EDS DL MQ: GaN HEMT Technology, Modeling, Applications

Holiday Inn Hotel Lodz, 229/231 Piotrkowska Street, June 22, 2016

Agenda

Time	Lecture
8.45-8.55	**Opening**
9.00-9.45	**Physics of III-N-based Field Effect Transistors**

Physics of III-N-based Field Effect Transistors

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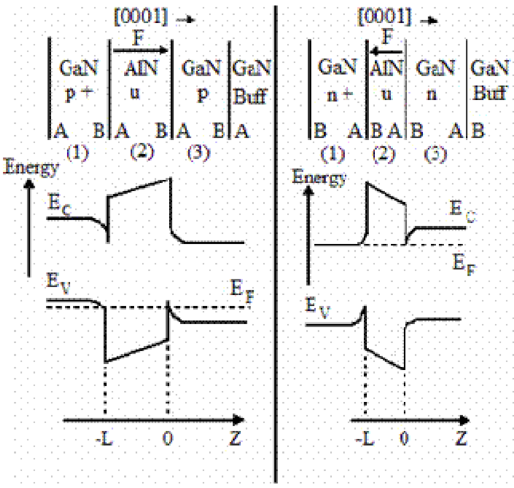
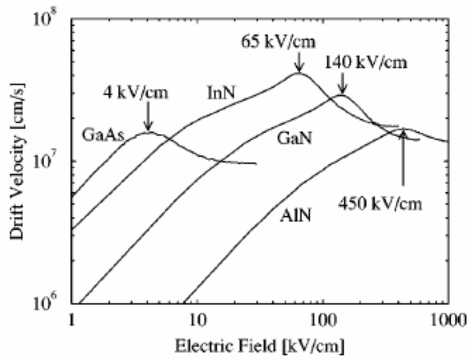
Abstract

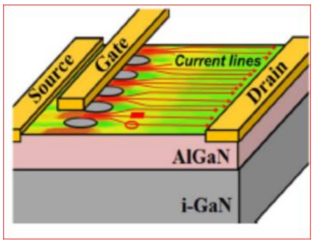
Wurtzite (hexagonal) symmetry makes the device physics of the GaN/AlN/InN heterostructure field effect transistors (HFETs) to be quite different from that of more conventional III-V and Si FETs. Spontaneous and piezoelectric polarization at AlGaN/GaN and AlGaInN/InGaN interfaces leads to the formation of a two-dimensional (2D) electron gas with concentrations up to $5x10^{13}$ cm^{-2}, much higher than those for more conventional FETs. High electric fields at the gate edges lead to an additional strain and hot electron effects causing the current collapse, gate lag, and reliability problems. Large electron densities in the HFET channels minimize the 1/f noise making it to be smaller than even in highly doped GaN films. The high electron density leads to a high frequency of plasma waves enabling THz detection and emission applications. High power handling capabilities make the thermal conductivity of a substrate to be a key factor for high power/high temperature performance. This device physics necessitates new approaches to the device design. Inverted HFET devices are expected to have a reduced access resistance, a larger current carrying capability, lower gate leakage and a better thermal control. Insulated gate heterostructure field effect transistors demonstrated superior performance and reliability. Field plates, recessed and double recessed gates, drain field controlled electrodes, and Low Conducting Layers (LCLs) control current collapse and improve the device reliability and reproducibility. Perforated channel designs minimize parasitics, improve heat removal, and decrease switching time. Power and RF switching applications of III-N based transistors take advantage of superior current carrying capabilities, low access resistance, and high breakdown voltage.



Polarization doping. Circles show 2D electron and hole gases. (From A. Bykhovski, B. Gelmont, and M. S. Shur, *J. Appl. Phys.* 74, 6734 (1993))



Electron velocities versus field. (from B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *J. Appl. Phys.* 85, 7727 (1999))



AlGaN/GaN Perforated channel HFET and simulated current spreading (From G. Simin, M. Islam, M. Gaevski, J. Deng, R. Gaska and M. Shur, Low RC-constant Perforated-Channel HFET, *IEEE Electron Device Letters*, 2014; 35(4) 449-451.)

