

## APPENDIX B: EUROPEAN SITE REPORTS

Site: **DaimlerChrysler**  
**Ulm, GERMANY**

Date Visited: 9 June 1999

TTEC Attendees: J. Zavada (report author)

Hosts: Prof. Hermann Schumacher, University of Ulm  
Dr. Andrei Vescan, DaimlerChrysler  
Dr. Helmut Leier, DaimlerChrysler

### DAIMLERCHRYSLER

#### Introduction

DaimlerChrysler is a German-American company that was formed by the merger of two industrial giants, Daimler-Benz and Chrysler, in 1997. On Wednesday afternoon, Dr. Zavada met with Dr. Helmut Leier, who is director of the high frequency electronics department, and with Dr. Andrei Vescan, who is involved with research technology of III-V components.

Dr. Leier gave an overview of DaimlerChrysler and its research activities. The central research center employs about 1,800 people and sponsors nearly 500 students. Since the main activity of the company is automobiles, much of the research activities concentrate on cars and traffic.

There are three main areas of research: microelectronics and micro-systems; information and communications; and high frequency devices. Currently, most of the high frequency device work is based on GaAs. High power ( $> 1$  W/mm), high frequency ( $> 10$  GHz) HEMTs and MESFETs are being developed. The research on GaN is directed at extending the performance of the GaAs devices. Dr. Leier emphasized the importance of minimizing the cost while extending device performance. High power GaN devices will not make a major impact until fabrication costs are competitive with GaAs devices. Dr. Leier also mentioned that DaimlerChrysler is part owner, with Thomson-CSF, in United Monolithic Semiconductor (UMS). DaimlerChrysler acquires the GaAs wafers for high power devices from UMS.

#### III-V Components

Dr. Vescan gave Dr. Zavada a presentation on the research at DaimlerChrysler concerning high frequency, high power GaN-based devices. He said that DaimlerChrysler is not presently involved with growth of GaN films. SVT Associates, in the United States, is collaborating with DaimlerChrysler and currently provides the necessary films. The work at DaimlerChrysler centers on the design, processing, and fabrication of GaN-based devices. Dr. Vescan said that the optimum processing conditions are very dependent upon the source of the GaN films. These conditions can be determined only after repeated trials and device testing. The group at DaimlerChrysler has been working in close collaboration with Prof. Kohn at the University of Ulm on device properties of AlGaIn/GaN MODFETs (modulation doped field effect transistors).

#### Clean Room Facilities

Later in the afternoon, Dr. Leier and Dr. Vescan took Dr. Zavada on a tour of the clean room facilities at DaimlerChrysler. The clean rooms are similar to the ones at the University of Ulm; however, they are larger, measuring approximately 1,000 sq. meters. Some areas are class 100 and others are class 10. Following the merger of Daimler-Benz and Chrysler, half of the clean space was divided between DaimlerChrysler and UMS. I was only shown the DaimlerChrysler clean rooms. Still they comprise a first-rate facility for processing III-V materials.

Site: **High Pressure Research Center (Workshop)**  
**Polish Academy of Sciences**  
**Ul. Sokolowska 29/37**  
**01-142 Warsaw POLAND**  
**+48-226-32-5010**  
**www.unipress.waw.pl**

Date Visited: 10 June 1999

TTEC Attendees: S. DenBaars (report author), M. Shur, U. Varshney, G. White

Hosts: Dr. W. Porowski (HPRC)  
Dr. I. Grzegory (HPRC)  
L. Leszynski (HPRC)  
L. Dobrzauski (IEMT)  
W. Wolosinski (Warsaw Univ. of Tech.)  
A. Jelenski (IEMT)  
J. Szmidt (Warsaw Univ. of Tech)  
Dr. J. Weyher (HPRC)  
R. Beck (Warsaw Univ. of Tech.)

## BACKGROUND

A comprehensive workshop on GaN activities in Poland was held for the panel members at the High Pressure Research Center (HPRC) in Warsaw, Poland. This included groups from Warsaw University of Technology, the HPRC research group Unipress, and the Institute of Technology of Materials and Electronics (IEMT).

## TECHNOLOGY DISCUSSION

Dr. Porowski of Unipress hosted the meeting at the High Pressure Research Center and had also invited representatives of several of the other leading Polish research efforts in wide bandgap semiconductors to the workshop. Within Poland there are 14 research efforts developing GaN materials and devices. Recently the Polish government has approved funding of the large national project "Development of Blue Optoelectronics". This program will focus on blue lasers, solar blind detectors, and full-color industrial displays.

### GaN Bulk Substrate

Unipress is the research group within HPRC working on GaN bulk crystal growth from a melt. One of the most impressive achievements the panel saw in Europe was the "defect free" bulk GaN wafers grown from melt under extremely high pressure. Dr. Isabel Grzegory gave an overview of the high pressure solution growth method used for depositing the bulk single crystals.

The size of the substrates has steadily increased up to 1 cm in 1999 from 5 mm in 1997. In comparison to GaN on sapphire technology which exhibits  $1 \text{ E}+9 \text{ cm}^{-2}$  defect densities, or ELO films, which are in the  $1 \text{ E}+6 \text{ cm}^{-2}$  to  $5 \text{ E}+5 \text{ cm}^{-2}$  range, the bulk GaN crystals possess 10 to 1 defect per square centimeter. These densities were estimated from etch pit counts and correlated to TEM measurements of higher defect densities found on standard GaN sapphire technology.

The team was allowed to observe the bulk crystals under both optical microscopes and field emission SEM. Both n-type bulk crystals and semi-insulating bulk crystal have been grown. The semi-insulating substrates were highly resistive  $1 \text{ E}+5 \text{ ohm-cm}$  and could be used for thin film deposition of high power AlGaIn/GaN microwave amplifiers (Litwin-Staszewska et al. 1999). Very high quality homoepitaxial growth of GaN by MOCVD was obtained on top of these substrates and the films exhibited narrow double-crystal x-ray diffraction (DCXRD) linewidths as low as 21 arcsec. The group at University of Ulm, in collaboration with

Unipress, has obtained thin films that exhibit the narrowest reported PL linewidths at low temperature (0.1 meV)—which is indicative of the uniform high quality film (Komitzer et al. 1999). MBE has also been performed on the bulk crystals. Both Ga-face and N-face polarity bulk substrates have been produced. The bulk crystals also display extremely smooth cleaved facets with rms roughness of 5 angstroms, which would make excellent laser facets.

Unipress is also investigating high power HEMTs, Schottky diodes, and UV detectors. Using MOCVD AlGaIn/GaN materials have been grown with sheet carrier charge of  $1.2 \times 10^{12} \text{ cm}^{-2}$ . Large geometry, 1 micron gate length FETs have been fabricated and FET characteristics obtained. High quality Schottky contacts were obtained using Pd/Au metallization, which exhibited barrier heights of 0.8 eV.

