Focuses and Concerns of Dynamic Test for Wide Bandgap Device: A Questionnaire-Based Survey

Peng Sun, *Student Member, IEEE*, Mingrui Zou, *Student Member, IEEE*, Yulei Wang, Jiakun Gong, Yuxi Liang, Fuli Niu, Ke Jiang, *Senior Member, IEEE*, Wei Gao, and Zheng Zeng, *Member, IEEE*

***Abstract*—Motivated by the excellent advantages of high switching speed, low ON-resistance, and high thermal conductivity, the wide bandgap (WBG) devices, including silicon carbide metal-oxide-semiconductor field-effect transistor and gallium nitride high electron mobility transistors, have received increasing attention. However, the high switching speed of WBG devices also brings more concerns and challenges for the dynamic test, which need to be clarified. Based on the questionnaire-based survey administered to engineers and researchers in both the power electronics industry and academia, the focuses and concerns of the dynamic test for WBG devices are investigated in this article. According to the professional background of respondents, the experience, focuses and concerns for the dynamic test of WBG devices are obtained. Subsequently, the correlation between designed questions is analyzed. It is concluded that the measurement probe has a critical effect on the confidence level of the test results, and needs to be improved in some key parameters, such as the bandwidth, common mode rejection ratio, cost, and consistency, to meet the demand of the dynamic test of WBG devices. In addition, the outcomes of this survey and future frameworks for the dynamic test of WBG devices are concluded, which provides a roadmap for researchers and industry professionals to tackle the challenges associated with the dynamic test of WBG devices.**

***Index Terms*—Device failure, dynamic test, probe bandwidth, questionnaire-based survey, wide bandgap (WBG) device.**

I. INTRODUCTION

THE wide bandgap (WBG) devices, particularly the silicon carbide metal-oxide-semiconductor field-effect transistor (SiC MOSFET) and gallium nitride high electron mobility transistor (GaN HEMT), have gained considerable attention due to their inherent advantages, such as high switching speed, high thermal conductivity, and low ON-resistance, making them a promising solution in some emerging applications, including the electric vehicle and data center [1], [2], [3], [4], [5]. Compared with the Si counterpart, the dynamic test technology for WBG devices is more complex due to its high switching speed, severe voltage overshooting, and ringing, which pose significant challenges for the packaging integration [6], [7], circuit design [8], [9], measurement instrument [10], and data analysis [11], [12]. However, despite the importance of the dynamic test, there is still no mature standard for the transient behavior measurement of WBG devices.

In general, the dynamic test of WBG devices consists of four sections: the arrangement for the dynamic test, development of platform, selection of the measurement probe, as well as data acquisition and analysis. Firstly, due to the variety in application and test objective for WBG devices [13], [14], [15], the arrangement for the dynamic test, such as customized fixture for different packages, needs to be conducted. Subsequently, the topology and voltage and current levels are selected before developing the test platform for the WBG device, as displayed in Fig. 1. Compared to the Si counterparts, WBG devices typically impose more stringent requirements on system parameters that may result in the device failure, such as parasitic inductance [16], [17], snubber circuit [18], [19], and protection circuit [20], [21]. Due to the very fast turn-ON and -OFF process of WBG devices, higher demands are placed on the measurement instrument, such as bandwidth [23], common mode rejection ratio (CMRR), precision, and cost [22], [24], [25], [26], [27], as depicted in Fig. 1. In addition, the dynamic test of WBG devices requires advanced oscilloscopes with high bandwidth and sampling rates for accurate data acquisition while the data analysis faces a lack of unified standards for further application, such as the assessment of power loss [28], resulted from severe ringing during the switching process.

While extensive research has been conducted on the dynamic test of WBG devices, there are still unclear concerns and expectations in the academic research and industrial field. Relevant questions remain, such as following.

1) What are the main challenges faced by industry and academia in the dynamic test of WBG devices?
2) What are the most critical factors that affect the accuracy and reliability of the test results?

Manuscript received 18 April 2023; revised 26 July 2023; accepted 2 September 2023. Date of publication 6 September 2023; date of current version 23 October 2023. This work was supported in part by the National Natural Science Foundation of China under Grant 52177169 and in part by the Chongqing Research Program of Basic Research and Frontier Technology under Grant cstc2022ycjh-bgzxm0155. Recommended for publication by Associate Editor N. R. Zargari. *(Corresponding authors: Fuli Niu; Zheng Zeng.)*

Peng Sun, Mingrui Zou, Yulei Wang, Jiakun Gong, Yuxi Liang, Fuli Niu, and Zheng Zeng are with the State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China. (e-mail: sunpeng_96@163.com; zoumingrui96@qq.com; yulei_wang@cqu.edu.cn; 1285646754@qq.com; 1181132344@qq.com; niufuli2010@163.com; zengerzheng@126.com).

Ke Jiang is with the School of Integrated Circuits, Tsinghua University, Beijing 100084, China. (e-mail: kejiang@tsinghua.edu.cn).

Wei Gao is with the China Advanced Semiconductor Industry Innovation Alliance, Beijing 100083, China. (e-mail: gaowei@casa-china.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2023.3312563.

Digital Object Identifier 10.1109/TPEL.2023.3312563

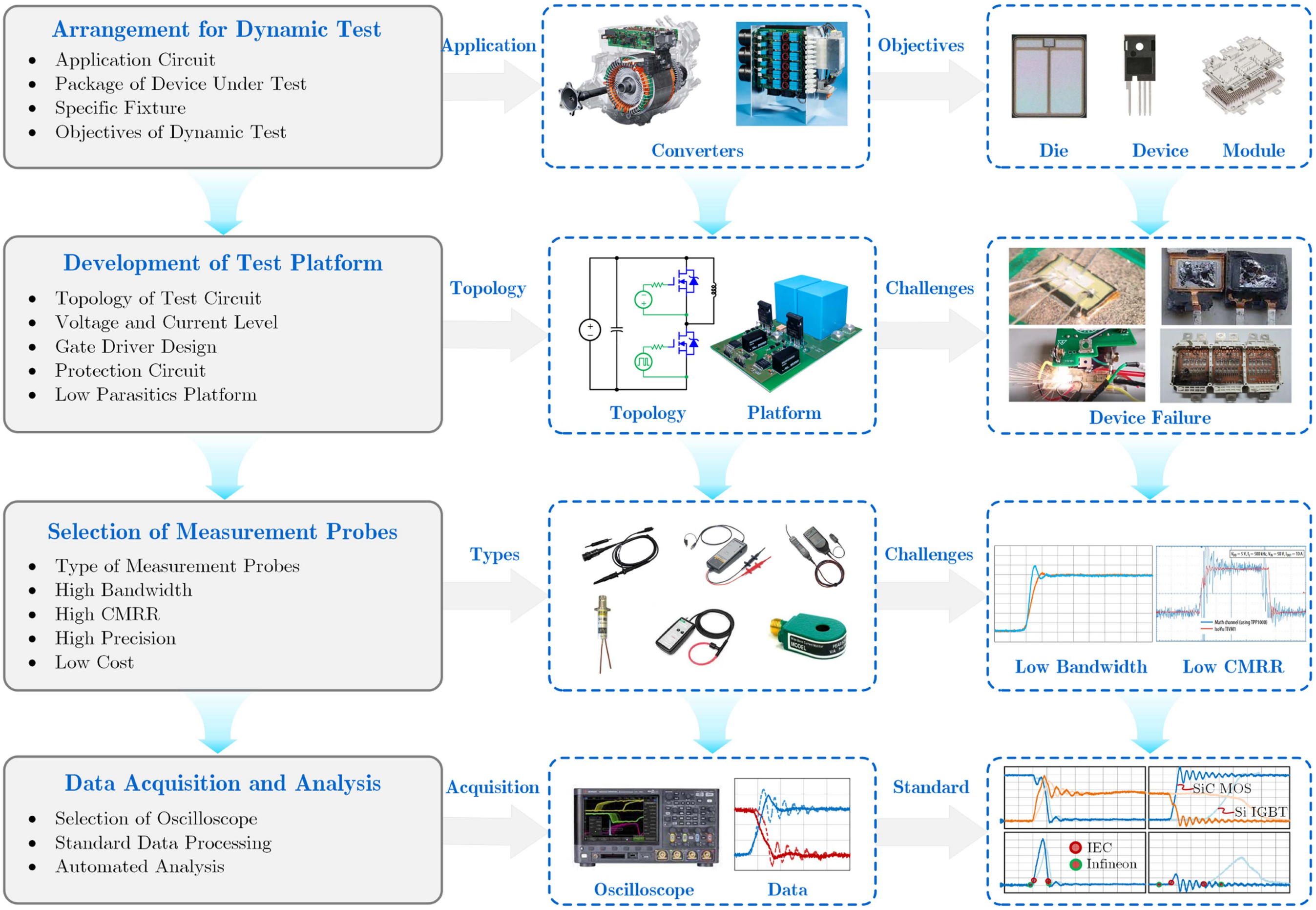


Fig. 1. Typical process of dynamic test for WBG devices.

