Challenges in the Automotive Application of GaN Power Switching Devices

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Abstract

GaN power devices are promising candidates for future application in vehicle electrification. Rapid progress in related material and device technology has been reported in the past decade. However, the chance of near-term implementation is still limited due to high cost and remaining technical challenges. This paper compares available GaN device technologies against automotive requirements, and discusses a few key difficulties hindering the adoption of GaN power electronics in automotive electric drive systems.

INTRODUCTION

High-voltage GaN power device research has gained momentum in recent years due to the superior material properties of GaN. Several critical advancements make its application prospect increasingly realistic, including the progress in native and GaN-on-Si substrates, development of normally-off gate structures, suppression of current collapse phenomenon, as well as demonstration of high voltage blocking capability. A highly attractive application for GaN power technology is the electric drive system used in hybrid electric vehicles. However, the stringent cost and reliability requirements of automotive components, together with a highly competitive silicon IGBT industry create barriers for the transition from silicon power electronics to a GaN-based one. In this study, we review the state-of-the-art technologies of GaN power transistors, and evaluate them against the automotive requirements on power devices.

TRACTION INVERTER IN HEV DRIVE SYSTEMS

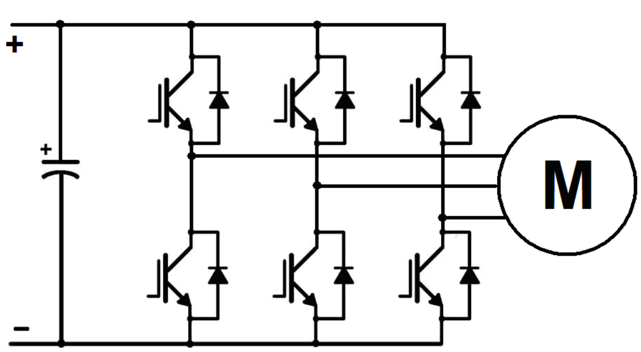

Figure 1 A three-phase power inverter circuit

In general, full HEVs today are equipped with at least one three-phase traction inverter circuit as shown in Fig. 1 to convert DC power from the high-voltage battery pack into AC form for motor drive. The input DC voltage is typically 300V~600V after an optional voltage booster stage. Six switch pairs consisting of silicon IGBT's and PiN diodes connected in anti-parallel fashion are configured in three phase legs. The voltage and current ratings for the silicon switches are in the range of 600V~1200V and 200A~600A, depending on the power rating. Each IGBT switch may be 1~3 cm^2 in die size (single or multiple dies). The cost of silicon devices is primarily dependent on the die areas, and is typically less than $10/$cm^2$. For GaN switching devices to compete with silicon in such applications, voltage blocking capability of at least 600V with single-die current rating of 100A or more would be required. The total semiconductor cost is also expected to be comparable to the silicon scenario, since the possible elimination of a separate cooling loop does not lower the system cost large enough to accommodate a substantial chip price hike.

SUBSTRATE CHOICES

Traditionally, most GaN devices are epitaxial grown by MOCVD or MBE on foreign materials, such as silicon carbide or sapphire. These structures have enjoyed great success in light emitting and high-speed electronic applications. However, for high power switching purposes, an ideal GaN structure would be formed vertically on native substrates where lattice and thermal mismatch is absent. Such vertical device constructions are also more suitable than lateral ones for high-current, high-voltage operation. [1]

The synthesis of GaN substrates by conventional Czochralski method is practically impossible. [2] Hence, HVPE and ammonothermal growth are the currently two major approaches in bulk GaN manufacturing. The wafer sizes are limited, and the price for a 2-inch substrate was reported to be about $5, 000 in 2010. [2] Although the cost per area of such substrates is expected to decrease as technology matures and volume increases, truly revolutionary breakthroughs would be required to make GaN native wafers feasible for automotive drive systems.

On the other hand, low-cost solutions for GaN-based power electronics systems have been actively investigated in the past 5 years. A key enabler of this concept is to grow GaN films on silicon substrates, which are widely available in large diameters and low cost. Although the mismatch between GaN and silicon lattices creates significant difficulties in epitaxial film growth, the promise of GaN performance at a cost comparable to silicon counterparts makes it a primary candidate of interest for the HEV application. This paper focuses on lateral GaN structures grown on silicon substrates, and discusses key issues that need to be addressed before such devices can be applied to HEV traction inverter systems.

