C3NiT Janzén

Swedish Center for III-Nitride Technology

C3NiT day 2021

11th November 2021

PROGRAM

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ABSTRACTS

C3NiT Day 2021

11th November 2021

PROGRAM

Join via Zoom: https://chalmers.zoom.us/j/61594639088
Password: upon request (email to philipp.kuhne@liu.se)

08.30	Welcome, Vanya Darakchieva, Center Director, LiU
08.40	**Keynote talk:** *Introduction to C-TEFs and wireless power transmission system using GaN-based devices*, Hiroshi Amano, Nagoya University
09.30	Project I: Advanced Epitaxial Growth, Vanya Darakchieva, LiU
09.45	PhD student and post doc projects: short presentations
10.15	**Break**
10.30	Project II: Vertical power devices, Mohammad Nawaz, Hitachi Energy Research/LiU
10.45	PhD student and Post doc projects: short presentations
11.15	Project III: Lateral HEMTs for high frequency and power applications, Niklas Rorsman, Chalmers
11.30	**Invited talk:** *GaN RF and power research at IEMN*, Farid Medjdoub, IEMN
12.00	**Lunch break**
13.00	**Relevance for industry I**, Jonas Nilsson, SweGaN
13.20	PhD student and post doc projects: short presentations
13.50	Project IV: MMIC technology, Anna Malmros, Chalmers/Gotmic
14.05	**Break**
14.15	**Relevance for industry II,** Jan R. Svensson, Hitachi Energy Research
14.30	PhD student and post doc projects: short presentations
15.00	Project V: Developing next generation high-power β-Ga_2O_3 material, Daniela Gogova, LiU
15.15	**Invited talk,** *Heat Transport across Interfaces for the Optimization of Heat Sinking in RF and Power Device Applications*, Martin Kuball, University of Bristol
15.45	**Award Ceremony**
16.00	Closing Remarks, Niklas Rorsman, Chalmers

ABSTRACTS

INVITED SPEAKERS

Introduction to C-TEFs and wireless power transmission system using GaN-based devices

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The purpose of our center, Center for Integrated Research of Future Electronics (CIRFE), is to gather specialists in different fields, such as the crystal growth of GaN, SiC, and carbon nanotubes, device fabrication and characterization, simulation, circuit design, module design, and system applications, who will work for realizing a carbon neutral society. To start providing nitride researchers with GaN-based devices such as laser diodes and horizontal and vertical high-power/high-frequency devices, we have developed a clean room dedicated for fabricating GaN devices. As one examples of our activities, I will explain the fabrication of GaN-based RF and microwave devices for compact wireless power transmission systems.
Our work is supported by MEXT, through its Program for Research and Development of Next-Generation Semiconductor to Realize Energy-Saving Society, Grant Nos JPJ005357: the Ministry of the Environment through its Project of Technical Innovation to Create a Future Ideal Society and Lifestyle: and CSTI, through its Cross-ministerial SIP: Energy Systems of an Internet of Energy Society.

About the author:

Hiroshi Amano was born in Hamamatsu, Japan. He studied electrical engineering at the university in Nagoya, which also awarded him his doctorate in 1989. In 2002 he became a professor at Meijo University in Nagoya and later moved to Nagoya University.
Lighting plays a major role in our quality of life. The development of light-emitting diodes (LEDs) has made more efficient light sources possible. Creating white light that can be used for lighting requires a combination of red, green, and blue light. Blue LEDs proved to be much more difficult to create than red and green diodes. During the 1980s and 1990s Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura successfully used the difficult-to-handle semiconductor gallium nitride to create efficient blue LEDs.
He received the Nobel Prize in Physics 2014 "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources."

Source: https://www.nobelprize.org/prizes/physics/2014/amano/facts/

GaN RF and power research at IEMN

Farid Medjdoub[1,*]

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GaN high electron mobility transistors (HEMT) are becoming the mainstream for high frequency and power switching applications. Devices and circuits based on these emerging materials are more suited to operate at higher voltages and temperatures than Si-based devices owing to their superior physical properties.