3) What are the different concerns and demands of different enterprises and research institutes regarding the dynamic test?
4) How can the challenges and limitations be mitigated or eliminated to improve confidence in the test results?
5) What are the future research directions and development trends for the dynamic test of WBG devices, and how can they be aligned with industrial and academic needs and requirements?

Several surveys have been conducted in the power electronics field, addressing popular topics, such as the finite-element analysis [29], converters [30], [31], and motors [32], which have yielded convincing conclusions and garnered significant citations. Therefore, the questionnaire-based survey is a useful method for collecting insights and opinions on the dynamic test of WBG devices from both power electronic industry and academia.

The rest of this article is organized as follows. Section II introduces different parts of the questionnaire and outlines the specific questions that are asked. Section III provides a brief overview of each section of the questionnaire and presents the key results that are obtained. In Section IV, the discussion of the feedback provided by the respondents is presented, along with the outcomes of the survey and future frameworks. Finally, Section V concludes this article.

II. QUESTIONNAIRE DESIGN: STRUCTURE AND CATEGORY

The questionnaire survey document is designed to cover various aspects of the dynamic test of WBG devices. It consists of five parts, including general information, test conditions, challenges, probes and confidence levels. Each part contains several questions that aim to collect valuable feedbacks from the industry and academia.

1) *Responder Sectors*
   a) Question 1: The types of institute.
   b) Question 2: The types of application field.
2) *Preference for the Dynamic Test*
   a) Question 3: the topology of the application circuit.
   b) Question 4: the applied stages of the dynamic test.
   c) Question 5: the targets of the dynamic test.
   d) Question 6: the package type of the tested device.
3) *Experience of Dynamic test From Respondents*
   a) Question 7: The rated voltage of the dynamic test.
   b) Question 8: The rated current of the dynamic test.
   c) Question 9: The topology of the test circuit.
   d) Question 10: The focuses of the dynamic test.
   e) Question 11: The frequency of the device failure.
   f) Question 12: The factors of the device failure.
4) *Selection and Concerns for Measurement Tools*
   a) Question 13: The types of the used probes.

TABLE I
RESPONDENT SECTOR STATISTICS

Respondent Sectors	Number
Die Manufacturer	31
Packaging Industry	27
Research/Academic Organization	49
Power Converter Supplier	25
Test Instrument Supplier	11
Others	5

   b) Question 14: The bandwidth of the voltage probe.
   c) Question 15: The bandwidth of the current probe.
   d) Question 16: The impact degree of the probe.
   e) Question 17: The items of concerns for the probe.

5) *Perception of the Dynamic Test*
   a) Question 18: The confidence degree about the test results.
   b) Question 19: The challenges of the dynamic test.
   c) Question 20: The impact factors of the dynamic test.

This article utilized the web-based questionnaire, which primarily employed checkbox responses allowing participants to select multiple provided options. In instances where the provided options did not align with their experiences, participants are able to provide their own responses. Additionally, several questions, such as Questions 12 and 20, utilized open-ended responses to gather more detailed information. The statistics and primary results derived from the questionnaire survey will be presented and analyzed in Section III.

III. KEY RESULTS

This article utilized the web-based questionnaire that was distributed to 411 individuals, consisting of engineers and researchers working in the manufacture and application of WBG devices. The participants were recruited through a variety of channels, including university and research institute contacts, as well as invitations via email or telephone to companies involved in the dynamic test of WBG devices. All contacts were made during the same time frame. A total of 124 responses from ten countries and regions were deemed effective and were subsequently analyzed. It should be noted that there are multiple respondents from several companies, as indicated by the statistical analysis. Respondents are allowed to select multiple options in their responses to one question. For instance, the company may operate in multiple application areas or produce different types of products.

To comply with the nondisclosure agreement of confidential business information, the identities and affiliations of all respondents have been kept confidential.

A. Characterization of Respondents and Testing Purposes

The participants of this study are categorized into six groups based on their responses to question 1, namely die manufacturers, packaging industry professionals, researchers from academic institutions, suppliers of power converter, test instrument suppliers, and others, as given in Table I. It should be noted that an enterprise may belong to more than one category, leading to a total number of participants exceeding 124. The results indicate that around 40% of the effective respondents are employed by academic organizations, while 25% work in the chip manufacturing industry and 22% have a position in the packaging industry.

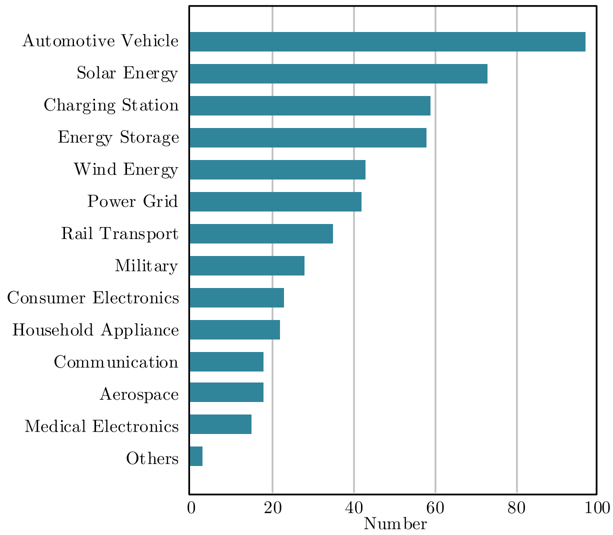


Fig. 2. Profile of respondents (question 2).

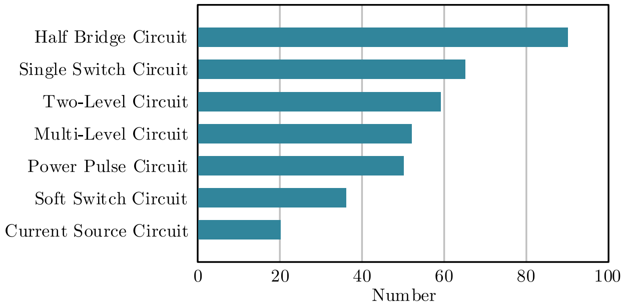


Fig. 3. Main application circuits in respondents (question 3).

Regarding the application areas of the dynamic test of WBG devices, as shown in Fig. 2(see question 2), the automotive vehicle is the most popular application field, accounting for about 78% of the respondents. The other three main application fields are solar energy, charging station, and energy storage, accounting for 59%, 48%, and 47%, respectively. Moreover, the statistics of the main circuit topologies according to the respondents is displayed in Fig. 3. The findings reveal that half-bridge circuit stands out as the most favored topology, constituting approximately 73% of all respondents. In comparison, the single switch circuit and two-level circuit account for 52% and 48%, respectively.

The study also includes an investigation into the various stages of the dynamic test in the WBG applications, which is illustrated in Fig. 4. Three distinct stages are identified as requiring dynamic tests: automation testing for the production line, incoming verification, and research and development (R&D). Most of the dynamic tests are conducted during the R&D period, accounting for approximately 92% of the total. Furthermore, this study also examines the ten most commonly targeted areas of the dynamic

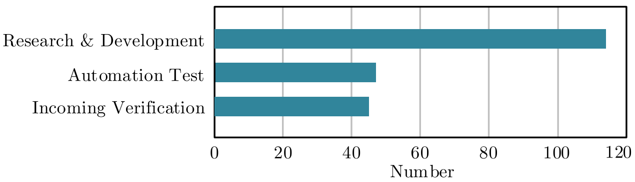


Fig. 4. Stages of dynamic test in WBG applications (question 4).

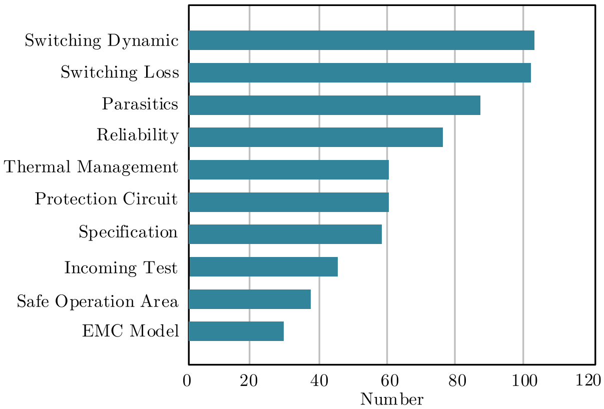


Fig. 5. Targets of dynamic test for WBG devices (question 5).

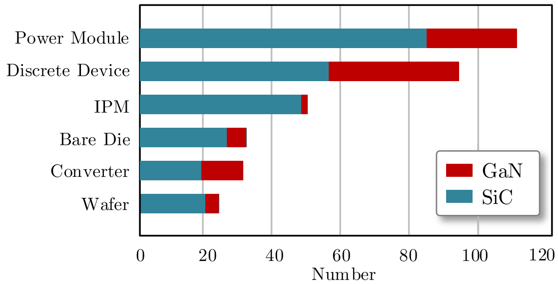


Fig. 6. Packaging types of WBG devices used in dynamic test (question 6).

test for WBG devices, which are displayed in Fig. 5. The results show that the most popular areas of focus for the dynamic test are the switching dynamics and switching loss, followed by the parasitic extraction and reliability evaluation of WBG devices.

