A New Hands-On Course in Characterization of Wide-Bandgap Devices

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***Abstract*—As wide-bandgap (WBG) devices and applications move from niche to mainstream, a new generation of engineers trained in this area is critical to continue the development of the field. This paper introduces a new hands-on course in characterization of WBG devices, which is an emerging and fundamental topic in WBG-based techniques. First, the lecture–simulation–experiment format based course structure and design considerations, such as safety, are presented. Then, the necessary facilities to support this hands-on course are summarized, including classroom preparation, software tools, and laboratory equipment. Afterward, the detailed course implementation flow is presented to illustrate the approach of close interaction among lecture, simulation, and experiment to maximize students' learning outcomes. Finally, grading for students and course evaluation by students are discussed, highlighting the findings and potential improvements. Detailed course materials are provided via potenntial.eecs.utk.edu/WBGLab for educational use.**

***Index Terms*—Electrical engineering education, hands-on training, power electronics, wide-bandgap (WBG) devices.**

I. Introduction

AT THE heart of modern power electronics converters are power semiconductor devices. In comparison with mature and well-established silicon (Si) technology, which has gone through many generations of development in the last 50 years and is approaching material theoretical limitations, the emerging wide-bandgap (WBG) power semiconductor devices promise to revolutionize next-generation power electronics converters. WBG refers to electronic energy bandgaps significantly larger than 1 eV. WBG materials have several characteristics that make them attractive compared to low-bandgap Si for power electronics converters. Fig. 1 highlights some key material properties of WBG semiconductor candidates as compared to traditional Si [1]. Generally, for WBG materials, their energy gap, breakdown electric field, thermal conductivity, melting point, and electron velocity are all greatly improved. These characteristics enable higher performance WBG semiconductor-based power devices than Si.

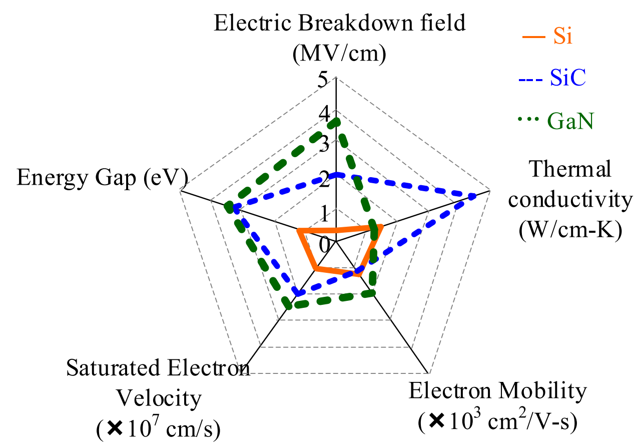

Fig. 1. Summary of Si, SiC, and GaN relevant material properties [1].

For example, higher breakdown field allows WBG devices to use thinner drift layer and/or a higher doping concentration with the given blocking voltage of Si counterparts. For a unipolar device, the combination of thinner blocking layer and higher doping concentration yields a decreased specific ON-resistance for WBG. The high-speed switching capability of WBG devices can also be expected due to higher breakdown field and electron velocity. First, with lower specific ON-resistance at the same breakdown voltage, a smaller chip size is achieved. Therefore, the junction capacitance is smaller due to the reduced size, resulting in a fast switching speed. Second, minority carriers are swept out of the depletion region at the saturated drift velocity during the turn-OFF transient. The electron saturated drift velocity of WBG is higher than that of Si, leading to an increased switching speed of WBG devices. Furthermore, the higher thermal conductivity allows WBG dissipated heat to be readily extracted from the device. Therefore, a larger power can be handled by the device at a given junction temperature. Also, higher thermal conductivity together with WBG makes it possible for WBG devices to operate at the increased temperature. In summary, WBG-based power devices offer low specific ON-state resistance, fast switching-speed, and high-operating

Manuscript received August 8, 2018; revised October 7, 2018; accepted December 17, 2018. Date of publication January 1, 2019; date of current version June 28, 2019. This work was supported in part by the U.S. Department of Energy's Wide Bandgap Traineeship Program and in part by Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program via Engineering Research Center Shared Facilities. Recommended for publication by Associate Editor A. Lindemann. *(Corresponding author: Zheyu Zhang.)*

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temperature and voltage capabilities. All of these are beneficial for the efficiency, power density, specific power, as well as reliability of power electronics converters [2], [3].

However, WBG devices, despite their similarity to Si power devices, suffer from underutilization, or in some cases result in degraded performance, when deployed as drop-in replacements for converters designed using traditional techniques from the Si era [4], [5]. In any physical implementation of a power converter, a wealth of various parasitics and design interdependencies exists beyond the capabilities of the traditional analysis and simulation approaches. Historically, the parasitics associated with high-voltage, high-power Si insulated-gate bipolar transistors (IGBTs) were sufficiently large such that all other parasitic behaviors were trumped by those of the IGBT itself. However, the performance of WBG semiconductors facilitates switching speeds multiple orders of magnitude beyond those present in Si converters of equal rating. Though these switching speeds are an enabling characteristic for much higher efficiency and higher power density designs, they also cause previously irrelevant facets of the converter design to become dominant factors in overall converter performance.

Consequently, if the superior characteristics of WBG semiconductors are to be fully leveraged in power electronics systems, a new design paradigm of power electronics is necessary. As prices for WBG power devices continue to decline due to advances in a wafer fabrication technology, a new generation of engineers trained in these techniques is critical to continue the development of the field [6]. To meet the needs of the next generation power engineering workforce, The University of Tennessee is developing a world-class WBG Traineeship Program—PoTenntial—in power electronics, leveraging WBG semiconductors [7].

