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An Automated Multi-Device Characterization System for Reliability Assessment of Power Semiconductors

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***Abstract* – In this paper, an automated setup is proposed for reliability studies which can characterize multiple power semiconductor devices simultaneously. A multi-channel test board is implemented to realize large-scale device characterization based on a conventional device characterization system. A LabVIEW virtual instrument (VI) is built as a state machine consisting of a measurement control program to achieve automated device switching and characterization. To verify the proposed hardware design's accuracy and consistency, repeated parameter measurements are conducted on the same SiC MOSFETs for error analysis. The measurement of critical parameters, such as leakage current, threshold voltage, and on-resistance, are validated experimentally. The results show that the proposed system enables power devices characterization with high accuracy and consistency.**

***Index Terms* – Device characterization, fault characterization, device parameters, reliability, test automation.**

I. INTRODUCTION

POWER semiconductor devices play a key role in power electronics systems, yet they are reportedly the most fragile components [1]. Thus, the power semiconductor devices' reliability is one of the most popular research topics through years of study and development in power semiconductor devices. Reliability-oriented studies are crucial for development in on-board condition monitoring and prognostics [2]-[5] such as failure mechanisms and lifetime models of both silicon (Si) device and wide bandgap (WBG) devices.

Reliability tests, including accelerated aging tests and device characterization tests, are the cornerstone of wide-range reliability studies. Most reliability tests require periodic temperature swings or changes in test conditions and always take thousands of hours, making it impossible to monitor the process manually. Therefore, various large-scale accelerated aging tests with on-board measurement functionality have been proposed [6]-[11]. These aging test systems realize accurate on-board measurement for on-resistance R_{DSON}, threshold voltage V_{GSTH}, and body diode forward voltage V_{SD}. On-line condition monitoring setups for SiC MOSFET have been proposed by utilizing these on-board measurement techniques [12]-[14]. However, other critical electrical parameters, such as leakage current and capacitances, must be measured off-line using device analyzers. The device analyzers provide an accurate evaluation of power semiconductor devices' electrical parameters; however, only one device can be characterized each time, which requires manual device switching. It is exceptionally labor- and time-consuming when characterization of multiple devices is needed. It is reported that most researchers have difficulties in characterizing power devices, and a few large-scale characterization designs have been proposed for the reliability studies [15],[16].

This paper proposes a fully automated, modularized power semiconductor device characterization system based on the conventional curve tracer. A high precision multi-channel characterization module is implemented to achieve large-scale device characterization. For this purpose, a LabVIEW program is developed to realize automated device switching and characterization. Besides, the proposed system also achieves automatic data extraction and collection.

In this paper, the details of the proposed modularized large-scale semiconductor device assessment system are introduced, and on-line test results are presented to support the functionality and feasibility. The hardware-level and software-level implementation are introduced in section II. In section III, on-board test results are discussed to verify the measurement accuracy and consistency of the proposed system. And the automation is verified by channel control signals during switching transitions. Section IV concludes the design and discussions through this paper.

II. SYSTEM DESIGN AND IMPLEMENTATION

A. System Overview

The overview of the proposed system, which consists of three subsystems, is presented in Fig. 1. A high-accuracy, modularized module board is designed to test up to 10 devices under test (DUTs). The National Instrument Data Acquisition (NI DAQ) generates digital signals to control DUT tests. And the DAQ is controlled by a LabVIEW virtual instruments (VIs) program. The VIs program enables or disables the required DUT channels in a designed sequence. Moreover, another LabVIEW program is developed to send commands, written in Fast LEXical analyzer generator (FLEX) language, to the curve tracer through the general-purpose interface bus (GPIB) interface. The curve tracer uses the received commands to control the source measurement units (SMUs) that installed in the curve tracer to measure the required electrical parameters [17]. Meanwhile, the curve tracer feeds the measurement status and error messages back to the control program. As a result, the automation between two LabVIEW control programs can be realized. This fully automated testing system also provides an automatic data collection functionality, which saves the measurement data into Excel sheets in real-time.