## IEMT

Researchers at the Institute of Technology of Materials and Electronics are focusing on device fabrication and bulk growth of novel substrates. Panelists toured the facilities for fabricating laser diodes and detectors. Dr. Dobrzauski has already fabricated a GaN UV detector, which showed a peak responsivity at 364 nm. Numerous bulk crystal pullers were in operation. Also, a wide range of high quality optical bulk substrates was being grown such as: Si, GaAs, InP, ZnSe, YAG, LiGaO<sub>2</sub>, and LiAlO<sub>2</sub>. Large banks of UPS backup are needed to ensure safe operation in event of a power failure.

## REFERENCES

- Litwin-Staszewska, E., T. Suski, I. Grzegory, S. Porowski, J. Robert, D. Wasik, A. Witowski, D. Cote, and B. Clerjund. 1999. Electrical Properties of GaN Bulk Single Crystals Doped with Mg. Paper We-P082, Proceedings of Intl. Conf. on Nitride Semiconductors, Montpellier, France, pg 124.
- Kornitzer, K., T. Ebner, M. Grehl, K. Thonke, R. Sauer, C. Kirchner, V. Schwelger, M. Kamp, M. Leszczynski, I. Grzegory, S. Porowski. 1999. High Resolution PL and Reflectance Spectra of Homoepitaxial GaN Layers. Paper Tu-17, Proceedings of Intl. Conf. on Nitride Semiconductors, Montpellier, France, pg. 49

Site: **IMC, ABB, and KTH**  
**Electrum Building**  
**Kistagangen 15**  
**Kista, Stockholm, SWEDEN**

Date Visited: 11 June 1999

TTEC Attendees: T.P. Chow (report author), V. Dmitriev, M. Spencer, S. DenBaars, M. Shur,  
 U. Varshney, G. White

Hosts (IMC): Dr. Christopher Harris, SiC Project Manager  
 Dr. Meitek Bakowski  
 Dr. Andrey Konstantinov

Hosts (ABB): Dr. Heinz Lendenmann, Project Leader, Switch Development, SiC Project

Hosts (KTH): Dr. Mikael Oostling  
 Dr. Nils Nordell

## **IMC**

IMC is an applied research company that facilitates technology transfer from the research and development stage to prototyping and manufacturing. It has received both industrial (80%) and government (20%) support to enhance Swedish competitiveness. Recently, it has merged with IOF to form a new company called ACLEO.

IMC has mostly performed research in microelectronics and IOF on optoelectronics. The new company has a wide range of interests in both of these technical areas and has more European presence. IMC has locations in Kista and Linköping. The Linköping location focuses on interconnect and packaging of electronics and optoelectronics systems.

There are 53 employees in Kista and 27 in Linköping. The budget for 1998 was 85 million SEK (\$10.5 million) and 120 million SEK (\$15 million) for Kista and Linköping, respectively. It spins off one new company per year on the average. There is a high labor turnover rate (15-20% per year) with the average age of its employees being 34.

Dr. Harris indicated that the researchers in the Kista facility perform work in a variety of areas, including (a) radiation detectors (QWIP, bolometers), (b) optoelectronics, (c) SiC electronics, particularly power devices and (d) microsystem technology (microstructures, sensors). The wide bandgap semiconductor technology has mostly focused on SiC and the application areas are:

- power devices (development for ABB)
- microwave electronics (Ericsson)—high power amplifiers for base stations, 3 GHz, 100 W, entirely SiC so far, but expecting GaN to be applicable at higher frequencies
- high temperature electronics
- sensors, e.g., SiC as X-ray detectors, sensitivity close to human tissues

The highlights of specific technical activities are:

- numerical simulations and design—TMA software based
- portfolio of SiC specific process technologies
  - epi growth (Emcore and Epigress reactors, process support for Epigress)
  - ion implantation
  - dry etching (ECR etching)

- dielectric growth and deposition
- device and characterization
  - IV, CV, DLTS, Hall
  - optical
  - SEM/TEM/SPM

One example of the application of these process technologies in device fabrication is the demonstration of a 16 GHz ( $f_{\max}$ ) 4 H-SiC implanted-channel SiC MESFET. The gate width is 0.8  $\mu\text{m}$  with optical lithography and 2x smaller with e-beam lithography. A channel mobility of 200  $\text{cm}^2/\text{V}\cdot\text{s}$  has been achieved. Also, measurements of basic material properties of SiC are also performed as part of the Swedish National SiC Program (SiCEP).

Dr. Bakowski presented the high temperature electronics work. This area can be broadly categorized into two sub-areas:

- 200-300°C
  - integrated motor control
  - smart fuel pumps
  - brake by wire
- 400-800°C
  - combustion
  - geothermal

The multi-chip module (MCM) concepts that are devised for these two temperature ranges are different.

- 200-300°C
  - power electronics SiC
  - sensor SiC
  - control electronics Si SOI
- 400-800°C
  - power electronics, sensors, control electronics, all SiC

Besides active devices, high temperature passive components also need to be addressed.

Dr. Konstantinov presented the high temperature sensor research. One approach is to use high temperature gas-absorbing metal-gate MOSFET. Using a Pd gate, hydrocarbons ( $\text{CH}_x$ ) decompose after adsorption to the Pd and the resulting  $\text{H}^+$  ions diffuse to the interface, thereby shifting the barrier height. The advantages of using SiC are:

- high operating temperature (e.g., engine exhaust at 600°C)
- fast operation

Other devices that can also be used are MOS capacitors, metal-semiconductor diodes (I-V shift) and MESFETs.

For automotive applications, compared to the conventional Lambda sensor which utilizes a thick Zr layer, the gas-sensor SiC MOSFET developed at IMC offers much faster feedback so that adjustment to each engine cylinder can be made. The salient features of this SiC MOSFET are:

- buried channel
- low threshold voltage
- high temperature operation (17 hrs at 600°C so far)
- high gas response

The goals of this program are:

- long term stability at 600°C
- sensitivity to exhaust products other than hydrocarbons
- electronic noses (MOSFET sensor arrays)

Different metal gates may be used to sense different gas products.

The panel was given a facility tour of the clean room area that is on the ground floor and where all the microelectronics device processing facilities of the three institutions are housed, though separately. The ABB facility includes a high-energy (3 MeV) ion implanter that has a heated end station and a laser direct write aligner. IMC processes a large variety of compound semiconductors for several applications (such as solar cells and optoelectronics). These facilities are very impressive and world-class.

## **ABB**

ABB is a large international industrial company that has a major presence in power generation, transmission and distribution. It was instrumental in getting the SiC program started in Sweden in 1988 and has sponsored many programs in developing the SiC infrastructure in Sweden.

