators can be strongly coupled to electric and thermal currents in adjacent conductors and we explore ways to utilize this coupling to control electric signals. While we focus on the theoretical and fundamental challenges facing Insulatronics, if we are successful, the use of spin signals in insulators with extremely low power dissipation may in the future enable superior low-power technologies such as oscillators, logic devices, interconnects, and non-volatile random access memories.

Our research is within the field of spintronics, the method of utilizing the electron spin in devices, and explores the frontiers of this field aiming to control the coupling between the spin dynamics and the electric currents in nanoscale magnetic materials, as sketched in figure 1.

For example, we have opened a route towards Terahertz antiferromagnetic spin-torque oscillators [1], see figure 2. By passing a dc electric current in a normal metal, the torque on the spins in the adjacent

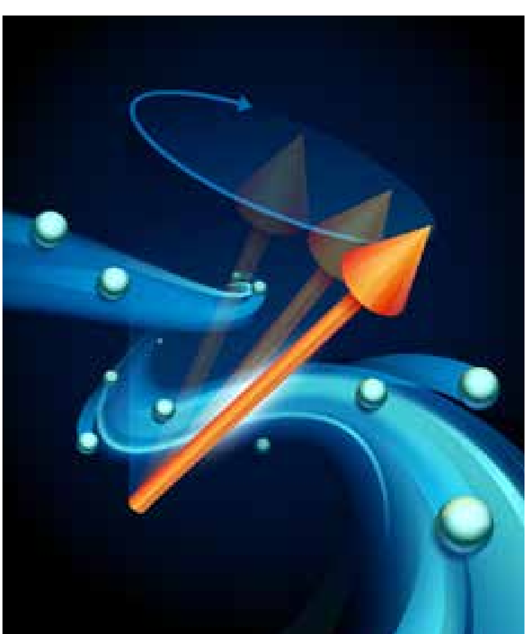


Figure 1: The coupling between spin dynamics and electric currents in magnetic materials.

Prof. Arne Brataas (Dept. of Physics) has received an ERC Advanced Grant for the project Insulatronics.

antiferromagnet causes spin precession that in term gives rise to a significant ac output current. The dc current controls the frequency of the ac output current so that the device functions as a Terahertz oscillator circuit. The frequency is a hundred times higher than conventional spin-torque oscillators based on ferromagnetic materials.

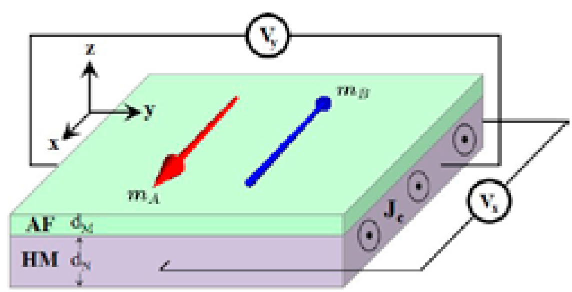


Figure 2: An insulating antiferromagnet-normal metal heterostructures.

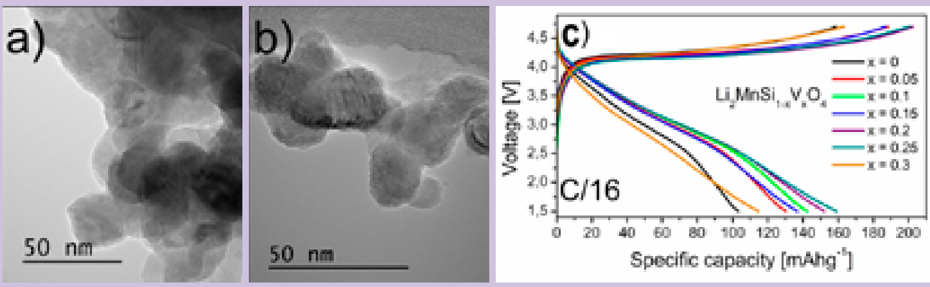
The applied dc current density drives the spins in the antiferromagnet via the spin Hall effect. The dynamics of the antiferromagnet pump spins back into the normal metal and convert the spin signal into an ac electric field via the inverse spin Hall effect.