B. Dynamic Test for WBG Device

Question 6 inquires about the packaging types of WBG devices utilized in the dynamic test. As illustrated in Fig. 6, the power module is the most frequently employed packaging type, followed in descending order by the discrete device, intelligent power module, bare die, converter, and wafer. The power module is the preferred packaging option for SiC devices, while the discrete device is the popular choice for GaN devices. Questions 7 and 8 evaluate the rated voltage and current levels of the dynamic test platform employed by the respondents. The results depicted in Figs. 7 and 8 indicate that the voltage levels in the range of 650–1000 V are the most commonly used among the respondents, and that the current levels between 50 and 100 A are the primary range. The voltage and current of GaN devices are mainly concentrated below 1200 V and 200 A, respectively.

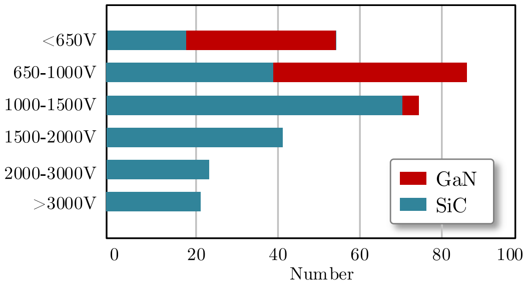


Fig. 7. Rated voltage levels of dynamic test platform (question 7).

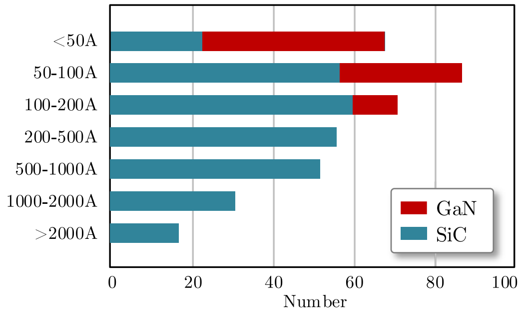


Fig. 8. Rated current levels of dynamic test platform (question 8).

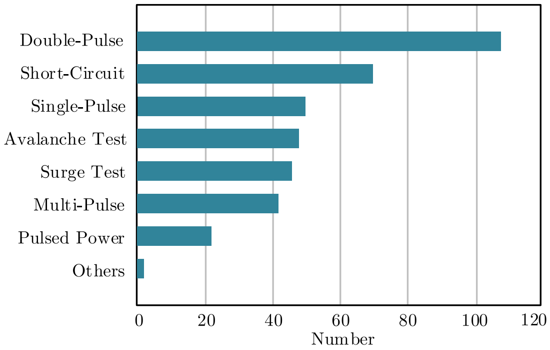


Fig. 9. Topologies of dynamic test circuit (question 9).

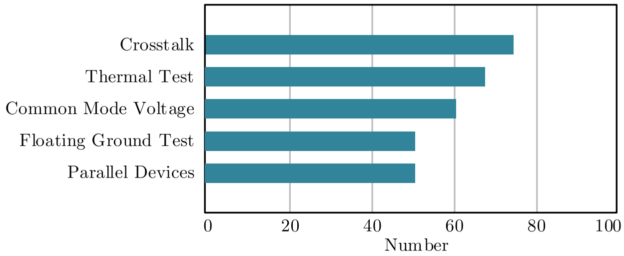


Fig. 10. Focus of respondents during dynamic test (question 10).

The choice of the topology for the dynamic test circuit is typically determined by the test targets. The double pulse test circuit is the most commonly used topology for the dynamic test of WBG devices, as indicated by the results in Fig. 9. Question 10 is designed to investigate the main focus of the respondents during the dynamic test. The study finds that the crosstalk, which has a greater impact on WBG devices because of their low threshold voltage, is the most popular focus of the respondents, as shown in Fig. 10 [33]. Other situations that receive much

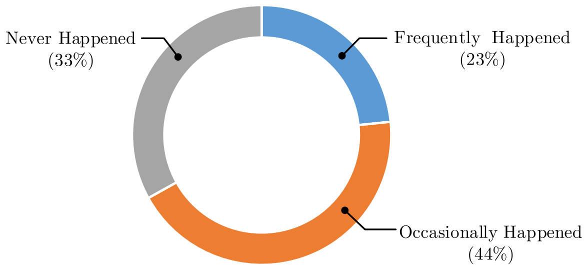


Fig. 11. Frequency of device failure during dynamic test (question 11).

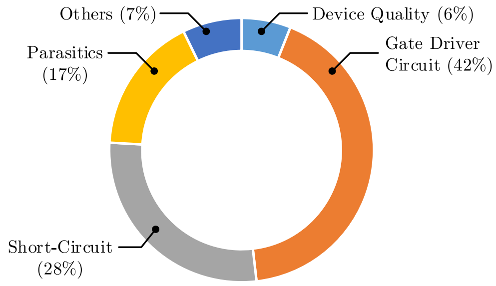


Fig. 12. Factors of device failure during dynamic test (question 12).

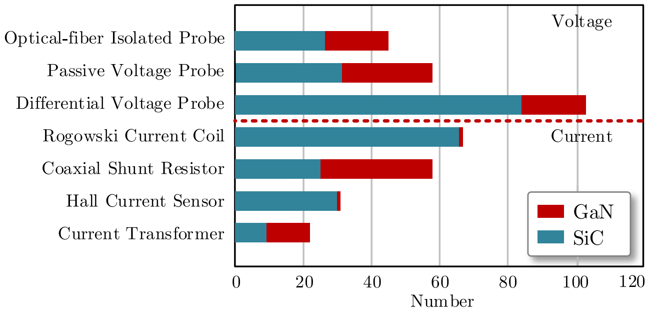


Fig. 13. Types of probes used for dynamic test (question 13).

attention from the respondents include the thermal test, common mode voltage, floating ground, and parallel devices.

Questions 11 and 12 are designed to assess the frequency and causes of the device failure during the dynamic test. The results are presented in Figs. 11 and 12, respectively. It is seen that about 44% and 23% of the respondents have experienced occasional and frequent device failures during the dynamic test of WBG devices, respectively. Moreover, according to their responses regarding the causes of the device failure, as shown in Fig. 12, the gate driver circuit is the primary factor, accounting for 42%, followed by the short circuit (28%), parasitics (17%), other factors (7%), and device quality (6%).

C. Selection and Impact of Measurement Instrument

In this section, the analysis of the selection of measurement probes and the concerns expressed by the respondents are presented. Specifically, the voltage and current probes used for the dynamic test of WBG devices are investigated, which are displayed in Fig. 13. The statistics reveal that the differential voltage probes are the most commonly used for the voltage measurement of SiC devices. It is noteworthy that the optical-fiber isolated probe has been widely accepted for the SiC and GaN devices, owing to its advantages in CMRR and bandwidth. The Rogowski coil is the most popular for the current measurement of SiC devices, while the coaxial shunt resistor is emerging as a trending solution for the current measurement of WBG devices, especially GaN devices.

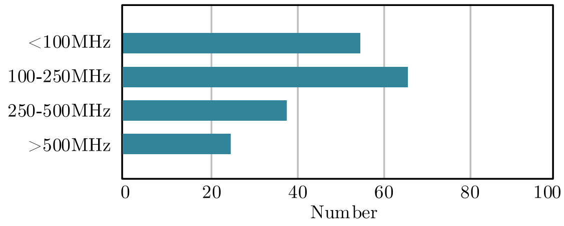


Fig. 14. Bandwidth of voltage probe (question 14).

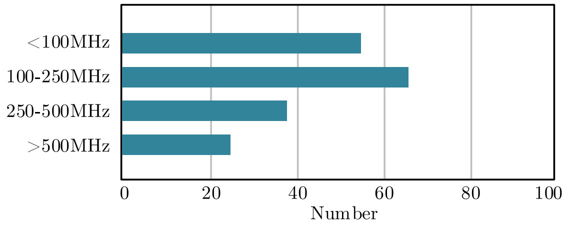


Fig. 15. Bandwidth of current probe (question 15).

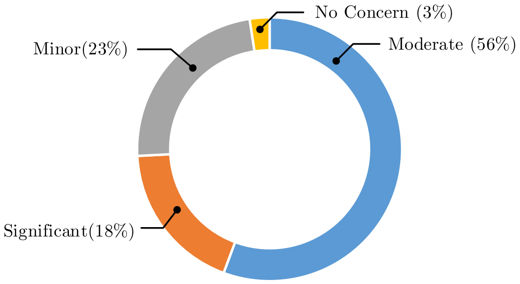


Fig. 16. Impact degree of probe on dynamic test (question 16).

To further investigate the probes employed by the respondents, Questions 14 and 15 are designed to assess the bandwidth of voltage and current probes, respectively. The results, depicted in Figs. 14 and 15, demonstrate that the range of 100–250 MHz is the most popular for both voltage and current probes. Overall, while a higher bandwidth is more precise for measuring the dynamic performance of WBG devices, it often comes with a higher cost that may not be affordable for some applications.

