Semiconductor Materials
RESEARCH DIVISION
Department of Physics, Chemistry and Biology (IFM), Linköping University

activity report

2014
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Kateryna Shavanova, Univ. of Life and Environmental Sciences, Ukraine

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Dmitry Sodzel, Inst. of Biophysics, Belarus
Nelya Slyshyk , Univ. of Life and Environmental Sciences, Ukraine
Makiko Suegetsu, Saitama Univ., Japan
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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 2014

Two new spin-out companies were formed from our research activities on silicon carbide and III-nitrides:

Classic - In spring 2014, Classic WBG Semiconductors AB was formed. The four founders of Classic all come from the division of Semiconductor Materials, having rich experience and knowledge in growth and characterization of nitrides and SiC materials. Classic is in a highly expansive phase and in 2015 the company will participate in two European projects with the aims (1) to fully exploit the high thermal conductivity of the isotope-pure SiC materials and (2) to be qualified as the European supplier of nitride based HEMT structures.

Polar Light Technologies AB - Based on a successful research project on nitride semiconductor quantum dots, a novel method for efficient generation of polarized light has been attained. A Swedish patent was finalized in the end of 2014, while an international patent will be finalized in the beginning of 2015. The concept has potential for applications such as optical interconnects, LCD back lighting and secure communication. For the further development of this concept into future commercialization of the innovation, a spin-off company, Polar Light Technologies AB, was started in Dec 2014.

Sweden – South Africa exchange program. Based on a program financed by a VR-Link program, there has been an extensive exchange series involving both junior and senior researchers during the period 2011-2014. For evaluations and conclusions, there has every year been a workshop arranged, every second year in South Africa and every second year in Sweden. During the period of 15-18 June, 2014, there was a final workshop within this VR-Link program, arranged in Karlskrona, attracting around 25 researchers from Linköping University and South African universities.

Olof Kordina received his Docent degree in June 2014.
RESEARCH FUNDING

The turnover for research in our division was about 55.1 MSEK during the period 140101-141231, including depreciation costs for equipment. 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. The instrument for precise measurements of the thermal conductivity is under development, to be delivered in the spring 2015. A new reactor designed to grow the isotope-enriched material using any sources was installed during 2014. We have investigated suitable process conditions for SiC epitaxy from SiF₄. Good crystal quality has successfully been achieved, however a more fundamental understanding of the growth behavior is still lacking. This work continues combining experimental and modeling efforts. 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. A new carrier lifetime limiting defect, RB₁, has been identified to be related to iron contamination. Iron is believed to originate from corrosion of reactor parts when using chlorinated chemistry. To further increase the understanding of the Cl-based epitaxy, growth using another halogen species was investigated, namely Bromine. By comparing the two different chemistries, both experimentally and theoretically, new insights have been achieved e.g. regarding important growth species. PI: E. Janzén.

Bridging the terahertz gap - In this project, financed by KAW, the Semiconductor Materials Division is working in close collaboration with Chalmers University in Gothenburg and KTH in Stockholm to develop new electronics for telecommunication in the terahertz frequency range. Excellent materials for the active area of such devices are indium nitride (InN) or indium rich indium gallium nitride (InGaN). The Semiconductor Materials Division is here focusing on understanding and developing the synthesis of very thin layers of InN and InGaN by chemical vapor deposition. The challenge lies in the high tendency for the indium atoms to desorb from the surface, which means that the materials synthesis must be performed at a low temperature. One approach for this is to steer the synthesis chemistry from the gas phase to the surface by using an atomic layer deposition approach where the In and N precursor molecules are sequentially pulsed into the reactor to saturate the surface with either In or N atoms. The surface chemistry of the In saturated surface can break down the N precursor at low temperature which enables a low overall synthesis temperature. Partner: E. Janzén.

European projects

Manga is an initiative 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. Parallel to Manga, additional minor national programs have been added. Part of these programs involve development of carbon doping using both residual and intentional carbon doping. Carbon doping of GaN is an important step to obtain semi insulating GaN buffer layer in the HEMT device. However, carbon can also cause trapping phenomena, which have been investigated within these national programs. 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 how to scale up the production of graphene. PI: R. Yakimova

GraphOhm is an ongoing 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 Nano-RF project, which is an ongoing collaboration on Carbon Based Smart Systems For wireless applications. Partner: R. Yakimova.

During 2014, 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. 6 researchers where involved in the staff exchange scheme of IFM during 2014. Partner: R. Yakimova.

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 project is now in its second phase (year 4-6). 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 are continuing 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 been built for temperatures above 1500 °C.