B. Hardware Implementation

1) Source Measurement Unit (SMU)

Most commercial curve tracers or device analyzers utilize the source measurement units (SMUs) to apply a voltage or current signal to the DUTs and perform measurement simultaneously. Each SMU has its own compliance limits to regulate the output voltage or current to prevent potential damage to the DUTs. Common SMU types are summarized in TABLE I with their functionalities, limitations, and connections to the DUT terminals. Different SMUs are actively selected by the control program to enable voltage/current sweeps, voltage/current pulses, or high frequency sweeps based on the measurement requirement. The SMUs measure the required parameters under the set conditions and output the measurement results to a data buffer simultaneously. Additional program can extract the data from the buffer and save into designed documents. Moreover, the SMUs also provide measurement status and errors as feedback signals to the device analyzer if any error exists. As a result, the proposed system utilizes the SMUs as the measurement hardware and status feedback provider.

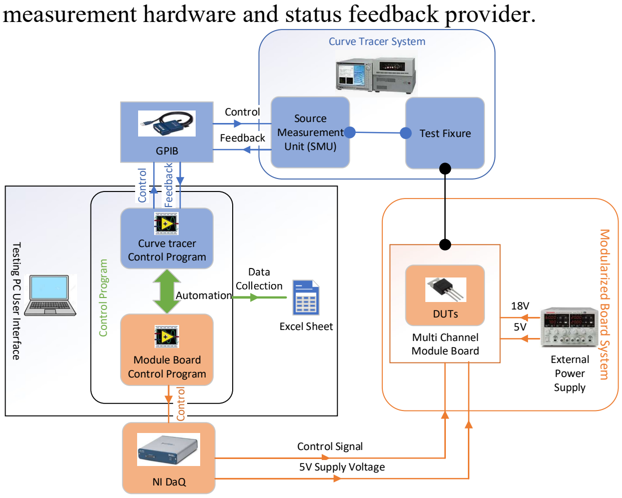

Fig. 1. Overview of the proposed system.

TABLE I
Summaries of common source measurement units (SMUs) in commercial device analyzers [18]

Type of SMU	Function	Electrical Limit	Connection to DUT
Medium Power SMU (MPSMU)	Apply and measure voltage or current	±100 V, ±100 mA, 2W	Drain/Collector
High Current SMU (HCSMU)		± 20 A (pulse), ± 1 A (DC) ± 40V, 40W	
High Voltage SMU (HVSMU)		3000 V/4 mA, -3000 V/-4 mA, 1500 V/8 mA, or -1500 V/-8 mA	
Medium Current SMU (MCSMU)		± 30 V, ± 1 A (pulse), ± 0.1 A (DC), 30W (pulse), 3W (DC)	Gate
Multi-Frequency Capacitance Measurement Unit (MFCMU)	Apply and measure capacitance	1kHz to 5MHz	Drain/Collector & Gate
Ground Unit (GNDU)	Ground	N/A	Source

2) Multi-Device Characterization Board

In order to assess multiple DUTs in an automatic sequence, a high-precision and modularized test board is designed and developed. Two relays are deployed to connect the DUT, a power MOSFET in this case, and the curve tracer in a single DUT channel as shown in Fig. 2. Specifically, a single-pole single-throw (SPST) relay controls the connection between the gate electrode of the DUT and the corresponding test port on the curve tracer. Similarly, a double-pole single-throw (DPST) relay with high voltage blocking capability connects the drain terminal of the DUT and the curve tracer. When both relays are triggered symmetrically, the DUT in this channel is connected to the curve tracer whereas the other DUT channels are isolated by disabling associated relays. As indicated in Fig. 2, the design employs an isolated driver to provide adequate current for relay toggling. Moreover, the voltage regulator and common-mode chokes are employed to maintain a consistent voltage during the channel's on-state by reducing ripples and mitigating noises in the loop. The sequence of characterization and tests can be arbitrarily defined through control signal programming.

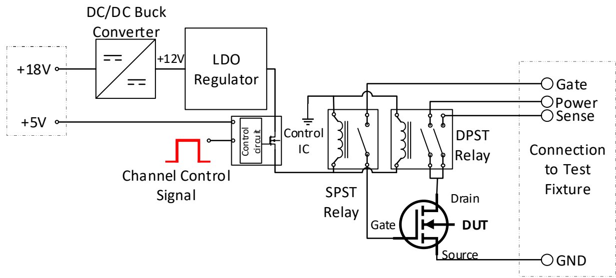

Fig. 2. Logic circuit of a single channel of the multi-DUT test board.