Dr. Lendenmann presented an overview of the ABB businesses and elements of the SiC device program. The power generation plants include hydro, “clean coal,” nuclear power and fuel gas cleaning types. ABB is very focused in getting SiC devices into power electronics systems. For example, for a 1-5 MW industrial converter system, it is estimated that Si device replacement with SiC can reduce the size by 1/3. Significant improvement in HVDC system is also projected with SiC devices, with the goal of 50 MW plant in 300 m<sup>2</sup> area.

A 3.5 kV, 200 A 4 H-SiC pin junction rectifier was presented. The diode structure consists of a deep boron junction for good junction leakage and a shallow aluminum implant topped with a p+ epi regrown region for optimal contact resistivity. A multiple-zone boron-implanted JTE has been used for junction termination, in conjunction with a SiN/polyimide over the field oxide as the passivation layer. A phosphorus-implanted n+ region was used as channel stop. Sensitivity analysis between device on-state voltage ( $V_F < 4$  V) vs. epi thickness has been shown for correlation. The leakage current density for diodes with three different areas was shown, with the largest device (7 x 7 mm<sup>2</sup>) size having a value of less than 10<sup>-5</sup> A/cm<sup>2</sup>, the best value to date for large-area devices. Dynamic switching of 150 A to 800 V with a dI/dt > 200 V/μsec results in an  $I_{RP} < 0.2 I_F$ . The goal is to first implement SiC diodes with Si IGBT, with the implementation of SiC three-terminal switching devices later. Actually, they project that at higher frequencies, the Si IGBT will be thermally limited. At present, there is no GaN work at ABB.

In summary, ABB focuses on the system application and leverage of SiC devices and is perhaps most advanced in the world in incorporating SiC devices into power electronics systems.

## **ROYAL INSTITUTE OF TECHNOLOGY (KTH – KUNGL TEKNISKA HOGSKOLAN)**

Prof. Oostling presented his work on semiconductor devices, including heterojunction SiC HBT with GaN emitter. Prof. Oostling collaborates with many researchers around the world. The SiC/GaN HBT consists of 10<sup>18</sup> cm<sup>-3</sup> SiC p-base, over which a n+ GaN emitter was grown by MBE. The p-base thickness can be either optimized for high-voltage power (1 μm) or microwave power (optimized for 2 GHz). The device work is largely supported by SiC EP program of the Swedish government. The heterojunction GaN/SiC diode has been improving, reaching a low value of  $I_R \sim 10^{-4}$  A/cm<sup>2</sup> at -50V, which is close to ideal. SiC MISFET with MBE grown 17 nm AlN has also been fabricated. The device is functional but the gate is still leaky. Prof. Oostling is well known for his contact work on SiC. TiC formation with CoSi<sub>2</sub>/Ti bilayer after 900°C anneal leads to a low contact resistivity (10<sup>-6</sup> Ω-cm<sup>2</sup>) on p-type, 10<sup>19</sup> cm<sup>-3</sup> doped epi of 6H-SiC. He is also exploring epi TiC layer on SiC that can be formed at 500°C or lower.

Dr. Nordell presented the clean room organization, funding structure and the various programs that utilize the facilities.

### **Addendum: High Temperature Packaging Capability (George White)**

Dr. Chris Harris indicated to us that most of the packaging efforts for IMC were being conducted in Linköping. However, the effort there is focused primarily on Si multi-chip modules. There they have demonstrated a 3" x 2" compact computing module which consists of a processor and memory chips.

Dr. Vladimir Dmitriev introduced us to Dr. Roumen Kakanakov of the Institute of Applied Physics of Plovdiv, Bulgaria. Dr. Kakanakov, who by chance was working at the offices of IMC during our visit, is a leading authority on high temperature packaging. He has started a small company, called "\_\_\_\_\_" which is doing R&D in microelectronics, optoelectronics and sensor semiconductor devices, on Si, GaAs and SiC substrates. Their expertise is in the field of ohmic contacts and packaging. Unfortunately, we were unable to meet with Dr. Kakanakov for any useful length of time, but we subsequently communicated with him via telephone and e-mail. Below is a summary of the conversation and correspondence with Dr. Kakanakov.

In our evaluation of high temperature electronics in Europe, there were very few programs associated with packaging of components for temperatures above 300°C. Therefore, Dr. Kakanakov was asked to comment on a number of questions. Below is a summary of his responses.

Q: What plans are in place to package SiC and GaN devices at temperatures above 300°C ?

A: The problems of high temperature electronics packaging were addressed through European project CP 94063 "Contacts encapsulants and packaging for high temperatures silicon carbide microelectronics", where Kakanakov et al. were responsible for:

- development and manufacture of high temperature packages for power SiC MESFET'S (300-350°C)
- R&D work on packaging processes for SiC chips, which involved the choice of SiC back side metallization, high temperature attach material and chip attachment process to the package—all of which contribute to device reliability at high temperatures (300-350°C)
- evaluation of the reliability of the SiC MESFETs and the packaging process during a 350°C storage test
- measurement of thermal resistance ( $R_{th}$ ) and its behavior during the storage test

After completion of this project in 1997, Kakanakov continued to make a small series of packages for power SiC MESFETs from Thomson-CSF. In early 1999, work began on the NATO project "High Power and High Frequency Devices on LPE-Grown SiC Films", where the packaging group was responsible for R&D of packages and packaging of power SiC diodes. It was also indicated that Kakanakov may have the possibility to get involved in packaging of GaN/SiC HBTs for this project.

An important element in the packaging of high temperature electronics is the base substrate material and attach material. Kakanakov was asked to comment on his work in this area.

As a material for the package base plate, Kakanakov chose a Mo-Cu alloy because of its high electrical and thermo conductivity, and good mechanical properties at high temperatures. Two gold based alloy materials were used as attach materials. The attach materials were gold based alloys of Au (6%) and Si, and Au (12%). The 6% alloy has a melting point of 373°C, and the 12% alloy melts at 363°C. Eventually the group primarily concentrated on the first alloy as the attach material. The backside contact metallization that was used was Ti-Pt-Au on SiC. The advantage here was no change in thermal resistance during high temperature testing. However, Pt and Ti will dissolve in the Au/Si solder when it is liquidus, thereby indicating that more suitable barrier metallurgies will have to be identified at the temperature extremes. Gold wiring bonding is performed using a ball bonder from K&S when making connections from the chip to substrate. When asked about the packaging of passive components, Kakanakov indicated that in principle the same attach material

could be used to attach the passives, but they have no experience with attaching cermet components at high temperature.

From a reliability standpoint Kakanakov agrees that new reliability test equipment and methodologies may be needed for high temperature reliability assessment. Limited reliability data exist for some of their systems; however, some reliability studies were done using thermal resistance measurements. An important need for the advancement of high temperature electronics packaging will be the advent of reliability modeling and simulation.