PUBLICATIONS
Research activities in this division during 2014 have produced 65 articles published in well-recognized international journals, 18 conference proceedings papers with peer review as well as 1 review article and 1 book chapter. During the year, 15 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 27500 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
Single spins in silicon carbide
Unpaired electrons at an electronic defect in solids possess an intrinsic angular momentum, often called spin. Single spins can be prepared in an arbitrary state and are basic elements for quantum computing where states of spins are used as quantum bits. Leading contenders such as defects in diamond or individual phosphorus dopants in silicon have shown spectacular progress, but either lack established nanotechnology or an efficient spin/photon interface. Silicon carbide (SiC) combines the strength of both systems: it has deep photoluminescence (PL) defects and benefits from mature fabrication techniques.

Research teams at Linköping, Takasaki, Stuttgart and Chicago have successfully designed and fabricated 4H-SiC single crystal samples with the Si vacancy (missing Si atom) or divacancy (missing neighbouring Si and C atoms) at low concentrations so that single defects can be observable in an optical confocal microscope and selectively detected by PL. Overcoming difficulties in control of the charge state of defects and other issues in the detection of weak light emission, the research teams have been able to manipulate and detect single spins in SiC at room temperature (for the Si vacancies) and at cryogenic temperatures (~253 °C for the divacancies), showing long spin coherent times up to 1.2 milliseconds. The demonstrated ability of optically single-spin control at room temperature shows the potential applications of defects in SiC for quantum processors that could operate at ambient conditions and paves the way for integrated spintronics. D. J. Christie et al., Nature Materials (2014) | doi:10.1038/nmat4144; M. Vidmann et al., ibid | doi:10.1038/nmat4145

Graphene on cubic SiC
We applied a high temperature process to grow graphene on cubic silicon carbide (3C-SiC). No buffer layer was observed for the graphene grown on the (001) plane, as confirmed by low energy electron microscopy (LEEM) and diffraction (LEED). The
cubic symmetry of 3C-SiC leads to a lack of spontaneous polarization, as confirmed by the mild n-doping \( (n = 7.4 \times 10^{17} \text{cm}^{-2}) \) observed in graphene grown on the (111) plane by angle-resolved photoelectron spectroscopy (ARPES). We demonstrated from different aspects that 3C-SiC is a good substrate for growth of epitaxial graphene. The 3C-SiC samples were grown in a well-controlled process for high crystalline quality without foreign polytype inclusions.

- P. Hens et al., Carbon 80 823 (2014);
- S. Mammadov et al., 2D Mater. 1 035003 (2014);

Assessing properties of mixed crystal structures in thin films

When grown under non-equilibrium conditions, crystals or thin films of technologically important materials may contain domains with different crystal structures. Here we develop and demonstrate nondestructive structural and optical methods to determine the ratio between different crystal phases and study the free-charge carrier and vibrational properties of mixed-phase films. Our approach allows us to establish the elusive properties of cubic InN.


Study of Ag-dopants on the structural and optical properties of ZnO nanorods

Zinc oxide (ZnO) is a semiconductor material promising for optoelectronics due to its efficient light emitting properties. However, the key challenge that must be solved before ZnO can be used as a LED material is to make it so-called p-type.

Substitution of some Zn atoms with silver (Ag) was recently proposed as an approach for obtaining p-type ZnO. Here we investigate the structural and optical properties of ZnO nanorods doped with Ag atoms. We demonstrate that Ag promotes the generation crystal defects and significantly modifies the optical spectrum of ZnO. These results can be of high importance for further progress on p-type ZnO.


Resolving the doping limitations in aluminum gallium nitride

We achieve better understanding of the complex growth phenomena underlying the deposition of aluminum gallium nitride (AlGaN) alloys and the related doping by silicon (Si). We can grow respective layers of such crystal quality and doping characteristics as to support the study of fundamental material properties of AlGaN. For that, an essential and sophisticated method such as the electron paramagnetic resonance (EPR) is implemented. We can explain the sharp increase of resistivity of Si-doped AlGaN layers with the increase of Al content.

- X. T. Trinh et al., Appl. Phys. Lett 105, 162106 (2014);
- D. Nilsson et al., Appl. Phys. Lett 105, 082106 (2014);
- A. Kakanakova-Georgieva et al., Solid State Phenom. 205-206 441 (2014);

**Micropyramid emits antibunched photons in the ultraviolet spectral region**

Linearly polarized photons emitted one by one form the basis for novel cryptography methods. Here we demonstrate that the photons emitted from a InGaN quantum dot grown on the apex of a GaN micropyramid exhibits single photon characteristics known as antibunching. Our experiments show that the quantum dot itself is a fast and close to perfect single photon emitter, but a superimposed background signal from the pyramid needs to be eliminated before utilization in polarization-based single photon applications.