Growth of Thick GaN on Large Silicon Wafers

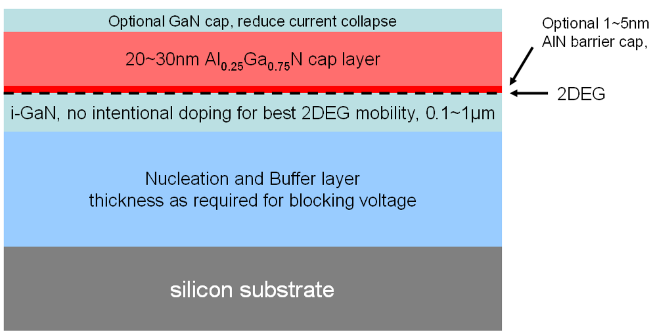

Figure 2 Epitaxial structure of a GaN-on-Si transistor

A typical epitaxial GaN transistor structure is shown in Fig. 2. The mismatch between silicon and GaN in both lattice constant and thermal coefficient of expansion causes threading dislocations and macroscopic film stresses, leading to wafer bow and cracks in the film. Currently, 6-inch silicon wafers have been shown to be feasible for nitride epitaxy with successful strain management. [3] However, for high-voltage devices, thicker epitaxial layers are required to support the voltage bias. For example, 300V/µm dependence is found between total epitaxial thickness and capable breakdown voltage in one report. [4] Together with large wafer sizes necessary for cost-effective microelectronic processing, the challenge in film stress control is compounded. Recently reported high voltage devices in the 1200V class are usually fabricated on smaller wafers of 4-inch or less. The feasibility of scaling such high-voltage devices up to 6-inch or larger wafers is yet to be verified.

In addition, the dislocation density of GaN epilayers on silicon (10^9~$10^{10}/cm^2$) is higher than GaN grown on native substrates ($10^5/cm^2$), and both are higher than silicon. It is under debate whether such defects will significantly degrade the power device performance over the long term and cause reliability issues or premature failure. Continued research is needed to ensure reliable, long-term device operation under harsh environments.

Normally-off Operation

To ensure system safety during gate drive failure events, the power switching transistors in motor drive systems are required to stay OFF at zero gate bias. Furthermore, modern silicon IGBT's in HEV inverters are designed with +5V or a higher gate threshold voltage (V_{th}) that leaves enough safety margin for noises. It is hence highly desired that next-generation power switches will inherit similar gate control characteristics for fail-safe purpose and compatibility with existing gate drive components.

Normally-off operation of GaN has been actively investigated in the recent years. However, achieving high V_{th} is still a serious challenge. Development in GaN switching transistors can be mainly categorized into four types: MOSFET, HEMT or HFET, hybrid MOS-HFET and GIT. The gate threshold voltages are determined by different principles for these structures. Normally-off MOSFET is usually not difficult to make, although V_{th} of GaN MOSFET seems not strongly affected by the depletion space charges under the gate, as in conventional silicon devices. However, GaN MOSFET is limited by the low field-effect mobility of channel electrons, and therefore has relatively high specific resistance. [5] The GIT structure developed by Panasonic features a p-AlGaN cap layer for gate electrode. [6] The p-AlGaN layer lifts up the energy potential at the AlGaN/GaN interface and depletes 2DEG to make the transistor normally off. The pn junction starts to turn on beyond 3V, and conductivity modulation occurs due to minority carrier injection from the gate. While positive V_{th} around 1V have been demonstrated for the GIT devices, further increasing it to 5V or so is not expected due to limitation of the pn junction potential.

