Semiconductor Materials

RESEARCH DIVISION

Department of Physics, Chemistry and Biology (IFM), Linköping University

activity report 2013
STAFF

Professors
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Peder Bergman
Per Olof Holtz
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Bo Monemar (Emeritus)
Nguyen Tien Son
Einar Sveinbjörnsson
Rositsa Yakimova (Emeritus)

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Urban Forsberg
Carl Hemmingsson
Ivan Ivanov
Anelia Kakanakova
Fredrik Karlsson
Plamen Paskov
Henrik Pedersen
Mikael Syväjärvi
Chariya Virojanadara
Qamar ul Wahab

Assistant Professors & Lecturers
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Jawad ul Hassan
Olle Kordina (Senior lecturer)
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Philip Hens (ended April.)
Chih-Wei Hsu (started Nov.)
Volodymyr Khranovskyy
Houssaine Machhadani
Nabiha Ben Sedrine (started Oct.)
Jianwu Sun (ended June)

PhD Students
Supaluck Amloy (PhD Feb.)
Chamseddine Bouhaafs
Ian Booker
Jr-Tai Chen
Daniel Duñaker (PhD June)
Martin Eriksson
Sadia Muniza Faraz
Andreas Gällström
Chih-Wei Hsu (PhD Sept.)
Tomas Jemson
Valdas Jokubavicius
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Xun Li
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Björn Magnusson
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Xuan Thang Trinh
Thien Duc Tran
Chao Xia
Milan Yazdanfar

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Roger Carmesten
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Valery Stanishev
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Roman Viter, Mekhnikov National Univ., Ukraine
Kateryna Shavanova, Univ. of Life and Environmental Sciences, Ukraine

Visiting Graduate Students (at least one month stay)
Shakila Bint Reyaz, Uppsala Univ., Sweden
Yusuke Hashimoto, Ritsumeikan Univ., Japan
Stefan Schöcke, Univ. of Nebraska-Lincoln, USA
Zhou Shuai, Beijing Univ., China.
Nelya Slyshyk, National Univ. of Life, Ukraine
Dmitry Sodzel, Inst. of Biophysics, Belarus
Alla Tereshchenko, Mekhnikov National Univ., Ukraine

INTRODUCTION
The Semiconductor Materials Division develops and investigates materials for novel electronics with the main focus on silicon carbide (SiC), III-nitrides (GaN, InN, AlN and their alloys) and graphene. The goal is to resolve fundamental and application-motivated issues of interest for Swedish and European industries. The research activities within the division cover a broad spectrum dominated by basic research, mainly funded by Swedish and European agencies, partly with industrial collaboration. There is a strong international cooperation within most research projects.

Current research activities

- Growth, simulation and characterization of epitaxial films and bulk crystals.
- Investigations of crystal defects and doping.
- Development and studies of nano- and heterostructures.

The growth is based on chemical vapor deposition (CVD) or sublimation techniques while the characterization includes surface and interface properties as well as structural-, optical- and transport properties probed by techniques such as photoluminescence spectroscopy, magnetic resonance, DLTS, ellipsometry, XRD, photoelectron spectroscopy and microscopy.
High frequency and high power

SiC is a semiconductor material that sustains higher frequencies, powers and temperatures than conventional silicon. This leads to smaller electronics and reduced power loss, with applications in electric power distribution and power electronics in hybrid cars. Significant efforts within the division are devoted to develop high quality SiC for devices. One ambition is to control the involved isotopes and thereby improve its thermal properties.

The III-nitrides is a class of materials that exhibit extremely good high-frequency characteristics, in addition to their outstanding light emitting properties. A project within the division aims to develop the nitride material for high electron mobility transistors, with applications in the next generation high-speed data transmission systems.

The division has recently gained attention also for graphene, in particular for a high temperature fabrication process of graphene on SiC. The exceptionally high carrier mobility in graphene makes it a promising material for new devices operating up to the terahertz frequency range.

Novel light sources

The optically efficient III-nitrides have enabled new and energy efficient light sources, such as LED-lamps and blue lasers. Within the division, there is a constant activity for deepening the understanding of the III-nitrides and for improving the material quality in order to further enhance its light emitting performance.

