Semiconducotr Device Characterization Tests and Evaluation Methodologies

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***Abstract* — This paper explores semiconductor device characterization, testing, and evaluation methodologies, focusing on techniques crucial for assessing the performance and reliability of devices in high-stakes applications. It highlights both static and dynamic characterization tests, including current-voltage (I-V) and capacitance-voltage (C-V) tests, switching assessments, and in-situ measurements like ON-resistance, all of which are essential for evaluating semiconductor devices. Through advanced comparative analysis, the study showcases how these tests offer a holistic view of device behaviors under various conditions, emphasizing the importance of dynamic tests in revealing operational characteristics and potential for long-duration reliability testing. Additionally, the paper discusses the integration of advanced data processing techniques, such as machine learning, for analyzing characterization data, thereby enhancing the evaluation process of the device's suitability. This research contributes to advancing semiconductor device characterization methodologies, particularly in applications critical to NASA's space missions, by improving understanding and analytical approaches to device performance evaluation.**

Keywords—semiconductors, device characterization, I-V, C-V, data analytics, machine learning, device parameter experiments

I. INTRODUCTION

The advancement in semiconductor technology has catalyzed rapid growth in electronics, impacting various sectors from consumer electronics to critical mission applications such as those led by NASA. At the heart of this revolution are research activities focused on semiconductor devices, whose performance significantly influences the reliability and efficiency of electronic systems. Given their critical roles, the characterization of semiconductor devices, through methods such as current-voltage (I-V) and capacitance-voltage (C-V) tests, is paramount for understanding their baseline characteristics. These tests provide essential insights into the devices' electrical properties, enabling end-users to predict their behavior under various operational conditions [1]-[2].

However, the static nature of traditional characterization techniques, while foundational, does not fully encapsulate the dynamic conditions semiconductor devices encounter in real-world applications. Hence, the incorporation of dynamic tests, such as switching assessments and in-situ measurements, becomes crucial. These dynamic characterization techniques, including the measurement of ON-resistance, offer a more nuanced view of device performance by simulating operational switching conditions. This is particularly relevant in high-stakes applications, where devices must perform reliably under a range of environmental and electrical factors. For instance, in aerospace applications, semiconductor devices are subjected to extreme temperature variations, radiation, and high-reliability demands, making rigorous and comprehensive characterization not just beneficial but necessary.

The importance of semiconductor device characterization is further exemplified in the context of NASA's applications. Space missions require electronic systems that can withstand the harsh conditions of space, including significant temperature fluctuations and high levels of cosmic radiation. The thorough characterization of semiconductor devices ensures that only the most reliable components are deployed, minimizing the risk of mission failure due to electronic system malfunction [3].

This paper delves into the realm of semiconductor device characterization, exploring both static and dynamic tests. It aims to highlight the critical role these methodologies play in enhancing device reliability and performance, with a particular focus on their application in high-reliability environments such as space exploration. By examining static and dynamic characterization techniques, experimental results, and advanced data processing methods, including machine learning, this paper seeks to underscore the importance of comprehensive device characterization in the development of reliable and robust electronic systems.

II. SEMICONUCTOR CHARACTERIZATION TESTS

A. Static Characterization Techniques

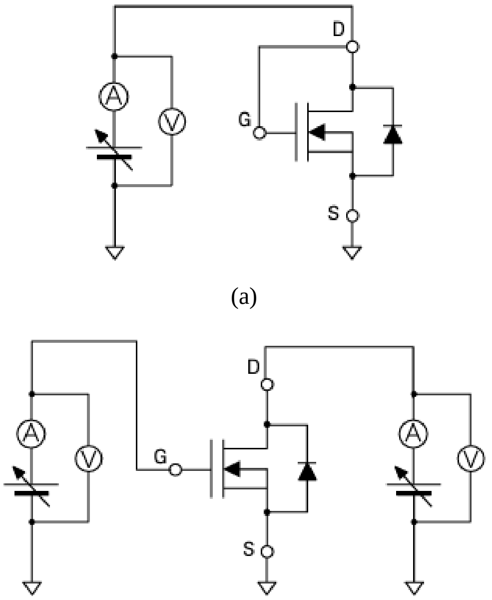
Static characterization techniques form the foundation of semiconductor device analysis. By establishing proper characterization setups, vital parameters such as threshold voltage (V_{th}), transconductance (g_m), and static ON-resistance (R_{ON}) can be extracted. These parameters are pivotal for understanding how a device behaves under the intended operating conditions, providing insights into its electrical performance [4]. There are several static characterization tests of interest for this work –

- *Transfer Characteristics* offer a perspective into the device's conductive properties by identifying the relationship between the gate-source voltage (V_{GS}) and the drain current (I_D). This relationship is crucial for determining the device's threshold voltage, beyond which it transitions from OFF to ON state.