Site: **Infineon Corporate Research (formerly Siemens AG)**  
**Siemens Munich Corporate Research Laboratory**  
**Otto-Hahn-Ring 6**  
**D-81-730 Munich GERMANY**  
**Tel: +49-89656-45230**  
**Fax: +49-89656-53294**

Date Visited: 9 June 1999

TTEC Attendees: S. DenBaars (report author), M. Shur, U. Varshney, J. Zavada, G. White

Hosts: Dr. Henning Reichert  
Dr. Walter Kellner  
Dr. Eckhard Wolfgang  
Dr. Peter Turkes

## **BACKGROUND**

The Siemens Munich Corporate Research Laboratory is the main research arm of Siemens' semiconductor business. Siemens has recently spun off Infineon Technologies which will be responsible for semiconductor components. Infineon and Osram also have a joint venture to develop GaN blue LEDs and solid-state white lighting using GaN based LEDs. Infineon has a large GaN on SiC LED fabrication facility at Regensburg, Germany. White LED products have recently been introduced by Osram under the trademarked name of TOPLED. In Munich the Central Research Laboratory is involved in GaN MBE (lead by Dr. Reichert), while the GaN optoelectronics effort at Regensburg is primarily using MOCVD.

## **TECHNOLOGY DISCUSSION**

Dr. W. Kellner gave a review of Infineon GaAs products and developments in electronics. As wide bandgap semiconductors may play a role in the microwave power electronic area, Dr. Kellner informed the panel of some recent developments in power electronics. Cellular phone base stations, radio links, and automotive radar are three large applications where semiconductor products are beginning to appear. The automotive radar application requires 77 GHz and only 20 mW; therefore GaAs products are most likely to be marketed first. In the cellular base station application very high powers of 20 to 100 Watts are required at frequencies above 2 GHz. It is unclear if GaN or SiC can address this market at this stage of development, but development on both materials is progressing.

The GaN molecular beam epitaxy (MBE) effort at Siemens was reviewed in detail by Dr. Henning Reichert. Currently the MBE effort is shifting its focus away from optoelectronics and is emphasizing the high microwave power electronic devices. However, Dr. Reichert recently carried out very good fundamental study of GaN and InGaN growth by MBE. P-type doping as high as  $1 \text{ E}+18 \text{ cm}^{-3}$  was achieved by MBE. This is important for low contact resistance to LEDs and lasers. A high growth rate of 1.4 microns/hr was achieved and mobilities as high as  $460 \text{ cm}^2/\text{V}\cdot\text{sec}$  by MBE growth of GaN on MOCVD GaN templates. An impressive study of InGaN growth yielded good PL as long as 540 nm. Recently single crystal InN was achieved at a growth temperature of  $400^\circ\text{C}$ . Dr. Reichert observes a thermal decomposition temperature of  $530^\circ\text{C}$  in MBE, which is close to the value obtained by Ombacher et al in 199???. P-type GaN studies indicate an activation energy of 150 meV. The future emphasis in the MBE lab will be on AlGaIn/GaN electronic devices and GaAsN for long wavelength lasers.

Siemens Corporate Research Laboratory also has a high temperature silicon electronics effort underway. Dr. Eckhard Wolfgang reviewed the status of silicon on insulator (SOI) and SiC technology at Siemens. SOI is the main material being developed, with SOI technology way ahead of other materials in terms of commercialization. Currently SOI is used for 8 kV thyristors and IGBT 3 kV with are used in railway tram. Eighteen modules are used for power switching of megawatts in railway systems. There is a small research

effort on investigating the new wide bandgap semiconductors (mainly SiC) for higher temperature operation. SiC is mainly being look at for high temperature applications. Currently, silicon is limited to operation temperatures below 200°C. Therefore SiC and GaN could play a role above 200°C. In automotive applications several areas have temperatures in which silicon based devices can be placed. These are in combustion, exhaust, on the engine, and mounted near the brakes. Even if wide bandgap semiconductors can operate at these temperatures, new packaging technology is needed to make devices stand-up to these harsh environments. In addition, reliability of 35 years before failure needs to be designed into the parts. Dr. Wolfgang concluded by saying that much work is needed before WBS can play a role in the high temperature automotive markets.

Pspice models for modeling power electronic devices are available on the web at [www.infineon.com](http://www.infineon.com).

Site: **Laboratoire d'Electronique de Technologie et d'Instrumentation (LETI)**

Date Visited: 7 June 1999

TTEC Attendees: M. Shur (report author)

Hosts: Dr. Serge Valette, Head of LETI programs  
 Dr. C. Brylinski, Thomson-CSF  
 Dr. Joly  
 Dr. J. Duboz  
 Dr. M. Deneville  
 Dr. H. Bergonzo

### LETI: THE LARGEST CLEAN ROOM IN EUROPE

LETI (Laboratoire d'Electronique de Technologie et d'Instrumentation) is one of France's largest research institutions. Nine hundred fifty people worked at LETI as of the end of 1998 (722 CEA personnel and 212 personnel of different affiliations, including 165 industrial researchers). LETI consists of five departments and several programs. Fig. 1 shows the organizational structure of LETI.

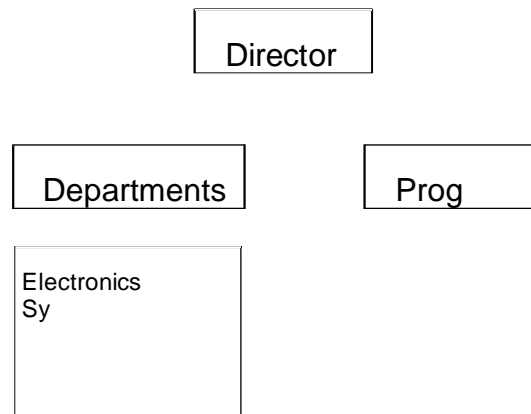


Fig. 1. LETI organizational structure.

LETI strongly emphasizes technology transfer. Feedback loops exist between LETI and French and European industry; LETI possesses hundreds of patents and encouraged spin-offs.

The largest efforts (by percent of total personnel involved) are in microelectronics (27%), defense (22%), nuclear electronics (13%), medical/biological electronics applications (8%), professional electronics (7%), information technology—hardware and software (7%), computer peripherals (6%), telecommunications (5%), and aerospace (5%).