As shown in Fig. 16, more than half of the respondents believe that the probe has a moderate but acceptable impact on the dynamic test of WBG devices. About 18% of the respondents consider that the probe has a significant impact on the dynamic test, which may lead to the oscillation, overshooting and even breakdown failure. Therefore, question 17 is subsequently designed to understand the concerns from the respondents regarding the probes used in the dynamic test of WBG devices. The results in Fig. 17 indicate that the most significant concern for WBG devices, particularly GaN devices, is the insufficient bandwidth. This is closely followed by considerations regarding CMRR, delay time, cost, and measurement precision. Additionally, the

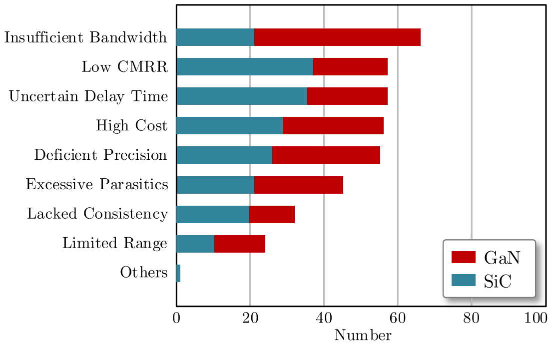


Fig. 17. Concerns for measurement probes for dynamic test (question 17).

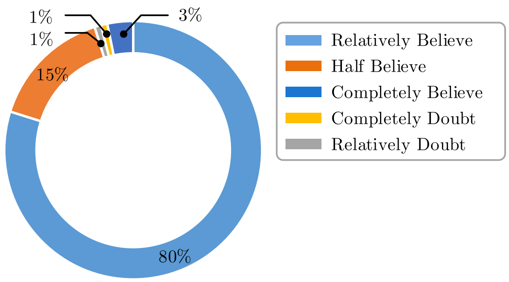


Fig. 18. Confidence degree about results of dynamic test (question 18).

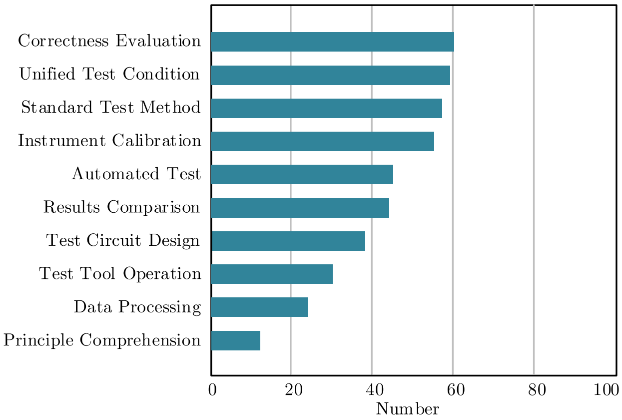


Fig. 19. Challenges of dynamic test (question 19).

CMRR of voltage probes is a major aspect of focus in the dynamic test of SiC devices.

D. Challenges and Focuses for Dynamic Test

Based on the confidence degree about test results shown in Fig. 18, 80% of the respondents relatively believe the test results, while 15% present half confidence about the test results. To identify the primary challenges encountered during the dynamic test of WBG devices, question 19 is designed with ten options.

The results in Fig. 19 reveal the opinions of the respondents regarding the challenges in the dynamic test of WBG devices. It is observed that assessing the accuracy of test results is considered the most significant challenge, followed by the need for a unified test condition and standard test method. The unified test condition necessitates maintaining the same test conditions during multiple dynamic tests to facilitate accurate comparison and assessment of test results. Besides, the calibration of test instruments is also recognized as a critical difficulty for the dynamic test of WBG devices. Although the understanding of the principle of dynamic test for WBG devices is considered one of the least focused challenges, it remains crucial for conducting the dynamic tests and analyzing the test results.

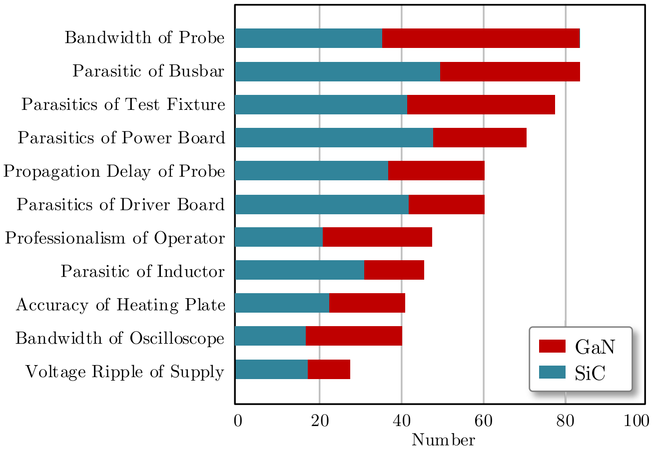


Fig. 20. Impact factors of dynamic test (question 20).

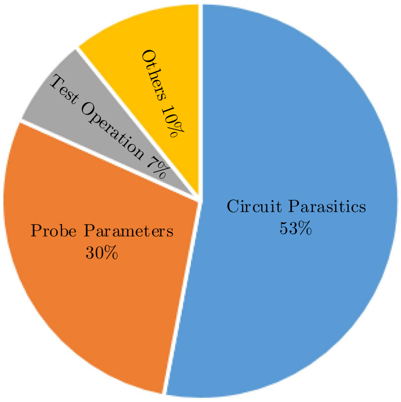


Fig. 21. Percentage of different impact factors for dynamic test (question 20).

Moreover, this survey has revealed several factors that affect the dynamic test of WBG devices, as shown in Fig. 20. According to the responses, the bandwidth and parasitic inductance of the busbar are considered the most significant impact factors in the dynamic testing of GaN and SiC devices, respectively. In addition, the parasitics of the test fixture and power board are also deemed essential factors for the dynamic test of WBG devices. In conclusion, the dominant factor affecting the dynamic test of WBG devices is the circuit parasitics, encompassing the busbar, test fixture, power board, driver board and load inductor. These parasitic elements collectively account for 53% of the overall impact, as displayed in Fig. 21. A total of 30% of the respondents believe that the probe parameters are another influential factor affecting the dynamic test of WBG devices.

IV. DISCUSSION AND OUTCOMES

In this section, the interrelationships between different respondent categories and the results obtained through the survey

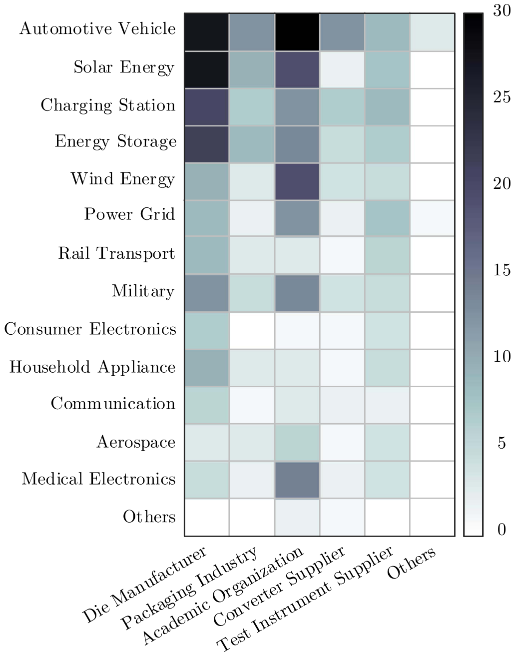


Fig. 22. Focuses of different institutes and enterprises (Q1 versus Q2).

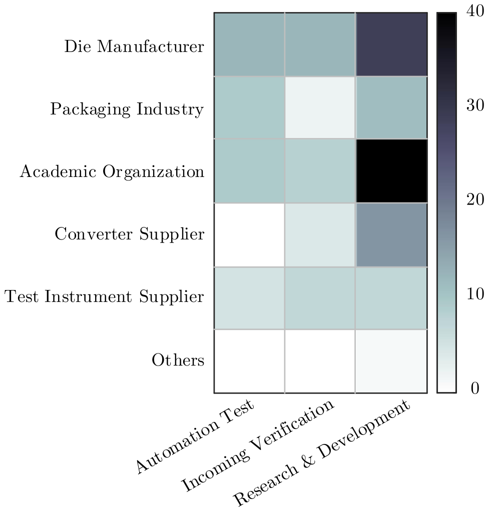


Fig. 23. Stages of different institutes and enterprises (Q1 versus Q5).

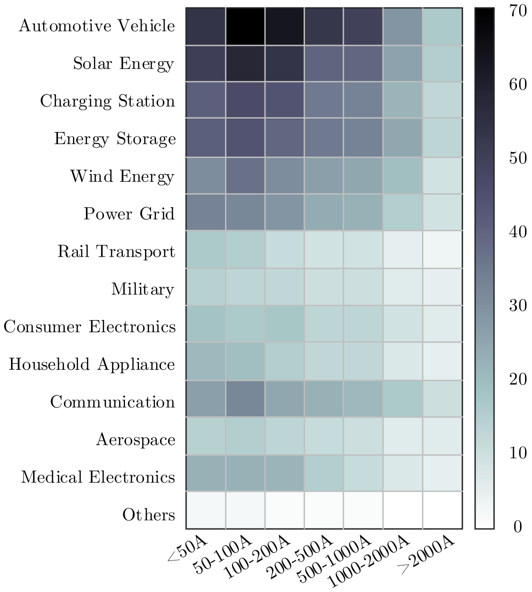


Fig. 24. Current levels of different application fields (Q2 versus Q8).