As shown in the dashed boxes in Fig. 2, accessible ports are placed to enable DUT's connection from the test board to the curve tracer. A 10-channel test board prototype, which can test power semiconductors with TO-247 packages with either a common source or the Kelvin gate-source connection, is presented in Fig. 3 [19]. Besides, it can be simply modified for devices in any package with appropriate device sockets. The DUT channels are designed to surround the curve tracer accessible ports to mitigate the measurement variances caused by channel impedances mismatch.

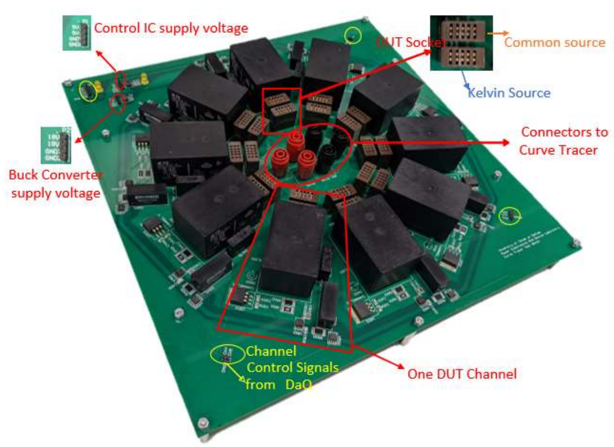

Fig. 3. Proposed multi-DUT test board.

Since the mechanical relays control the connection between the DUT and the curve tracer, measurement errors may occur due to the potential contact resistance inconsistency. The trace impedance between the DUTs and the curve tracer is optimized with the Kelvin connections to reduce the on-board measurement errors. As shown in Fig. 4, each channel's power loop is also optimized to be identical to minimize variations between channels.

C. *Software Design*

The source measurement units (SMUs) installed in the curve tracer provide the functionality to apply/measure electrical parameters of the DUTs, and the proposed test board realizes the feasibility of testing multiple devices. LabVIEW control programs are developed in the proposed system to control the SMUs and the proposed test board. One control program is designed to enable the DUT's parametric measurement and receive the curve tracer's status through the GPIB interface. And another program controls the test board and enables the DUT channels in a designed sequence. Finally, a fully automated device characterization program is implemented in order to integrate control programs

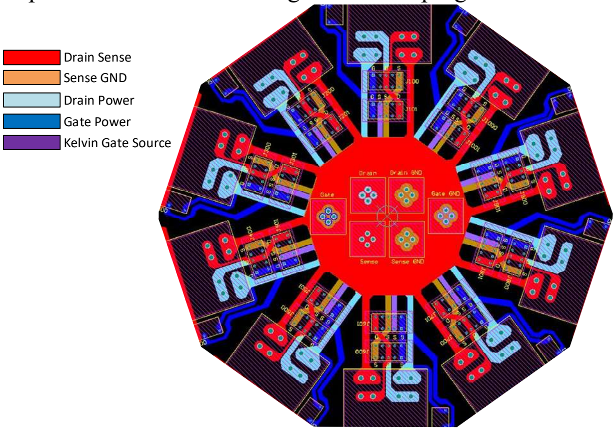

Fig. 4. DUT measurement trace loop layout and optimization.

1) Curve Tracer Measurement Control Program

A LabView program utilizing Virtual Instrument Software Architecture (VISA) is developed in this study to control the GPIB to forward and feedback commands. Since different parameter measurements require variant test voltage/current ranges, various SMUs need to be actively selected for each measurement. Therefore, individual measurement programs are developed to enable the required SMUs for test condition settings. Each measurement program includes three stages, measurement setup, measurement execution, and data collection. At the end of each measurement, the control program automatically saves all tested data into an excel sheet on the test PC. Fig. 5 illustrates the measurement control algorithm. The program stops upon receipt of status feedback when the curve tracer finishes measurements.

2) Multi-DUT Test Board Control Algorithm

The developed multi-DUT test board prototype has ten device channels, whereas only one channel should be toggled during the device characterization. Recall the overview of the test board control system, as shown in Fig. 6, a National Instrument Data Acquisition instrument communicates the test board and control program. Each channel of the test board is wire-connected to one signal port on the DAQ. The developed LabVIEW program triggers the DAQ signal port corresponding to the DUT channel required for measurements while the program holds off other signal ports.