9.55-10.40

Current status of wide bandgap device research from power system perspective

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Abstract

It is now well believed that silicon carbide (SiC) based power devices offer potential replacement to silicon counterparts on many fronts in high power electronic fields. Recently, SiC MOSFETs with discrete packages (e.g., TO-247 with single die) and in power module footprint where several parallel dies are sitting in parallel, are introduced in the commercial market by many vendors. Before realizing their true potential in the field, these devices should be assessed under various test conditions for their stability, robustness and reliability judgment. This talk will primarily focus on the diverse range of static and dynamic measurements performed for SiC devices. Furthermore, fresh results on compact modeling for 1.2 - 1.7 kV and with current ranging from 120 to 800 A for SiC-MOSFET modules will be presented and analyzed under various conditions to support the design of power converter circuits.

10.50-11.10

Coffee break

11.10-11.55

MOCVD epitaxy on bulk GaN substrates for HEMT RF application.

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Abstract

GaN based high-electron-mobility transistors (HEMTs) demonstrated excellent performance in terms of high power, high temperature and high frequency operation thanks to their wide bandgap, high breakdown voltage, high electron saturation velocity and high thermal conductivity. To get the ultimate quality of such devices, their structures should be grown on native GaN substrates. Unfortunately, due to limited availability and high costs of large GaN substrates most of high performance transistors are heteroepitaxially grown on SiC substrates.

AlGaN/GaN heterostructures grown on Silicon Carbide demonstrate important disadvantages originating mainly from lattice and thermal mismatches resulting in threading dislocations creation at the GaN/AlN/SiC interface. Moreover, there is an additional thermal resistance created at this interface, what limits significantly the heat dissipation rate in high power HEMT devices on SiC.
Further improvements of GaN-HEMTs towards their applications at higher temperatures, higher frequencies and with higher efficiency require defect-free structures without lattice- and thermal-mismatch.

In our work we developed HEMT growth process using Ammono-GaN semi-insulating substrates with record-high thermal conductivity of around 2.5W/m*K [1]. The proposed optimized growth of these structures consists in the following steps: i) four step buffer with carbon doped insulating layer, ii) AlGaN barrier with AlN insertion, and iii) low temperature MOCVD regrowth of highly n-type doped GaN and InGaN sub-contact layers.

The multi-step MOCVD GaN buffer growth allows for smooth cleaning of the substrate surface while maintaining its structural perfectness. The compensation control of second GaN layer enables formation of highly electrically resistive insulation thanks to residual carbon doping. Main, third part of GaN buffer provides additional spacing between transistor channel and GaN:C layer to minimize possible deep trapping effects which usually lead to current collapse under high electric field.. Optimized growth of GaN channel allows for very low carrier scattering within 2DEG. Next, the barrier part is grown, consisting of thin AlN-spacer to reduce alloy-scattering and AlGaN layer. Influence of surface states change can be further reduced by GaN capping or in-situ Si3N4 passivation. The HEMT structures have sharp interfaces and atomically smooth surface with AFM rms roughness equal to half of a monolayer value. Absence of threading dislocations in active area results in very low gate leakage current of the final device. Also no shunting path in buffer GaN was detected by temperature-dependent Hall measurement. In optimized HEMT structures we measured the following low field electrical properties of 2DEG at room temperature: n_s=1.44e13cm^{-2}, μ=1650cm^2/Vs, ρ=268Ω/sq, what is close to the AlGaN/GaN system limit.

Forming the ohmic contacts to low threading dislocation density structure, homoepitaxially grown on Ammono-GaN (TDD<5e4cm^{-2}), is very a very challenging task due to limited lateral diffusion during alloying metal stacks at high temperatures. However, low access resistance (<1Ωmm) should be created in reproducible manner, to take full advantage of this technology in high performance RF applications. Therefore, within

device processing-flow, we also developed low temperature MOCVD regrowth of highly n-type doped GaN and InGaN sub-contact layers. The small contact resistance in the range of 0.3-0.6 Ωmm was obtained for a nonalloyed metallization.

MOCVD epitaxy of HEMT structures using high quality bulk GaN semiinsulating substrates open new opportunities for improving the reliability of AlGaN/GaN devices. We may expect more power density load, reduction of device area, possibility of the operation in harsh environment, and improved radiation resistance in comparison to HEMT counterparts heteroepitaxially grown on SiC substrates.

