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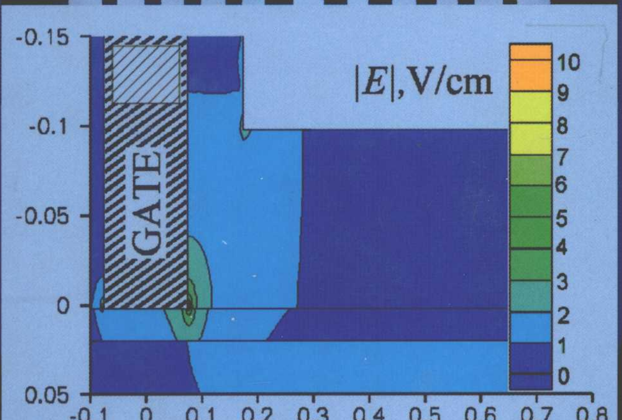
ADVANCED SEMICONDUCTOR DEVICES

Proceedings of the 2006 Lester Eastman Conference

Editors
Michael S. Shur
Paul Maki
James Kolodzey



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PREFACE

This volume contains Proceedings of the 2006 biennial Lester Eastman Conference (LEC), which was held on the Cornell University campus on August 2-4, 2006. Originally, the conference was known as the IEEE/Cornell University Conference on High Performance Devices. It was renamed Lester Eastman Conference (LEC) to honor Prof. Lester Eastman, a renowned device pioneer and leader, in 2002 and held at the University of Delaware. The next LEC was held at the RPI campus in 2004 before coming back to Cornell in 2006.

Professor Lester Eastman

Just after the conference, on the afternoon of Friday, August 4, 2006 a terrible tragedy cast a great sadness over the week's events. Mr. Navan Parthasarathy, a participant and a presenter at the LEC conference, had drowned in Fall Creek on Cornell Campus. He was a graduate student at the University of California, Santa Barbara. We dedicate the LEC-06 Proceeding to Mr. Navan Parthasarathy to honor his memory.

UCSB Ph.D. student
Navan Parthasarathy
Passed away on August 4, 2006

The Proceedings cover five emerging and traditional areas of advanced device technology: wide band gap devices, terahertz and millimeter waves, silicon and silicon-germanium devices, nanoelectronics and ballistic devices, and photoluminescence and photocapacitance characterization of advanced photonic and electronic devices.

The papers by M. Sugimoto et al. entitled "Wide-bandgap semiconductor devices for automotive applications" and by B. Green et al. "A GaN HFET device technology for wireless infrastructure applications" define existing and future applications of the wide band gap electronic devices and, hence, set the stage for many outstanding papers describing physics, chemistry, device design, fabrication, and modeling of these device.

Papers on terahertz and millimeter include papers describing terahertz emission and sensing (from the Delaware group), the paper from Marc Rodwell's group on new millimeter wave phase array architecture, and the paper on millimeter wave heterostructure diode.

Papers dealing with Si and SiGe technology cover new device designs, fast trapping devices, and SiGeC/Si IR photonics. It is interesting to compare the paper on SiGeC/Si IR photonic with Stiff-Roberts' paper on hybrid nanomaterials for IR photo detection.

A thought provoking paper from Lester Eastman's and Brian Ridley's group discusses ballistic electron acceleration and negative differential conductivity devices.

M. Wraback et al. describe how dependent time-resolved photoluminescence helps understand the physics of ultraviolet AlN/GaN/InN based emitters.

All in all, these proceedings will bring the reader to the forefront of advanced device technology.

The Editors would like to thank the authors, anonymous reviewers who were also the key contributors to the success of these proceeding.

The conference was under the technical sponsorship of the Institute of Electrical and Electronic Engineering (IEEE). We are grateful to the Air Force Office of Scientific Research (AFOSR), the Defense Advanced Projects Agency (DARPA) and the Office of Naval Research (ONR), The Northrop Grumman Corporation, and the Cornell University College of Engineering for their support of the Lester Eastman Conference 2006.