- *Output Characteristics*, on the other hand, represent how the drain current varies with the drain-source voltage (V_{DS}) for different gate voltages. This test is important in understanding the saturation behavior of the device, which measures its current-carrying capacity and power dissipation characteristics.

- *Capacitance Measurements* (C-V) are also critical, especially for devices like metal–oxide–semiconductor field-effect transistors (MOSFETs), where dynamic charge storage mechanisms significantly impact performance. Capacitance-voltage profiles helps in understanding the charge distribution within the device, which is important for optimizing switching speed and minimizing power loss.

Fig. 1 shows examples of the device characterization tests, including the gate threshold in Fig. 1(a) and the transfer measurement setup in Fig. 1(b).



(a)

(b)

Fig. 1 – Connection diagram of the gate threshold (V_{th}) characterization test shown in (a) and the transfer test (I_D-V_{GS}) illustrated in (b).

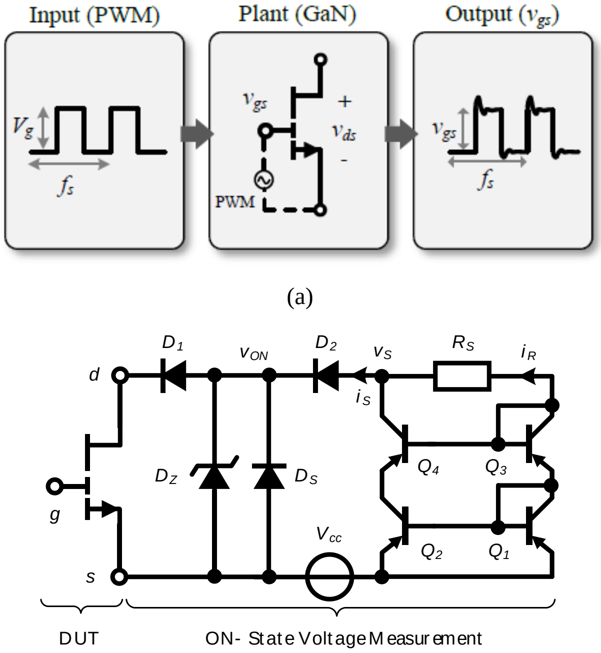
B. Dynamic Characterization Techniuqes

Dynamic tests simulate the operational conditions that devices face in real-world applications, ranging from rapid switching in power converters to fluctuating load conditions in RF amplifiers. These tests are crucial for predicting device behavior under transient conditions and assessing operation under biasing conditions while ensuring performance consistency [5]. Two dynamic characterization tests of interest in this work are –

- *Switching Tests* evaluate the device's ability to transition between ON and OFF states swiftly. This includes measuring parameters like turn-ON and turn-OFF times as well as the transient behaviors, such as the undershoot and overshoot under different switching frequencies

- *In-situ Measurements*, including ON-resistance (R_{ON}) are pivotal for switching devices, particularly in high-power applications, as they highlight the device's resistance under the conduction state and transient thermal characteristics of the device. In-situ R_{ON} is a challenging measurement as it requires special or custom-designed electronics to measure such a parameter.

Fig. 2 illustrates the dynamic characterization tests, where Fig. 2(a) applies continuous switching pulses to the gate and source terminals of the device under test (DUT) and Fig. 2(b) shows how the ON-resistance measurement circuit is designed and implemented in-situ with the DUT.