[1] A. Jeżowski et all, Solid State Communication, 128, 2-3, 69 (2003)

12.05-12.50

Development of AlGaN/GaN High Electron Mobility Transistors on Semi-Insulating Ammono-GaN Substrates

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Abstract

AlGaN/GaN high electron mobility transistors (HEMTs) due to combination of excellent electrical parameters of III-N heterostructures (high mobility, saturation velocity and density of two dimensional electron gas in the channel along with high critical electric filed), are the choice for high frequency and high power microwave monolithic integrated circuits and devices. Up to now, AlGaN/GaN HEMT structures were grown mainly on semi-insulating silicon carbide substrates. Recently, ammonothermal growth of high quality, truly bulk semi-insulating gallium nitride substrates was developed by Ammono S.A. The Ammono-GaN substrates are characterized by low threading dislocation density of $1x10^4$ cm^{-2} and negligible wafer bow. What is more, homoepitaxial layers grown on these substrates have the same excellent crystalline quality and a very low surface roughness. Additionally, there is no thermal boundary resistance between GaN layers and the substrate. These advantages may lead to better reliability, radiation hardness, high yield and repeatability of the final devices.

In this talk we will present the latest results on the development of AlGaN/GaN HEMTs on semi-insulating Ammono-GaN substrates realized within the framework of PolHEMT project. Key technological steps will be discussed, in particular planar isolation using Al+ ion implantation and the fabrication of low resistivity regrown ohmic contacts to AlGaN/GaN HEMT structures on Ammono-GaN. By using optimized implantation parameters resistances of isolation region over 1×10^{14} Ω/□ were obtained. The ion implantation isolation was thermally stable up to 600°C. The ohmic contacts formed on highly doped regrown graded InGaN:Si,/GaN:Si subcontact layers yielded contact resistances typically in the range of 0.3-0.6 Ωmm. The DC electrical measurements of fabricated devices show high output current density of the order of 1000 mA/mm, a 220 mS/mm transconductance and a low 4.4 Ω/mm on-state resistance. Additionally, there was no sign of leakage current through the substrate or the buffer layers. The high frequency performance was evaluated by measuring the S-matrix elements over the frequency range 45 MHz to 24 GHz. For the devices with rectangular, 0.8 μm gate the maximum frequency (fmax) and cut-off frequency (fmax) were 30 GHz and 21 GHz. The insertion gain |S21| attains 0 dB for frequency (fs) of 22 GHz. The maximum available gain (MAG) and |S21| was 22.7 dB and 15.3 dB at 2GHz and 19.8 and 12.7 dB at 4 GHz. The extraction of equivalent circuit elements shows lack of any significant parasitic elements. We expect that the RF parameters can be further enhanced by applying optimized gate design and length.

ACKNOWLEDGEMENT:

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13.00-13.45

Terahertz Imaging With GaAs and GaN Plasma Field Effect Transistors Detectors Arrays

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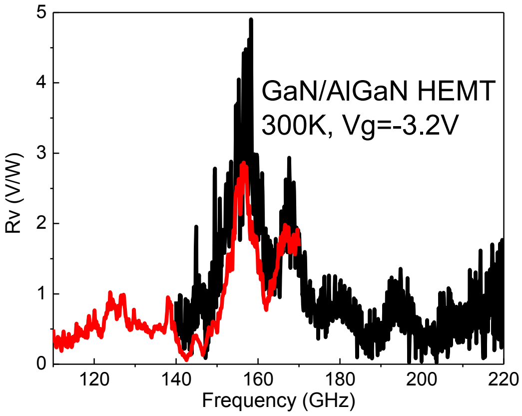
Short Abstract - An overview of main results concerning THz detection related to plasma nonlinearities in nanometer field effect transistors is presented. In particular nonlinearity and dynamic range of these detectors are discussed and two different technologies GaAs and GaN are compared. As a conclusion, we will show first real world applications of the FET THz detectors: demonstrators of the imagers developed for fast postal security and for nondestructive industrial quality control.

Abstract

We will present an overview of some recent results concerning THz detection related to plasma nonlinearities in nanometer field effect transistors [1, 2]. The subjects were selected in a way to show physics related limitations and advantages rather than purely technological or engineering improvements. We address the basic physics related problems like temperature dependence of the response [3], helicity sensitive detection [4] and nonlinear/saturation response at high incident power [5]. The results will be discussed in view of their application for terahertz imagers [6,7].

The possibility of the THz detection by FETs is due to nonlinearities of the plasma in the transistor. They lead to the rectification of the ac current induced by the incoming radiation. As a result, a photoresponse appears in the form of a dc voltage between source and drain which is proportional to the radiation intensity (photovoltaic effect). Example of the responsivity versus incoming radiation frequency for one of GaN/AlGaN transistors is shown in Fig.1. The antenna pattern was calculated to have responsivity at ~160GHz with ~20GHz bandwidth. Two colors/curves correspond to two bands of the THz spectrometer 110-170 GHz and 140-220GHz. The responsivity of the order of a few Volts per Watt was obtained.