One challenge tackled by the division is to develop a III-nitride based light emitting material for deep ultraviolet lasers. The disinfecting properties of ultraviolet light can be utilized for water cleaning. III-nitride based single-photon emitters are fabricated and investigated for their potential use in quantum information applications. Other optically efficient materials, e.g. zinc oxide (ZnO), are also studied.

SPECIAL EVENTS 2013

Bo Monemar was awarded an honorary degree from Meijo University, Japan.

Vanya Darakchieva was selected for SSF’s Future Research Leaders programme for "THz Ellipsometry of high-speed electronic materials". She also received the prestigious 2013 Paul Drude award for her contributions to spectroscopic ellipsometry.

Per Olof Holtz received the Junior Faculty Prize of Linköping University for creating a sustainable research environment.

RESEARCH FUNDING

The turnover for research in our division was about 52.6 MSEK during the period 130101-131231, excluding equipment grants. The major part of this budget comes from external sources. The faculty support for research was about 7 MSEK for the year. External grants originate mainly from the Swedish Research Council (VR), the Knut and Alice Wallenberg Foundation (KAW), the Swedish Strategic Research Foundation (SSF), Swedish Energy Agency, Swedish Innovation Agency (VINNOVA), European Defense Agency (EDA/FMV) and EU. In addition there is a strong support from and an intimate cooperation with several industries, mainly LG Innotek, Norstel AB, and Aixtron AB, and with the Defense Research Institute FOI.
SELECTED RESEARCH PROJECTS

Major national projects
Isotope project – A major part of the KAW grant is devoted to isotope enriched SiC, mainly for improved thermal conductivity. Isotope enriched SiC layers manifest a number of interesting properties useful for scientific and industrial applications. Among them is a very narrow spectral linewidth, which enables detailed measurements of defect centers. Another interesting phenomenon of the enriched layers is that they exhibit significantly higher thermal conductivity due to a reduced isotope scattering process in the material. We have during 2013 produced the first isotope-enriched SiC. Preliminary measurements show an increase of the thermal conductivity by at least 20% compared to that of natural SiC, while theoreticians predict 25% increase. The instrument for precise measurements of the thermal conductivity is under development, to be delivered in mid 2014. We have secured a large amount of enriched gas sources to continue our experiments. The enriched gas that we have at our disposal is in the form of SiF₄, which is not considered suitable for growth of SiC due to hazardous rest products. Therefore we are working with two companies in Norway for converting the SiF₄ into silane. However, we are also considering using SiF₄ directly, taking the necessary precautions required. A new reactor is under development and it will be delivered in mid 2014. It is designed to grow the isotope-enriched material using any sources.

PI: E. Janzén.

The SSF project SiC – the Material for Energy-Saving Power Electronics started in 2012 and is focused on determining, understanding and improving material related issues in SiC epitaxy and gate dielectrics, which today are the limiting factors for the SiC power device technology. The project includes: (i) Understanding and control of carrier lifetime limiting defects in SiC material and devices, (ii) Characterization and identification of device-critical epitaxial defects, (iii) Investigation novel alternative gate dielectrics and novel fabrication techniques, (iv) Develop on-axis and/or low-off angle epitaxy for power device applications and (v) Develop Cl-based epitaxy for high growth rates. The identification and control of the lifetime limiting defects is correlated with the growth conditions and also with the growth modeling. A lot of time has been devoted to studying the growth behavior of different hydrocarbons and the observations have been correlated with the modeling work. Some initial very exciting indications that we have seen is that depending on which hydrocarbon that is used, the surface will reconstruct in a different manner. In the extension this may answer questions such as how the carbon vacancy is formed during growth.

PI: E. Janzén.

European projects
Manga and EuSiC are two initiatives to develop nitride-based technology. The Manga project is a European large-scale project to develop GaN HEMT structures. Our contribution is to investigate heat transport in a HEMT device and optimize nucleation layer to improve heat dissipation of the HEMT device. This is a very important part since it improves the reliability of the transistor. The goal of the EuSiC program is to develop high quality European GaN-Wafer on SiC substrates for space applications and to create an independent European supply chain for space technology. We have been growing HEMT device structures on 3” wafers that have been processed by partners in Europe. We have demonstrated a new process for optimizing the GaN buffer layer and thereby reducing/eliminating trapping phenomena due to carbon related defects. The EuSiC program ended during 2013.

