

# Development of AlGaN/GaN HEMT Technology For Highest Frequency Operation: An Undergraduate Research Experience at the Forshungszentrum Jülich (Germany)

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*ABSTRACT: The ever increasing demand for high power, high frequency, and high temperature devices has prompted much research into AlGaN/GaN High Electron Mobility Transistors (HEMTs) because of their high breakdown voltage and excellent electron transit properties. Optimized AlGaN/GaN HEMTs promise to play a pivotal role in next generation mobile phone base stations, radar, mixers, oscillators, and attenuators in both commercial and military applications. This work characterizes the performance of AlGaN/GaN HEMTs on SiC in relation to source-gate spacing. Development of HEMT technology is explored utilizing T-gates and optimized ohmic contacts for improving the high frequency operation of future HEMT generations.*

*This research was conducted at the Forshungszentrum Julich by Mr. Wiliam Roman as part of the IREE program. This activity was part of the educational activities of the NationalNanotechnology InfrastructureNetwork, conducted to provide superior participants in the NNIN REU program with a second summer international research experience. Through this activity, NNIN seeks demonstrate to thses students that nanotechnology research is an international enterprise and that approaching their research careers with an international perspective is both beneficial and critical to their success.*

## INTRODUCTION

GaN HEMTs excel over competing technology for high power, high frequency applications. GaN HEMTs have an order of magnitude higher power density and higher efficiency over Si and GaAs transistors, allowing a ten time size reduction for the same output power, while simultaneously saving material cost. The wide band gap (3.4 eV) allows for rugged high-voltage, high-temperature application extensively covering both commercial and military markets. [1]

AlGaN/GaN HEMTs with varying source-gate spacing were fabricated using a standard technology process developed in our lab. HEMTs were characterized by their DC, I-V, C-V characteristics, Hall measurements, and High Frequency (HF) measurements. A hydrogen silsesquioxane (HSQ)/polymethyl methacrylate (PMMA) T-Gate process was then developed to increase the ft and fmax of the next generation HEMTs. Ohmic contacts with improved morphology and line edge definition after annealing were also investigated.

This international activity was carried out as part of the educational program of the National Nanotechnology Infrastructure Network, operated by Cornell University; This IREE award was a

supplement to the main Cooperative Agreement funding NNIN operations (ECS-0335765). Mr. William Roman was an undergraduate at the University of Rhode Island at the time of this program., having completed his Junior year in Electrical Engineering. He was resident in Julich from May 28 to Aug. 14, 2009. Mr. Roman was one of three students participating in this program.

## RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

In the transistor experiment, source resistance  $R_s$ , was decreased by aligning the gate closer to the source during the gate fabrication process step. As intended, the external transconductance  $g_{m,ext}$  increased with a decreasing source resistance (Figure 1).

Moving the gate from the drain towards the source increases gate-drain distance simultaneously. For a

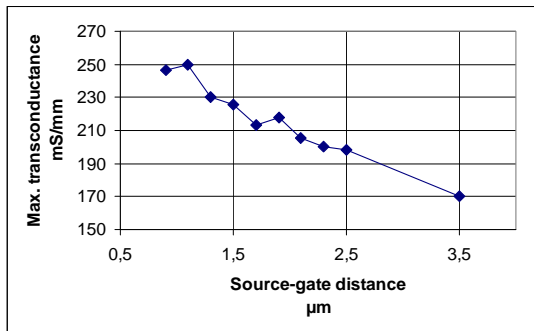


Figure 1: Maximum Transconductance

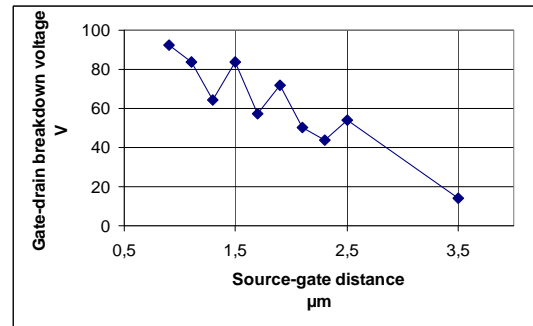


Figure 2:  $V_{gd}$  breakdown

HEMT, the largest potential difference can be found between the gate and the drain if a common bias point is considered. In this way an increased source-gate distance lowers the gate-drain breakdown voltage  $V_{gd,breakdown}$  (Figure 2).