Dr. Serge Valette, Head of LETI programs, described the LETI organizational chart and the major research thrusts. The areas of research and development include

#### Microelectronics

- CMOS 0.12 - 0.18
- SOI
- Single electron transistor

#### Microtechnologies

- Sensors

- MEMs
- Recording and displays (fluorescent tip displays)
- Silicon microwave power
- Packages and interconnects

### **Optoelectronics**

- Infrared photodetection (cooled and uncooled)
- Materials for optics

### **Microlasers**

- Laser induced damage threshold from UV to infrared
- Physico-chemical characterization of materials and thin films

### **Systems**

- Electronics for medical applications
- Medical imaging
- Biochip
- Information technology
- Nuclear instrumentation
- Sensors
- Organic components (polymers for optical applications)
- Organic LEDs and flat screens

## **SILICON-ON-INSULATOR**

Drs. B. Aspar and J. L. Pelloie presented the results of silicon-on-insulator (SOI) research at LETI. He described the Smart Cut® process and demonstrated that the quality of Si bonded using the Smart Cut® process is similar to that of the starting material. This technology is applicable not only to Si but also to GaAs-based materials and SiC. For silicon technology, SOI technology demonstrates a higher temperature performance.

## **SiC ACTIVITIES IN FRANCE**

Dr. C. Brylinski of Thomson-CSF reported on the results of SiC research in France. This is his summary of the status of SiC research in France:

- Crystals: research stage
- Wafers: started development
- Devices: started development
- Equipment: first demonstration

SiC epitaxy activity is primarily in LETI and in approximately 10 universities.

Funding sources include: CNRS, industry, and defense programs. SiC projects are divided into those that are part of national programs and those that are part of European programs.

Two national programs in SiC include "Saut Technologique", which is a three-year program (funded by the government and coordinated by industry, with industrial partners contributing some funding as well).

The European SiC program has a goal of achieving 3 inch wafers with no micropipes in three??? and to obtain a low defect density on 2 inch wafers (less than 10 micropipes per cm<sup>2</sup>). Under the auspices of this project, the French have teamed with a Swedish-Finnish company, Okmetic.

More detailed goals include cheaper and bigger crystals, lower defect density, the development of a SiC fabrication process compatible with a silicon line, the development of MOS and HBT devices.

Thomson-CSF is developing recessed SiC MESFETs. They fabricated modules with the total 14.4 mm gate periphery with four chips. For devices with wide gates (a few mm), the microwave power was on the order of 1 W/mm; for narrow gate devices, it was about 4 W/mm. The devices were operational up to 500°C in Copernicus package (AlCuMo frame package). In devices fabricated on semi-insulating SiC substrates, the current decreased with time and disappeared in approximately 100s. (Most likely this is a trapping program, most likely associated with vanadium.) The devices fabricated on conductive substrates did not exhibit this effect.

Dr. Joly described the bulk SiC material grown at LETI. The boule diameter was 50 mm. However, the material quality was inferior at the edges. They are using an Epigress two reactor system. The effort at LETI also includes the simulation of crystal growth. Best results achieved at LETI include 95 mohm cm,  $p = 10^{19} \text{ cm}^{-3}$ , 14% activation for  $10^{21} \text{ cm}^{-3}$  of Al acceptors. A p-n junction operated at 650°C. The junction depth was 220 nm.

There are two European projects dealing with SiC. The funding scale is on the order of one million dollars per year. The first project is called TECSICA. This project provided the basic research funding.

The participants are:

- T.U.B. Berlin
- UAB/CCM (Barcelona)
- Aristoyeles Univ. (Thessaloniki)
- F.O.R.T.H. (Crete)

Endorsers:

- Schlumberger (Clamart)
- C. S. GmbH (Munich)
- LETI (Grenoble)

The second project is called SICOIN. This is an industrial project. Its main goal is to develop a high temperature pressure sensor.

The participants are

- Daimler
- Schlumberger (Clamart)
- T.U.B Berlin
- Aristoyeles Univ. (Thessaloniki)
- Epichem

## **GaN-RELATED RESEARCH IN FRANCE**

Dr. J. Duboz gave an overview of GaN-related research in France.

- Lille: CNRS—Process, electronics
- Caen: CNRS and University—Crystallography
- Strasbourg: CNRS—Nonlinear optics

- Orsay: Thomson-CSF—Everything
- Clermond Ferran: University—Growth, optical
- Lyons: University—Optical
- Grenoble: CEA—Growth (MBE), optical
- Montpellier: ???—Growth (MOCVD), characterization)
- Valbonne: CNRS—Growth optical studies
- EEC project

ANISSET: Material oriented. Developed a commercial reactor (available from Riber). Also ECR source and thermal cracker

LAQUANI: Material and device oriented

- Nottingham, Madrid, Lausanne, CNRS (finished), EPFL
- Valbonne (finished)

RAINBOW: Multicolor LEDs and blue laser

- Thomson-CSF
- Philips
- Axion
- Epichem
- University of Seville
- Valbonne
- Erlangen
- Surrey
- Aveires

MIGHT: Material and device oriented high power, high frequency electronics ???/ HEMT 5 W, 10 GHz, - goals;

- GEC, Thomson-CSF
- Siemens
- Thomas Swan, Univ. Nottingham, Univ. of Gent

Started this year

Total budget 3-4 million Euro per project per year

Results:

Materials

- P doping  $5 \times 10^{17}$  (Valbonne, 3 MBE, 5 MOCVD), conductivity 1 ohm-cm
- InGaN bulk FWHM 50 meV at 10 K, 400 nm, Stokes shift < 30 meV
- InGaN QW FWHM 35 meV at 10 K
- GaN/AlGaIn QW FWHM 15 meV at 10 K

ELOG-HVPE

- GaN on Si (111) quality similar to sapphire

- GaN/AlGa<sub>N</sub> quantum dots: intense, large Stark effect (red PL)

#### Process:

- n-contact  $10^{-6}$  ohm  $\text{cm}^2$
- p-contact  $10^{-3}$  ohm  $\text{cm}^2$
- Etching: vertical facets by CAIBE and optically pumped laser

#### LEDs

- $< 1$  mW ???
- GWHM 15 nm at 235 nm
- High turn-on voltage

#### Laser

- Optical pumped

#### FETs

#### MESFETs

2 micron gate, breakdown  $\sim 300$  V, for a 0.3 micron gate,  $f_1 = 12$  GHz  $f_{\text{max}} = 25$  max  $I_{\text{dss}} = 330$  mA/mm

#### Photodetectors

#### Photoconductive

3000 A/W

UV-visible  $10^4$  to  $10^7$

1/f noise is large

Schottky photovoltaic on GaN

$n_s$  response

$10^{-8}$  A reverse current

Johnson noise low bias

$r_o$  A  $10^8$  W  $\text{cm}^2$

Schottky photovoltaic on AlGa<sub>N</sub>

Cutoff at 320 nm

4-year delay compared to US

Materials are catching up. Devices behind, except for photodetectors (state of the art)

### DIAMOND RESEARCH IN FRANCE

Drs. M. Deneville and P. H. Bergonzo discussed diamond research in France.