We have also explored spin superfluidity, dissipationless transport of spins, which for magnetic materials may occur even at room temperature. In magnetic materials, magnons may condense into a single quantum state. Analogous to superconductors, this quantum state may support transport without dissipation. We show that, although intriguing, this tantalizing picture ignores long-range dipole interactions and that such interactions dramatically affect spin-transport [2]. As a result, over long distances, dipolar interactions destroy spin superfluidity. Nevertheless, we predict the re-emergence of spin superfluidity in trilayer ferromagnet-normal metal-ferromagnet films.

[1] R. Cheng, D. Xiao, and A. Brataas, Terahertz Antiferromagnetic Spin Hall Nano-Oscillator, Physical Review Letters 116, 207603 (2016).
[2] H. Skarsvåg, C. Holmqvist, and A. Brataas, Spin Superfluidity and Long-Range Transport in Thin-Film Ferromagnets, Physical Review Letters 115, 237201 (2015).

Tailoring electronic properties by atomic substitution

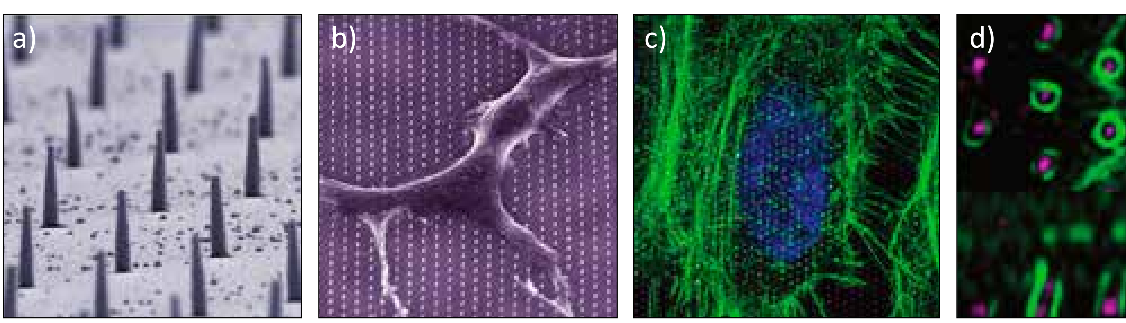
Rechargeable Li-ion batteries require materials which possess good electronic and ionic conductivities. For the cathode materials this is one of the greatest limitations. Three different ways of modifying these properties are generally explored: partial substitution of higher or lower valent cations, conductive surface coatings, and nanostructuring. All of these are incorporated in this research. However, the main focus has been on the atomic substitution. We have, thus, synthesized carbon coated nanoparticles with the composition $Li_2MnSi_{1-x}V_xO_4/C$ where x varies between 0 and 0.3. Figure a) and b) below show TEM images of particles for x = 0 and x = 0.25, respectively. In c) charge/discharge data show how variations in x affects the capacity of the battery during cycling. The work has been carried out at the Dept. of Materials Science and Engineering, NTNU.



Ref: N. Wagner, P. E. Vullum, M. K. Nord, A. M. Svensson, F. Vullum-Bruer, J. *Phys. Chem. C* 2016, accepted for publication.

Tunable high aspect ratio polymer nanostructures for cell interfaces.