Both results, extracted from DC measurement data, showed an improvement of the device regarding  $g_{m,ext}$  and the  $V_{gd,breakdown}$ . Cut-off frequency,  $f_t$ , increases inversely with gate-source capacitance,  $C_{gs}$ , and proportionally with  $g_{m,ext}$ . However, high frequency measurements do not exhibit an increase in  $f_t$  despite the lowered source resistance and higher  $g_{m,ext}$  (Figure 3). The reason for the decrease of both operating frequencies with a lowered source-gate distance is believed to result from more  $C_{gs}$  than  $g_{m,ext}$  increase.

A reproducible two-step e-beam T-Gate process was successfully developed (Figure 4) with HSQ/PMMA. An excellent gate foot width of 90 nm was achieved with experiments yielding good results down to 40nm. Future work will consist of gate recess etching in order to keep a reasonable aspect ratio of the HEMT gate

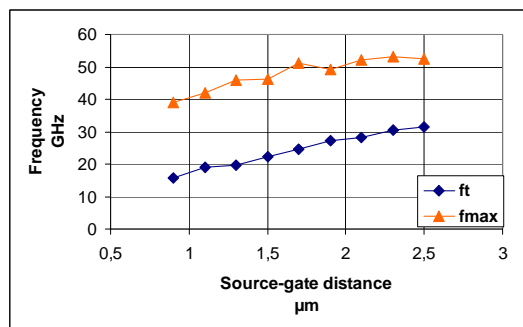


Figure 4: Maximum transit frequency ( $f_t$ ) and maximum frequency of oscillation ( $f_{max}$ )

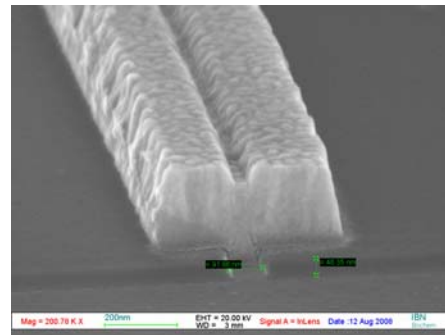


Figure 5: T-Gate with 90nm gate foot width, 46nm gate foot height, 250nm gate head height, and 490nm gate head width

structure.

Ti/Al/Mo/Au based ohmic contacts yielded better morphology and line edge definition after annealing than our previously optimized Ti/Al/Ni/Au contacts. In comparison to optimized contacts, Ti/Al/Mo/Au contacts had double the contact resistance ( $R_c = 1.2 \Omega/\text{mm}$ ) and resulted in an order of magnitude higher contact resistivity of about  $\rho_c = 3.82 \cdot 10^{-5} \Omega \cdot \text{cm}^2$ , indicating that more investigation of layer properties would be needed to lower resistance.

## BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

The specific goals of this program were to provide an advanced nanotechnology research experience in an international context and to use our talented undergraduates as a bridge to establish important international linkages from NNIN to partner international laboratories. This program builds upon the success of the NNIN REU program which provides introductory nanotechnology research experiences to approximately 70 talented students each year. The NNIN REU program was used as the sole feeder for this IREE effort; the best and most promising students from the prior year REU program were offered an opportunity for a 2<sup>nd</sup> year undergraduate research experience in an international environment. This was intended to serve the two fold purpose of reinforcing their interest in pursuing a nanotechnology research career and to provide these promising researchers with exposure to research in a global context at an early career stage. By selecting only the best students with whom we had already had a direct experience with, students who were well trained in our own REU program, we could place these students in an international program at a high level with confidence that they would represent themselves, NNIN, and the US well.