3) Automation Program

Since the developed LabVIEW programs can control both curve tracer and test board, the automated multi-device characterization is achieved by integrating two control programs. The automation program adopts the state machine technique to realize automatic signal switching and parameter measurements [20]. The proposed state machine's operating principle is depicted in Fig. 7 by illustrating the algorithm between channel 1 and channel 2. The 'ON' state of each DUT channel is treated as the 'state' where a series of events can conduct. The states are controlled by the developed test board control program. In the proposed state machine, the curve tracer control program is the 'event' that conducts in each state. For example, the curve tracer control program starts running all measurements required for the device in this channel when the DUT channel 1 is turned on. After all measurements are conducted, the curve tracer feedbacks a termination signal which can be utilized as the 'action executor' in the proposed state machine. This 'action executor' manipulates the test board control program to turn off channel 1 and trigger channel 2. Then the state machine proceeds into the next 'state'. Similarly, the curve tracer control program runs the designed measurements for the device in channel 2. Besides, the utilization of the state machine allows different measurement types or sequences for different DUT channels. As a result, automated measurements of multiple channels can be achieved by using the developed state machine.

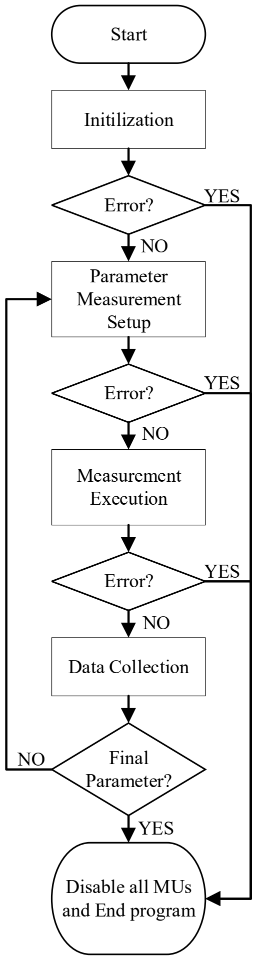

Fig. 5. Measurement control and sanity check algorithm.

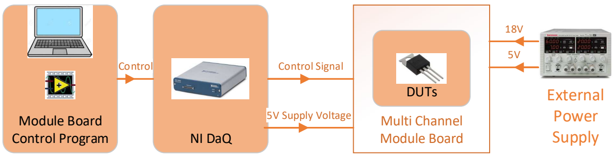

Fig. 6. Test board control system

The algorithm of the automation program is illustrated in Fig. 8. After initializing the hardware communications and turn on the board supply voltage, a starting channel should be selected. Upon selection, the program steps into the state machine and starts the automated device characterization. After the measurements of all DUTs, the program disables the hardware and saves the captured characterization data.

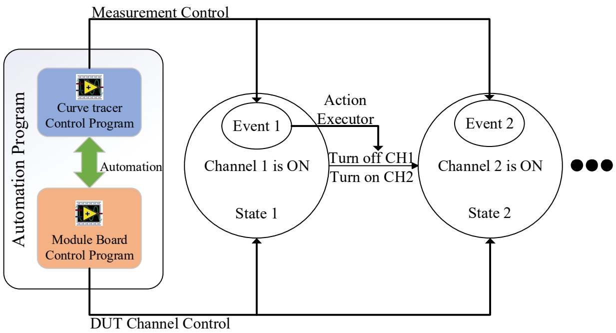

Fig. 7. State machine used in the proposed automation program.