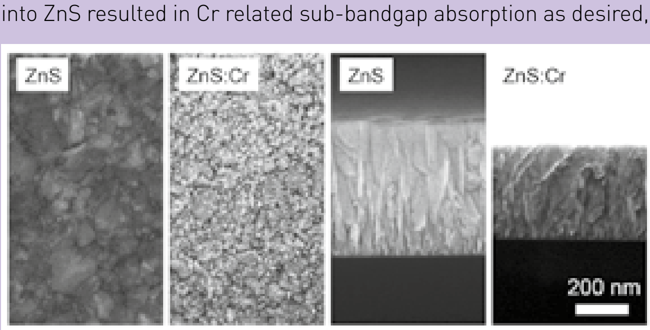
Precisely engineered nanostructured surfaces are emerging as an important tool for cell perturbation and study in fields such as neuroscience, tissue engineering and basic cell biology. Combination of electron beam lithography (EBL) and SU-8 as a highly sensitive EBL resist opens new options for fabrication of nanostructures for applications in biophysics and cell biology research. We have used an EBL system in NTNU NanoLab to develop a flexible SU-8 based platform for biological applications, with emphasis on high aspect ratio nanostructures (a,b). The fabrication of the nanostructures directly on glass cover slips for convenient integration with typical cell biology research procedures has been optimized. Thiol–epoxide reactions were implemented to selectively alter SU-8 surface chemistry. Furthermore, cell responses to different high aspect ratio SU-8 nanostructures have been studied (c,d).



Ref: K. S.Beckwith; S.P. Cooil; J. Wells and P. Sikorski, *Nanoscale 7* (2015) 8438.

Chromium doped zinc sulfide for solar cells

Cr-doped ZnS (ZnS:Cr) has been suggested as a material for so-called intermediate band solar cells, that are 50 % more efficient than conventional solar cells. We have deposited ZnS:Cr films with between 0 and 7.5 at.% Cr, on silicon substrates using both molecular beam epitaxy (MBE) and pulsed laser deposition (PLD). Introducing Cr into ZnS resulted in Cr related sub-bandgap absorption as desired, but also reduced the grain size. The sub-bandgap absorption increased with increasing Cr content, and with increasing growth temperature, but did not depend on the growth method. In contrast, the crystallinity depended strongly on the growth method, and smoother and highly textured films were obtained by PLD.



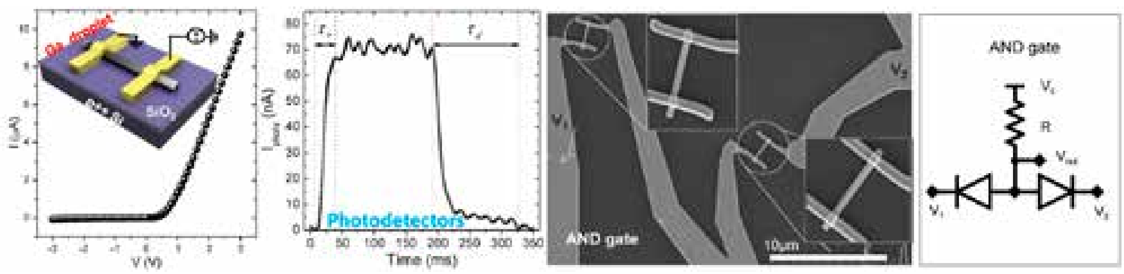
Top view (2 left images) and side view (2 right images) SEM images of a ZnS film and a ZnS:Cr film made by PLD.

Contact: Turid W. Reenaas, Dept of Physics, NTNU.

Ref. M. Nematollahi et al., *Solar Energy Materials and Solar Cells* 141 (2015) 322.

Rectifying Single GaAsSb Nanowire Devices

Semiconducting nanowires (NWs) have been intensively explored due to their abilities to overcome the limitations of conventional semiconductors. We have reported on a highly reproducible rectifying behaviour in single GaAsSb NWs. From results of confocal micro-Raman spectroscopy, electron microscopy and electrical measurements, it has been found that the rectification is due to radial Sb out-diffusion during the NW growth. This unique characteristic of GaAsSb NWs enables direct utilization of NW-based functional devices without any complex processes. As a proof of concept, we have demonstrated NW-based photodetectors and simple logic circuits. The GaAsSb NWs were grown by molecular beam epitaxy at the Dept of Electronics and Telecommunication and all NW devices including the photodetectors and the logic circuits were fabricated with E-beam lithography in NTNU NanoLab.