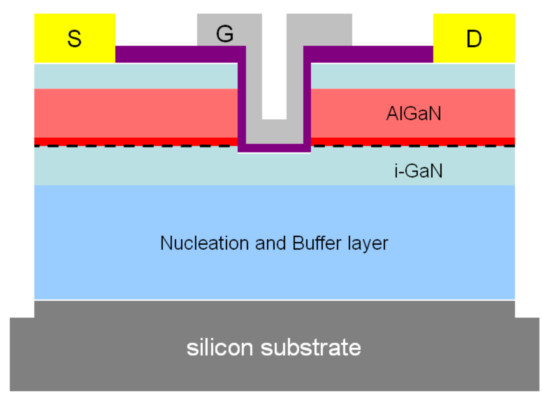

Figure 3 GaN hybrid MOS-HFET

HEMT and hybrid MOS-HFET are similar structures except for gate region treatment. In this paper, we use the HEMT term for AlGaN/GaN HFET structures without or with limited gate recess etch so that the AlGaN/GaN interface is not removed in the gate region. Hybrid MOS-

HFET specifically refers to those with deep gate recess etching into the underlying GaN layer, as shown in Fig. 3.

GaN HEMT structures are naturally conductive at zero gate bias due to large amount of 2DEG carriers formed under the AlGaN cap layer. Making them normally-off often involves a recess etching process and/or fluorine ion treatment in the gate region. Kanamura et. al. conducted a study on the gate recess approach and found strong and sensitive dependence of the recess etching depth and the gate threshold voltage. [7] While 3V V_{th} was demonstrated after 24nm of etching, the etched surface became extremely close to the 2DEG channel. Lacking a good etch stopper in the AlGaN layer, such an approach demands high-precision depth control that can result in very low manufacturing yield and wide spread in V_{th} distribution. An alternative method was developed by K. Chen and others by fluorine plasma treatment, implanting negative charges under the gate to dispel 2DEG carriers. [8] This procedure is more controllable with plasma power and treatment time, but its capability of delivering V_{th} higher than 1V and the long-term stability of F- ions are yet to be demonstrated.

The hybrid MOS-HFET is an interesting and promising structure combining normally-off gate characteristics of a MOSFET and the low-resistance drift region due to 2DEG. By deep etching through the AlGaN layer into GaN, relatively high V_{th} between 2~3V has been reported. [4] The hybrid structure is partially affected by the low field-effect mobility in the gate region, and therefore often shows higher specific resistance than devices without full AlGaN removal. While the V_{th} and specific resistance (R_{on_sp}) of such structures still needs further improvement, latest progress is encouraging with 7.1 mΩ·cm^2 R_{on_sp} measured on a 1200V device. Fig. 4 shows the R_{on_sp} vs. breakdown voltage performance chart of GaN transistors reported by leading research teams. Devices are grouped according to their V_{th}. It is seen that the V_{th} level is still too low for automotive application for the majority of these results.

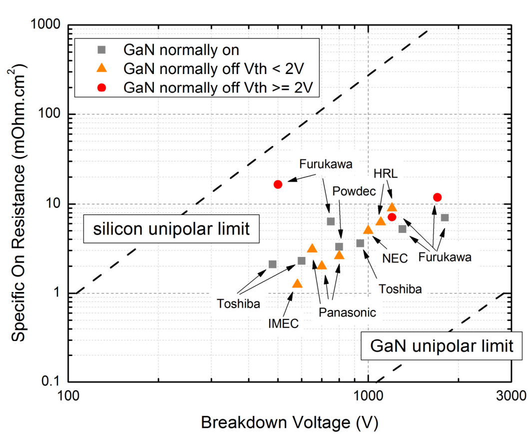

Figure 4 Performance chart of GaN power devices

CURRENT COLLAPSE

Current collapse is a frequently discussed problem for GaN devices and has been identified as a key disadvantage for lateral structures. [1] Multiple approaches have been reported to suppress this phenomenon, including optimized surface passivation (e.g. silicon nitride), GaN cap layer, and field plates. Recent studies show that this issue can be managed up to 600V or more. [9, 10] However, the breakdown voltages of these devices are often twice or more as high as the voltage demonstrated for current collapse control. Since the peak surface electric field plays a dominant role in the severity of this problem, which becomes stronger at high voltage bias, [11] it seems further optimization is still required to manage the issue up to the rated voltage of the switching device. Furthermore, long-term electron trapping and degradation of on resistance may not be detected by the conventional test method for dynamic R_{on}. These will however define failure criteria of the device in its qualification tests. We expect that significant effort is needed in physics understanding and structure optimization to fully eliminate the current collapse issue of GaN devices for high-voltage and long-term operation.