Understanding the behavior of WBG devices and best practice of characterization of WBG devices to confidently use WBG devices in future power electronics converter designs is critical. For mature Si devices, their characteristics are readily available from datasheets. For WBG devices, it is often necessary to characterize these devices by application engineers for various reasons, which can be categorized as follows.

1) Even though the WBG device manufacturers generally provide a datasheet for their devices, these devices are new and relatively immature. As a result, WBG device characteristics often show high variability from device to device. It is prudent to characterize the devices to know their real behavior, especially during the design and development stage.
2) The datasheet may not be complete for some new WBG devices; or the provided data may not cover the conditions needed for a particular design. For example, the WBG device datasheet often only provides switching characteristics at limited voltage and temperature points and are not sufficient for some converter designs.
3) WBG device characterization requires careful testing setup design. For example, a circuit layout with low parasitics is needed for accurate switching characteristics measurement. The process of designing the characterization circuit can directly help the converter design.
4) Characterization of WBG devices is an excellent way to learn about these new emerging devices. In fact, the authors have gained much of their hands-on experience with WBG devices through characterizing various silicon carbide (SiC) and gallium nitride (GaN) devices in the laboratory.

In principle, similar general procedures in characterizing Si devices can be applied to WBG device characterization. For example, characterizing Si and WBG devices involves both the static and dynamic characterizations. The dynamic or switching characterization for Si and WBG devices is generally performed through the so-called double-pulse test. However, due to the significantly different properties of Si and WBG devices, the details in carrying out WBG device characterization are different from those in Si device characterization.

Accordingly, a new course in characterization of WBG devices, summarizing the best practice of characterization of WBG devices with hands-on training added, is essential. This paper introduces the development of the course from the perspective of the WBG device users and targeted for graduate students who are major in power electronics. This paper is unique as the following.

1) It presents a practice to introduce the most recent research into graduate education for the next generation of engineers so as to accelerate the adoption of emerging technologies in the field of power electronics.
2) It demonstrates the comprehensive development of a hands-on course based on lecture–simulation–experiment format to maximize student's learning outcomes, including design considerations, required facilities, step-by-step guides, and student evaluation.
3) It provides sufficient details for other universities to reproduce this course and/or can act as a potential template to develop other similar courses.

The rest of the paper is organized as follows. Section II presents the course structure and design considerations. Section III provides the needed facilities, including laboratory, software, and equipment used in the course. Section IV describes the step-by-step design and implementation of the course. Section V discusses the performance evaluation and grading for students. Section VI reports the student evaluation/assessment of the course along with the potential improvement in the future. Finally, the conclusion is given in Section VII.

II. Course Structure and Design Considerations

A. Course Structure

Unlike traditional theory-centric coursework, the developed course is lecture–simulation–experiment based. As shown in Fig. 2, ten lectures were prepared to summarize the basics of WBG device characterization. These mainly cover the fundamentals of static characterization and dynamic characterization. Regarding the dynamic characterization, which is more challenging, several key topics are included, such as gate drive design, switching analysis, layout design and parasitic management, high-speed measurement, protection, and data processing. With this, students can learn the principle and best practices of how to characterize WBG devices.

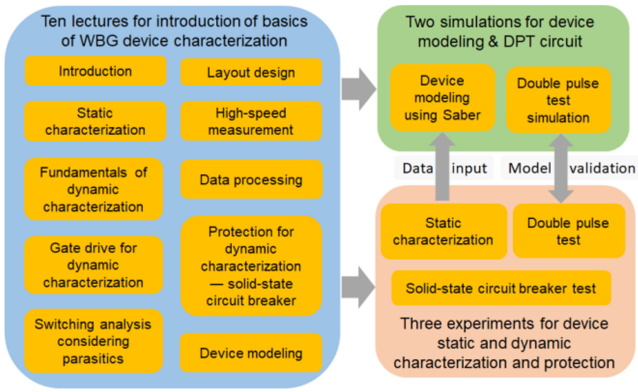


Fig. 2. Lecture–simulation–experiment format based course structure.

In the meantime, hands-on practice is involved to implement the theory taught in lectures for real hardware design and testing. In the course, three experiments are designed, including static characterization using a curve tracer, protection with solid-state circuit breaker for dynamic characterization, and dynamic characterization based on double-pulse test. Tips and tricks summarized in lectures will be practically implemented to accumulate hands-on experience and enhance understanding of knowledge and skills.

One step further, simulation is introduced as well, first to help students better understand the theory before the experiment, and later as a validation tool for hardware debugging, better understanding the test results, and in the end, establishment of a more relevant relationship between theory and experimental results. Note that test results in experiments are also used as the data inputs for the modeling in the simulation. For example, in the course, data experimentally acquired from the static characterization are imported to build the device model of the double-pulse test simulation platform for the validation of dynamic characterization.

B. Design Considerations

To best serve every student with a maximized learning outcome of the course, several special considerations are implemented and summarized as follows.

1) WBG Devices Selection: Many III–V and II–VI compound semiconductors with WBGs exist. Among the possible WBG semiconductor material candidates, SiC and GaN demonstrate the best tradeoff among theoretical characteristics (e.g., high switching frequency, operation temperature, and blocking voltage), real commercial availability of the starting material (e.g., wafers and epitaxial layers), and maturity of their technological processes [8]. Consequently, most WBG semiconductor power devices on today's market or in research and development phase are SiC and GaN based. The availability of high-quality SiC wafers allows the vertical structure for high-voltage devices (≥650 V). Currently, SiC metal-oxide semiconductor field-effect transistors (MOSFETs) are the most developed active switches, with some junction gate field-effect transistors (JFETs), IGBTs, bipolar junction transistors (BJTs), and thyristors also available. On the other hand, a GaN wafer fabrication technology is still a major challenge for vertical devices. Currently, lateral devices with Si substrate are most popular. They are called heterojunction field-effect transistors also known as high-electron mobility transistors (HEMTs). Due to the limitation of the lateral structure, GaN transistors target low voltage (≤650 V) applications. Also, in comparison with the normally-ON device, normally-OFF one is preferred for most power electronics applications.