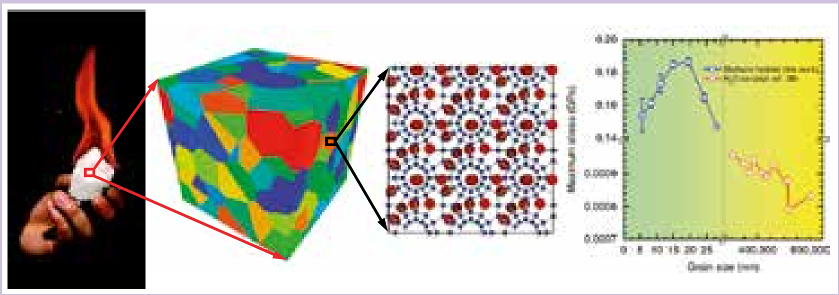


GaAsSb NW-based photodetector and logic circuit.

Ref: J. Huh, H. Yun, D.-C. Kim, A. M. Munshi, D. L. Dheeraj, H. Kauko, A. T. J. van Helvoort, S. W. Lee, B.-O. Fimland, and H. Weman, *Nano Letters* 15 (2015) 3709

Mechanical instability of methane hydrates

The mechanical properties of sediment-hosted gas hydrates play a crucial role in gas recovery and understanding their evolution. However, the deformation mechanisms of gas hydrates have not yet been elucidated. Here, we report direct molecular dynamics simulations of the material instability of monocrystalline and polycrystalline methane hydrates under mechanical loading. The results show dislocation-free brittle failure in monocrystalline hydrates and an unexpected ductile ultimate strength as a result of crossover from grain-size strengthening to weakening in polycrystals. Upon uniaxial depressurization, strain-induced hydrate dissociation accompanied by grain-boundary decohesion and sliding destabilizes the polycrystals. In contrast, upon compression, appreciable solid-state structural transformation dominates the response. These findings provide molecular insights into the destabilization mechanisms of gas hydrates caused by deformation beyond the conventionally thermodynamic instability.

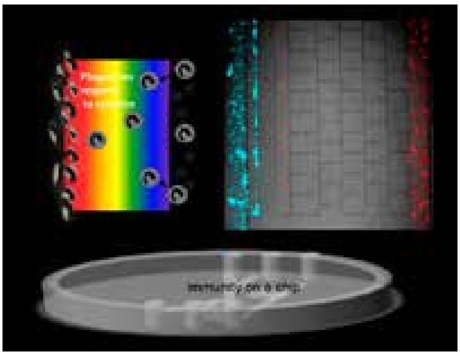


Molecular model of polycrystalline methane hydrate and grain size dependent maximum tensile stress.

Ref: J.Y. Wu, F. Ning, T. Trinh; S. Kjelstrup, T.J.H. Vlugt, J.Y. He, B. Skallerud and Z.L. Zhang, *Nature Comm.* 6, (2015) 8743.

Immunity-on-a-chip

The immune system is a dynamic and complex defence function for infections and cancers. The immune cells are constantly migrating between different organs and tissues during their life. The way these cells self-organize is difficult to approach both *in vivo* and in tradition cell cultures. Our group at Dept of Cancer Research and Molecular Medicine turned to NTNU NanoLab to create structures mimicking basic microanatomical features to make our research more life-like. In this paper, we report fabrication of segregated microcompartments by soft lithography and filming of the migration of T cells, a type of immune cells, towards different inflammatory reactions such as bacterial infections, and thus providing fundamental information on system performance.



Infection and immunity on a chip: a compartmentalised microfluidic platform to monitor immune cell behaviour in real time.

N. Gopalakrishnan, R. Hannam, G.P. Casoni, D. Barriet, J.M. Ribe, M.Ø. Haug, *Halaas Lab Chip*. 2015 Mar 21;15(6):1481. doi: 10.1039/c4lc01438c.