#### Applications

- window (microwave and laser)

- pressure sensors and SAW
- UV, V, X, and particle detectors

**Coating**

- Electrochemical reactions

p-n junction 900 °C

Schottky 700 °C

MESFET 500 °C

**Groups in France**

Window (microwave and laser)

Thomson, CEA in Bordeaux

LPL Paris

SAW (with AlN), Univ. Lens

Pressure sensors and SAW

Univ. of Nancy

UV, V, X, and particle detectors

Coating

University of Orleans

Electrochemical reactions:

LCTMR, CNRS

Basic research

Reactor modeling

Large monocrystalline substrates

Physical and electrical properties

Device

Schottky

MESFET

Surface studies

At LETI, they have grown 0.5 cm 250 micron diamond crystal film.

Site: **Russian GaN-based Research**  
Virtual Site Report

Date: 12 June 1999

Report Author: M. Shur

There is now a considerable and growing interest in GaN research in Russia. Fig. 2 shows the number of GaN-related papers at the All-Russian Conference on Nitrides of Gallium, Indium, and Aluminum: structures and devices—altogether, reaching approximately 90 participants in 1999.

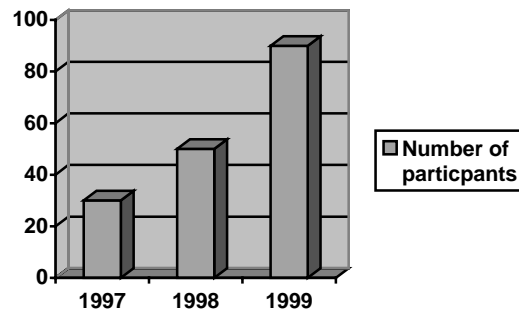


Fig. 2.

The Russian universities and research organizations involved include:

- A.F. Ioffe Institute of Physics and Technology of the Russian Academy of Sciences
- Lomonosov Moscow State University
- Lebedev Institute of Physics and Technology of the Russian Academy of Sciences
- GIREDMET
- NPVF "Svecha"
- Crystal Growth Research Center in St. Petersburg
- ELMA-MALAKHIT in Zelenograd
- Moscow Institute of Electronic Technology
- Institute of Physics and Chemistry of the Russian Academy of Sciences
- Moscow State Institute of Steel and Alloys
- St. Petersburg State Technical University
- Institute of Physical Chemistry of the Russian Academy of Sciences
- Institute of Crystallography of the Russian Academy of Sciences
- Institute of Nuclear Physics
- Sigma Plus in Moscow
- Baikov Institute of Metallurgy of the Russian Academy of Sciences
- "Polyprovodnikovye Pribory" in St. Petersburg
- "SAPHFIR" in Moscow
- Institute of Chemistry of Silicates in St. Petersburg
- Vologda State Technical University

- Udmurtsky State Technical University
- VNII of Optical and Physical Measurements in Moscow
- OPTEL in Moscow
- St. Petersburg Institute of Technology
- Frumkin Institute of Electrochemistry
- NITI "TEKHNOMSH" in Moscow
- MAR State Technical University in Iohskar-Ola.

### **INTERNATIONAL COLLABORATIONS**

Russian international collaborations include:

- TDI, Inc. in Gaithersburg, Maryland
- Howard University in Washington, DC
- Rensselaer Polytechnic Institute in Troy, NY
- Naval Research Laboratory in Washington, DC
- University of Ulm in Germany
- University of Karlsruhe in Germany
- Technical University of Berlin in Germany

### **RESEARCH AREAS**

The largest effort is at A.F. Ioffe Institute. The areas of research and development include:

- crystal growth (with emphasis on HVPE, MOCVD, MBE, and sputtering)
- fabrication and characterization of ion-implanted p-n junctions
- the development of production equipment (at ELMA-MALAKHIT)
- research on ternary and quaternary AlGaInAs solid state solutions
- investigations of basic materials properties
- growth and characterization of wurtzite and cubic BN
- research on GaN and InGaN based LEDs and optically pumped lasers
- white LEDs
- research on doping of GaN
- the development of GaN/GaP and GaN/Si heterostructures
- studies of piezoelectric properties
- the research on defects, studies of mechanical properties
- cathodoluminescence studies
- Raman and lattice dynamics studies
- applications of blue, green, orange, and red LEDs for materials testing
- studies of acoustic surface waves

### **APPLICATIONS**

The Russian company, SVECHA, has taken a lead in production of traffic signals using green GaN LEDs. They had the first installation of such traffic signals in Moscow in 1997. They are involved in the development of LED-based lighting for airplanes, of LED-based navigation lights, and lighting sources for

other applications. NII OPTEL is using imported green InGaN LEDs for river navigation lights. One blue LED is visible for two kilometers.

## **CONCLUSION**

The research level on devices is relatively small compared to the United States. Only two teams have demonstrated p-type GaN (Alferov's team by MOCVD and Dmitriev's team by HVPE). However, several excellent groups are involved in basic GaN research. Even at this level, there is a company pursuing practical applications (traffic lights) using imported GaN LEDs.

Site: **Siemens-Erlangen**  
**Paul-Gossen Str. 100**  
**D-91052 Erlangen GERMANY**

Date Visited: 8 June 1999

TTEC Attendees: T.P. Chow, (report author), V. Dmitriev, M. Spencer

Hosts: Dr. Dieter Stephani  
Dr. Roland Rupp  
Dr. Mitlener  
Dr. Peter Friedrichs

## INTRODUCTION

Siemens is an international industrial company that has major businesses in power generation, transmission and power electronics. There are significant technology development efforts in its research and development laboratory in Erlangen, involving SiC materials growth and processing, device design, fabrication and characterization and prototype device/circuit demonstrations. This group is expected to remain with Siemens after the Infineon spinoff, though some SiC team members have left to join the new company.

Dr. Stephani, who is the project leader, gave an overview of their SiC device program, emphasizing exclusively power electronics applications. The focus of their effort is to replace silicon power devices where SiC can offer better performance, including large-volume applications. There are about 20 people in their group, including epitaxial growth, device design, fabrication and characterization. Over the last few years, the researchers at Siemens have demonstrated many high-voltage power switching devices. They are clearly one of the top SiC device research groups in the world. The devices they have reported include:

- 600-1,200 V Schottky rectifiers
- 3,000 V (soon to be 5-6 kV) pin junction rectifiers in 4 H-SiC
- 1,800 V power DMOSFETs in 6 H-SiC
- high voltage JFET in 4 H-SiC (with a Si MOSFET gate driver)
- first 15 R-SiC MOSFET

They all have very impressive performance characteristics, such as specific on-resistance and short circuit capabilities. For example, 1,200 V 4 H-SiC Schottky diodes have a specific on-resistance of  $2 \text{ m}\Omega\text{cm}^2$ . Their vertical DMOSFETs have the lowest specific on-resistance of  $25 \text{ m}\Omega\text{cm}^2$  for an 1,800 V inversion mode SiC MOSFET. Actually, panelists were shown a hybrid package that incorporates the SiC JFEET and Si power MOSFET driver. Also, they have demonstrated the advantage of using 15 R polytype for MOSFET, instead of 4 H polytype (Schorner et al. 1999). The reason for this is that there apparently are few localized trap states near the conduction band edge in 15 R-SiC and, consequently, a much higher inversion electron mobility can be achieved than in 4 H-SiC ( $33$  vs.  $0.4 \text{ cm}^2/\text{V-s}$ ). Besides, while 6 H-SiC also has similar inversion electron mobility values, the anisotropy in bulk mobilities is much less in 15 R-SiC than in 6 H-SiC. Nevertheless, there is no 15 R-SiC commercial wafer supplier at present.