(a)

(b)

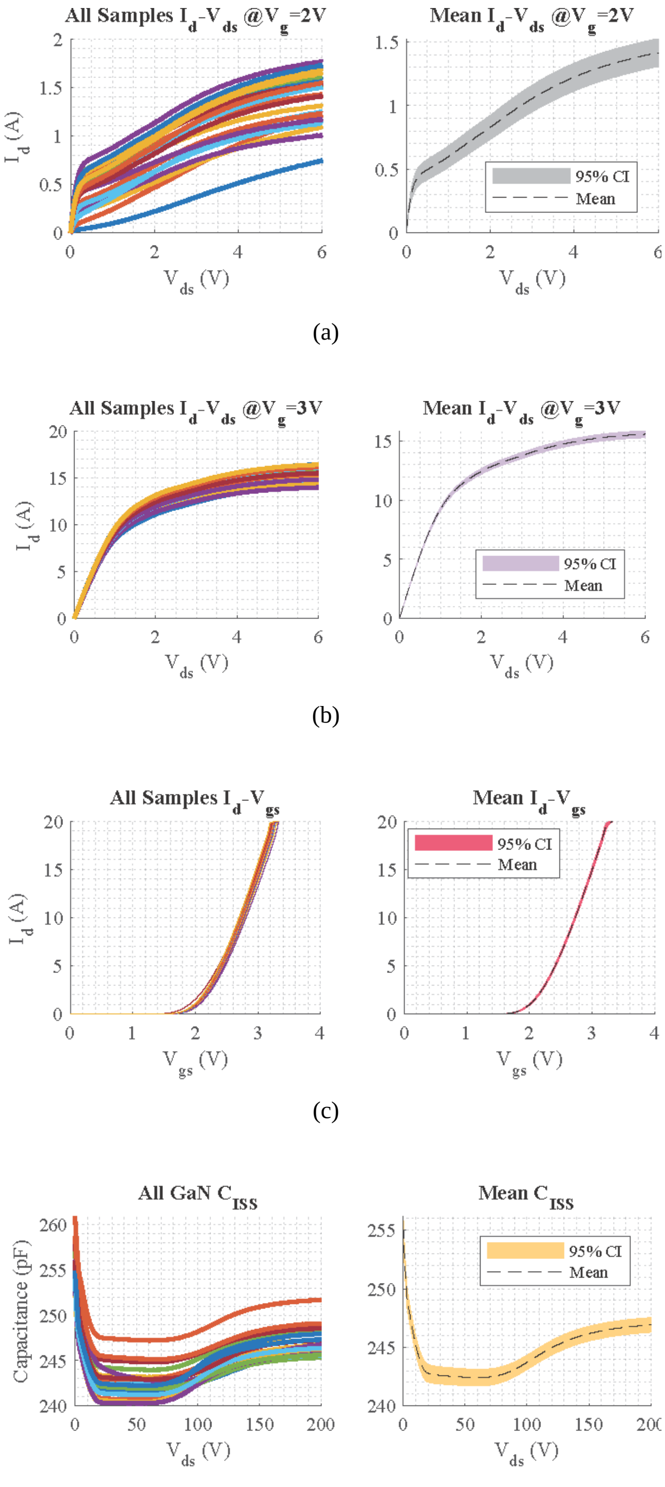
Fig. 2 – Dynamic device characterization tests describing the switching test in (a), and ON-resistance measurement test depicted in (b).

III. CHARACTERIZATION EXPERIMENTAL RESULTS

Various semiconductor devices have undergone both static and dynamic characterization tests, as introduced in the previous sections. This section details the measurement results, providing a comprehensive overview of the experimental outcomes and their significance.

A. Static Characterization Measurement Results

Devices with the same part number have been screened and subjected to the static characterization tests. To visualize the electrical specification measurement results and analyze the sample statistics, Fig. 3 illustrates several device characterization measurements across the device population. Fig. 3(a) and (b) display the output characteristics at V_{GS} = 2V and V_{GS} = 3V, respectively, alongside the population mean and the 95% confidence interval (CI) for each test condition. Fig. 3(c) presents the transfer characteristics, including the measurement mean and the 95% CI. Lastly, Fig. 3(d) showcases the input capacitance of the population, followed by the population mean and the corresponding 95% CI. Note that several other test conditions, such as the output characteristics at higher gate voltages and the output and reverse capacitances, have been omitted from this paper for brevity.



(a)

(b)

(c)

(d)

Fig. 3 – A summary of the experimental measurement data on power transistor characteristics, including the transfer, output, and capacitance characteristics.