NorFab Nano-Matchmaking Seminar in Trondheim, June 2, 2015

In order to promote collaboration, representatives from Norwegian industry and academia were invited to a one-day seminar at Scandic Hotel Lerkendal. The seminar gathered 53 participants, representing 11 companies, 4 institutes and 4 universities as well as the Research Council of Norway (RCN). Special adviser Aase Marie Hundere (Devision of innovation, RCN) opened the seminar by presenting the funding opportunities for collaborations between academia and industry. Other participants followed up with 28 short presentations describing their competence and which expertise they were seeking. In addition, the study program in nanotechnology at NTNU was presented. Most importantly, there was ample time for mingling, discussions and matchmaking.

DTU – NTNU NanoTech Seminar in Copenhagen, November 2-3, 2015

Nano@NTNU participated in organizing a rector headed visit to DTU. The meeting was a direct follow-up of an NTNU hosted visit by DTU representatives in 2014. The aim was to promote collaboration through joint projects between the universities. The program consisted of plenary talks, lab tours and targeted 1:1 meetings between participants from both universities. Nano@NTNU supported 14 participants from NTNU, including 3 MSc students in nanotechnology. This meeting has resulted in a collaborative project between the groups of Prof. Catharina Davies (NTNU) and Prof. Thomas Andresen (DTU) involving 2 common PhD students.

NorFab – Myfab User Meeting in Lund, April 21-22, 2015

The second joint Myfab-NorFab User Meeting was facilitated by Lund Nano Lab at Lund University. Around 250 active cleanroom users from Sweden, Denmark, Finland and Norway participated.The program included four invited plenary speakers:

- Lars Samuelson, Lund University, Sweden
- Lennart Ramberg, entrepreneur, Sweden
- Helinor Johnston, Heriot-Watt University, Edinburgh, United Kingdom
- Peter Bøggild, DTU NANOTECH, Copenhagen, Denmark

The remaining presentations were organized in four parallel sessions with presentations and "tutorials" focusing on the following topics:

- Materials analysis and characterization
- Thinfilm technologies
- Etching technologies
- Lithography

In addition, there was a poster session displaying 54 posters and guided tours of Lund Nano Lab, MAX-lab and MAX IV. The 35 norwegian participants were sponsored by NorFab and NTNU NanoLab.

Grey Goo Symposium at NTNU, February 7, 2015

The annual Grey Goo Symposium is a meeting place for companies and students enrolled in the master program in nanotechnology at NTNU. The aim of the symposium is to promote exchange of knowledge and ideas, and to prepare the ground for an increase in the number of collaborative master projects with the industry. Both students and industry representatives were thus given the opportunity to present their expertise, creating an atmosphere for further talks during the breaks. Around 80 students from NTNU, 16 guest students from the University of Aarhus in Denmark and representatives from 6 companies participated. The symposium was organised by Timini, the association of the nanotechnology students at NTNU, and was sponsored by NTNU@NTNU.