In summary, the SiC research performed in the Siemens group is extremely impressive due to its breadth and outstanding performance characteristics.

## REFERENCES

Schorner, R., P. Friedrichs, D. Peters, and D. Stephani. 1999. *IEEE Electron Device Letters*, vol. 20, pp. 241-244.

**University of Erlangen-Nurnberg**  
**Marenstrasse 7/ Institute Bld. V, Rm 368**  
**D 91058 Erlangen, Germany**  
**Tel: +49 9131 852 7634 or +49-91 31 852 8426**

Date Visited: 9 June 1999

TTEC Attendees M.G. Spencer (report author), T.P. Chow, V. Dmitriev

Hosts Dr. Dieter Hoffmann, Electronic Engineering Materials Group  
Prof. Gerhardt Pensel, Dept. of Physics  
Prof. Winnacker, Dept. of Physics  
Dr. Eckstein, SiCrystal

## INTRODUCTION

At the University of Erlangen the panel visited two separate departments. The first department was the Department of Materials Science and Engineering. This department forms part of the Technische Fakultat (Faculty of Engineering Sciences). The second group that we visited was a part of the traditional physics department of the university. Both groups were extremely active in materials growth and characterization of SiC.

## DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

In the Dept. of Materials Science and Engineering most of the work in wide bandgap technology is done in the Electronic Engineering Materials Group. Professor Winnacker gave an overview of the efforts in that group. Major topics under investigation were:

- bulk crystal growth of GaAs, InP and SiC
- modeling of the growth process
- development of phosphorus for blue light conversion

Dr. Dieter Hoffmann gave the panelists a detailed presentation on the research for the bulk growth of SiC. Most of this effort is supported by a research grant from Bavaria. This research grant, ~ \$1 million/year, has also supported SiCrystal in their effort to commercialize bulk crystal growth in Germany.

Dr. Eckstein of SiCrystal was present and gave a brief overview of the progress and direction of the company. During the talk by Dr. Hoffman he described efforts to understand the basic thermodynamics of bulk crystal growth and defect formation. Of special interest, micropipes and their formation and research results on formation mechanisms were presented. These topics are investigated experimentally in a sublimation reactor, which is currently growing 1.5" SiC boules. Theoretical modeling of heat transfer is closely linked to this effort.

Another technique for the production of bulk SiC is Liquid Phase Growth. The group in Erlangen and another group in Russia are unique in their efforts to investigate the possibility of large area growth of SiC by this technique. The Erlangen group is producing SiC at 2100°C and 150 torr of pressure. Under these conditions the growth rate is 0.6 mm/hr. The potential advantages of this technique include improved mass transfer and easier scaling.

Dr. Eckstein described SiCrystal, which was formed in August 1996. They are currently producing SiC principally for use in LED technology. This material is 2" in diameter. The company estimates that 90% of their market is based on nitride technology. They expect this number to decrease to 50% when manufacture of SiC based devices commences. When the demand for SiC material increases they will start production of 4" SiC.

**DEPARTMENT OF PHYSICS**

In the afternoon panelists met with Professor Pensel and Professor Helbig of the Dept. of Physics. In the Department of Physics there is significant activity on crystal growth and characterization. The specific topics were:

- bulk crystal growth—zero micropipes (6 H), 15 R polytype (in collaboration with Kyoto University)
- ion implantation—intrinsic defects, effects of non stoichiometry, diffusion (Boron)
- reconstruction of SiC surface
- MOS interface state density studies—admittance and constant capacitance DLTS

Most of the work is funded by the German Science Foundation. There is, however, no national program on SiC. The group does participate in a European program, which funds some of the ion implantation work.

In informal discussions with Professors Pensel and Helbig, they both agreed that 15 R had great potential for MOS applications. They indicated that in collaboration with Prof. Matsunami of Kyoto they had obtained inversion layer mobility of  $70 \text{ cm}^2/\text{V}\cdot\text{sec}$ .

Site: **University of Linköping**  
**Dept. of Physics and Measurement Technology**  
**IFM-FOA S-581 83 Linköping, Sweden**  
**Tel 46 13 8 1765 or 46 13 28 1797**

Date Visited: 10 June 1999

TTEC Attendees M.G. Spencer (report author), T.P. Chow, V. Dmitriev

Hosts Professor Bo Monemare  
Professor Erik Janzen

## INTRODUCTION

In Linköping the panel visited the Dept. of Physics and Measurement Technology. This organization employs over 350 people, including approximately 115 graduate students (who are government employees). The concentration in solid state physics and materials studies is broken down into several topics:

- materials physics—125 people
- thin film physics
- chemical physics
- surface physics—this where the sensor work is taking place
- theory group
- device modeling
- biology
- chemistry

The materials under study, ordered by research support, are:

- SiC—good support from several sources
- III/V nitrides /II-VI –III/ V nitride do not currently have local industrial support ???
- III/V quantum structures
- silicon and SiGe

In general the group at Linköping is interested in the studying the physics of the material topics are: ???

- Electronic Properties of Quantum Structures
- Electronic Properties of Defects
- Properties and Characterization of Epi and Bulk Material
- Bulk and Surface Band Structures

## SIC ACTIVITIES

Professor Janzen described the SiC activities, which involve two professors, 20 seniors???, 7 PhD students and 6 technical support staff. These activities receive funding from several sources:

### SiCep

This is a national program on SiC which provides a total of 18 million SEK of funding for SiC per year. Of that total Linköping receives 8 million SEK.

**Jesica**

Joint European SiC Activity: funding from this program totals one million SEK/year. This money is split with Okmetic, a wafer growth startup company.

**Okmetic**

A wafer growth startup company which is partnering with Grenoble to grow semi-insulating and n+ SiC.

**ABB**

Linkoping is in direct partnership with ABB (a major multi-national company) for development of materials growth processing and the basic understanding necessary to fabricate high voltage rectifiers.