GATE DIELECTRIC

The successful commercialization of GaN-based RF devices provides an excellent platform for developing GaN power switching devices. However, the differences in the operation conditions dictate necessary structural changes between these two types of products. For example, traditional Schottky gates are generally not acceptable in high power application due to excessive leakage current. Unlike silicon or silicon carbide, GaN does not offer a high-quality native oxide as the gate insulator. Therefore commonly used insulation materials are by deposition, such as silicon nitride, aluminum oxide, and silicon dioxide. Key requirements for them are low leakage current, low interface charges, and long-term stability. The optimal gate insulator material and deposition conditions are under debate and this research seems still in its earlier stage.

CURRENT RATING AND SHORT-CIRCUIT CAPABILITY

The power requirements of automotive traction inverters translate into typical current ratings of 200~600A per semiconductor switch. Although connecting multiple silicon dies in parallel is common, a single die needs to be rated at least 100A practically. Up to date, no GaN high-voltage switches have been reported capable of such high current level with a forward voltage drop below 2V. Since lateral power devices require interdigitated electrodes at transistor level on the top surface, the limited current carrying capacity of these metal fingers introduces a scaling limitation for the die size. This is a fundamental challenge for lateral structures, which may be partially mitigated by optimized metallization strategy but not completely avoided.

Short-circuit withstand capability is another challenge that we are particularly concerned of from the application point of view. Unfortunately this is an area yet to be explored by the GaN researchers, and little data is available at this time for quantitative judgments. In traction inverter application, a short-circuit event occurs when the motor windings are accidentally shorted, subjecting the on-state power switch to high drain bias and pushing it into current saturation mode. Extreme power dissipation follows the event and the gate drive circuit must turn off the device promptly to protect it from catastrophic failure. The manufacturer's specification on short-circuit withstand capability is typically 10μs, which is dependent on the reaction speed of the gate drive circuit. Modern silicon IGBT's designed for low conduction loss and high-temperature operation (e.g. 175^{o}C) already face challenges for this short-circuit criterion. The expected capability of GaN lateral switches will only be more limited. The power dissipation density during short-circuit event is proportional to the electric field strength (E) and current density (J). GaN, as a wide bandgap material, will be designed according to its breakdown field strength for the drift region width. This leads to over ten times higher electric field in the drift region when high drain bias is applied, compared to the silicon counterpart. In addition, high surge current is concentrated at the AlGaN/GaN interface, instead of spread out in the bulk material in silicon vertical IGBT, triggering extremely localized heat dissipation. The saturation current for GaN devices may also be determined by 2DEG electron saturation velocity, a different mechanism from the MOSFET saturation for the IGBT that could indicate much higher short-circuit current amplitude. In light of these factors, plus the relatively low thermal conductivity of GaN, we suspect that the hot-spot temperature surge will be extremely fast in a short-circuit event, and GaN lateral power transistors will be seriously challenged by the short-circuit specification from automotive manufacturers. The solution to this problem will likely require development of advanced gate drive and protection circuits that reduce the required short-circuit withstand time for the device.

SUMMARY AND DISCUSSION

This paper presents a vision of Ford Motor Company on the potential application of GaN power devices in our next-generation electrified vehicles. We recognize the superior material properties of GaN and its suitability as power switching transistors. These properties not only promise lower conduction and switching losses than existing silicon devices, but also enable reduction in chip sizes and cost due to lower cooling demand. However, major technical challenges still limit the near-term implementation of GaN power electronics in automotive systems, as detailed in this paper specifically for lateral structures grown on silicon substrates. Vertical devices formed on native GaN wafers are not elaborated due to their high cost. It is anticipated that GaN researchers make breakthroughs in these aspects, and thereby prepare their devices for the stringent qualification process of automotive components.

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ACRONYMS

IGBT: Insulated Gate Bipolar Transistor
HEV: Hybrid Electric Vehicle
MOCVD: Metal-organic Chemical Vapor Deposition
MBE: Molecular Beam Epitaxy
HVPE: Hydride Vapor Phase Epitaxy
HEMT: High Electron Mobility Transistor
HFET: Heterojunction Field-effect Transistor
GIT: Gate Injection Transistor
2DEG: Two-dimensional Electron Gas