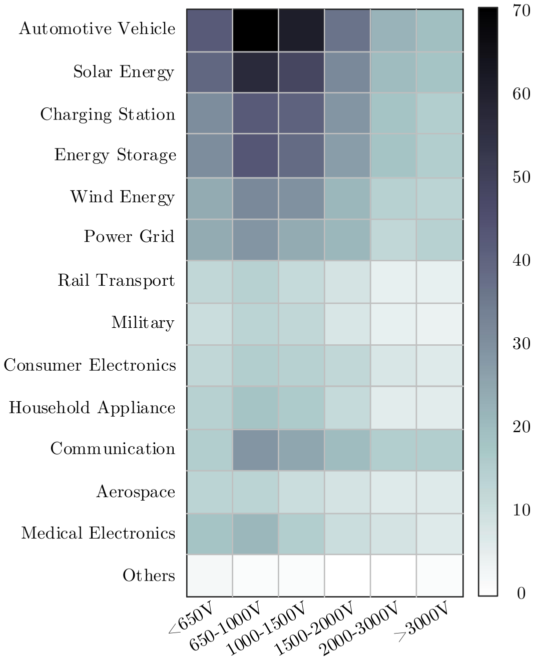


Fig. 25. Voltage levels of different application fields (Q2 versus Q7).

are analyzed through the correlations between questionnaire questions.

A. Preference of Dynamic Test in Different Applications

The application fields of the dynamic test conducted by different institutes are presented in Fig. 22. The analysis shows that the automotive industry is the most common application field for all three types of institutes. In addition, the solar energy and energy storage fields are emerging areas of interest for both die manufacturers and packaging industry, while the academic organizations focus on the solar energy and wind energy.

The stages of dynamic test for WBG devices being carried out by different institutes are displayed in Fig. 23. The current and voltage levels of the dynamic test for various WBG applications are counted and presented in Figs. 24 and 25, respectively. The majority of institutes apply the dynamic test for R&D purposes. The voltage and current levels for most applications are below 1500 V and 1000 A, respectively. Rail transport applications require higher voltage and current levels, which can exceed 3 kV and 2 kA, respectively. In contrast, the voltage and current levels for the automotive vehicle typically range from 650 to 1500 V and 50 to 500 A, respectively. Similarly, the voltage and current levels for the solar energy are typically within the range of 650 V to 2 kV and 50 A to 1 kA, respectively.

The popular test circuits and packages utilized for the dynamic test in various WBG applications are presented in

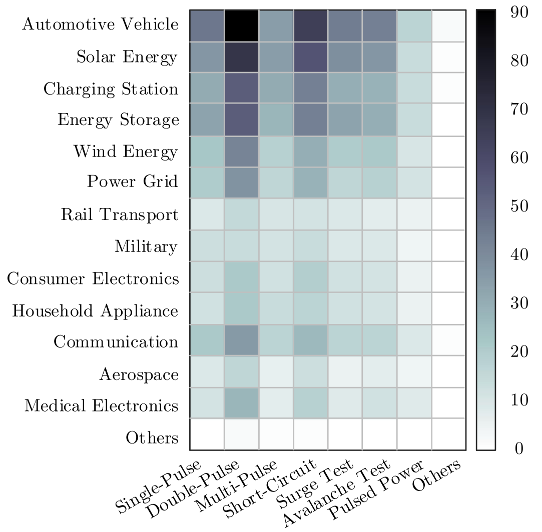


Fig. 26. Test circuits applied in different application fields (Q2 versus Q8).

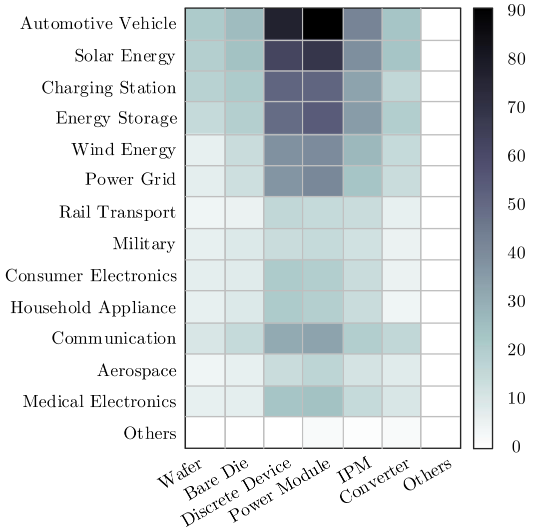


Fig. 27. Packaging levels used in different application fields (Q2 versus Q6).

Figs. 26 and 27. The double pulse and short circuit are the most frequently used test circuit for almost all applications. In addition, the automotive vehicle, solar energy, and energy storage industry also place significant emphasis on the surge and avalanche tests. The discrete device and power module are the most popular packages tested across all applications.

The differences in focuses for various test circuits during the dynamic test of WBG devices are illustrated in Fig. 28. The double pulse test is primarily focused on the floating ground test and parallel device test, as well as on issues related to crosstalk and common mode voltage. In addition, the surge test is focused on robustness evaluation of WBG devices, and the avalanche test is focused on the reliability assessment under high voltage condition. The voltage levels used in various test circuits during the dynamic test are displayed in Fig. 29. The results show that the most popular voltage range falls between 650 and 1500 V for the double pulse circuit and short-circuit.

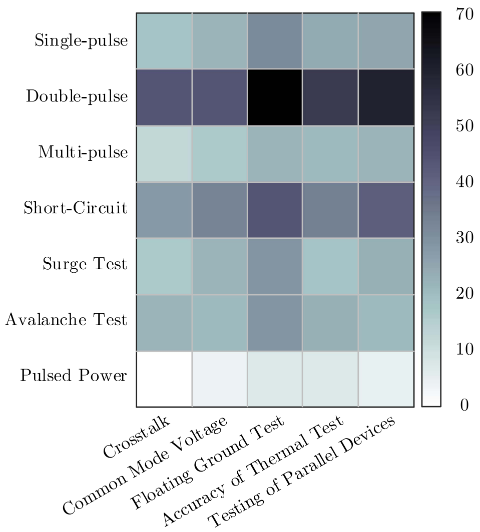


Fig. 28. Concerns of different test circuits (Q9 versus Q17).

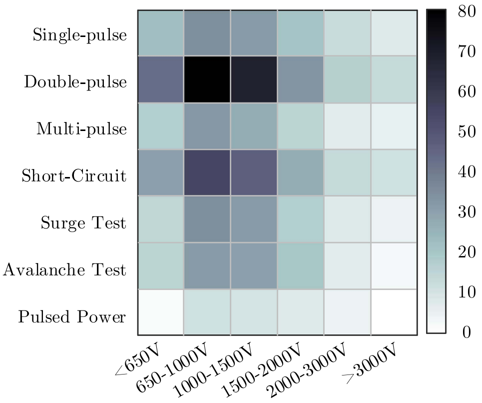


Fig. 29. Voltage levels of different test circuits (Q9 versus Q7).

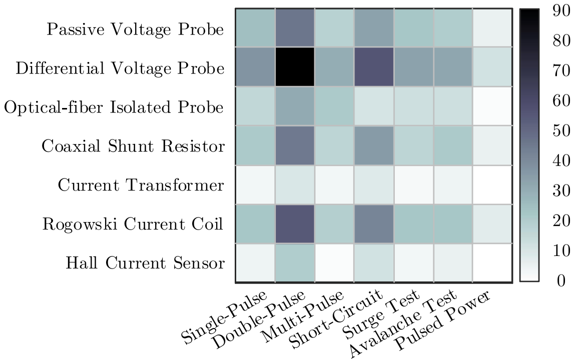


Fig. 30. Probes applied in different test circuits (Q9 versus Q13).

B. *Impacts and Limitations of Measurement Probes*

The preferred measurement probes for various test circuits based on the responses of the survey participants are depicted in Fig. 30. For the double pulse test circuit, the passive voltage probe is commonly used to measure the gate voltage, while the differential voltage probe is preferred for measuring the drain-source voltage of WBG devices. In cases where the voltage measurement of the floating ground point is involved, such as in

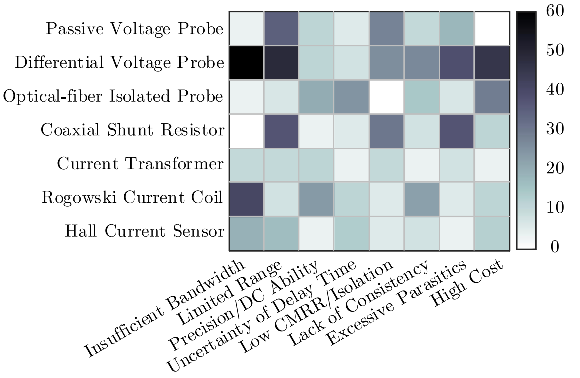


Fig. 31. Concerns for different probes (Q9 versus Q17).