TABLE I
WBG DEVICES SELECTED IN THE CLASS

Supplier	Part number	Description
Cree/Wolfspeed	C3M0065090D	900-V/36-A SiC MOSFETs w/ TO-247-3 package
Cree/Wolfspeed	C3M0065090J	900-V/35-A SiC MOSFETs w/ D2PAK-7 package
GaN Systems	GS66508B-E01-MR	Normally-off 650-V/30-A GaN transistor
EPC	EPC2010C	Normally-off 200-V/22-A GaN transistor

To make the hands-on practice more general, four WBG devices are selected, including two SiC MOSFETs and two GaN HEMTs with the details summarized in Table I. The selection considerations are highlighted as follows.

1) Two SiC MOSFETs from Cree/Wolfspeed are selected. They have similar voltage/current ratings but different packages (e.g., through-hole, non-Kelvin connection for C3M0065090D, surface mount, Kelvin connection for C3M0065090J). Device package is critical to affect the design of the characterization setup and the device's characteristics. The direct comparison between the results of these two different packaged devices can enhance students' understanding on the key takeaways in the class.
2) Unlike SiC devices selection, two normally-OFF GaN HEMTs with similar package but different current/voltage ratings from two suppliers (GaN Systems and efficient power conversion (EPC)) are selected. Note that the packages of GaN HEMTs are usually leads-free surface mount with Kelvin connection.

In the end, students can characterize devices with a large degree of freedom. Also, the generality of the device characterization methodology taught in the class for different devices with different packages is demonstrated.

Each student in the class only selects one WBG device out of four candidates. To best fit the interests of students at the beginning of the course, students are requested to complete a questionnaire about their research background and the types of WBG devices they found most interesting. Accordingly, students are divided into several teams based on common interest in WBG devices, while also ensuring that each team included students with a diverse range of research experiences. The feedback from the questionnaire enables a customized learning experience for each student in the class.

Also note that WBG rectifiers (diodes) are important to be covered in the class. In the lecture sessions, the basics of characterization for WBG rectifiers have been introduced, which are actually similar to that of active WBG switches. However, considering the implementation for WBG rectifier characterization is less complex, it is believed that if the students can characterize active WBG devices, they are expected to be capable to test the static and dynamic characteristics of WBG rectifiers. As a result, the WBG devices under test in the class focus on active SiC MOSFETs and GaN HEMTs.

2) Instructional Materials: WBG device technology is emerging and is still an active research area. Instructional materials of the new course are mostly based on authors' own research experience at The University of Tennessee. In most cases, our own results in SiC and GaN characterization have been used as examples. Two related educational seminars presented by authors at IEEE conferences prior to the course, along with the audience feedback, provide the baseline for the lecture note preparation [9], [10]. Additionally, the methodologies presented are generalized including referencing other literature in the area [11]–[29]. In the end, a handbook entitled "Characterization of Wide Bandgap Power Semiconductor Devices" is written as the reference for the course [30].

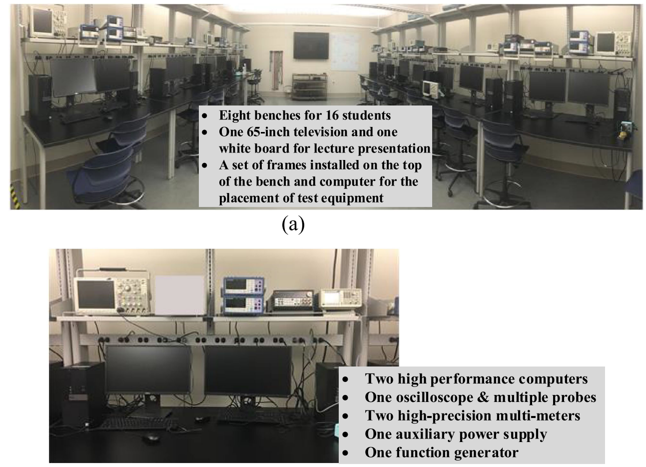
In each lecture, in addition to the methodology description, examples and case studies are presented, offering a step-by-step guidance for students to later design their own implementation. Both SiC MOSFETs and GaN HEMTs examples are given, highlighting their unique aspects and special design considerations. Although these two types of devices are the main focus due to their overwhelming dominance in availability, research, and application, the basic principle of device characterization introduced in the lectures can be applied to other types of WBG devices, such as SiC BJTs, SiC IGBTs, SiC thyristors, and vertical GaN FETs. Therefore, the generality of the instructional materials for WBG device characterization is not lost.

For readers to easily reproduce the course, detailed course materials are provided and can be found at the web link potential.eecs.utk.edu/WBGLab. After clicking on the link "Instructor Resources," it will download a ZIP file that has all the materials. Specifically, it includes a syllabus, inventory of lab equipment, lecture notes (ten lecture sessions and three lab sessions), printed circuit board (PCB) files, and homework templates. Note that these materials are intended only for educational purposes.

3) Safety Consideration: To comply with stringent university safety requirements, a safety assessment is conducted and risk mitigation plan is devised. The safety concerns in this hands-on course include high voltage (up to 600 V for 900-V SiC MOSFETs characterization), large current under short-circuit fault, and high temperature for soldering.

According to the identified risks from the safety assessment, a mitigation plan is prepared and summarized as follows.

1) Online safety training is required before the laboratory work. It includes the following:
   a) workplace safety orientation;
   b) hazard communication: an employee's right to know;
   c) NFPA 70E electrical safety in the workplace;
   d) personal protective equipment;
   e) electrical safety;
   f) job hazard analysis;
   g) lock-out/tag-out for authorized persons;
   h) portable fire extinguishers;
   i) others as necessary.