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Section I.
Wide Bandgap Devices

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WIDE-BANDGAP SEMICONDUCTOR DEVICES FOR AUTOMOTIVE APPLICATIONS

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In this paper, we discuss requirements of power devices for automotive applications, especially hybrid vehicles and the development of GaN power devices at Toyota. We fabricated AlGaN/GaN HEMTs and measured their characteristics. The maximum breakdown voltage was over 600V. The drain current with a gate width of 31mm was over 8A. A thermograph image of the HEMT under high current operation shows the AlGaN/GaN HEMT operated at more than 300°C. And we confirmed the operation of a vertical GaN device. All the results of the GaN HEMTs are really promising to realize high performance and small size inverters for future automobiles.

Keywords: GaN, HEMT, HV, inverter, normally-off, vertical device

1. Introduction

Development and improvement of hybrid vehicles (HVs), electric vehicles (EVs) and fuel cell hybrid vehicles (FCHVs) are now widely recognized as one of the solutions of the CO_2 problem of the earth and the exhaust gas problem of urban areas. These vehicles need high electric power inverters with high energy conversion efficiency. Si Insulated Gate Bipolar Transistors (Si-IGBTs) are widely used in the inverters, but these devices have a limitation of performance due to their material properties. Devices with higher performance have been strongly required for future vehicles. In this paper, we discuss requirements of automotive applications of wide-bandgap semiconductor devices, especially hybrid vehicles, and our development of GaN power devices.

Figure 1 shows the road map of the power density [1]. The power density has been increasing year after year. The inverters installed in Toyota's hybrid vehicles, such as Prius and RX400h have 3 times higher power densities than other applications as shown in the figure. However, HV and FCHV systems of the next generation will require much higher power densities with lower energy loss, smaller size and lower cost. It is difficult to realize such higher power density systems with Si-IGBTs, because of their material properties. Therefore, we should develop novel power devices made of new materials for these systems. Theoretical performance of several semiconductor materials are shown in Table 1, where wide-bandgap semiconductors clearly have advantages compared with Si. This is the big motivation for us to develop novel switching devices made of wide-bandgap semiconductors such as SiC and GaN.

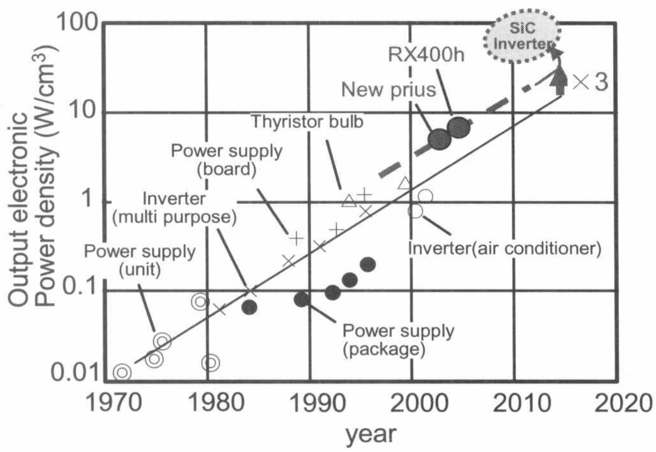

Fig.1 Road map of power density

Table 1. Normalized figures of merit of various semiconductors

	Si	GaAs	4H-SiC	GaN
JFM	1	11	410	790
KFM	1	0.45	5.1	1.8
BFM	1	28	290	910
BHFM	1	16	34	100

JFM : Johnson's figure of merit for high frequency devices $=(E_bV_s/2\pi)^2$

KFM : Keyes's figure of merit considering thermal limitation $=\kappa(E_bV_s/2\pi\varepsilon)^{1/2}$

BFM : Baliga's figure of merit for power switching $=emE_g^3$

BHFM: Baliga's figure of merit for high frequency power switching$=\mu E_b^2$

2. Requirements of Automotive Applications for Power Device in the Future

To realize the next generation hybrid systems, the following performance will be required for power devices in the future.