In this presentation, I will show the current status of III-Nitride based technologies for RF and power applications that have been developed within the nanofabrication center of IEMN in France through partnerships with industrials. In particular, the evolution of the promising approach based on GaN HEMTs with Al-rich ultrathin barriers for future millimeter-wave applications will be described. Furthermore, I will discuss some potential solutions that we are pursuing with the aim of pushing the limits and address new requirements of high voltage power devices. In this frame, various device designs and preliminary results of novel GaN-on-Silicon vertical transistors and AlGaN-channel Ultra-Wide Band Gap lateral devices will be presented.

About the author:

Farid Medjdoub received the Ph.D. degree in electrical engineering from the University of Lille, Lille, France, in 2004. After working as a research associate at the University of Ulm in Germany, he became a CNRS Senior Scientist with IEMN, Villeneuve d'Ascq, France, where he resides to date. He is also part of the French observatory of wide-bandgap devices. His research interests are the design, the fabrication, and characterization of innovative GaN-based devices. For example, he worked on field effect transistor with world record breaking thermal stability of up to 1000°C, best combination of cut-off frequency / breakdown voltage or highest lateral GaN-on-silicon breakdown voltage using a local substrate removal. He is author and co-author of more than 130 papers and holds several patents.

Sources: https://ieeexplore.ieee.org/author/38579117000
https://mtt.org/profile/farid-medjdoub/

Heat Transport across Interfaces for the Optimization of Heat Sinking in RF and Power Device Applications

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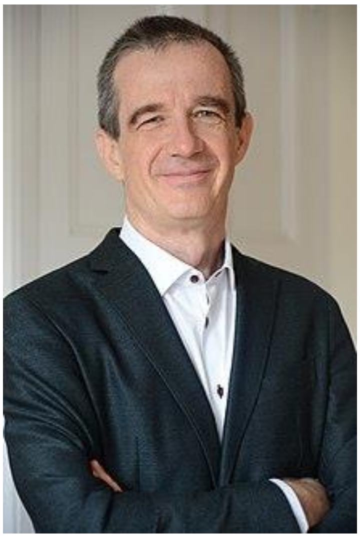
Heterogenous integration of materials and devices opens huge opportunities for exploiting RF and power device structures which benefit from an optimal combination of electronic and thermal material properties. It is critically important to assess heat transfer across their interfaces to avoid thermal bottlenecks resulting in excessive device temperatures though. The latest results in this field will be reviewed, including GaN-on-Diamond and Ga_2O_3-diamond technology.

About the author:



Martin Kuball received the Ph.D. degree from the Max Planck Institute for Solid State Research, Stuttgart, Germany. He was the Feodor-Lynen Post-Doctoral Fellow with Brown University, Providence, RI, USA. He is currently a professor of physics and the Director of the Center for Device Thermography and Reliability, University of Bristol, Bristol, U.K.
Kuball is known for his research into thermal characterization and reliability of electronic materials and devices, with particular focus on wide-bandgap semiconductors, and RF and power electronic devices. He pioneered techniques such as Raman thermography, to determine the temperature in devices with submicron spatial resolution and nanosecond time resolution.
He presently leads the £5M EPSRC Programme Grant GaN-DaME which develops GaN-on-Diamond technology for ultra-high-power RF devices, and the £2M EPSRC Platform grant MANGI which implements this technology for next generation internet applications.

Sources: https://ieeexplore.ieee.org/author/37275505600
https://en.wikipedia.org/wiki/Martin_Kuball

ABSTRACTS

PhD Students
&
POST DOCS

Electron effective mass enhancement in GaN and GaN HEMTs studied by THz optical Hall effect

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In addition to the processing and packaging steps in the production of GaN transistors, the fundamental properties of the active materials play a crucial role in the final device performance. Free charge carrier (FCC) mobility, which depends on scattering time and effective mass parameters, affects maximum device current density, operation frequency, and efficiency. However, the temperature dependence of the scattering time and effective mass parameters in GaN and GaN high electron mobility transistor structures (HEMTs) is not fully understood, especially at terahertz frequencies.[1,2]

We employ terahertz (THz) and mid-infrared (MIR) optical Hall effect (OHE)[3,4] to study the temperature dependence of FCC effective mass along with carrier density and mobility in GaN HEMTs and epitaxial GaN layers on 4H-SiC substrates. THz OHE measurements reveal strong effective mass enhancement in epitaxial GaN (up to 40%) and GaN HEMTs (up to 150%) at temperatures above ~200 K. Contrarily, the MIR OHE does not indicate any effective mass enhancement in epitaxial GaN, suggesting frequency dependence of the FCC properties. In this work, we review possible origins of the detected effective mass enhancement in the terahertz frequency range.