(a)

(b)

Fig. 3. Lecture–simulation–experiment based classroom. (a) Classroom layout for eight test stations. (b) Enlarged setup per bench.

2) Safety guideline and testing procedure are required before the laboratory work. Lecturer gives the safety guideline before the beginning of the laboratory session. Students make testing procedure considering safety issues, which is reviewed and approved by the lecturer, and implemented for each laboratory session.
3) Personal protective equipment is prepared, such as safety glasses, enclosure/container for energized circuit, etc.
4) Safety placard is required as the caution sign for both students and visitors.
5) Necessary protection circuit/switch is required for the test setups. For example, a solid-state circuit breaker is employed for the short-circuit protection in the double-pulse test. Also, an emergency cutoff switch was installed in the laboratory. The location and operation of the emergency switch are clearly identified.
6) Two-person rule must be followed (there must always be at least two trained persons present for all testing).

III. Course Facilities

One of the significant challenges for this hands-on course is facilities, due to the key feature of the course, which is the close interaction among lecture, simulation, and experiment. First, a new and unique classroom was set up, including multi-media equipment for lecture, high-performance computer for simulation, and well-equipped laboratory for experiment. Second, software tools were required for the circuit simulation, PCB design, and data processing and analysis. Third, the state-of-the-art laboratory equipment was needed to support the high-speed WBG device characterization. The details are presented as follows.

A. Lecture–Simulation–Experiment Based Classroom

The classroom used in the course is renovated based on a computer laboratory, which has 8 benches and 16 high-performance computers. With the given computers for the simulation, two sets of equipment are installed to support the lecture and experiment, as shown in Fig. 3.

TABLE II
MAIN SOFTWARE TOOLS USED IN THE COURSE

Software	Description
Synopsis/Saber	For WBG device modeling and double pulse test circuit simulation of dynamic characterization
Altium Designer	For PCB board design of the double pulse test circuit
Matlab	For data acquisition, processing, and analysis

To support the lecture, a computer with a 65-in television as the display is installed in front of the room for instructional presentations. Also, there is a white board next to the display for Q&A as necessary. A telephone is installed as well for the remote communication/education.

To serve the hands-on practice, a set of frames was installed on the top of the bench and computer for the placement of test equipment. Some of the test equipment can also be located between two benches, such as power supplies, signal generators, oscilloscope and probes, multimeters, and soldering machine. A storage cabinet is equipped as well with general-purpose laboratory items, such as tapes, wires, soldering materials, fixtures, connectors, kits, and other assembly tools.

B. Software Tools

Dedicated software is needed for the simulation and experiment in the course. It mainly includes three tools, Synopsis/Saber, Altium Designer, and MATLAB with the brief description summarized in Table II. Their detailed usage will be given in Section IV when the design and implementation flow of the course is introduced.

C. Laboratory Equipment

Due to the inherent properties of the small and fast WBG device, the state-of-the-art laboratory equipment is necessary for high-precision static characterization and high-speed dynamic characterization.

Table III summarizes the key equipment used in the course. It primarily includes high-power curve tracer for static characterization, double-pulse test equipment and components for dynamic characterization, and high-precision high-speed measurement equipment. Considering some of the equipment are high priced, such as curve tracer (Keysight B1505A) and impedance analyzer (Agilent 4294A), in practice, these two pieces of equipment are lent from the Power Electronics Research Laboratory at The University of Tennessee during the needed laboratory session. The rest of the equipment is purchased for the dedicated use for the hands-on practice in the course.

Also note that the key laboratory equipment examples are targeted for WBG devices under test in the class listed in Table I. For devices with higher voltage rating, such as 1.2–10 kV WBG devices, several modifications are required for the device characterization setup.

Specifically, for the static characterization, several device characteristics are voltage dependent, such as leakage current, breakdown voltage, and voltage-dependent junction capacitance. Keysight, B1505A curve tracer used in the class is rated at 3 kV. For devices with voltage ratings in the range from 3 to 10 kV, a fixture N1268A ultra-high-voltage expander needs to be introduced to extend the voltage capability of the curve tracer up to 10 kV.

TABLE III
KEY LABORATORY EQUIPMENT FOR WBG DEVICE CHARACTERIZATION

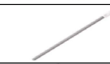
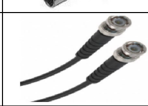
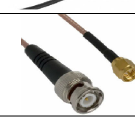
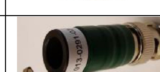
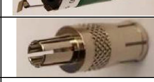
Example part number	Description	Image for equipment
Static characterization equipment		
Keysight, B1505A	High power curve tracer	
Dynamic characterization equipment and components		
Sorensen, XG 850 W	DC power supply – 600 V, 1.4 A	
Tektronix, 2230-30-1	Power Supply, Triple Output, 30 V, 5 A, 120 W	
Tektronix, AFG1062	ARB Function Generator, 2 Channel, 60 MHz	
Micrometals, FS-300060-2	Powder core for double pulse test load inductor	
MWS Wire Industries, HPN, 12 Gauge, MW80-C	Magnet wire for double pulse test inductor	
High-precision high-speed measurement equipment		
Agilent, 4294A	Precision impedance analyzer for double pulse test inductor high frequency impedance measurement	
T & M research products, SSDN-10	0.1-ohm 2 GHz shunt resistor for drain current measurement	
Tektronix, TPP1000	1 GHz, 10X, 300 V, passive, for gate-source voltage measurement	
Tektronix, TPP0850	800 MHz, 50X, 2.5 kV, single-ended, for drain-source voltage measurement	
Tektronix, DPO4104B-L	Oscilloscope, 4 Analog Channels, 1 GHz BW, 5 GS/s, 5 M points	

For the dynamic characterization, component selection and layout design for double-pulse test circuit, dc power supply, voltage measurement, and protection circuit need to be re-evaluated as device voltage rating increases. For example, with respect to the items listed in Table III, maximum output voltage of the dc power supply, wire insulation of double-pulse test inductor, and dynamic measurement range of the high-voltage probe may not be sufficient to support the characterization of higher voltage devices and need to be updated as necessary.