PI: E. Janzén.

The Graphene flagship started in October 2013, involving 126 academic and industrial research groups in 17 European countries with an initial 30-month-budget of 54 million euro. We are partner in this project with focus on sublimation growth of graphene on SiC. This initiative will help us to implement our ideas on how to scale up the production of graphene.

PI: R. Yakimova

In the EPIGRAT project was our role to develop graphene growth technology on semi-insulating 4H-SiC substrates using Si and C polarities. The main emphasis has been to optimize the electronic properties of graphene layers, concentrating on band engineering, hydrogen intercalation, the role of substrate interactions and its impact on electronic mobility. Numerous samples have been fabricated for the EPIGRAT partners for device processing and other material characterizations. The project ended in June 2013. Project leader: E. Janzén.

GraphOhm is a EU Joint Research Project that started June 2013 on Quantum resistance metrology based on graphene. Our contribution is epitaxial graphene on SiC.

PI: R. Yakimova

We have also been providers of graphene on SiC in the following two high-frequency projects: Nano-RF is an ongoing collaborative project on Carbon Based Smart Systems For wireless applications. Graphic-RF within Eurographene was a project about Graphene on SiC wafers for high performing RF transistors. It ended in May 2013. In addition we participated with fabrication in ConceptGraphene – a collaborative project that ended September 2013 on New Electronics Concept: Wafer-Scale Epitaxial Graphene.

PI/ WP-leader: R. Yakimova.
During 2013, we participated in two projects within the Marie Curie Actions Research Fellowship Program: NetFiSiC is a project on interfaces on SiC that has been funding one PhD student for researching graphene on SiC since 2012. BIOSENSORS-AGRICULT is a project on developing nanotechnology-based biosensors for agriculture with partners from France, Latvia, Belarus and Ukraine. Eight researchers were involved in the staff exchange scheme during 2013. Partner: R. Yakimova

The division has two projects within the Swedish Innovation Agency VINNOVA - VINNMER – Marie Curie international qualification programme with the topics: THz ellipsometry and optical Hall effect: important techniques to study graphene and InN PI: V. Darakchieva, and Development of AlN semiconductors for applications in energy and environment, PI: A. Kakanaokova.

Other major international projects
LG-Innotek – The project, which is sponsored by LG Innotek and the State of South Korea, strives to develop uniform epitaxial layers for power device material on 4” wafers using the chlorinated epitaxial process that has been studied here for several years. The first phase (three years) of the project has been concluded and the second phase has just started. The focus is on reducing the density of structural defects that are harmful to the device performance and increase and control the carrier lifetime of the material, which is an essential part in the fabrication of bipolar devices. The lifetime of the carriers is strongly correlated with various defects in the material. The dominating defect in as-grown material is the carbon vacancy and it is manifest in the epitaxial material at different concentrations depending on growth conditions. We have started to map out the correlation between the carrier lifetime with the growth conditions. Ways of improving the lifetime, such as high temperature oxidation, is also under investigation. For this reason, an oxidation furnace has been built for temperatures above 1500 °C.

PUBLICATIONS
Research activities in this division during 2013 have produced 71 articles published in well-recognized international journals, 31 conference proceedings papers with peer review as well as 1 review article. During the year, 25 invited talks were given by the staff at international conferences or symposia. The researchers of the division are well cited in international journals with more than 25000 ISI citations.

Details and highlights of the research work as well as updated publication lists are available at our website: www.ifm.liu.se/semicond.

SELECTED RESEARCH HIGHLIGHTS

World’s first isotope enriched SiC
Some properties of SiC, such as the thermal conductivity, are negatively affected by the natural occurrence of different isotopes of silicon and carbon. We have, for the first time, produced isotope-enriched SiC using only one isotope of each element. Preliminary measurements show an increase of at least 20 percent of the thermal conductivity, while theorists predict 25 percent increase. These results are highly relevant from both scientific and commercial points of view, and device manufacturers exhibit a great interest.