**High thermal stability quasi-free-standing graphene on silicon carbide through Platinum functionalization**

Graphene grown on silicon carbide (SiC) provide solutions for high frequency electronics operating at high temperature. However, a major obstacle is that the electrons are substantially slowed down due to the first carbon layer formed on the SiC. Here we report on quasi-free-standing graphene layers with potentially fast electrons even at very high temperatures (1200°C), achieved by letting Platinum penetrate into the graphene-SiC interface.

- C. Xia et al., Carbon 79, 631 (2014)

**Resonant ionization of shallow donors in electric field**

Semiconductors are non-conductive at low temperatures because the electrons freeze in their lowest energy state at impurities. However, a sudden rise of the conductivity can occur at very high electric fields due to resonant ionization. We discuss this effect using a simplified model of the energy states of donor impurities, and our results are similar to the predictions of more advanced models and in very good agreement with our experiment.

Layer-number determination in graphene on SiC by reflectance mapping
Graphene attracts much attention due to its exceptional properties for future electronics. Growth of graphene on silicon carbide is promising for large-scale device-ready production. A significant parameter characterizing the quality of the grown material is the number of layers. Here we report a simple, handy and affordable optical approach for precise number-of-layers determination of graphene based on the reflected power of a laser beam.

I. G. Ivanov et al., Carbon 77 492 (2014)

Nano-resolution reveals the true nature of graphene
Graphene grown on the basal planes of silicon carbide is considered a most promising route for carbon-based nano-electronics. Two nonequivalent faces of silicon carbide can be used for this purpose, the carbon-face and the silicon-face. It was claimed that these two faces result in graphene with fundamentally different electronic properties. Here we reveal the actual similarity between graphene layers on the two faces by experiments on a nanometer scale. Moreover, the apparent difference previously seen in standard experiments can now be explained as the collective effect of microscopic grains of graphene formed on the carbon-face.


Plasma chemistry gets a boost from pulsed power
In the plasma state, free electrons and ions open up new low temperature reaction pathways, enabling thin film deposition on sensitive materials such as plastics. We recently presented the concept of high power pulsed plasma enhanced chemical vapor deposition (HiPP-PECVD), which use plasmas thousands of times more electron rich than conventional PECVD. By using carbon films as model system, we now show that more film is deposited from the same amount of acetylene and power when the power is delivered as high power pulses. This is attributed to a more efficient plasma chemistry due to the increased number of electrons.


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

STUDENT THESES

Doctoral theses
Milan Yazdanfar: Precursors and defect control for halogenated CVD of thick SiC epitaxial layers
Daniel Nilsson: Doping of high-Al-content AlGaN grown by MOCVD

Licentiate theses
Thien Duc Tran: Investigation of deep levels in bulk GaN
Xuan Thang Trinh: Electron Paramagnetic Resonance Studies of Negative-U centers in AlGaN and SiC

Master theses
Fatima Akhtar: Study the effect of ambient conditions on epitaxial graphene
Fang-Wei Chen: Growth of Carbon Nanomaterials on SiC

Bachelor theses
Jimmy Thörnberg: Investigation of Hexagonal GaN Pyramids and InGaN Quantum Dots

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 2014
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 2014
Properties of III-nitride semiconductors (Paskov)
CAD of scientific use (Kordina)
Growth perspectives III-V materials (Kakanakova)
Raman spectroscopy (Ivanov)
Trends in the periodic chart (Pedersen/Högberg)
Growth and characterization of ZnO (Khranovskyy)
Popular science activities
The Semiconductor Materials division arranged a study visit by about 70 junior high school students from Vadstena with help from the Biomolecular and organic electronics division. The students spent 5 hours at IFM, learning about our research and its relation to energy and sustainable development. They participated in lectures about semiconductor growth, energy saving power electronics, graphene and organic solar cells. The youth also visited our research labs with exciting hands-on experiments and demonstrations. The event involved five senior researchers and four PhD students.

Philipp Kühne demonstrates polarized light for interested students.

Our division also participated with exhibitions and hands-on experiments at LiU’s Popular Science Week, mainly targeting high-school students and teachers. We demonstrated the effects of polarized light in connection to our research on ellipsometry, as well as photoluminescence and III-nitride LEDs linked to our research on optical properties and spectroscopy of semiconductor materials.

Olle Kordina visited Soltorgsgymnasiet in Borlänge and talked about electricity usage and SiC based power electronics. Bo Monemar, Per Olof Holtz and Carl Hemmingsson gave lectures about the Noble Prize in Physics 2014 – a topic strongly related to our research on III-nitrides.