References

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Improved Passivation, Ohmic Contacts, and 'Buffer-Free' Structure of GaN HEMTs for High-Frequency Applications

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GaN HEMTs have been anticipated to play an important role for high-power amplifiers beyond Ka-band. However, poor passivation quality, high contact resistance, and weak backside confinement limit the device performance. In this work, several SiN passivation by LPCVD and MOCVD, low-temperature Ti-based deeply recessed ohmic contacts, a buffer-free HEMT heterostructure with different GaN channel thickness were studied to address the issues stated above. Preliminary results of SiN passivation indicate that the LPCVD SiN has a larger shift of Ga binding energy as compared to that on MOCVD SiN, while the refractive indexes are identical for both materials. Record low contact resistance of 0.13 ohm-mm was achieved on 30% and 50% AlGaN barrier materials with a low annealing temperature of 550 C. The device with a gate length of 100 nm on a buffer-free structure with a 150 nm GaN channel shows a solid pinch-off and good 2DEG confinement with a DIBL of 7.4 mV/V (V_{DS}= 1 to 25 V).

High Temperature Treatment Effects on Fluorine-based Gate-Recess Etching of First Passivation SiNx AlGaN/GaN HEMTs

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In the pursuit of achieving high frequency (W-band and above) performance of AlGaN/GaN High electron Mobility Transistors lateral and vertical downscaling is of essence. Whereas gatelength (L_g) downscaling, yields lower gate capacitance, it also causes undesirable short-channel effects (SCE), which can be counteracted by vertical downscaling enabling a preserved gate control. Typically, a ratio between L_g and gate to channel distance (d) of $L_g/d \geq 5$ needs to be maintained to curtail SCE. In our passivation first technique, the etching of the passivation is critical to define L_g, while limiting d is planned to be done by increasing the polarization effect induced by the top barrier through increasing the Al-content. Here, an extensive study into the impacts of recess etching of SiNx, utilizing NF_3 or CF_4 by Inductive Couple Plasma (ICP), combined with high temperature annealing post recess etch $(600 - 800$℃$)$ to repair the crystal structure damaged by the etching process is presented.

Exploring hot-wall MOCVD for high-quality homoepitaxial GaN with low impurity levels

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The need to build a sustainable and efficient energy system motivates the development of vertical GaN transistors for applications with power ratings of 50-150 kW, e.g., in electric vehicles and industrial inverters. The key is to grow GaN layers with low concentration of defects (impurities and dislocations), which enables an expansion in both voltage and current ratings and reduction of cost.

In this work, we explore hot-wall MOCVD for the development of GaN homoepitaxial growth. We propose a new approach to grow high-quality homoepitaxial GaN in N_2-rich carrier gas based on thermal stability studies under different MOCVD conditions. Extensive structural characterization shows that there was no generation of additional dislocations during homoepitaxial growth. GaN with atomically flat and smooth epilayer surfaces with a rms value as low as 0.021nm and low background Carbon concentration of 5.3 x 10^{15} cm^{-3} has been achieved. Our results demonstrate the potential of the hot-wall MOCVD technique to deliver high-quality GaN material for vertical power devices.