Micro-pyramids offer route to polarization controlled photon emitters
We have developed a concept for emission of strongly polarized light with good control of the linear polarization direction. The light is generated by quantum dots formed on top of elongated hexagonal micro-pyramids. Our results could find use in applications such as energy-efficient backlighting of displays and polarized single-photon sources for quantum communication.

Unpaired holes probe quantum dot asymmetry
We demonstrate that two unpaired holes trapped within a nanometer sized quantum dot acts as an efficient probe of the dot symmetry. Our finding enables highly accurate characterization of dot asymmetry, and it may therefore be used to locate quantum dots with the high symmetry needed to generate polarization-entangled photons required for applications within quantum cryptography and quantum computing.

Towards Terahertz technologies
Using a novel Optical Hall technique, we have been able to determine, for the first time, how fast the free electrons can travel in thin aluminum-rich AlGaN layers and how they scatter. We also studied stacks of graphene layers and could identify extremely mobile electrons in perfect and non-interacting layers. In addition, channels with slow and very slow electrons were identified, where the reduced mobility is caused by interactions among graphene layers as well as with the underlying substrate. These results are prerequisites for THz device design and operation.

Towards Terahertz technologies

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<td>2013</td>
<td>V. Darakchieva et al.</td>
<td>Appl. Phys. Lett.</td>
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Graphene formation mechanisms on SiC polytypes – a way to optimize graphene quality
We use a high temperature sublimation technique to grow a single layer of graphene on SiC substrates. The structural and electronic properties of the resulting graphene are dependent on the detailed characteristics of the surface on which it grows, which is different for different SiC polytypes. We have grown, for the first time, large area graphene with superior uniformity on the unconventional cubic polytype of SiC (3C). A comparison is made with results on two hexagonal polytypes. The present work contributes to understanding and quality control of graphene growth on SiC.

G. R. Yazadi et al., Carbon 57 477 (2013)

Low temperature buffers offer the possibility to produce large-area GaN substrates at lower cost
GaN devices are often grown on foreign substrates such as sapphire or SiC, which give rise to problems with defects and cracking. We have developed a technique to manufacture freestanding native GaN substrates. The technique uses a thin so-called buffer layer of GaN, grown on sapphire at low temperature (~600 °C). On this buffer layer, thick GaN is grown at standard temperature (~1000 °C). Layers thicker than one millimeter spontaneously self-separate from the sapphire substrate. This low cost process has importance for the development of ultra-high brightness LEDs.


Impact of residual carbon on electrical properties of GaN transistor structure
A very precise amount of carbon atoms should be incorporated into GaN based high electron mobility transistors for optimal performance and reliability. We demonstrate that the carbon concentration effectively can be controlled by the temperature in the fabrication process, letting us reach excellent uniformity of the electrical properties with very high free electron density and high mobility. Our result is relevant for developing energy efficient high power and high frequency electronic devices.

J. T. Chen et al., Appl. Phys. Lett. 102, 193506 (2013)

Understanding magnesium impurities in GaN
Light-emitting diodes and laser diodes rely on holes provided by impurities. For GaN is magnesium the only impurity that is useful for this purpose. The exact properties of the magnesium impurity have long been controversial, partly due to instability of its spectral features. We have been able to spectrally identify isolated magnesium impurities as well as impurities near stacking faults in the GaN crystal. Our experimental results are in conflict with recent theoretical predictions about magnesium in GaN.


Defects engineering of quantum wells in a single semiconductor material
One of the most promising materials for optoelectronics is zinc oxide, with efficient blue and ultraviolet light emission. A zinc oxide crystal consists of stacked layers of atoms, and two different stacking sequences known as wurtzite and zincblende can occur. Our study shows that faults in the stacking sequence in fact are minimal segments of zincblende inserted into a wurtzite crystal. A zincblende insertion traps and confines electrons, but not holes, acting as an electron quantum well. Once the insertions of zincblende are controllable, they can be used for tuning the electronic and optical properties of the material.