Also, several general-purpose laboratory materials were required to support the WBG device characterization, including, but not limited to tape and wire, soldering materials (including soldering station for small WBG device reflow soldering), connectors, mechanical supplies, and personal protectionxbrk equipment.

Table IV lists the special laboratory materials for WBG device characterization, mainly including small WBG device soldering materials for two GaN transistors in the course and cable/fixture/adapter for high-speed measurement of dynamic characteristics. Also, an example part number for each item that has been used in the course is listed as a reference.

TABLE IV
SPECIAL LABORATORY MATERIALS FOR WBG DEVICE CHARACTERIZATION

Example part number	Description	Image for material
Small WBG device soldering materials		
Desco, 16310	Anti-static mat for device electrostatic discharge (ESD) protection	
Desco, 09028	ESD wrist strap for device ESD protection	
Aoyue 968A+	Hot air gun for reflow soldering	
Chemtronics, 48040	Swab for soldering and PCB board cleaning	
Chip Quik, SMD291AX10T5	Solder paste	
Chip Quik, SMD291	Soldering flux	
Techspray, 1621-10S	Flux remover alcohol	
Apex Tool Group, XN100B	Precision cutter for small WBG device positioning	
Fixture, connector, kits for high-speed dynamic characterization		
TE Connectivity AMP Connectors, 5227222-3	Jack for drain-source voltage measurement	
Amphenol RF, 115101-19-24.00 (24 inch) or 115101-19-36.00 (36 inch)	50-ohm BNC cable for drain current measurement	
Johnson/Cinch Connectivity Solutions, 415-0028-036	SMA to BNC cable for double-pulse signal transmission	
Tektronix, Connector 136-0962-00 & 131-4209-00	Gate source voltage measurement tip adapter	
Tektronix, 013-0291-02	Drain source voltage measurement tip adapter	
Tektronix, 13036700	BNC to probe tip adapter	
TDK Corporation, ZCAT3035-1330-BK	Split ferrite core (choke) for noise immunity enhancement of double pulse test logic circuit and high-speed measurement	

IV. DESIGN AND IMPLEMENTATION FLOW

The course was limited to an enrollment of 16 students because of limited laboratory space. For the lecture, simulation, and pre-laboratory assignment, each student works individually. For the laboratory session, eight groups are assigned with two students per team to characterize one WBG device out of four WBG device candidates. In the course, students need to study individually and work in a two-person team to complete the following three tasks:

1) use Keysight B1505A high-power curve tracer for WBG device static characterization;
2) model WBG devices and simulate double-pulse test circuit for better understanding of characteristics of WBG devices;
3) design, build, and debug double-pulse test circuit board for WBG device dynamic characterization.

Detailed implementation flow of the course is introduced in the following.

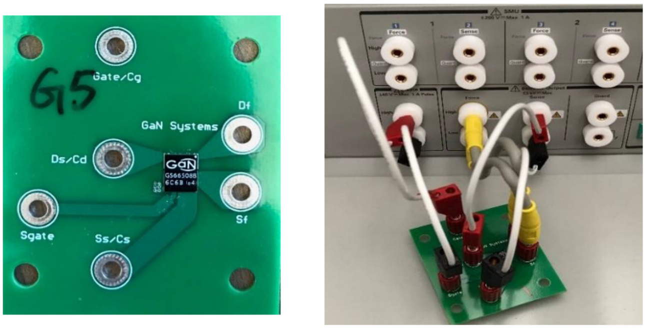
A. Step1: Pre-Course Questionnaire and Grouping

To stimulate the passion of students and best serve their research activities or potential research interests, a questionnaire was designed and given to students before the course to allow the lecturer to understand the research background and device preference for each student. Accordingly, two students with common interests in WBG devices are grouped.

In the meantime, students' existing research experiences and their proficiency in three software packages that will be used in the course (see Section III-B) are also considered such that within one group, there will be a diverse range of research experiences and software skills. Therefore, students can conveniently learn from each other during the teamwork to enhance the learning outcome.

B. Step 2: Introduction of Basics of WBG Device Static Characterization

This is a lecture session to introduce the operating principle of WBG device static characterization, including multi-pulse based *V–I* testing for device output characteristics, transfer characteristics, and ON-state resistance, leakage current/ breakdown voltage testing, and junction capacitance and gate charge measurement. Also, the special considerations for WBG devices are highlighted, such as self-heating issue and mitigation, Kelvin connection for high-precision measurement, and steady-



(a) (b)

Fig. 4. Pre-laboratory preparation–Test fixture for static characterization (for GaN Systems GS66508B-E01-MR). (a) Adapter board. (b) Connecting with curve tracer.

state gate current for emerging GaN transistors (e.g., gate injection transistor (GIT) based GaN). Additionally, the junction temperature control and monitoring for temperature-dependent device characterization are summarized.

C. Step 3: Implementation and Experimentation of WBG Device Static Characterization

Right after the lecture session, a laboratory session is conducted for implementation and experimentation of the WBG device static characterization. Keysight B1505A high-power curve tracer is used. First, the lecturer presents a step-by-step example based on a WBG device that is different from the course-used devices as a guideline to introduce the usage of the curve tracer. Then, each student works with their team members to test one device. With this, one group will have two sets of test results for two device samples, which have the same model number. Finally, two students work as a team to summarize the test data, compare the results between themselves as well as with the data provided in manufacturer's datasheet, and in the end, generate a laboratory report.