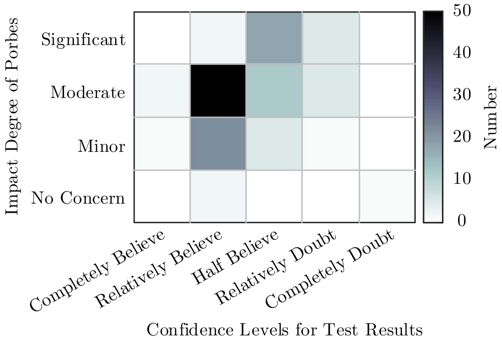


Fig. 32. Correlation between impacts of probes and confidence for tested results (Q16 versus Q18).

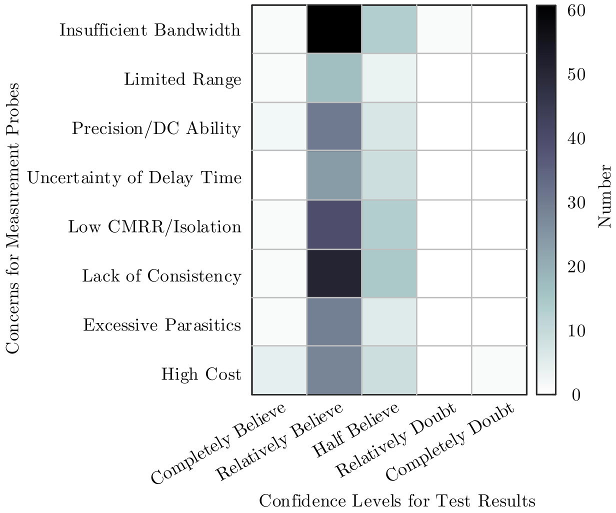
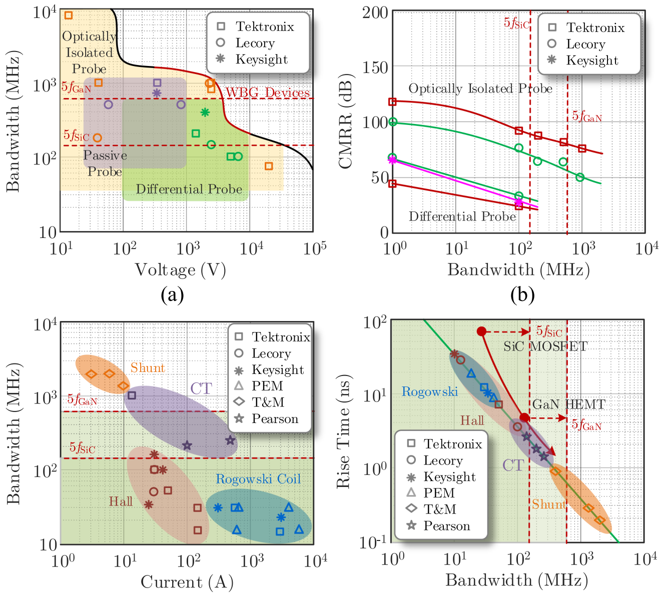


Fig. 33. Correlation between concerns of probes and confidence for tested results (Q17 versus Q18).



(a) (b) (c) (d)

Fig. 34. Statistics of commercial probes. (a) Bandwidth of voltage probes, (b) CMRR of voltage probes, (c) bandwidth of current probes, and (d) rise time of current probes.

the double pulse and multipulse circuits, the optical fiber isolated probe is frequently applied. The Rogowski coil and coaxial shunt resistor are also popular probes for current measurement for the double pulse and short circuit tests.

The limitations of various probes used in the dynamic test are highlighted in Fig. 31. Based on the survey responses, the measurement range of the passive voltage probe is limited, while the differential voltage probe is constrained by its insufficient bandwidth and low CMRR. Although the optical fiber isolated probe has advantages in terms of CMRR and electrical isolation, it is often prohibitively expensive and has a high degree of uncertainty regarding its delay time. The Rogowski coil, on the other hand, typically presents a limited bandwidth and dc capability, resulting in lower consistency of the tested results.

In order to identify the potential influence of employed probes on the confidence levels of the dynamic test results, the analysis of their correlation is conducted and presented in Fig. 32. The results indicate that a majority of respondents believe that the probes have a negative impact on the confidence level of the test results. However, the specific concerns for the measurement probes may have different impacts on the confidence level. The bandwidth, CMRR/isolation, and test consistency, as displayed in Fig. 33, are identified as the three primary factors that influence confidence level of the test results according to the respondents. Due to the fast switching transient and complex switching dynamic of WBG devices compared to Si counterparts, these limitations may lead to untrustworthy or incorrect test results. Therefore, an effective and feasible approach to enhance confidence level in the test results is to mitigate or eliminate the impacts of the probes.

To assess the development status and limitations of probes for the dynamic test of WBG devices, various parameters of commercial probes, such as bandwidth, CMRR, and rise time, are summarized and presented in Fig. 34. As depicted in Fig. 34(a), the bandwidth of the differential probes is suitable for SiC devices, but it falls short for GaN devices, given their higher speed and faster switching transients. On the other hand, the passive probe, despite having sufficient bandwidth, exhibits relatively lower voltage capability for WBG devices, particularly SiC devices. In contrast, the optically isolated probe emerges as a dependable option for the dynamic test of WBG devices, boasting sufficient bandwidth and voltage capabilities.

TABLE II
LIMITATIONS OF PROBES FOR DYNAMIC TEST OF WBG DEVICES

Probe Type	Parameters (Typical)	Test Applications	Limitations
Passive Voltage Probe	Bandwidth:200 MHz Input capacitance:12 pF Max voltage: 300 V	Gate signal measurement	Limited voltage range Nonisolation
Differential Voltage Probe	Bandwidth:200 MHz CMRR: -20 dB@100 MHz Max voltage: ±1500 V	Drain-source voltage of WBG device	Bandwidth likely too low for GaN device Large parasitics
Optically Isolated Probe	Bandwidth:1 GHz CMRR: -90dB@1 GHz Max voltage: ±2500 V	Measurement of high-side devices; Switching transient of GaN devices	High cost Customized fixture Temperature drift
Rogowski Coil	Bandwidth: 100 MHz Precision: ±2% Max current: 300 A	Drain current of WBG devices	Low bandwidth DC bias; Large noise
Shunt Resistor	Bandwidth: 1.2 GHz Max energy: 3 J Resistance: 25 mΩ	Gate current; Drain current of WBG devices	Thermal problem in high power application Nonisolation
Hall Current Sensor	Bandwidth: 50 MHz Max current: 150 A	Drain current of WBG devices	Low bandwidth Temperature sensitivity
Current Transformer	Bandwidth: 400 MHz Max current: 500 A	Drain current of WBG devices	Size and Space Constraints Inability for DC current

In addition, the optically isolated probe demonstrates superior CMRR performance compared to the differential probe, making it suitable for the floating measurement, as shown in Fig. 34(b).

The bandwidth of the commercial current probes is presented in Fig. 34(c)–(d). It is worth noting that the Rogowski coil and hall current probe fail to provide sufficient bandwidth for both SiC and GaN devices. On the other hand, the current transformer is fully suitable for SiC devices but only partly suitable for the GaN devices in terms of the bandwidth. As for the shunt resistor, its bandwidth is sufficient for both devices, but the current it can handle is relatively small.

In addition, other limitations of different probes under various applications are also given in Table II. The nonisolation characteristic of the passive probe restricts its application position. The differential probe introduces additional parasitics, leading to potential measurement errors. Although the optically isolated probe is increasingly favored for the voltage measurement of WBG devices due to its competitive advantages, its high cost and the need for customized fixtures limit its widespread adoption. Additionally, the inability of the Rogowski coil to measure dc current hinders its potential, and the shunt resistor often faces thermal issues in high-power applications. Moreover, the lack of the isolation capability further limits the practical deployment of the shunt resistor. The hall current probe suffers from limitations related to its low bandwidth and temperature sensitivity, whereas the current transformer is constrained by its relatively large size.

C. Concerns and Challenges for Dynamic Test of WBG Devices

As for the dynamic test of WBG devices, different enterprises and research institutes may have varying concerns and demands, which are analyzed and presented in Fig. 35. It is clear that automated test of the dynamic test is the primary focus for the industrial sector, followed by the need for a standard test method and unified test conditions. Generally, extensive tests are required in the industrial sector to assess the performance of WBG products. For research institutes, establishing a standard test method and condition is a pressing need due to the absence of mature test standard and data analysis method. Besides, it is also an obstacle for evaluating and comparing test results of the dynamic test. Thus, it is crucial to establish a test standard to guide the dynamic test of WBG devices.