**Other**

Linkoping receives about 3 million SEK from the Swedish Engineering Research Council (TFR), Science Research Council (NFR), and the Defense Department (FOA).

Looking in more detail at SiCep, the work is split as follows:

- technology (bulk growth, epi and defects)— 8 million SEK, Linkoping
- devices (power devices, high voltage diodes, high voltage switches)—KTH (KTH is also known as the Royal Institute)
- ion implantation, contacts—KTH
- dielectrics—Chambers

The SiCep program is funded by a private foundation (strategic research foundation???) with government interest or direction; the funds are only for universities. A separate foundation funds equipment.

The emphasis in Janzen's group is to provide a technology for high voltage devices. To that end they have developed high temperature epi for SiC and are using a variant of this technology for bulk crystal growth. The results for the high temperature epi are impressive. They have obtained a background doping of  $2-4 \times 10^{14} \text{cm}^{-3}$  with a growth rate of 40 microns per hour. For the HTCVD (as applied to bulk growth) they have achieved a growth rate 0.5 - 0.8 mm/hr.

**III/V Nitrides**

Professor Bo Monemare discussed the nitride efforts. The goal of the work is to measure the basic materials parameters. Professor Monemare feels that because the quality of the material is currently so poor all the basic measurements are suspect and need a second look. In an effort to obtain high quality material the group has decided to develop HVPE. The specific topics mentioned were:

- homo epi—HVPE
- thick epi—HVPE
- bulk GaN—high speed HVPE
- physics of AlGaIn/GaN and GaN/InGaIn multi quantum wells

**FACILITIES TOUR**

Panelists were shown the facilities at Linkoping. All the growth equipment was designed in collaboration with Epigress (a local equipment supplier). After development at Linkoping this equipment is available on the open market. The Linkoping facilities were about three years old and very impressive. All the equipment was "state of the art" and often brand new. The panel was told that the equipment was purchased with funds from a private foundation as indicated earlier in the report.

Site: **University of Ulm**  
**Albert-Einstein-Allee 45**  
**D-89081 Ulm, Germany**  
**Tel: +49-73150-26454-26050**  
**Fax: +49-73150-26454-26049**

Date Visited: 8 June 1999

TTEC Attendees: J. Zavada (report author), S. DenBaars, M. Shur, U. Varshney, G. White

Hosts: Dr. Markus Kamp  
Prof. Erhard Kohn  
Prof. Hermann Schumacher

## INTRODUCTION

At the University of Ulm, the panel visited the Department of Electron Devices and Circuits and the Department of Optoelectronics, each of which is headed by two professors.

Prof. Kohn, who is with the Department of Electronics and Circuits, gave the panel an overview of the University of Ulm. There are approximately 5,000 students at the university, which is only 30 years old. There are nearly 300 students in the Electrical Engineering Department. Only five students are involved with GaN research at present. However, there is a very active program in GaN materials growth, optical and electrical characterization, and device fabrication and testing.

## DEPARTMENT OF OPTOELECTRONICS

Professors K. Ebeling and P. Unger are the two professors in charge of Optoelectronics. Neither one was at the university during the panel's visit. Dr. Kamp gave the panel an overview of the research activities in this department. At present, the main areas of investigation are:

- vertical cavity surface emitting lasers (VCSELs) having low threshold currents
- optical interconnects for high data rate transmission
- high power laser diodes based on InAlGaAs compounds
- high brightness light emitting diodes (LEDs), which encompasses the GaN research

Dr. Kamp gave panelists a detailed presentation on the research on GaN LEDs and laser diodes. Most of this effort is supported by a research grant from state government and includes GaN growth, optical characterization, device fabrication and testing.

Initially, Dr. Kamp's group was using gas source molecular beam epitaxy (MBE) to synthesize the GaN layers. However, due to the unimpressive device results with this method, the group is now using chemical vapor deposition (CVD) to grow the GaN layers. Much improved optoelectronics devices have resulted using this approach.

The group has grown GaN LED structures on sapphire substrates and on GaN bulk crystals obtained from UNIPRESS in Poland. In general, GaN homoepitaxy leads to much improved optical characteristics. Photoluminescence (PL) taken at 20 K shows all of the relevant excitonic features and linewidths as narrow as 1 meV. The LEDs grown on GaN substrates are nearly twice as bright as the ones grown on sapphire. These results are similar to those found with LEDs grown on GaN lateral overgrowth epitaxy (LEO) substrates. In spite of the large reduction of dislocation defects in the GaN films, the LEDs only show a two-fold improvement in brightness.

Dr. Kamp also described efforts to develop GaN waveguide structures. The intent is to design and fabricate suitable laser structures and to produce a room temperature, cw laser.

## **DEPARTMENT OF ELECTRON DEVICES AND CIRCUITS**

Prof. E. Kohn and H. Schumacher are the two professors in charge of Electron Devices and Circuits. The main research activities in this department relating to GaN are electronic device modeling and characterization.

Prof. Hermann Schumacher's group is mainly involved in the modeling and device characterization of SiGe heterostructure bipolar transistors. This research is being done in close collaboration with Temic Semiconductors GmbH, which is a spin-off company of Siemens AG.

Prof. Schumacher gave a presentation on the advantages of SiGe devices for telecommunications. He described his research in exploring the performance potential of SiGe integrated circuit technology, at frequencies above 3 GHz, for front-end receivers.

Prof. Kohn gave the panel a detailed presentation on his research concerning electrical characterization of GaN-based devices. His group has been involved in the small and large signal dispersion analysis of AlGaIn/GaN MODFETs (modulation doped field effect transistors) and AlN/n-GaN FETs (field effect transistors). The device structures were grown by SVT Associates, in the United States, and processed into devices at DaimlerChrysler in Ulm. Their results indicate that the I-V characteristics of these devices change with heat treatment. A degradation of the I-V curves occurs after treatment at 600°C. These effects may be due to a materials problem (defects in the buffer layer) or to changes in the electrical contacts (surface charge).

Later Prof. Schumacher gave a tour of his labs for device characterization. These labs have also been used for the signal dispersion analysis of AlGaIn/GaN MODFETs done by Prof. Kohn's group. Some of the research concerning electrical characterization of GaN-based devices has not as yet been published.

## **CLEAN ROOM FACILITIES**

Later in the day, Dr. Kamp took the panel on a tour of the clean room facilities in the microelectronics technology center at the University. There is approximately 600 sq. meters of clean room space; some areas are class 100 and others are class 10. All the growth equipment was located in the center. There are a total of seven growth reactors for synthesis of different compound semiconductors. Currently, no synthesis of Si is being undertaken.

At present two Aixtron reactors are being used for GaN thin film growth, one for CVD and the other for hydride vapor phase epitaxy. Three other reactors are being used for growth of InAlGaAs compounds. One reactor is not presently in service.