For this program, NNIN partnered with the laboratories of Herr Professor Ranier Waser, Director of the Institute for Solid State Research (IFF) and the Center for Nanoelectronics Systems (CNI) at the Forschungszentrum Jülich (Germany). The **Forschungszentrum Jülich GmbH (FZJ)** (*Jülich Research Centre Ltd.*) is a member of the Helmholtz-Gemeinschaft or Hermann von Helmholtz Association of National Research Centres (one of fifteen) and is one of the largest interdisciplinary research centres in Europe. FZJ employs more than 4,300 members of staff (2006) and works within the framework of the disciplines physics, chemistry, biology, medicine and engineering on the basic principles and applications in the areas of health, information, environment and energy. Jülich itself is a small town located in Federal state of North Rhine-Westphalia at the western edge of Germany, near Belgium and relatively close to the University at Aachen, RWTH.

This activity took place in the summer of 2007. Alice and the other participants were escorted to Germany by Julie Nucci, Ph.D., Director of Education Programs at the Center for Nanoscale Systems at Cornell. CNS is a related nanotechnology research effort with many ties to the Cornell Nanoscale Science and Technology Facility (CNF). Julie as a graduate student in CNF in the 1990s, and prior to returning to Cornell in 2007, was a member of the technical staff at the Max Planck Institute for Metals Research, Stuttgart, Germany for 10 years. She was thus excellently suited to escort the students and to introduce them to their German hosts and to daily life in Germany. Dr. Nucci returned to the US after one week. The students were in Germany for a total of 13 weeks, from late May to mid August.

The Jülich Forschungszentrum being centrally located in Europe near the intersection of Germany, Belgium, and The Netherlands attracts students and researchers from all over the world. The host institution is home to Europe's fastest super computer and a Nobel Prize physicist. Mr. Roman observes that, at first, the language barrier was difficult to get past in public settings, but he was able to pick up a few words and get past the fact that he could not simply read and understand everything. For the most part, while performing the research, interaction was primarily in English although some group members only spoke German.

Being in Europe and especially Germany in June for the the Euro Cup had a great cultural impact on Mr. Roman. Europeans love soccer and the country was literally dancing in the streets the night that Germany beat Turkey to go to the finals. Much German talk directed towards him also centered around Obama, questioning President Bush, and the ongoing presidential campaign. It was also interesting seeing Berlin's

welcome reaction to every event held in the city, which was displayed shortly after the public viewings of the Eurocup to the large turnout to hear Obama speak in Berlin a few weeks later.

Adjustment to German culture was abrupt because the students were suddenly immersed in a new place with different ways of doing things. Especially difficult to getting used to was the much earlier closing of stores, which were open no later than 8pm and were never open on Sundays. \

Because of the research center's location and reputation the IREE students had the opportunity to meet and interact and discuss views with people from many different countries including Belgium, France, Cameroon, Germany, India, Georgia, Ukraine, etc. They propelled this opportunity by organizing weekly cookouts every Friday where students at the guesthouse and those living in Jülich got together.

### **DISCUSSION AND SUMMARY (LIMIT: 1 PAGE)**

Analysis of standard technology fabricated transistors with varying source-gate distances was performed to establish a starting point of further investigations. A HSQ/PMMA T-gate process was successfully developed for next generation AlGaIn/GaN HEMTs. Currently, the T-gate process step is being integrated into the standard HEMT process with a gate recess etch, and gate dimension optimization to reduce Cgs and improve ft will follow soon thereafter. To allow automated e-beam T-Gate alignment, Ti/Al/Mo/Au e-beam markers with lower resistivity will also be further investigated.

For this IREE project, Mr. Roman researched High Frequency GaN HEMT transistors in Jülich, Germany at the Jülich Forschungszentrum. He was a member of Dr. Michel Marso's III-V and Nitride Devices Group and worked closely with Benjamin Strang on his Phd research of using a T-Gate process to achieve high frequency transistor operation. From a cultural perspective, researching at an internationally known research center allowed him to interact with and gain much insight from many international and German researchers alike. Through this experience, he learned a great deal about himself, performing well-planned research, and international culture.