Terahertz power dependence of the photoresponse of field effect transistors, operating at frequencies from 0.1 to 3 THz for incident radiation power density up to 100 kW/cm^2 was studied for Si metal–oxide–semiconductor field-effect transistors and InGaAs and GaN high electron mobility transistors [5]. The photoresponse increased linearly with increasing radiation intensity up to the kW/cm^2 range. Nonlinearity followed by saturation of the photoresponse was observed for all investigated field effect transistors for intensities above several kW/cm^2.The observed photoresponse nonlinearity is explained by the saturation of the transistor channel current. The theoretical model of terahertz field effect transistor photoresponse at high intensity was developed. The model explains quantitatively experimental data both in linear and nonlinear (saturation) range. Our results show that dynamic range of field effect transistors is very high and can extend over more than six orders of magnitudes of power densities (from ~ 0.5 mW/cm^2 to ~ 5 kW/cm^2). Comparison of different technologies show that GaN based transistors have the highest dynamic range.

The active THz scanning systems present on the market require THz radiation source with specially adapted optics. The first THz imaging systems were two axes raster scanning setups containing single point source and a single detector. They provided high quality images but the scanning time was relatively long, mainly limited by the speed of (XY) mechanical scanners. However, it appeared that to get the imaging speed acceptable for practical applications like postal security and on line nondestructive quality control so called linear scanners can be used. In these scanners the object moves on the transportation belt and the image is constructed line by line using linear multi-detector system. Recently diffractive elements that shape the illuminating divergent beam coming from the point-like source into a line segment in the given plane have been developed [6]. Together with a linear array of FET-THz detectors they allowed construction of a fast on line imaging system operating at 0.3 THz atmospheric window– fast postal scanner [7].

ACKNOWLEDGEMENTS:

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[1] W. Knap and M. Dyakonov, in Handbook of Terahertz Technology edited by D. Saeedkia (Woodhead Publishing, Waterloo, Canada, 2013), pp. 121-155.
[2] W. Knap, S. Rumyantsev, M. Vitiello, D. Coquillat, S. Blin, N. Dyakonova, M. Shur, F. Teppe, A. Tredicucci and T. Nagatsuma, Nanotechnology 24 (21), 214002-214002 (2013).
[3] O. A. Klimenko, W. Knap, B. Iniguez, D. Coquillat, Y. A. Mityagin, F. Teppe, N. Dyakonova, H. Videlier, D. But, F. Lime, J. Marczewski and K. Kucharski, J. Appl. Phys. 112 (1), 014506-014505 (2012).
[4] C. Drexler, N. Dyakonova, P. Olbrich, J. Karch, M. Schafberger, K. Karpierz, Y. Mityagin, M. B. Lifshits, F. Teppe, O. Klimenko, Y. M. Meziani, W. Knap and S. D. Ganichev, J. Appl. Phys. 111 (12), 124504-124506 (2012).
[5] D. B. But, C. Drexler, M. V. Sakhno, N. Dyakonova, O. Drachenko, F. F. Sizov, A. Gutin, S. D. Ganichev and W. Knap, J. Appl. Phys. 115 (16), 164514 (2014).
[6] J. Suszek, A. Siemion, M. S. Bieda, N. Blocki, D. Coquillat, G. Cywinski, E. Czerwinska, M. Doch, A. Kowalczyk, N. Palka, A. Sobczyk, P. Zagrajek, M. Zaremba, A. Kolodziejczyk, W. Knap and M. Sypek, IEEE Transactions on Terahertz Science and Technology 5 (2), 314-316 (2015).
[7] Mail scanner: http://www.orteh.pl/page/22/research-development

13.55-14.45 **Lunch**

14.45-15.30

Highly resistive GaN substrates obtained by ammonothermal method for microwave applications

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Abstract

Highly resistive bulk GaN substrates are demanded for microwave electronics and electronic devices operating at high power levels. Recently, a large interest has been dedicated to ammonothermal method, which is at present regarded as one of the key technologies for bulk GaN substrates manufacturing. It is regarded as an analogue of hydrothermal method, commonly used in industrial quartz production. In this method, GaN feedstock is dissolved in supercritical ammonia in one zone of high pressure autoclave, then transported to another one via convection, where crystallization on GaN seeds takes place due to supersaturation of the solution. The crystal growth proceeds in temperature range T=500-600°C and pressure p= 0.2-0.4 GPa. GaN crystals produced this way have very good structural properties, such as exceptionally low FWHM value of X-ray rocking curve (20 arcsec), large lattice curvature radius (R~100 m) and the lowest dislocation density (up to 10^4 cm^{-2}). First attempts to grow highly resistive GaN crystals resulted in homogeneous resistivity in the range $\rho \sim 5x10^{11}$ Ω cm ÷ $7x10^{11}$ Ω cm. Such resistivity was obtained by compensation of residual donors (of the concentration of 10^{19} cm^{-3}) by acceptors.