Timini 10^{-9}

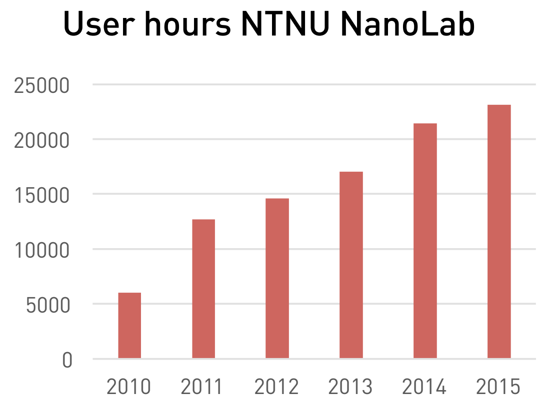
NTNU NanoLab

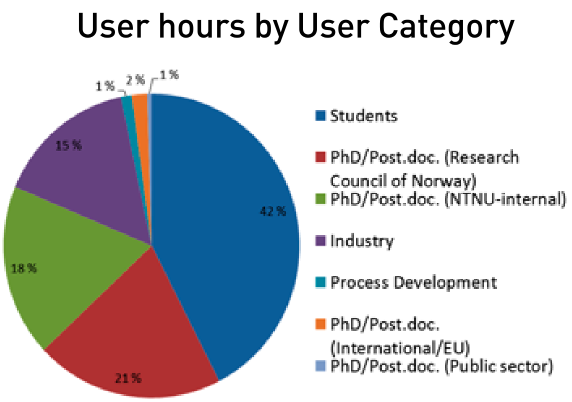
2015 was a year marked by reorganization of the infrastructure to adapt to a steadily growing user group.

Electron Beam Lithography (EBL) is a key technique within NanoLab's responsibility for nanolithography in NorFab. The capacity of the old EBL system has been a severe bottleneck in our nanostructure fabrication line. In 2015, a state-of-the-art EBL was installed. The new Elionix ELS-G100 is a 100KV EBL system with a 100MHz pattern generator, which can expose samples from 3x3 mm up to 8" with a resolution is down to 6 nm! This investment required a major reconstruction of the cleanroom in order to give the EBL an optimal location.

In addition, a complete reorganization of the lithography facilities in the cleanroom was planned and initiated in 2015. The aim was to improve the work flow, space economy and HSE aspects related to lithographic methods.

Creating interdisciplinary meeting places is an important part of Nano@NTNU's mandate, and the establishment of a large meeting room by the NanoLab offices was a leap forward in this respect. NanoLab members now have a new area available for seminars, cleanroom courses, informal meetings, chats with the staff and coffee breaks.





Official opening of NTNU NanoLab's new Elionix ELS-G1, November 16, 2015

The opening of NTNU NanoLab's new state-of-the-art EBL from Elionix was celebrated with a half-day seminar of greetings, scientific presentations and lunch. The program included official greetings from Anne Borg (the Dean of the Faculty of Natural Sciences and Technology and head of the board of Nano@NTNU), Ken Koseki (Elionix), Aase Marie Hundere (The Research Council of Norway and Ragnar Fagerberg (SINTEF). After the official opening, 8 scientific presentations featuring various applications of EBL in NanoLab were given.

From the left; Aase Marie Hundere (RCN), Anne Borg, (NTNU), and Kay Gastinger inspect the new EBL.

Ken Koseki (Elionix Inc) illustrates efficient and seamless cooperation between NTNU and Elionix Inc.

Nano@NTNU Symposium in Trondheim, November 11, 2015

The annual Nano@NTNU Symposium took place at Skistua outside Trondheim. The focus of the symposium is to feature nanorelated research at NTNU in at cross-disciplinary forum. The scientific program consisted of 24 scientific presentations and a poster session exhibiting 18 posters. A total of 107 PhD-students, post docs and scientific staff participated.This year, Nano@NTNU established two prizes. These were awarded to Ambjørn Dahle Bang for the best oral presentation and Samuel Dingeman Slöetjes for the best poster presentation.

Skipnes Kommunikasjon AS

Dissertations

The following candidates obtained a PhD degree at NTNU in fields related to nanoscience,nanotechnology and functional materials in 2015. Highlighted candidates have carried out part of their work in NTNU NanoLab.