V. Khanovskyy, A. M Glushenkov et al., Nanotechnology 24 215202 (2013)

Shortcomings of growth modelling of SiC
Simulations can provide a better understanding of the chemical vapor deposition process of SiC to improve material quality, film thickness, uniformity and the yield. However, the current models have shortcomings prohibiting accurate simulations. In this work we point out that improvements are very much needed in both the chemical species’ thermodynamic data and the gas phase reaction models, as well as in the surface reaction descriptions. For example, we show that the current surface reaction models do not provide realistic predictions, and we suggest that several hydrocarbon molecules may have higher reactivities with the SiC surface than previously accepted values.

Aluminum tunes the electronic properties of graphene on SiC
Graphene has unique and superior electronic properties. It can be grown on SiC by a graphitization process, enabling development of single layer graphene based electronic devices for high temperature and high voltage operation. Aluminum is a commonly used contact material for electronics, but its stability on graphene has not been investigated. We show that a distinct change in the electronic properties of graphene occurs for temperatures above 350 °C, when aluminum penetrates into the graphene-SiC interface. Our results evidence the importance of temperature of the graphene device, when selecting aluminum as contact material.

C. Xia, L. I. Johansson et al., to be published.

Quantum dot light emitters on top of micrometer-sized pyramids
Nitride-based quantum dots populated with two or four charge carriers have previously been studied. Rather surprisingly, no such quantum dots populated with odd number of charge carriers have been evidenced earlier. In our work, we investigate an InGaN quantum dot populated with three charge carriers, two electrons and one hole, forming a negative trion. Our research improves the fundamental understanding of these quantum dots, which are highly potential for future applications, such as quantum cryptography.

C. W. Hsu, E. S. Moskalenko, M. O. Eriksson et al., Appl. Phys. Lett. 103, 013109 (2013)

Growth of high quality electronic grade SiC using methane
Methane is hardly ever used for growing SiC but it is interesting to study to shed light on the differences in gas phase reactions using different hydrocarbons and the differences in surface reactions of the specie that reach the surface. We observe that methane plays a considerable role for the growth of SiC and it has a much higher probability to stick to the surface than previously believed. We also show that high quality layers may be grown using methane if the carbon to silicon ratio is carefully tuned.


Please visit www.ifm.liu.se/semicond for details and more highlights.

PhD THeses
Supaluck Amloy: Polarization-resolved photoluminescence spectroscopy of III-nitride quantum dots
Daniel Dufäker: Few particle effects in pyramidal quantum dots - a spectroscopic study
Chih-Wei Hsu: InGaN quantum dots grown on GaN pyramid arrays

Master Theses
Niklas Mårtensson: Evaluation of charge carrier concentration in particle assisted, Sn doped GaAs nanowires
Chun-Yi Chen: Spectroscopic ellipsometry study of epitaxial graphene and effect of oxygen treatment
Sin Jhou: Optimizing MOCVD process of AlN-on-SiC layered structure
Po-Hsun Chen: Stability of bulk cubic silicon carbide (3C-SiC) on off oriented hexagonal silicon (4H-SiC) substrates

Teaching
The division is very active in teaching and it has responsibility of about 20 undergraduate and graduate courses at IFM.

Undergraduate & master courses offered 2013
TFFM08 Experimental Physics (Son)
TFYY51 Engineering Project Y (Forsberg)
TFYY70 Physics of Cond. Mat. I (Virojanadara)
TFYA20 Surface Physics (Virojanadara)
TFYY47 Semiconductor Physics (Karlsson)
TFYY57 Nanophysics (Paskov)
TFYA15 Models in Physics (Karlsson)
TFYY68 Mechanics (Hemmingsson)
TFYY55 Physics (Bergman)

PhD courses offered 2013
Properties of III-nitride semiconductors (Paskov)
Many body effects in quantum dots (Karlsson)
CAD of scientific use (Kordina)
Aspects of MOCVD growth of III-Vs (Kakanakova)
Raman spectroscopy (Ivanov)
Chemical vapour deposition (Pedersen)
Growth and characterization of ZnO (Khranovskyy)
Advanced semiconductor materials (Darakchieva)

Popular science activities
Kordina gave energy-related talks about electricity usage and SiC based power electronics at the Popular Science Week organized by the university.