Foreword
Special Issue on Wide Bandgap Power Switching Devices for Energy Efficiency and Renewable Energy Integration

WIDE bandgap (WBG) semiconductors, especially silicon carbide (SiC) and gallium nitride (GaN), promise transformational advances in electrical power systems, with increased power conversion efficiency for transportation and renewable energy utilization. Compared with the semiconductor silicon, SiC and GaN materials offer significantly higher electrical and thermal conductivities, increased avalanche breakdown field strength, and improved ruggedness under extreme environmental operating conditions. These basic material properties translate into more compact and lightweight power conversion systems with significant energy savings, much improved signal sensing and transmission characteristics, and longer operating life in the field.

However, the progress has been slow despite heavy investment and scientific development in the past three decades. For example, today, single-chip WBG power devices and packaged WBG power modules are prohibitively expensive compared with silicon devices and modules with identical voltage and current ratings. The situation is further complicated by the fact that the reliability and expected lifetime of WBG power devices in end-customer applications are not known. This problem is exacerbated because of incomplete and inaccurate commercial WBG power semiconductor product data sheets, and lack of honest communication among the key stakeholders in the WBG industry supply chain that extends from materials to end applications.

This Special Issue is assembled with an objective to unlock this dilemma and open up the technical field for further meaningful innovation and advancement. It contains both invited and contributed papers from leading experts in the field. Each paper was critically reviewed by at least two anonymous reviewers who have been working on technology and application of silicon and WBG power devices for many years. This Special Issue is divided into four sections and consists of a total of 26 full-length papers.

The section on manufacturing and applications consists of a total of six papers. The section begins with a paper by Shenai that presents the state of the art of commercial discrete SiC power MOSFETs. This paper emphasizes the need for improved product data sheets and discusses the future prospects, considering daunting material challenges and thermal management issues. The paper by Tanimoto *et al.* discusses recent packaging advances for high-frequency and high-temperature operation. The next four papers focus on application aspects of WBG power devices. The paper by Huang *et al.* makes a critical assessment of the cascode GaN power switch in power converter applications. Hamada *et al.* discuss the requirements of WBG power devices in environmentally friendly electric vehicle applications. The paper by Wu *et al.* makes a critical evaluation of commercial SiC power MOSFETs in medium-voltage and high-power modular multilevel power converters and concludes that system-level efficiency gains may be feasible with SiC power MOSFETs compared with silicon IGBTs with careful application-level engineering of device technology. The last paper in this section by Shen *et al.* pertains to unique advantages of WBG power switching devices in circuit breaker applications in emerging DC power systems.

The second section on novel phenomenon and reliability consists of a total of seven papers. The first four papers in this section deal with MOS interfaces in SiC and discuss threshold voltage instability and gate oxide reliability. Advanced characterization as well as improvement of the MOS interface characteristics are discussed. The paper by Chen *et al.* models the nonlinear drain–source and freewheeling diode capacitances, and discusses the impact of capacitance nonlinearity on switching transients. Chang *et al.* discuss the drain current instability in p-GaN gate AlGaN/GaN lateral HEMTs. The last paper in this section by Shen *et al.* pertains to packaging considerations of WBG power devices, especially in extreme environmental operating conditions.

The third section consists of a total of nine papers on high-voltage SiC and GaN power switching devices. The first paper by Huang *et al.* discusses how to achieve high tolerance from excessive surface charge in the junction termination extension of ultrahigh voltage SiC power devices. The paper by Shenai and Chattopadhyay demonstrates a reverse-engineering methodology to extract the key device design and doping layer parameters of a high-voltage power diode from simple static current–voltage (I–V) and capacitance–voltage (C–V) measurements. Their results clearly suggest that commercial unipolar WBG power devices employ a buffer layer and resort to a punch-through structure to avoid

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premature device breakdown caused by the excitation of crystal defects in the drift region of the device. This is followed by two ultrahigh-voltage 4H-SiC power diode papers by Bakowski *et al*. and Kaji *et al*., which clearly show promise for >25-kV single-chip SiC power devices. The next three papers present the technology and characteristics of the latest high-voltage 4H-SiC power diodes, MOSFETs, and IGBTs. The last two papers in this section pertain to GaN power devices. The first paper by Kuzuhara *et al*. discusses lateral GaN power transistors, whereas the paper by Kizilyalli *et al*. pertains to high-voltage vertical p-n-junction diodes on bulk GaN material.

The fourth and last section of this Special Issue consists of a total of four papers on modeling and simulation. The first two papers by Mantooth *et al*. and Santi *et al*. present comprehensive reviews of the current state of the art of circuit models of both unipolar and bipolar power devices. The third paper by Ghosh *et al*. presents a compact circuit model for lateral GaN HEMT power transistors. The last paper in this Special Issue is by Arribas *et al*., which presents and validates a simple and accurate circuit simulation model for SiC power MOSFETs and discusses its implications in power module and power converter designs.

It is clear that WBG power devices are poised to make transformational advances in emerging power and energy systems. Although the current market potential for WBG power devices exceeds \$5 billion per year, SiC power devices could net only about \$200 million in sales last year and most of these revenues were generated from power diode sales. On the other hand, GaN power switching devices could net only about \$2 million last year, and these revenues were generated from low-voltage lateral normally OFF power transistors and early high-voltage test device samples. The papers presented in this Special Issue have pointed out the reasons for this poor market performance—higher chip cost/ampere, unknown field reliability, poor data sheets, and lack of demonstrated increased energy efficiency at higher junction temperatures. Improved honest interaction across the WBG industry supply chain is essential to circumvent some of these barriers, especially since there is a significant void in vertically integrated industries. The primary factor that limits device yield and reliability is the high density of crystal defects in the starting material used for the fabrication of WBG power devices. These crystal defects have their origin in the crystal seeding process and thermal history used in commercially viable material synthesis procedures today. The cost of the starting material is also prohibitively high owing to slow growth rates, smaller wafer size, reduced wafer throughput, and exceedingly high growth temperatures needed for the physical vapor transport process used in the industry.

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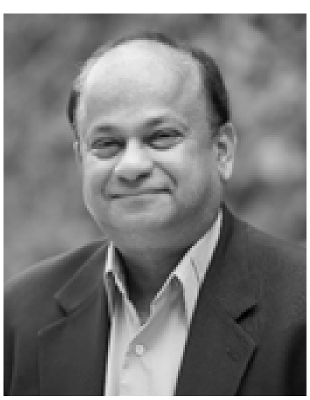

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He joined the Advanced Technology Research Laboratories, Nippon Steel Corporation, Tokyo, in 1984, where he was responsible for leading several research projects on semiconductor materials and devices, in particular silicon carbide (SiC) semiconductor materials, until moving to Kwansei Gakuin University, Nishinomiya, Japan, in 2008. He is currently a Professor of the School of Science and Technology and the Director of the Research and Development Center for SiC materials and processes with Kwansei Gakuin University. He has authored, co-authored or edited one book, 21 book chapters and over 100 peer-reviewed technical papers in science and technology of semiconductor materials and devices.