2.1. Normally-off operation

Most effort on GaN based devices has been directed toward normally-on ones, and only a few normally-off ones have been reported. In normally-off devices, the drain current does not flow at the gate voltage of 0V. Si-IGBTs used in the present inverters are normally-off operation devices. Likewise, a normally-off operation device is required for future automobiles in order to simplify the inverter circuit and make effective use of design techniques and mounting technologies for the inverters.

2.2. High breakdown voltage

Figure 2 shows the relationship between the motor power of Toyota's HVs and power source voltages of these systems. The first generation Prius was on the market in 1997. Through the inverter of this hybrid system, the battery voltage of 277V was directly connected to the motor. The new Prius has been on the market since 2003. In its HV system, the battery voltage is once raised to a power source voltage by a voltage booster and then supplied to the motor through the inverter. The raised voltage can take values from 202V of the battery up to a maximum of 500V [2]. The new Toyota's HVs need high motor power with high power source voltage as shown in Fig. 2. The breakdown voltage of devices used in these inverters is about 1.1kV [3]. The breakdown voltage of devices used in the inverters will probably become higher in the future due to protection against surge voltage and so on. On the other hand, A upper limit of the breakdown voltage of them may depend on the withstand voltage of condensers, discharge inception voltages between phases of the motors, etc.

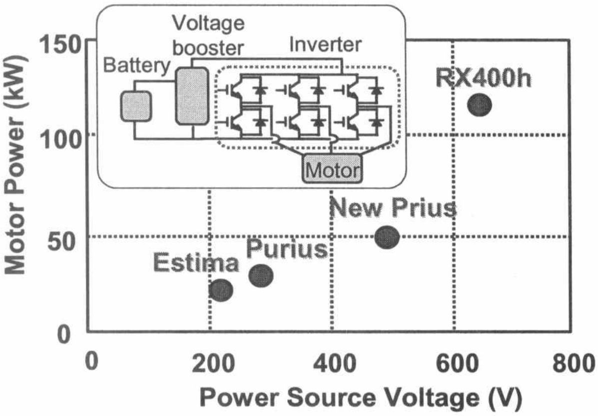

Fig.2 Power source voltage vs. motor power

2.3. Low on-resistance and high current density

In order to increase the energy conversion efficiency of inverter systems, it is necessary to decrease the on-resistance of the devices. Moreover, it is demanded for miniaturization of inverters to increase the current capacity up to several hundreds A/cm^2.

2.4. High temperature operation

Si devices stop working over 150°C, because a power loss increases due to an increase of a leakage current in the off state under high temperature envirronments. Whereas, GaN devices can probably work over 200°C, because the energy bandgap of GaN is wider than that of Si. The present hybrid systems have two cooling systems, one is for the engine and the other is for the inverter, and the temperature of coolant water for the inverter is lower than that for the engine. If GaN devices work over 200°C, the cooling system of hybrid vehicles will be simplified and its cost will be reduced.

2.5. Vertical operation

Up to date, most of efforts on development of GaN based devices have been directed toward lateral operation ones. However, vertical operation devices are demanded for automotive applications. First, vertical devices will meet the requirement of the above 3). Secondly, design techniques and mounting technologies developed for Si IGBT will be utilized effectively.

3. Our Development of GaN Power Devices

3.1. Normally-off operation

Studies of GaN based device have been mainly focused on the normally-on operation devices for microwave power applications, for example, the base station. Recently, a few normally-off operation GaN devices for power electronics applications have been reported, and the threshold voltages (Vth) of these devices are around +0.3V [4] [5]. However, no device with a high drain current and a very low on-resistance has been realized yet, because most of these devices are Schottky gate type. In the Schottky type devices, a current begins to flow drastically from the gate to the source at the gate voltage of around +2V. Therefore, it is impossible to control high current by the Schottky gate electrode. On the other hand, in case of insulated gate type devices, the higher voltage than around +2V can be applied to the gate electrodes. In order to realize the normally-off devices with the high current operation and the low on-resistance, the key issue is formation of gate insulator films with good quality. We investigated SiO_2 films formed by Low Pressure Chemical Vapor Deposition (LP-CVD) at a high temperature [6]. Results of the interface-state density calculated by the Terman method are shown in Fig. 3. The curve of the interface state density had two peaks at about -0.4eV and -0.7eV from