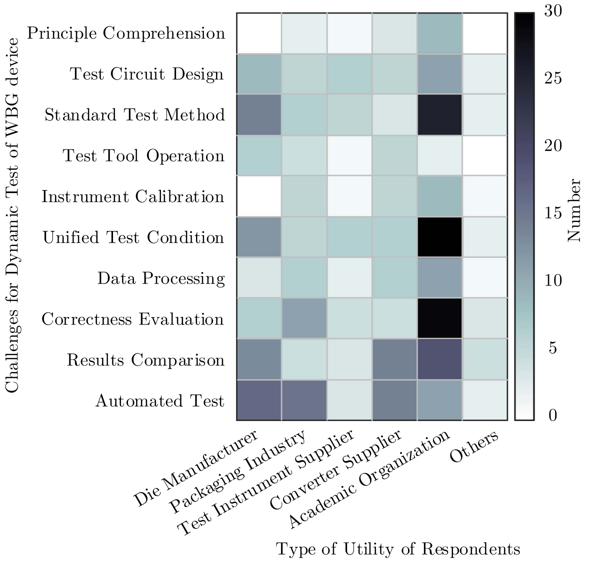


Fig. 35. Challenges from different institutes and enterprises (Q1 versus Q19).

Based on the data collected from the respondents, it is evident that the challenges faced during the dynamic test have a significant impact on the confidence of the test results, as presented in Fig. 36. Respondents with varying perspectives on the challenges of dynamic test for WBG devices exhibit different levels of confidence in the test results. Specifically, the difficulties in the cross-sectional comparison of the test results, correctness evaluation of the test results, and unified test conditions are the three dominant factors affecting the confidence level of the respondents for the test results of the dynamic test. Therefore, the establishment of a standardized test method and unified conditions can be instrumental in building confidence of the test results.

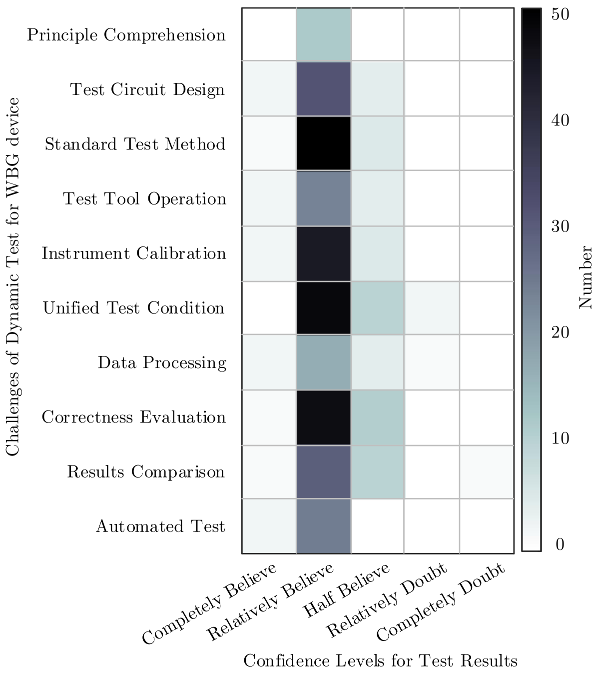


Fig. 36. Correlation between challenges and confidence for test results (Q18 versus Q19).

TABLE III
OUTCOMES OF THIS SURVEY

Outcomes	Demands	Priority
Focuses	Switching Dynamic	☆☆☆☆☆
	Parasitics	☆☆☆
	Switching Loss	☆☆☆☆
	Reliability of Protection Circuit	☆☆
Impact Factors	Limitations of Probes	☆☆☆☆☆
	Professionalism of Operator	☆☆☆
	Parasitics of Test Circuit	☆☆☆☆
Concerns	Correctness of Test Results	☆☆☆☆☆
	Performance of Probes	☆☆☆☆
	Device Failure	☆☆☆

TABLE IV
FUTURE FRAMEWORKS OF DYNAMIC TEST FOR WBG DEVICES

Future Works	Demands	Priority
Test Platform	Low Parasitics	☆☆☆☆☆
	Driver with High Reliability	☆☆☆☆
	Protection Circuit	☆☆☆☆
	Customized Fixture	☆☆☆
Probes	High Bandwidth	☆☆☆☆☆
	Low Cost	☆☆☆
	High CMRR/Isolation	☆☆☆☆
	High Consistency	☆☆☆☆
Test Standard	Unified Test Conditions	☆☆☆☆☆
	Evaluation Methods	☆☆☆☆☆
	Data Processing Method	☆☆☆☆
Others	Automated Test	☆☆☆
	Industry-Academia Collaboration	☆☆☆☆☆

D. Outcomes and Future Frameworks

The outcomes obtained from this survey can be categorized into three groups: focuses, impact factors, and concerns, as given in Table III. The respondents identified the switching dynamics, parasitics, and switching losses as the three primary focuses. Additionally, the reliability of the protection circuits or components is identified as an important consideration. The survey results and subsequent analysis reveal that the most prevalent impact factors are the probe, parasitics of the test circuit, and professionalism of the operator. These factors should be given careful attention by researchers and engineers when conducting the dynamic test of WBG devices. The respondents also expressed concerns regarding the dynamic test for WBG devices, which are further summarized. The most significant concern is related to the accuracy of the test results, followed by the limitations and impacts of probes. Furthermore, the device failure during the dynamic test of WBG devices is also a common concern.

Generally, the future trends in the dynamic test of WBG devices are geared toward achieving the high-speed, high-frequency, high-precision, and high-reliability. To achieve these goals, future frameworks are proposed based on the survey results and analysis, focusing on four aspects: test platform, probes, test standard, and others, as given in Table IV. First, the experimental platform should prioritize low parasitics, followed by the reliable gate driver with protection circuits, and customized fixtures for various packaging types of WBG devices. The development of a universal test fixture capable of accommodating all package types of WBG devices is a critical undertaking for future endeavors. The performance of probes, in terms of the bandwidth, cost, CMRR/isolation, and consistency, should also be improved to meet the measurement demands of WBG devices. In addition, a general standard for the dynamic test of WBG devices should be established, covering test conditions, evaluation methods, and data analysis methods to obtain convincing test results and enable comparison with other dynamic tests. Furthermore, other measures such as automated testing and industry-academia collaboration would also be helpful in mitigating concerns surrounding the dynamic test of WBG devices.

To ensure the accuracy of the results of this survey, the questionnaire is carefully designed and analyzed. However, this survey has certain limitations and may not encompass all possible aspects of the topic. These limitations arise from factors such as the quality of the questions, the level of detail in the responses, and the limited sample size of the respondents. Despite these limitations, the effective response rate of 30% is considered acceptable. The proposed future work in this article serves as a reference for engineers and researchers, but it is subject to potential variations and adjustments in light of advances in the probe technology and WBG device industry. Therefore, continuous efforts and adaptations are required to keep up with the rapidly changing landscape and ensure the relevance and effectiveness of the research in the dynamic test of WBG devices.

V. CONCLUSION

The dynamic test is widely used to design and assess WBG devices, including SiC MOSFET and GaN HEMT. Focusing on concerns and challenges associated with the dynamic test of WBG devices, a web-based questionnaire is designed and conducted in this paper. First, the preference and experience of the respondents for the dynamic test of WBG devices is obtained. Subsequently, the concerns and challenges of the dynamic test of WBG devices, which are answered by the respondents based on their professional background, are collected. The correlation between questions is also analyzed to provide valuable insight into concerns and expectations of both the industry and academia. Based on the analysis, the measurement probe is considered as the essential obstacle, which imposes a significant impact on the confidence level of the test results, thus needing to be enhanced in terms of the bandwidth, CMRR, cost and consistency to meet the demand of the dynamic test of WBG devices. Additionally, the outcomes of this survey and future frameworks for the dynamic test of WBG devices are concluded. This survey provides valuable insight into the dynamic test of WBG devices, which gives a reference for researchers and industry engineers to mitigate their concerns related to the dynamic test of WBG devices.

REFERENCES

[1] X. Ding et al., "Analytical and experimental evaluation of SiC-inverter nonlinearities for traction drives used in electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 146–159, Jan. 2018.

[2] G. Moreno, S. Narumanchi, J. Tomerlin, and J. Major, "Single-phase dielectric fluid thermal management for power-dense automotive power electronics," *IEEE Trans. Power Electron.*, vol. 37, no. 10, pp. 12474–12485, Oct. 2022.

[3] Y. Han, H. Lu, Y. Li, and J. Chai, "Analysis and suppression of shaft voltage in SiC-based inverter for electric vehicle applications," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6276–6285, Jul. 2019.

[4] Z. Zeng, X. Zhang, F. Blaabjerg, H. Chen, and T. Sun, "Stepwise design methodology and heterogeneous integration routine of air-cooled SiC inverter for electric vehicle," *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3973–3988, Apr. 2020.

[5] M. Dong, H. Li, S. Yin, Y. Wu, and K. Y. See, "A postprocessing-technique-based switching loss estimation method for GaN devices," *IEEE Trans. Power Electron.*, vol. 36, no. 7, pp. 8253–8266, Jul. 2021.

[6] N. Zhu, H. A. Mantooth, D. Xu, M. Chen, and M. D. Glover, "A solution to press-pack packaging of SiC MOSFETs," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8224–8234, Oct. 2017.

[7] C. M. DiMarino, B. Mouawad, C. M. Johnson, D. Boroyevich, and R. Burgos, "10-kV SiC MOSFET power module with reduced common-mode noise and electric field," *IEEE Trans. Power Electron.*, vol. 35, no. 6, pp. 6050–6060, Jun. 2020.