- Nazanin Davari, *Molecular modeling of ionization processes relevant for electrically insulating liquids*
- **Kai Sandvold Beckwith, *Micro- and nanostructured devices for cell studies***
- Marit Takla Børset, *Energy dissipation and recovery in the context of silicon production Exergy analysis and thermoelectricity*
- Anh Hoang Dam, *Bimetallic Catalyst System for Steam Reforming*
- Siv Eggen, *Ultrasound in Imaging and Delivery of Nanomedicine in Cancer Tissue*
- Kristin Elisabeth Haugstad, *The role of oligosaccharide decorations in mucin interaction capacities: Assessment by high resolution force probes*
- **Luky Hendraningrat, *Unlocking the Potential of Hydrophilic Nanoparticles as Novel Enhanced Oil Recovery Method: An Experimental Investigation***
- Jon Holmestad, *(Scanning) Transmission Electron Microscopy Studies of Grain Boundary Segregation relevant to Intergranular Corrosion in Al-Mg-Si-Cu Alloys*
- **Liudmila Ilyukhina, *Characterisation of iridium oxide by scanning probe, electrochemical, and photoelectrochemical methods***
- **Birgitte McDonagh, *The nanoparticle protein corona – properties, dynamics and implications for nanoparticles in biomedicine***
- Stefanus Lumban, *High Temperature corrosion and corrosion protection of metallic interconnects for SOFC*
- **Fredrik Aleksander Martinsen, *Silicon microwires as solar cells***
- **Maryam Gholami Mayani, *Intermediate Band Solar Cells Simulations and quantum Dot Studies***
- Julie Nilsen-Nygaard, A*mphiphilic polysaccharides – stabilization of dispersed two-phase systems and gelling properties of chitosans and propylene glycol alginates*
- **Muhammad Saeed, *Development of Mimic Enzyme-based Membrane and Membrane contactor for CO_2 Capture***
- Thomas Tichelkamp, *The Effect of Calcium Ions on Oil-Brine-Surfactant Interfacial Properties and the Relation to Surfactant Enhanced Oil Recovery at Low Salinity*
- Daniele Toniolo, *Phase transitions in low dimensional systems via spontaneous symmetry breaking and topology*
- **Andrey Volynkin, *The role of carbon supports in platinum catalyzed hydrogenation/dehydrogenation model reactions***
- Peng Wang, *Design of Nanoscale CMOS Integrated Circuits for Ultrasound In-Probe Electronics*
- Espen Tjønneland Wefring, *Lead-Free Ferroelectric Materials based on $BiFeO_3$ and $Bi_{0.5}K_{0.5}TiO_3$*
- Øivind Wilhelmsen, *Equilibrium and Nonequilibrium Thermodynamics of Planar and Curved Interfaces*
- **Song Zhang, *The effects of impurities on the properties of Cz-grown silicon for solar cells***

Photo: Per Henning, NTNU

The Nano@NTNU Prizes 2015 for best oral presentation and best poster at the Nano@NTNU Symposium 2015 were awarded to Ambjørn Dahle Bang (left), Samuel Dingeman Slöetjes.

Photo: Ida Noddeland, NTNU

Board of NTNU NanoLab

- Prof. Anne Borg, Dean of the Faculty of Natural Sciences and Technology, NTNU (head of the board)
- Prof. Stig Slørdahl, Dean of The Medical Faculty, NTNU (until 12.06.2015)
- Prof. Bjørn Gustafsson, Dean of The Medical Faculty, NTNU (from 13.06.2015)
- Prof. Ingvald Strømmen, Dean of The Faculty of Engineering Science and Technology, NTNU
- Prof. Geir Øien, Dean of The Faculty of Information Technology, Mathematics and Electrical Engineering, NTNU
- Dr. Ellen Dahler Tuset, President, Kongsberg Norspace AS

Management

Director: Dr. Kay Gastinger
Coordinator: Dr. Hanna Gautun

Permanent Technical Staff

- Head of Laboratory Ida Noddeland
- Senior eng. Mathilde Barriet
- Senior eng. Mark Chiappa
- Senior eng. Ken Roger Ervik
- Senior eng. Espen Rogstad
- Senior eng. Trine Østlyng Hjertås

Leader Group

- Director Kay Gastinger
- Prof. Bjørn-Ove Fimland (from 01.10.2015)
- Associate Prof. Jianying He
- Associate Prof. Hilde Lea Lein
- Prof. Øyvind Halaas
- Prof. Pawel Sikorski
- Prof. Erik Wahlström
- Prof. Helge Weman (until 31.09.2015)
- Research manager Ragnar Fagerberg
- Coordinator Hanna Gautun
- Head of Laboratory Ida Noddeland