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Design, fabrication and modelling of lateral and vertical GaN-based power electronic devices

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The wide band gap semiconductor material gallium nitride (GaN) and its compounds has gained prominence over the past three decades due to their high critical electric fields and saturation velocities. This work focuses on investigating GaN-based semiconductor devices in terms of their power electronic capabilities. We attempt to explore different fabrication techniques to examine the true material limits of the semiconductor. In lateral GaN high electron mobility transistors (HEMTs), 1^{st} and 2^{nd} passivation, gate dielectrics, field plates, and isolation techniques are being tested on buffer-free AlGaN/GaN heterostructures (QuanFine) for the purpose of maximizing breakdown voltage and minimizing on-state resistance. In semi-vertical GaN Schottky barrier diodes (SBDs), different anode metal stacks, annealing and etching techniques are being analyzed. Additionally, we have developed technology computer aided design (TCAD) models for fully vertical GaN-based pin diodes which will be used as a basis for future growth and processing.

Influence of Al content on the two-dimensional electron gas properties in AlGaN/GaN high-electron-mobility transistor structures

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AlGaN/GaN high-electron-mobility transistor (HEMT) structures are important components in modern high-power/high-frequency electronics. High Al-content AlGaN barriers are needed to allow aggressive downscaling in order to increase f_{max} beyond 250 GHz and to enhance output power. A good understanding of the effects of Al content in the barrier on the two-dimensional electron gas (2DEG) properties is thus required for device design and optimization. In this work, we employ the terahertz optical Hall effect (THz-OHE),[1,2] which allows to study the 2DEG properties of AlGaN/GaN HEMTs at their operational frequencies 300 GHz – 1 THz. The 2DEG charge carrier density, mobility, and effective mass are determined as a function of Al content in the AlGaN barrier layer and found to be in good agreement with results from Hg-probe C-V measurements and simulations based on solving the Poisson and Schrödinger equations. Surprisingly, we find the 2DEG effective mass decreases with increasing Al content. Considering mass hybridization by barrier penetration of the electrons, an opposite trend is expected. Other possible contributions, such as polaronic effects at the interface are further discussed.

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2. S. Knight et al., Rev. Sci. Instr. **91**, 083903 (2020) (DOI link)

Compositionally graded channel HEMTs towards improved linearity for low-noise RF amplifiers

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The rapidly evolving RF communication technology requires utilization of optimized devices to meet the demands of high-frequency power amplifiers.[1] AlGaN/GaN HEMTs with high power and current gain have been demonstrated in RF device applications. However, at high signal operation they show an inherent non-linear behavior which leads to gain compression and signal distortion.[2] Polarization-doped AlGaN/GaN HEMT, with a compositionally graded channel[3] enables a linear response improvement through formation of a 3-D electron gas.[4]

In this work, we develop the growth process of graded channel HEMTs in a hot-wall MOCVD reactor. Control of grading profile is established through growth parameter tuning in combination with energy dispersive spectroscopy that allows for precise determination of Al composition across the channel. Conventional and graded channel HEMTs were fabricated for comparison with the mobility of the former, ~2350 cm^2/V.s, being among the highest reported in literature. Furthermore, the sheet resistance, carrier density and mobility in HEMTs with different grading profiles were compared and discussed.

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GaN pyramidal doping defects: Where did the Mg go?

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GaN, a wide bandgap (3.4eV) semiconductor useful for opto- and high-power electronics, has limited options of p-dopants, where Mg remains the most useful and studied acceptor.[1] However, the activation energy of Mg is high, requiring a high doping concentration for a high hole concentration.[2] High concentration of Mg causes structural defects, e.g. pyramidal polarity inversion domains (PID),[3] leading to reduced hole concentration.[4] The Mg accumulates at the PIDs but the distribution has been difficult to previously determine exactly.

Here, we study the PIDs using scanning transmission electron microscopy. Using a spectroscopic mapping algorithm, along with imaging sensitive to lighter elements we observe the otherwise obscured Mg atoms. The images are compared to simulations, confirming the Mg to be lining the whole pyramid with a fixed thickness, causing the inversion. This shows how Mg incorporates during growth, making it possible to evaluate formation energies and how to reduce their concentration.

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Filtering dislocations and reducing surface roughness in N-polar GaN: insights from aberration-corrected STEM.

