SiC, GaN And Si Power Semiconductors Received Special Attention At IEDM

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The IEEE International Electron Devices Meeting (IEDM) is considered the pre-eminent forum for reporting technological breakthroughs in the areas of semiconductor and electronic device technology, design, manufacturing, physics, and modeling. IEDM is the flagship conference for nanometer-scale CMOS transistor technology, advanced memory, displays, sensors, MEMS devices, novel quantum and nano-scale devices and phenomenology, optoelectronics, devices for power and energy harvesting, high-speed devices, as well as process technology and device modeling and simulation. The conference scope not only encompasses devices in silicon, compound and organic semiconductors, but also in emerging material systems.

At the 2014 edition of this conference held December 15 – 17 in San Francisco, power devices were among the topics receiving increased emphasis. Consequently there were numerous talks and presentations, some by luminaries in industry and academia, on research and development with direct relevance to power electronics. The power devices discussed at IEDM not only encompassed both silicon and compound semiconductors but also a wide range of voltage ratings to address even some of the highest-power applications. Several of these talks are highlighted here with the abstracts provided below.

"SiC MOSFET Development for Industrial Markets," opening plenary by John Palmour of Cree

SiC power devices have the ability to greatly outperform their silicon counterparts. SiC material quality and cost issues have largely been overcome, allowing SiC to start competing directly with more traditional Si devices. 150-mm substrates and epitaxy are now commercially available. Commercially released 4H-SiC MOSFETs with a specific on-resistance (Ron,s) of 5 mΩ·cm² for a 1200-V rating are now available, and research has further optimized the device design and fabrication processes to greatly expand the voltage ratings from 900 V up to 15 kV for a much wider range of high-power, high-frequency energy-conversion applications.

Performance for voltage ratings from 900 V up to 15 kV have been achieved with a Ron,s as low as 2.3 mΩ·cm² for a breakdown voltage (BV) of 1230 V and 900 V-rating, 2.7 mΩ·cm² for a BV of 1620 V and 1200 V-rating, 10.6 mΩ·cm² for a BV of 4160 V and 3300-V rating, 123 mΩ·cm² for a BV of 12 kV and 10 kV-rating, and 208 mΩ·cm² for a BV of 15.5 kV and 15 kV-rating. All of these devices exhibit very high frequency switching performance over silicon IGBTs. For even higher voltages, bipolar devices in SiC have been demonstrated from 15 kV up to 27 kV. SiC GTOs have been shown up to 22 kV with 200-A capability. SiC n-IGBTs are reported up to 27 kV, with 20-A capability. This is the highest-voltage semiconductor device reported to date.


If microprocessors are the brains of a circuit, then power semiconductors used to control electrical power—such as IGBTs—are the muscles. B. Jayant Baliga of North Carolina State University, inventor of the IGBT while at General Electric in the early 1980s, explained the ever-increasing role of power semiconductors as enablers of societal progress. At IEDM, he argued that IGBT technology has reduced gasoline consumption by 1 trillion (1x10¹²) gallons, and electricity consumption by more than 50,000 terawatt-hours over the past three decades. This corresponds to 75 trillion pounds of global carbon dioxide emissions reductions. He detailed the growing societal impact of power semiconductor devices, given the anticipated introduction in the next decade of new cost-competitive wide-bandgap semiconductor-based power devices.

"Progress in Ultrahigh-Voltage SiC Devices for Future Power Infrastructure," paper 2.5 by T. Kimoto et al, Kyoto University

There is an effort underway to develop more efficient and reliable "smart" power grids to replace existing electrical transmission and distribution systems, but smart grids require reliable high-voltage switches (>10 kV). Most silicon semiconductor switches can’t handle these high voltages. Silicon carbide (SiC) has 10X the breakdown voltage of silicon, but it’s more difficult to fabricate. Nonetheless, Kyoto University researchers were able to build three different types of ultra-high voltage power devices from SiC—PIN diodes, bipolar junction transistors and IGBTs—each of which exhibited outstanding performance. In particular, the PIN diodes achieved a breakdown voltage of ≥26.9 kV at a low on-resistance of 10 mΩ/cm². This is said to be the highest
breakdown voltage any solid-state device has ever demonstrated, and was at the limit of the measurement instrumentation. By comparison, silicon fails at just 600 V at that on-resistance.

"600 V JEDEC-Qualified Highly Reliable GaN HEMTs on Si Substrates,” paper 2.6 by T. Kikkawa et al, Transphorm

Power conversion, or changing electrical power from one form to another by varying/regulating voltage, current and/or frequency for a specific application is usually accomplished by switching high-power semiconductors on and off quickly, but this often comes at the cost of energy efficiency. A team from Transphorm detailed 600-V gallium-nitride (GaN)-on-silicon HEMTs, which overcame this limitation and also deliver outstanding reliability. The devices use a cascode-configuration architecture to reduce energy leakage in the off-state, with breakdown voltages >1,700 V observed, along with stable dynamic on-resistance, meaning reliability at typical 600-V operating voltage would be superior to existing devices. In fact, these devices have a projected mean-time-to-failure of >1x10^7 hours at 600 V (80ºC), and researchers claim they meet JEDEC requirements for commercial products. Use of silicon as a substrate implies they may be suitable for cost-effective mass-production.

"SiC Power Devices for HEV/EV and a Novel SiC Vertical JFET,” paper 2.2 by T. Ishikawa, et al, Toyota Central R&D Labs

A novel SiC VJFET with low feedback capacitance (C_{rss}) was described in the presentation. By inserting a p+ screen grid between the gate and drain, C_{rss} is effectively reduced by 80% compared to a conventional VJFET, resulting in the lowest total power dissipation among existing SiC power devices.

"Application-Specific Tradeoffs for Wide Bandgap SiC, GaN and High-end Si Power Switch Technologies,” paper 2.3 by R. Rupp, et al, Infineon Technologies AG

In the last decade, competition between power semiconductor switch technologies has seen the addition of SiC FETs (MOSFETs & JFETs) as well as lateral GaN-HEMTs. SiC devices deliver superior performance, yet still experience higher wafer costs and wafer diameter limitations, while GaN-HEMTs have lower manufacturing costs (on Si wafers), but still have ruggedness deficiencies and require significant voltage derating. Meanwhile, traditional Si-based technologies (IGBTs and compensation MOSFETs) have continuously improved, creating competition in the 600-V – 1,200-V blocking range. This paper presented some of the application trade-offs and development trends for these technologies.

High Voltage Silicon-Based Devices for Energy Efficient Power Distribution & Consumption,” paper 2.4 by A. Kopta, ABB Switzerland

An overview of future requirements and recent progress in silicon-based semiconductor technology, the presentation detailed future requirements for device design and performance in power transmission applications, as well as elaborating on recent advances for bipolar power devices and corresponding packaging technologies for these high-power applications.

Copies of the papers mentionned in this article should be available in the near future from IEEE xPlore.

In addition to the technical presentations described above, in one of the 90-minute tutorial sessions, Ichiro Omura of the Kyushu Institute of Technology discussed “Power Semiconductor Device Basics: History, Application & Physics.”

This session covered the history of power semiconductor devices, circuit principles and major application areas for these devices, and the structure and physics of power MOSFETs/superjunction MOSFETs, IGBTs, power diodes (PIN & Schottky barrier diodes), lateral devices (LD-MOS, LIGBT) and thyristors (GTOs and GCTs). Also presented were the current status and expected future advances in wide bandgap (SiC & GaN) power devices; as well as the protection, packaging and reliability of power semiconductors. More details can be found at http://www.his.com/~iedm/program/tut-1-omura.pdf.