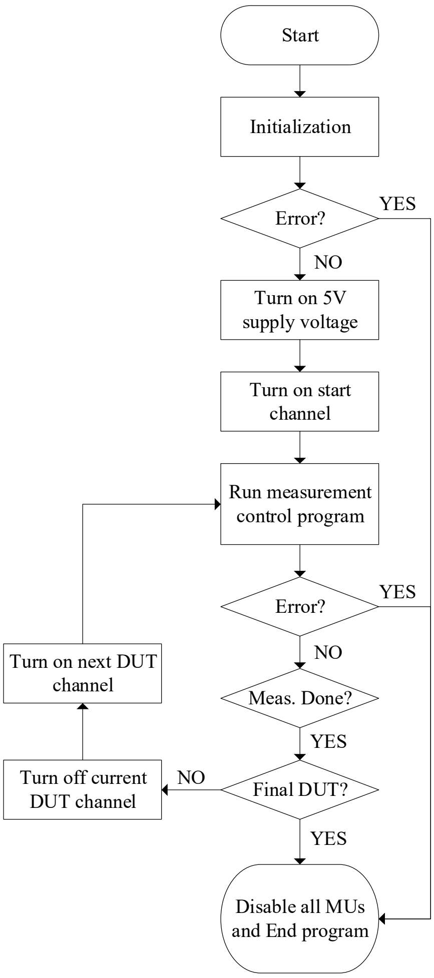

Fig. 8. Proposed algorithm of the automation program.

III. Results and Discussions

The proposed large-scale automated power device test system is shown in Fig. 9. The multi-channel board is designed for up to 10 power devices, but the test board is highly modularized, allowing more DUTs based on the requirements. The NI DAQ instrument, USB 6351 is used to generate the digital control signals to trigger corresponding channels on or off. An external power supply is used to provide the test board's supply voltages. The curve tracer test fixture is cable-connected to the test board. Moreover, the multi-channel test board and the curve tracer are fully controlled by the LabView program on the test PC.

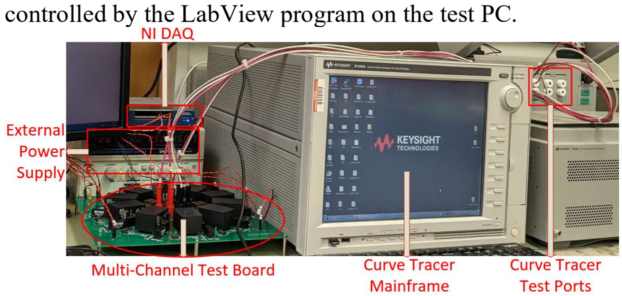

Fig. 9. Proposed large-scale power device automated test system.

A. Measurement Accuracy

Repeated tests were conducted on the same SiC MOSFET by using the implemented test board and the conventional curve tracer adaptor to verify the measurement accuracy. The averages of the on-board results were compared to the mean results from the conventional adaptor for offset analysis. The comparison between the average on-board and off-board measurement results is shown in Table II. It can be observed that most of the parameters, except the on-resistance (R_{DSON}) shows minor errors. The on-board on-resistance (R_{DSON}) measurement shown in Fig. 10 exhibits a constant offset no more than 10mΩ over a wide range of load current. This offset is caused by the relays' contact resistance and the loop resistance of the PCB trace. Higher accuracy of the R_{DSON} measurement can be achieved by offset compensation. By applying a negative offset to the collected on-board R_{DSON} measurement result, highly accurate R_{DSON} measurement data can be collected with negligible errors, as shown in Fig. 10.

Table II
Comparison of on-board and off-board measurement

TSEP	On-board average	Off-board average	Offset
Threshold Voltage V_{TH} (V)	2.407	2.404	0.104%
Drain Leakage Current I_{DSS} (nA)	19.3	19.5	0.10%
Gate Leakage Current I_{GSS} (pA)	25.1	25.35	0.10%
R_{DSON} vs. I_D (Ω)	Compare value at each I_D level		Constant 10 mΩ

B. Measurement Consistency

1) Single Channel measurement consistency

Each electrical parameter was repeatedly measured using the same device by turning on and off the relays to evaluate the single DUT channel's measurement consistency. The measurement's consistency is evaluated by using relative standard error (RSE). RSE can be calculated by using (1), where n is sample size, x_0 is the mean of the sample, and x_i is the value of each sample. Representative critical electrical parameters were repeatedly measured through 5 consecutive tests. The calculated RSE values are presented in Fig. 11. The measurements of each parameter exhibit very low RSE indicating excellent measurement consistency.

$$Relative\ Standard\ Error = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - x_o)^2}{n-1}}}{\sqrt{n} \times x_o} \times 100 \qquad (1)$$

2) Measurement Consistency Between Channels

Other than the measurement consistency of a single channel, the trace impedance induced measurement mismatch is further evaluated. To evaluate the measurement consistency between channels, the same DUT is plugged into all channels in sequence and the same parametric measurements are conducted. The comparison results of exemplary parameters (R_{DSON}, V_{TH}, I_{DSS}, I_{GSS}) are illustrated in Fig. 12. It can be concluded that the measurement difference between each channel is negligible.