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Nitrogen-polar (N-polar) high electron mobility transistors (HEMTs) based on AlGaN/GaN/AlN heterostructures opens for tunable spontaneous polarization fields.[1,2] This is highly relevant for realizing improved charge carrier confinement, low ohmic contacts, and device scalability.[2] However, N-polar growth is challenging because of spontaneous formation of mixed polarity domains. Nevertheless, N-polar GaN/AlN has been reported,[3] although with increased surface roughness and dislocation incorporation, that in turn prevents two-dimensional electron gas (2DEG) formation at the AlGaN/GaN interface of the HEMTs structure.

In this report, we demonstrate a two-step GaN growth process the limits the surface roughness and filter dislocations, while at the same time maintaining N-polarity across the III-nitride layers, a prerequisite for 2DEG generation. Structure characterization is carried out by aberration-corrected scanning transmission electron microscopy and electron energy-loss spectroscopy.

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High-field frequency-scanning EPR-Ellipsometry of Fe in Ga_2O_3

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Gallium oxide Ga_2O_3 is a promising wide-bandgap semiconductor for high-power electronics. As-grown β-Ga_2O_3 exhibits n-type conductivity. Insulating material is obtained by Fe-doping - better understanding of Fe as compensating acceptor (defect energy levels, charge states, lattice sites) is required for device optimization.

Here, we present first results obtained by a novel method for electron paramagnetic resonance (EPR) spectroscopy employing frequency-domain terahertz (THz) ellipsometry.[1] We examine Fe^{3+}, the neutral, non-compensating state. The s=5/2 *high spin* system is governed by large zero-field splitting (ZFS) that resembles the monoclinic crystal symmetry[2,3]. In contrast to conventional EPR using X-band (~10GHz) or Q-band (~35GHz), our high-field/high frequency setup (110-170 GHz) gives access to all five allowed transitions simultaneously. No cavity is required, allowing for frequency sweeps and disentangling *g*-factor and ZFS parameters. From angular scans of a single crystal, we distinguish Fe^{3+} on octahedrally and tetrahedrally coordinated Ga sites and determine the ZFS parameters.

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Non-Debye Relaxation Time Approximation Model for Thermal Conductivity Calculations in Wide-Bandgap Semiconductors

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In the frame of high-power electronic devices, wide-bandgap semiconductors attract great attention due to their high figure-of-merit (FOM). Their thermal conductivity then becomes an important parameter which determines strategy for heat management of the devices. Debye-approximated relaxation time approximation (RTA) model as an excellent tool for understanding thermal conductivity, has been widely applied so far.[1] The use of fitting variables with the simplification for phonon parameters is the greatest weakness of the model. In this study, we apply RTA model without using the Debye approximation for thermal conductivity calculations in (Al)GaN. This study requires accurate phonon parameters including phonon dispersion, group velocity, and mode Grüneisen parameters of acoustic and optical modes, which can be achieved via first-principles calculations. We show that this approach is capable of predicting the thermal conductivity and heat transport properties of materials. Our values agree very well with the results from the first-principles BTE calculations and experimental data.[2] Furthermore, the role of various defects to thermal conductivity degradation could be well described by the model.

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Polarity control and crystalline quality improvement of N-polar GaN on SiC (000-1)

Hengfang Zhang,[1,*] Alexis Papamichail,[1] Ingemar Persson,[2] Per Persson,[2] Plamen P. Paskov,[1] Jr-Tai Chen[1,3] and Vanya Darakchieva[1,4]

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N-polar high electron mobility transistors offer improved two-dimensional electron gas confinement, better dynamic performance and reduced resistance of ohmic contacts in comparison to Ga-polar devices.[1-3] The main challenge is to control polarity and avoid the formation of polarity inversion domains, as well as to obtain N-polar layers with high crystalline quality and low surface roughness.

In this work, we demonstrate hot-wall MOCVD epitaxy of N-polar GaN/AlN structures on SiC (000-1) where polarity control is achieved via a combination of reduced supersaturation and use of off-cut substrates. Comparison between layers grown on off-cut substrates of different degrees towards m- and a-planes are presented and discussed. Finally, high-crystalline quality GaN/AlN structures with low root mean square surface roughness of 0.5 nm is demonstrated via a four-step temperature growth process.

References

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