Prior to this laboratory session, several dedicated adapter boards are designed and fabricated for the connection between non-TO-247 packaged device and curve tracer, as shown in Fig. 4. Note that the test fixture for TO-247 packaged device exists in the curve tracer used in the course. Also, the boards are laid out carefully to provide a Kelvin connection for the high-precision measurement.

D. Step 4: Introduction of Basics of WBG Device Dynamic Characterization

This step includes two lecture sessions to present the fundamentals of double-pulse test, which is a widely applied method for the device dynamic characterization.

The first lecture starts with the analysis of the basic switching commutation and device dynamic characteristics, then specifically introduces double-pulse test circuit, including its operation principle, configuration, design consideration, control scheme, and, finally, gives a case study to implement the design and control methodology step by step based on an actual WBG device.

The second lecture focuses on the gate drive design for the dynamic characterization with the special consideration of challenges posed by high-speed WBG devices, such as common-mode noise immunity, gate driving capability, etc. Similar to the first lecture, a design example is presented to establish the relevance between the theoretical methodology and practical implementation.

In the end, a homework is assigned individually to complete an electrical design of the double-pulse test circuit (including gate drive) based on the parameters of the actual device that will be tested later.

E. Step 5: Introduction of Layout Design and Parasitic Management of Double-Pulse Test Circuit

WBG device with high-speed switching capability intensifies the influence of the circuit parasitics on its dynamic characteristics. Therefore, in addition to the electrical design completed in Step 4, the physical implementation, including layout design and parasitic management, is also critical. This step includes two lecture sessions and one simulation session.

The first lecture focuses on the understanding of device dynamic characteristics considering circuit parasitics. Specifically, starting from an analysis excluding the influence of parasitics, the basic device dynamic performance is described, which is valid for traditional Si devices with relatively slow speed. Later, in addition to this simplified analysis, the influence of each circuit parasitic on the device dynamic characteristics is illustrated and summarized. Accordingly, the most critical parasitics for the high-speed switching of WBG devices are identified and understood.

To enhance the understanding of device dynamic characteristics considering parasitics, a simulation session is conducted after the first lecture. Synopsis/Saber is used for the double-pulse test circuit simulation. Considering some of the students may not be familiar with the software, the simulation file, including a WBG device model, was prepared by the lecturer. Students use the provided simulation circuit, observe the dynamic characteristics of the fast-switching devices with different values of parasitics, and, finally, generate a report summarizing the simulation data as a function of parasitics along with the data analysis based on the theory discussed in the first lecture.

According to the outcome of the prior lecture and simulation sessions, the following lecture summarizes the basics of layout design for parasitics minimization, especially for the critical parasitics identified earlier. Since the specific layout design is highly dependent on device packages, multiple case studies are demonstrated based on the most popular packages of WBG devices, such as TO-247, surface mount, etc. Both power stage and gate drive are covered as well. More importantly, although the lecture focuses on layout design concepts and implementation for the double-pulse test circuit, it is also important to consider other design constraints in an actual converter. From the WBG device users' perspective, the goal for the double-pulse test is to best serve the future converter design and optimization. In this lecture, the thermal management system is specifically considered. As a result, the technique for the layout design and parasitic management introduced in the lecture can lead to more valid double-pulse test results for future converter design and development.

In the end, a homework is assigned for each team to complete a PCB board design of double-pulse test circuit (including gate drive) based on the electrical parameters designed in Step 4. Altium Designer is used for this assignment.

F. Step 6: Introduction of High-Speed Measurement and Data Processing

This is a lecture session to introduce the basics and best practices of high-speed measurement and data processing for WBG device dynamic characterization. Specifically, for the high-speed measurement, it includes measurement requirements for fast-switching WBG devices, state-of-the-art voltage and current measurement techniques, and measurement induced grounding effect. Also, all the measurement equipment used in the laboratory are introduced and justified based on the theory taught earlier. Regarding the data process, MATLAB is used. An example of the .m code was prepared by the lecturer to demonstrate a case study on the basis of authors' previous research work. Also, a flowchart is generated to make the MATLAB code more readable and user-friendly. Later, students will update this code to process their own double-pulse test data.

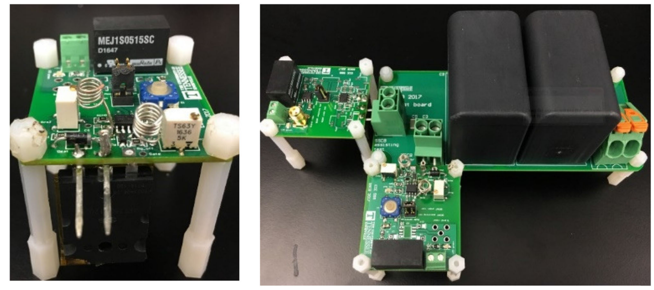
After the completion of Steps 4–6, the needed knowledge and skills for WBG device dynamic characterization have been introduced.

G. Step 7: Introduction and Experimentation of Protection for WBG Device Dynamic Characterization

Before the laboratory session for the device dynamic characterization, one more step is needed, that is, to build a solid-state circuit breaker to protect the devices and double-pulse test circuit in case there is a short-circuit fault during the test. This is critical for WBG devices due to their limited short-circuit withstand capability. Special attention must be paid on the short protection response time and high noise immunity capability.

A lecture is presented to introduce the basics of the solid-state circuit breaker, such as operation principle, circuit implementation, and design consideration. Next, a design example suitable for the protection of high-speed WBG devices is provided, and finally, the testing setup and procedure for the performance verification of the designed solid-state circuit breaker circuit is discussed.