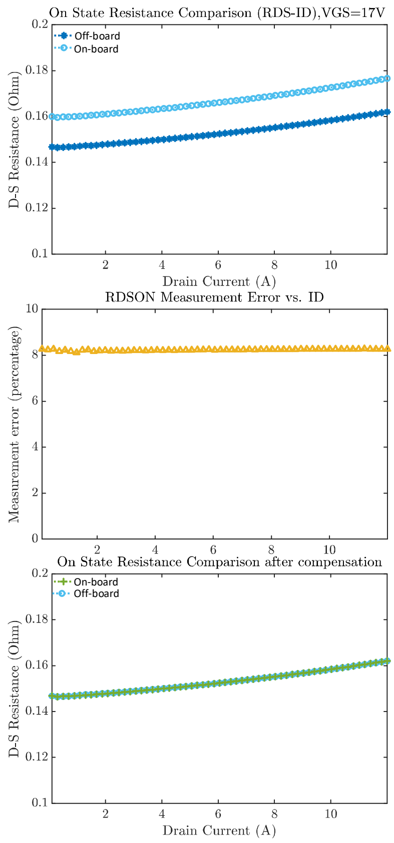

Fig. 10. On-board and off-board on-resistance R_{DSON} measurement results.

C. Automation Verification

As discussed, the automation of the system is realized by switching DUT channels on and off in a designed sequence. As an example, the characteristic of switching transitions between DUT channel 1 and channel 2 is presented in Fig. 13 by capturing the voltages across the relays in each channel. The curve tracer performs the DUT measurements when channel 1 is on. When measurements are finished in channel 1, the control voltage is turned off automatically then channel 2 voltage is turned on after a certain delay time. Noticeably, it shows that it takes approximately 2.6ms for the relays to turn off and 7.8ms to be fully turned on. Therefore, the delay time must be designed with adequate dead-time to avoid overlapping. In this study, the delay time is adjusted to 50ms to ensure reliable channel switching, as shown in Fig. 14.

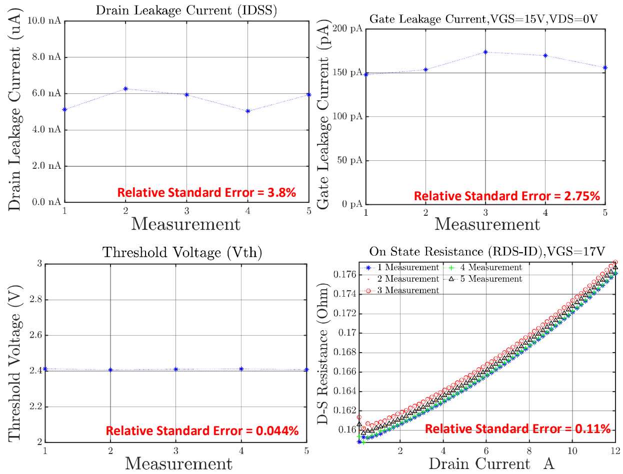

Fig. 11. Consistency verification on critical parameters at single DUT channel.

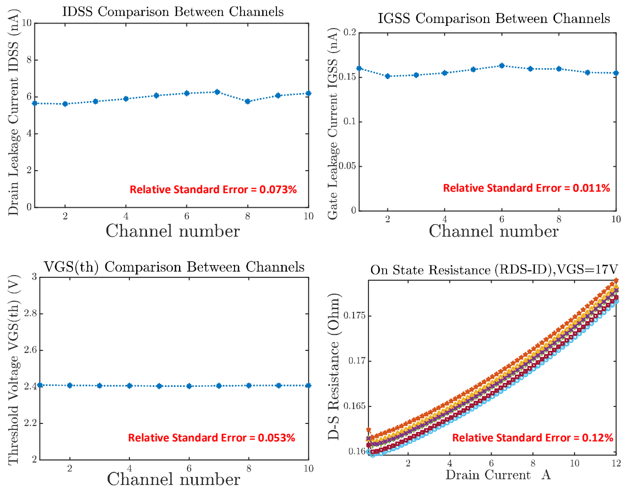

Fig. 12. Measurement comparison of critical parameters between all DUT channels.