As an international enrichment experience this program was also hugely successful for the three student participants. This program was largely successful for a number of reasons. First and foremost was the quality of the participating students. Since they had already participated in the NNIN REU program for one summer, the NNIN staff was able to select only the most talented and most mature participants. It is not enough to merely be scientifically talented; a successful experience requires the proper mixture of maturity and a sense of adventure, so that the maximum amount of the international aspects of science can be adsorbed. This program would not have been possible with students with no prior research experience. Furthermore, their known experience in the NNIN REU program gave us the confidence necessary to place them into a prestigious international research program in Germany, which would not have been possible with untested participants.

Secondly, it was successful due to the quality of the international partners and the projects supplied. FZJ is a large research organization, with a large number of visiting scientists from around the world. The cosmopolitan nature of the laboratories is critical; at least in the laboratory, language was not an issue since most people were conversant in English, as they only language that most of them had in common.

Mr. Roman and the other IREE students under this award were escorted to Germany by an NNIN staff member who had lived in Germany for many years and had worked in similar German national laboratories. She was able to help ease the students into the lifestyle and into executing daily activities without apprehension.

It was somewhat of a shock to the students that the labs work a strict 8-5, M-F schedule. While this was great for tourism and cultural acclimation, it put additional pressure on time management for research. The clean room opened at 8 am, and they needed to be there at 8 am, or it might reach capacity and they would be stuck on the outside. This is quite different from the model that they had become used to in the US and in the NNIN REU program.

FZJ had excellent support facilities, including a guest house. So, almost no effort needed to be expended by NNIN staff in arranging logistics. One downside, however, was the lack of internet access at the guest house. While they had access at the lab, they could not communicate to the NNIN office or elsewhere in the evenings.

In the end, the program was extremely successful, and was organized with a minimum of hassle on both ends. The students had successful projects and were thrilled with the experience. They were exposed in a real way that will have lasting career impact to the international dimensions of nanotechnology research. And our German partners were most pleased with the level of preparation, level of performance, and maturity of the student participants. Despite the fact that this was a one year IREE supplement, both parties have agreed to continue this exchange in coming years, using alternative funding arrangements.

### **ACKNOWLEDGEMENTS**

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We also acknowledge the support of Herr Professor Ranier Waser and Dr. Wolfgang Albrecht and their colleagues at the Institute for Solid State Research and the Center for Nanoelectronics Systems at the Forschungszentrum Jülich. In particular we thank Dr. Michel Marso for his guidance and his support of this particular research project.

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### **BRIEF BIOGRAPHIES OF RESEARCHERS**

**William Roman** is a undergraduate in Electrical Engineering at the University of Rhode Island. He expects to graduate in May 2010. Prior to the experience described in this report, Mr. Roman participated in the NNIN Research Experience for Undergraduates in the summer 2007 at the Georgia Tech NNIN site.

**Lynn Rathbun** received the BS in Physics from The Ohio State University in 1971, and an MS and PhD in Physics from the University of Illinois in 1973 and 1979 respectively. In 1979 he joined the newly established National Research and Resource Facility for Submicron Structures at Cornell University. Through the years, NRRFSS facility has evolved to the current Cornell Nanoscale Science and Technology Facility (CNF), and the user facility concept embodied in NRRFSS has evolved to the 14 site National Nanotechnology Infrastructure Network. Dr. Rathbun is currently both the Laboratory Manager for the Cornell Nanoscale Facility, and the Program Manager for the National Nanotechnology Infrastructure Network. As NNIN Program Manager he is responsible for directing a variety of network wide research and education programs, including this international undergraduate research program, at the 14 NNIN sites.

**Sandip Tiwari** is the Charles N. Mellowes Professor of Electrical Engineering at Cornell University. He received the Ph.D. in Electrical Engineering from Cornell University in 1980. Prior to returning to Cornell he was at IBM Research from 1982 to 1999. He served as Director of the Cornell Nanoscale Science and Technology Facility from 1999 to 2005. He is the Director of the National Nanotechnology Infrastructure Network, a position he has held since 1999.