[8] S. Lee, K. Kim, M. Shim, and I. Nam, "A digital signal processing based detection circuit for short-circuit protection of SiC MOSFET," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 13379–13382, Dec. 2021.

[9] Y. Fu, Z. Ma, and H. Ren, "A low cost compact SiC/Si hybrid switch gate driver circuit for commonly used triggering patterns," *IEEE Trans. Power Electron.*, vol. 37, no. 5, pp. 5212–5223, May 2022.

[10] Z. Zeng, X. Zhang, F. Blaabjerg, and L. Miao, "Impedance-oriented transient instability modeling of SiC MOSFET intruded by measurement probes," *IEEE Trans. Power Electron.*, vol. 35, no. 2, pp. 1866–1881, Feb. 2020.

[11] X. Li et al., "A SiC power MOSFET loss model suitable for high-frequency applications," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8268–8276, Oct. 2017.

[12] A. Anurag, S. Acharya, and S. Bhattacharya, "An accurate calorimetric loss measurement method for SiC MOSFETs," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1644–1656, Jun. 2020.

[13] W. Mu et al., "Direct integration of optimized phase-change heat spreaders into SiC power module for thermal performance improvements under high heat flux," *IEEE Trans. Power Electron.*, vol. 37, no. 5, pp. 5398–5410, May 2022.

[14] F. Yang et al., "Interleaved planar packaging method of multichip SiC power module for thermal and electrical performance improvement," *IEEE Trans. Power Electron.*, vol. 37, no. 2, pp. 1615–1629, Feb. 2022.

[15] S. Seal, M. D. Glover, and H. A. Mantooth, "3-D wire bondless switching cell using flip-chip-bonded silicon carbide power devices," *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8553–8564, Oct. 2018.

[16] S. K. Roy and K. Basu, "Measurement of circuit parasitics of SiC MOSFET in a half-bridge configuration," *IEEE Trans. Power Electron.*, vol. 37, no. 10, pp. 11911–11926, Oct. 2022.

[17] P. Nayak and K. Hatua, "Active gate driving technique for a 1200 V SiC MOSFET to minimize detrimental effects of parasitic inductance in the converter layout," *IEEE Trans. Ind. Appl.*, vol. 54, no. 2, pp. 1622–1633, Mar./Apr. 2018.

[18] X. Han et al., "PZT-based mitigation of voltage overshooting and switching oscillation for SiC MOSFET," in *Proc. IEEE Int. Power Electron. Appl. Conf. Expo.*, 2022, pp. 60–65.

[19] J. Kim, D. Shin, and S.-K. Sul, "A damping scheme for switching ringing of full SiC MOSFET by air core PCB circuit," *IEEE Trans. Power Electron.*, vol. 33, no. 6, pp. 4605–4615, Jun. 2018.

[20] S. Lee, K. Kim, M. Shim, and I. Nam, "A digital signal processing based detection circuit for short-circuit protection of SiC MOSFET," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 13379–13382, Dec. 2021.

[21] W. Ouyang, P. Sun, M. Xie, Q. Luo, and X. Du, "A fast short-circuit protection method for SiC MOSFET based on indirect power dissipation level," *IEEE Trans. Power Electron.*, vol. 37, no. 8, pp. 8825–8829, Aug. 2022.

[22] Z. Xin, H. Li, Q. Liu, and P. C. Loh, "A review of megahertz current sensors for megahertz power converters," *IEEE Trans. Power Electron.*, vol. 37, no. 6, pp. 6720–6738, Jun. 2022.

[23] W. Zhang, Z. Zhang, F. Wang, E. V. Brush, and N. Forcier, "High-bandwidth low-inductance current shunt for wide-bandgap devices dynamic characterization," *IEEE Trans. Power Electron.*, vol. 36, no. 4, pp. 4522–4531, Apr. 2021.

[24] V. Dubickas and H. Edin, "High-frequency model of the Rogowski coil with a small number of turns," *IEEE Trans. Instrum. Meas.*, vol. 56, no. 6, pp. 2284–2288, Dec. 2007.

[25] A. J. L. Joannou, D. C. Pentz, J. D. van Wyk, and A. S. de Beer, "Some considerations for miniaturized measurement shunts in high frequency power electronic converters," in *Proc. IEEE Eur. Conf. Power Electron. Appl.*, 2014, pp. 1–7.

[26] L. Shillaber, L. Ran, Y. Shen, and T. Long, "Gigahertz current measurement for wide band-gap devices," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2020, pp. 2357–2363.

[27] Y. Wang, Z. Zeng, T. Long, P. Sun, L. Wang, and M. Zou, "Impedance-matching shunt: Current sensor with ultrahigh bandwidth and extremely low parasitics for wide-bandgap device," *IEEE Trans. Power Electron.*, vol. 37, no. 10, pp. 11528–11533, Oct. 2022.

[28] Z. Zeng, J. Wang, L. Wang, Y. Yu, and K. Ou, "Inaccurate switching loss measurement of SiC MOSFET caused by probes: Modelization, characterization, and validation," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–14, 2021.

[29] X. Song, V. Pickert, B. Ji, R. T. Naayagi, C. Wang, and Y. Yerasimou, "Questionnaire-based discussion of finite element multiphysics simulation software in power electronics," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 7010–7020, Aug. 2018.

[30] J. J. Cochrane, M. P. Emerson, J. A. Donahue, and G. Wolf, "A survey of HVDC operating and maintenance practices and their impact on reliability and performance," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 514–518, Jan. 1996.

[31] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May/Jun. 2011.

[32] P. O. Donnell, "Report of large motor reliability survey of industrial and commercial installations, Part II," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 865–872, Jul. 1985.

[33] Z. Zhang, F. Wang, L. M. Tolbert, and B. J. Blalock, "Active gate driver for crosstalk suppression of SiC devices in a phase-leg configuration," *IEEE Trans. Power Electron.*, vol. 29, no. 4, pp. 1986–1997, Apr. 2014.

Peng Sun (Student Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from China University of Petroleum, China, in 2017 and 2020, respectively. He is currently working toward the Ph.D. degree in electrical engineering with Chongqing University, Chongqing, China.

His research interests include advanced packaging and industrial application of wide bandgap power devices.

Mingrui Zou (Student Member, IEEE) received the B.Sc. degree in electrical engineering from Kunming University of Science and Technology, Kunming, China, in 2020. He is currently working toward the Ph.D. degree in electrical engineering with Chongqing University, Chongqing, China.

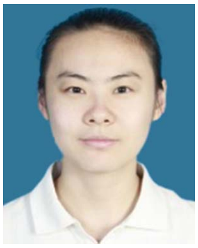
His research interests include advanced packaging and industrial application of wide bandgap power devices.

Yulei Wang received the B.Sc. degree in electrical engineering from China University of Mining and Technology, Beijing, China, in 2019. He is currently working toward the M.Sc. degree in electrical engineering with Chongqing University, Chongqing, China.

His research interests include advanced packaging and industrial application of wide bandgap power devices.

Jiakun Gong received the B.Sc. degree in electrical engineering in 2022 from Chongqing University, Chongqing, China, where he is currently working toward the Ph.D. degree in electrical engineering.

His research interests include advanced packaging and industrial application of wide bandgap power devices.



Yuxi Liang received the B.Sc. degree in electrical engineering in 2021 from Chongqing University, Chongqing, China, where she is currently working toward the M.Sc. degree in electrical engineering.

Her research interests include advanced packaging and industrial application of wide bandgap power devices.

Fuli Niu received the B.Sc. and M.Sc. degrees in electrical engineering in 2010 and 2013, respectively, from Chongqing University, Chongqing, China, where she is currently working toward the Ph.D. degree in electrical engineering.

Her research interests include advanced packaging and industrial application of wide bandgap power devices.

Ke Jiang (Senior Member, IEEE) received the Ph.D. degree in physics from the University of Munich and Max Planck Society, Munich, Germany, in 2011, and the Executive M.B.A. degree from the University of Cambridge, Cambridge, U.K., in 2022.

He is a Technical Executive with Nexperia Executive Management Team, Nijmegen, The Netherlands. He is currently the Chair Professor with Tsinghua University, Beijing, China, with primary research interest in semiconductor technology and plasma engineering.

Dr. Jiang was the recipient of the Marie Curie Host Fellowships for Early Stage Researcher from European Union, between 2007 and 2011.

Wei Gao received the B.Sc. degree from Shandong University, Jinan, China, in 2004, and the Ph.D. degree from Beijing University of Technology, Beijing, China, in 2011, both in microelectronics.

She is currently the Deputy Secretary-General with China advanced semiconductor industry innovation alliance. Her research interests include standardization of wide bandgap semiconductor industry.

Zheng Zeng (Member, IEEE) received the B.Sc. degree from Wuhan University, China, in 2009, and the Ph.D. degree from Zhejiang University, China, in 2014, both in electrical engineering.

In 2014, he was with the School of Electrical Engineering, Chongqing University, Chongqing, China, where he was promoted to an Associate Professor in 2017 and a Full Professor in 2022. From 2018 to 2019, he was also a Research Fellow with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore.

His research interests include advanced packaging for wideband gap power device and grid-connected inverter for renewable energy integration.