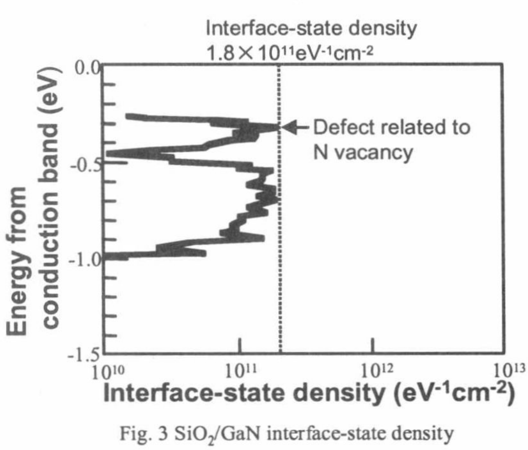

Fig. 3 SiO_2/GaN interface-state density the conduction band, and both of the interface state densities were about $2x10^{11}/cm^2eV$. We are developing normally-off devices using SiO_2 films. We will show some of their characteristics next.

3.2. High breakdown voltage

A GaN-HEMT with break down voltage of 1.3kV was reported in recent years [7]. We fabricated the insulated gate HEMTs, and measured the breakdown characteristics. Figure 4 shows the result of breakdown characteristic at the gate bias of -30V. The gate-drain length and the gate width of this device are 20μm and 440μm, respectively. The breakdown voltage was over 600V.

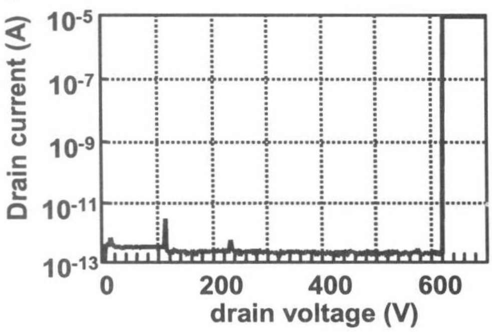

Fig. 4 Breakdown characteristics

3.3. Low on-resistance and high current operation

To examine a possibility of GaN power devices, we fabricated a large size GaN power HEMT with a gate width of 31 mm (Fig. 5), and verified a high current operation [6]. The drain current reached over 8A under pulse measurement (Fig.6). The specific on-resistance was about $5m\Omega\text{-}cm^2$.

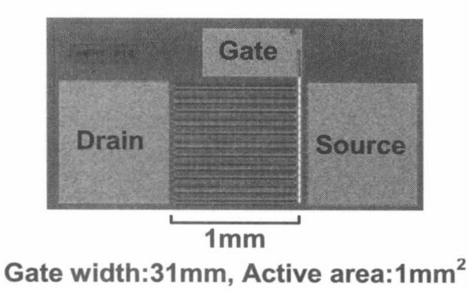

Fig. 5 Photograph of fabricated GaN-HEMT

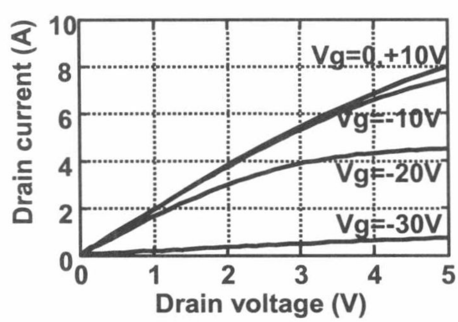

Fig. 6 I_D-V_D characteristics under pulse condition

3.4. High temperature operation

An observation on the device under high current operation with thermograph (Fig.7) showed the GaN HEMT operated at more than 300ºC [8]. The gate width and the chip