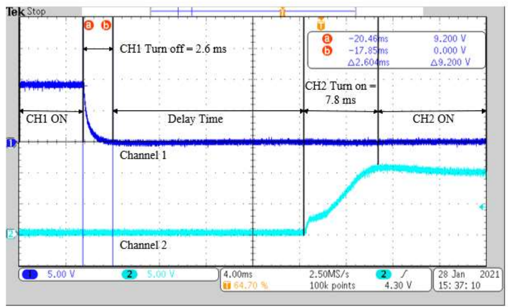

Fig. 13. Experimental switching waveform during the transition from channel 1 to channel 2.

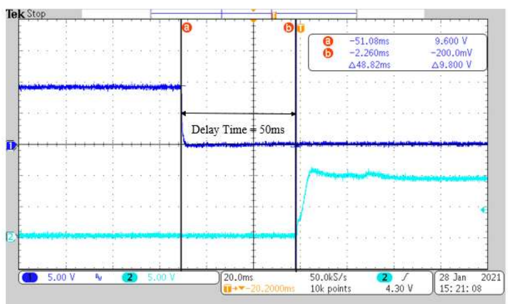

Fig. 14. Designed delay time between channel turn-on and turn-off.

IV. Conclusion

In this paper, a fully automatic modular power device characterization system is proposed to acquire high-resolution and accurate device parameter measurements. This setup is essential for massive device aging tests during comprehensive reliability studies. The proposed multi-channel device test board consists of 10 isolated and modularized device channels, and it is scalable if more channels are required. The on-board measurement consistency and accuracy are verified by comparing the on-board and off-board measurements results. The experimental results demonstrate a consistent and negligible on-board measurement offset that can easily be compensated. The proposed test system realizes high automation at measurement execution, device switching, and data collection. The fully automatic system enables (1) testing multiple power devices without manual device switching; (2) automatic parameter selection and measurement; and (3) automated data collection.

V. Acknowledgment

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VI. References

[1] B. Wang, J. Cai, X. Du and L. Zhou, "Review of power semiconductor device reliability for power converters," in CPSS Transactions on Power Electronics and Applications, vol. 2, no. 2, pp. 101-117, 2017.

[2] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran and P. Tavner, "Condition Monitoring for Device Reliability in Power Electronic Converters: A Review," in IEEE Transactions on Power Electronics, vol. 25, no. 11, pp. 2734-2752, Nov. 2010.

[3] J. Millán, P. Godignon, X. Perpiñà, A. Pérez-Tomás and J. Rebollo, "A Survey of Wide Bandgap Power Semiconductor Devices," in IEEE Transactions on Power Electronics, vol. 29, no. 5, pp. 2155-2163, May 2014.

[4] H. Oh, B. Han, P. McCluskey, C. Han and B. D. Youn, "Physics-of-Failure, Condition Monitoring, and Prognostics of Insulated Gate Bipolar Transistor Modules: A Review," in IEEE Transactions on Power Electronics, vol. 30, no. 5, pp. 2413-2426, May 2015.

[5] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran and P. Tavner, "Condition Monitoring for Device Reliability in Power Electronic Converters: A Review," in IEEE Transactions on Power Electronics, vol. 25, no. 11, pp. 2734-2752, Nov. 2010.

[6] U. Choi, F. Blaabjerg and S. Jørgensen, "Power Cycling Test Methods for Reliability Assessment of Power Device Modules in Respect to Temperature Stress," in IEEE Transactions on Power Electronics, vol. 33, no. 3, pp. 2531-2551, March 2018.

[7] R. Ouaida et al., "Gate Oxide Degradation of SiC MOSFET in Switching Conditions," in IEEE Electron Device Letters, vol. 35, no. 12, pp. 1284-1286, Dec. 2014.

[8] Z. Chen, Y. Yao, M. Danilovic and D. Boroyevich, "Performance evaluation of SiC power MOSFETs for high-temperature applications," 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC), Novi Sad, 2012, pp. DS1a.8-1-DS1a.8-9.