This communication presents the progress in ammonothermal growth and properties of truly bulk highly resistive GaN monocrystals, obtained by this method (in so-called ammonobasic regime). The progress in purity of such crystals will be emphasized. We decreased by about one order of magnitude the concentration of both donors and compenating acceptors. Two types of semi insulating material will be presented: 1) the substrates in which non-intentional oxygen donors are compensated by shallow Mg acceptors, 2) the ammonothermal GaN substrates doped with deep acceptors in form of transition metal ions. Both types of material show dielectric properties, with improved resistivity of at least 10^{11} Ωcm, being stable after annealing at 1100 °C. Extrapolation of high temperature dependence of resistivity gave room temperature resistivity of $8x10^{12}$ Ω cm in case of type-2) substrate. Taking advantage of scalability of ammonothermal method, successful growth of 2 inch highly resistive substrates has been accomplished. Such substrates are characterized by outstanding crystallographic quality (curvature radius are in the range of several tens of meters, dislocation density $2x10^4$ cm^{-2}). This will enable an efficient production of high-power, high-frequency devices, making use of GaN-based homoepitaxy.

ACKNOWLEDGEMENTS:

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15.40-16.25

Compact modeling of GaN HEMTs

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Abstract

A Quite Universal Circuit Simulator (Qucs), originally developed as an open source electronic circuit simulation program has become also an efficient tool supporting a compact modeling of novel solid-state devices. The software not only undertakes automatic synthesis of the C++ code based on Verilog-A, but also dynamically links it with the circuit simulator program core. Furthermore, Verilog-A synthesis based on circuit schematics has been implemented. A number of other useful features, like Equation Defined Device (EDD) objects or GNU Octave interfaces are available. Recently Qucs has been used as a platform for compact modeling of GaN HEMTs,

In the talk the following issues will be addressed:

1. A review of the GaN HEMT compact models;
2. A very short overview of Qucs compact modelling capabilities - this will include the new modelling features in Qucs-S_RC6;
3. Qucs modelling of a published EPC GaN SPICE device model + synthesis of Verilog-A code from model schematic; this will be illustrated by test simulation results;
4. Development of Qucs version of MVSGRF GaN model: problems due to ADMS, work-arounds and typical simulation results.

We hope that this presentation will be useful for the researchers and engineers actively involved in development, modeling and characterization of GaN HEMT devices.

16.35-17.20

FOSS TCAD/EDA tools for compact modeling and its Verilog-A standardization

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Abstract

Compact/SPICE models of circuit elements (passive, active, MEMS, RF) are essential to enable advanced IC design using nanoscaled semiconductor technologies. Compact/SPICE models are also a communication means between the semiconductor foundries and the IC design teams to share and exchange all engineering and design information. To explore all related interactions, we are discussing selected FOSS CAD tools along complete technology/design tool chain from nanascaled technology processes; thru the compact modeling; to advanced IC transistor level design support. New technology and device development will be illustrated by application examples of the FOSS TCAD tools: Cogenda TCAD and DEVSIM. Compact modeling will be highlighted by review topics related to its parameter extraction and standardization of the experimental and measurement data exchange formats. Finally, we will present two FOSS CAD simulation and design tools: ngspice, GnuCap, Xyce and Qucs. Application and use of these tools for advanced IC design (e.g. analog/RF IC applications) directly depends the quality of the compact models implementations in these tools as well as reliability of extracted models and generated libraries/PDKs. Discussing new model implementation into the FOSS CAD tools (ngspice and Qucs as well as others) we will also address an open question of the compact/SPICE model Verilog-A standardization. We hope that this presentation will be useful to all the researchers and engineers actively involved in the developing compact/SPICE models as well as designing the integrated circuits in particular at the transistor level and then trigger further discussion on the compact/SPICE model Verilog-A standardization and development supporting FOSS CAD tools.

17.30

Closing