Afterward, a laboratory session is conducted to assemble and debug the solid-state circuit breaker board. Note that to save time and allow students to concentrate on the experimentation of the dynamic characterization in the next step, the solid-state circuit breaker board and its corresponding testing circuit are designed and fabricated prior to the laboratory session, as shown in Fig. 5. Each team is responsible to test one solid-state circuit breaker board. Although this laboratory session is pre-prepared and less challenging, it is designed such that students are able to



(a) (b)

Fig. 5. Pre-laboratory preparation–Solid-state circuit breaker board for protection of dynamic characterization. (a) Solid-state circuit breaker board. (b) Test setup for experimental verification of solid-state circuit breaker board.

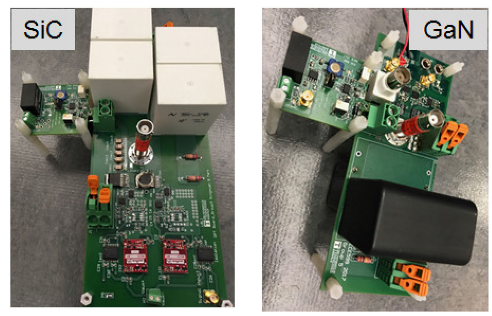


Fig. 6. Two examples of double-pulse test board developed in the course for dynamic characterization.

be familiar with the test equipment and ready to test their own designed double-pulse test board later.

H. Step 8: Experimentation of WBG Device Dynamic Characterization

This is the key laboratory session to assemble and debug the double-pulse test board designed by students in Step 5 for WBG device dynamic characterization. The purpose of the experimentation is to enhance students' understanding of the key takeaways in the lecture and accumulate hands-on experience. Specifically, it is able to, first, verify the design of double-pulse test circuit, gate drive, and low-parasitic layout in Steps 4 and 5; and second, implement the best practice of high-speed measurement and data processing in Step 6. Additionally, the outcome of the laboratory session (i.e., device dynamic characteristics data) can be used for the simulation model validation in the next step. Fig. 6 shows one SiC-based board and one GaN-based double-pulse test board built in the course.

I. Step 9: Model Validation of WBG Device Dynamic Characterization

The last step is to build a device model, simulate the model in a double-pulse test circuit, and validate the model based on the comparison between simulation results and test data, which are acquired in Step 8. The design consideration of this step is to establish the relevance between the theory and experiment, and demonstrate the test results are reasonable and can be understood. One lecture session to introduce the WBG device modeling using Synopsis/Saber and one simulation session for the model validation are included in this step.

In the lecture session, the Power MOSFET Tool in Synopsis/Saber is used to build the WBG device model. The input data needed for the Power MOSFET Tool are primarily from the test results of device static characterization in Step 3, such as output characteristics, transfer characteristics, and junction capacitances. An example is presented as a step-by-step guideline for students to build their own device models based on their own test data.

In the simulation session, a simulation file is built based on the double-pulse test circuit used in Step 5 with necessary modifications, such as device model replacement with the new one made by each student, gate drive parameter updates, and parasitic value estimation according to the actual double-pulse test board built and tested by each team. With this, students in each group work together to run the simulation file, compare simulation results with the test data, analyze the mismatch between them, update the simulation model accordingly as necessary, and, finally, complete the model validation. As the ultimate outcome, the test results should be reasonably reproduced by simulation and explained by the theory.

In the end, a final report will be generated, including the test results obtained in Step 8 and model validation in Step 9. Also, a student presentation is requested for each team to summarize their results and findings in Steps 8 and 9 at the end of the course. This presentation session is designed for the following:

1) to evaluate the learning outcome of each student in the team based on the individual presentation and technical Q&A;
2) to provide an opportunity for students to be aware of the findings from other teams and enrich their own experience;
3) to train students not only from the technical perspective but also enhance their presentation and communication skills.

Table V summarizes the unique considerations for WBG device-based characterization as compared to its Si counterpart.

TABLE V
SUMMARY OF UNIQUE CONSIDERATIONS FOR WBG DEVICE-BASED CHARACTERIZATION

Static characterization	
Pulsed V-I testing	• Junction temperature control during the pulsed V-I testing is challenging because of the self-heating induced by smaller device die and increased current density, especially for GaN HEMTs. As a result, the pulse duration needs to be carefully set. • High precision measurement with Kelvin connection is required due to lower specific on-state resistance of WBG devices and relatively large measurement error introduced by connecting wires. Dedicated fixture for surface mount small package devices, such as GaN HEMTs, is recommended.
Gate characteristics	• Steady-state gate current, which is not necessary to be characterized for Si devices, is important for certain GaN transistors (e.g., GIT GaN) due to the unique gate structure.
Dynamic characterization	
Gate drive	• Considering faster speed switching of WBG devices, special considerations for gate drive design are needed, such as common mode noise immunity, gate driving capability, etc.
Layout design	• Due to intensified influence of parasitics on the fast switching WBG devices, layout design and parasitic management for WBG based double pulse test circuit are more crucial. For certain packages (e.g., bottom cooled GaN transistor), optimal layout design must take the cooling system into account.
Measurement	• Sharp rise/fall edges of WBG devices during the fast switching transient challenge the measurement fidelity. Hence, special attention has to be paid to 1) measurement techniques for high-speed voltage and current, 2) a mitigation scheme for common mode current due to measurement induced grounding effect, and 3) the utilization of a tip adapter for grounding loop minimization.
Protection	• Due to limited short-circuit withstand capability for fast switching WBG devices, protection for WBG based setup should be designed with short protection response time and high noise immunity.

TABLE VI
PERFORMANCE EVALUATION AND GRADING SYSTEM (WEIGHT PERCENTAGE PROVIDED HERE IS USED IN THE CLASS)

Group	• Lab completion and reporting — 25% of total grade • Final report — 20% of total grade
Individual	• Homework — 20% of total grade • Participation & lab demonstrations — 20% of total grade • Presentation and Q&A — 15% of total grade

V. PERFORMANCE EVALUATION AND GRADING

As a hands-on course, the performance evaluation and grading for the individual student is challenging since considerable amount of the work is conducted as a group. To differentiate the grade based on the true performance of each student, an evaluation system consisting of two portions is implemented in the course and summarized in Table VI.