[9] B. T. Vankayalapati, F. Yang, S. Pu, M. Farhadi and B. Akin, "A Highly Scalable, Modular Test Bench Architecture for Large-Scale DC Power Cycling of SiC MOSFETs: Towards Data Enabled Reliability," in IEEE Power Electronics Magazine, vol. 8, no. 1, pp. 39-48, March 2021,

[10] F. Yang, E. Ugur and B. Akin, "Evaluation of Aging's Effect on Temperature-Sensitive Electrical Parameters in SiC mosfets," in IEEE Transactions on Power Electronics, vol. 35, no. 6, pp. 6315-6331, June 2020.

[11] C. Xu, F. Yang, Y. Ramadass and B. Akin, "Performance Degradation of Automotive Power MOSFETs Under Repetitive Avalanche Breakdown Test," in IEEE Transactions on Transportation Electrification, vol. 7, no. 1, pp. 58-68, March 2021.

[12] E. Ugur, C. Xu, F. Yang, S. Pu and B. Akin, "A New Complete Condition Monitoring Method for SiC Power MOSFETs," in IEEE Transactions on Industrial Electronics, vol. 68, no. 2, pp. 1654-1664, Feb. 2021.

[13] S. Pu, F. Yang, B. T. Vankayalapati, E. Ugur, C. Xu and B. Akin, "A Practical On-Board SiC MOSFET Condition Monitoring Technique for Aging Detection," in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 2828-2839, May-June 2020.

[14] S. Pu, E. Ugur and B. Akin, "Real-time degradation monitoring of SiC-MOSFETs through readily available system microcontroller," 2017 IEEE 5th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Albuquerque, NM, USA, 2017, pp. 378-382.

[15] J. Sun, H. Xu, S. Yang and K. Sheng, "Electrical characterization of 1.2kV SiC MOSFET at extremely high junction temperature," 2018 IEEE 30th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Chicago, IL, USA, 2018, pp. 387-390.

[16] A. Marzoughi, R. Burgos and D. Boroyevich, "Characterization and Performance Evaluation of the State-of-the-Art 3.3 kV 30 A Full-SiC MOSFETs," in IEEE Transactions on Industry Applications, vol. 55, no. 1, pp. 575-583, Jan.-Feb. 2019.

[17] C. Pace, A. Piacente, F. Vescio, S. Pierro, R. Dalia and G. S. Bisht, "An ultra-low-noise Source-Measuring Unit for semiconductor device noise characterization," 2010 IEEE Instrumentation & Measurement Technology Conference Proceedings, Austin, TX, 2010, pp. 482-485.

[18] Keysight Technologies Japan K.K. 9-1, Takakura-cho, Hachioji-shi, Tokyo, Japan. "Keysight Technologies B1506A Power Device Analyzer for Circuit Design," pp. 1-26 – 1-39 [Online]. Available: https://literature.cdn.keysight.com/litweb/pdf/B1506-90000.pdf?id=630939.

[19] V. Crisafulli, "A new package with kelvin source connection for increasing power density in power electronics design," 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, 2015, pp. 1-8.

[20] R. Bitter, "LabVIEW Advanced Programming Techniques," Boca Raton: CRC Press LLC, 2001 [Online]. Available: http://www.physics.utah.edu/~jui/3620/supp/LV_Adv_Prog/2049ch03.pdf.

VII. Biographies

Nathan Zhang received the B.S. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 2016, and the M.S. degree from The University of Texas at Dallas, Richardson, TX, USA, in 2021.

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Bilal Akin (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the Texas A&M University, College Station, TX, USA, in 2007.

From 2005 to 2008, he was an R&D Engineer with Toshiba Industrial Division, Houston, TX, USA. From 2008 to 2012, he was an R&D Engineer with C2000 DSP Systems, Texas Instruments Incorporated, Dallas, TX, USA. Since 2012, he has been with The University of Texas at Dallas, Richardson, TX, USA, as a Faculty. His research interests include the design, control, and diagnosis of electric motors and drives, digital power control and management, and the fault diagnosis and condition monitoring of power electronics component and ac motors.

Dr. Akin was the recipient of the NSFCAREER'15 Award, IEEEIAS Transactions First Place Prize Paper Award, Top Editors Recognition Award from IEEE TVT Society, Jonsson

School Faculty Research Award, and Jonsson School Faculty Teaching Award. He is an Associate Editor for the IEEE TRANSACTION ON INDUSTRY APPLICATIONS and IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.