The first portion is related to the group outcome, including laboratory completion and reporting for each laboratory session, and a final report at the end of the course. Students within a group are requested to work together, and the mean score in this portion will be assigned for each student.

The other part is related to the individual performance. It includes homework, participation and laboratory demonstration, student presentation, and Q&A performance. In general, individual endeavor is more heavily weighted as compared to the group accomplishment.

VI. STUDENT EVALUATION AND COURSE ASSESSMENT

To maximize the learning outcome of the students and improve the course in the future, student evaluation and course assessment are important. Table VII summarizes the anonymous faculty evaluation questionnaire and scores by the end of the semester with eight enrolled students responded.

TABLE VII
QUESTIONS AND SCORES (EIGHT STUDENTS RESPONDED)

Questions	SA	A	N	D	SD	M
Instructor contributed to your understanding of course content	8	0	0	0	0	5.00
Instructor created an atmosphere that invited you to seek additional help	8	0	0	0	0	5.00
Instructor responded to your inquiries about the course	8	0	0	0	0	5.00
Instructor created a respectful and positive learning environment	8	0	0	0	0	5.00
Instructor provided useful feedback on course assignments	8	0	0	0	0	5.00
Instructor challenged you to learn something new	7	1	0	0	0	4.88
Class sessions were well organized	7	1	0	0	0	4.88
The course materials enhanced your learning in this course	8	0	0	0	0	5.00

Note: SA–Strongly Agree = 5, A–Agree = 4, N–Neutral = 3, D–Disagree = 2, SD–Strongly Disagree = 1, and M–Mean.

The average score of 4.97 out of 5.00 indicates that the majority of the students were quite satisfied with the course. Combining with the students' assignment performance and in-laboratory demonstration, the pedagogical objective of this hands-on course has been fulfilled. Several findings and potential improvements are highlighted in the following.

1) Workload of this three-credit course is reasonable. According to the industry-standard Carnegie Unit definition, hours per week outside of the class for a 14-week three-credit course are 6 h [31]. Based on the anonymous questionnaire, 75% students spent on average 4–5 or 6–7 h per week outside of the class, whereas the other 25% spent either 2–3 h or 8–9 h per week. It indicates that, in general, the course workload is reasonable, but it also depends on the proficiency of the graduate students with different research backgrounds on the course contents.
2) Grade expected by students meets the actual final scores. Still based on the anonymous questionnaire, 87.5% students were expected to get an A while the expectation of the other 12.5% is A−. The actual scores follow the student expectation from the percentage perspective. It indicates that the performance evaluation and grading system discussed in Section V is reasonable. Also, outstanding learning outcome is justified.
3) Classroom space limits the course participants. Since the topic of this course is emerging and critical to the research of WBG-based power electronics, there were more than 16 students who wanted to take the course. The limited space results in a long waiting list. To partially improve this situation, one alternative solution is to schedule all the lecture sessions in a regular classroom with larger space. Therefore, more students who are interests in this topic can at least have the chance to audit the course and learn the basics.

VII. CONCLUSION

A newly developed hands-on course in characterization of WBG devices is introduced. The following conclusions can be made based on the lecturer observation, course outcome, and student feedback.

1) This course is popular based on the number of enrolled students and students in the waiting list, which indicates the necessity of curriculum revision in power electronics education with more involvement of emerging techniques, such as WBG techniques, as well as hands-on practice.
2) Hands-on course with close interaction among lecture, simulation, and experiment is an effective approach to maximize the learning outcomes according to the final grading of students and anonymous evaluation scores by students. This process allows students to learn the theory, model the real-world circuits based on the theory, validate the model with hands-on practice, and finally establish the relevance between the theory and real-world needs.
3) Several effective and important practices are implemented in this hands-on course, it includes the following.
   a) Pre-course questionnaire to fully understand the background and interests of the students.
   b) Well-equipped classroom with the integration of lecture, simulation, and experiment facilities.
   c) Comprehensive implementation of safety assessment and mitigation plan.
   d) Lecture notes with multiple case studies based on authors' own research findings and results.
   e) Carefully designed syllabus where simulation and hands-on practices are scheduled right after the corresponding lecture session.
   f) Reasonable performance evaluation and grading system with individual efforts more heavily weighted.
4) High-priced laboratory equipment is a potential issue to reproduce this course in other universities. Even in this course, the curve tracer and impedance analyzer were lent from the Power Electronics Research Laboratory at The University of Tennessee. To overcome the barrier and improve the education for the next generation power engineering workforce, the support from government agencies is important and appreciated, such as the U.S. DOE Traineeship Program in this case.
5) For readers to easily reproduce the course for educational purposes, the detailed course materials are provided and can be downloaded via potenntial.eecs.utk.edu/WBGLab. Also, the handbook of [30] could be used as the course reference book.

ACKNOWLEDGMENT

The authors would like to thank Dr. E. A. Jones from Efficient Power Conversion (EPC) for the contribution of collecting and organizing course materials and giving lectures. The helps from students in ECE 599 at The University of Tennessee are acknowledged.

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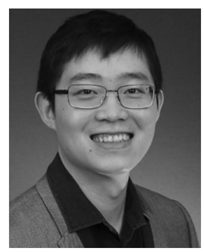

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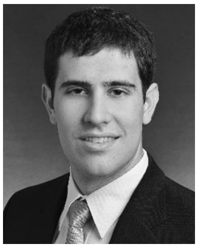

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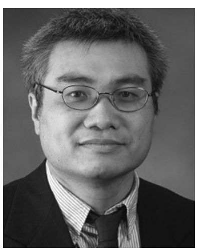

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