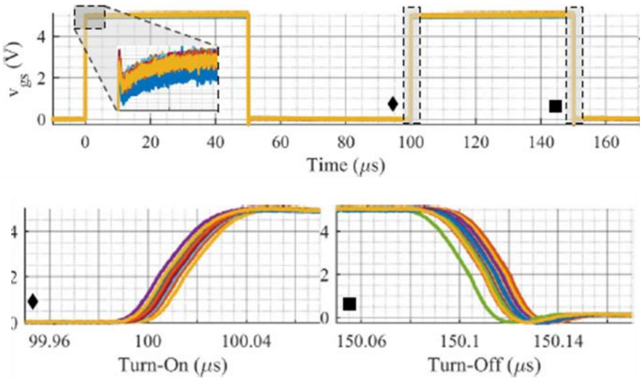
While static characterization tests provide essential insights into semiconductor devices' electrical properties, they often fall short of capturing the full spectrum of behaviors devices exhibit under real-world operational conditions. This gap emphasizes the necessity for dynamic characterization tests, which are more representative of the devices' end-use applications. Static tests, by their nature, cannot fully account for the complex interactions and transient phenomena that occur during actual device operation. As a result, a reliance solely on static measurements may overlook critical performance aspects and variability under dynamic conditions. This realization points to the importance of integrating dynamic characterization methods to achieve a more comprehensive and accurate assessment of device performance.

B. Dynamic Characterization Measurement Results

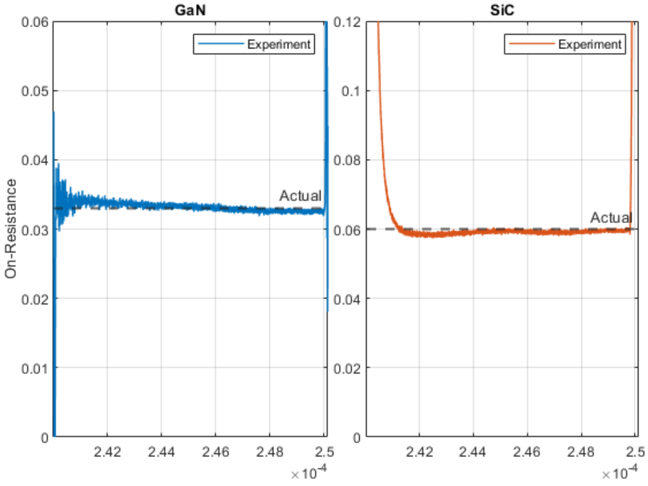
In practical applications, semiconductor devices are subjected to a variety of stresses, from rapid switching in power converters to fluctuating load conditions in RF amplifiers. Understanding how these devices behave under such transient conditions is crucial for ensuring their reliable operation across their intended applications. This section provides the experimental results of both switching tests and in-situ measurements, capturing the nuances of their behavior under conditions that closely mimic their end-use environments.

Figure 4(a) presents the excitation response output signals, measured at the gate-source terminals of each transistor sample in the time domain. An analysis of the waveforms reveals subtle variations among samples in terms of overshoot, settling time, steady-state response, and switching ON-OFF transitions. These minor differences challenge the evaluation and comparison of part-to-part electrical performance, complicating assessments that span both static and dynamic characteristics.

Figure 4(b) displays the experimental results of ON-resistance measurements conducted on semiconductor devices composed of two different materials. These results demonstrate that the measurement circuit outlined in Figure 2(b) can accurately determine the devices' conduction state ON-resistance. This capability provide health monitoring and reliability evaluation studies. In these contexts, ON-resistance serves as a critical indicator, potentially predicting device failure or estimating the remaining useful life of devices [6].



(a)



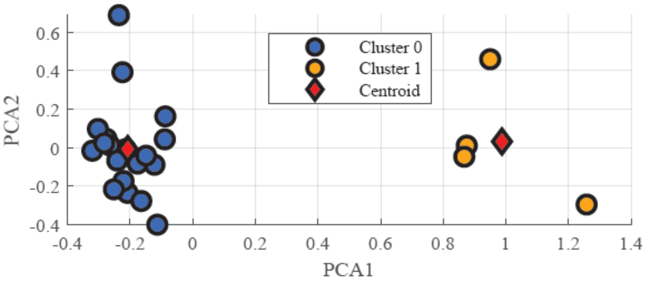
(b)

Fig. 4 – Experimental results of in-situ ON-resistance values on two different device materials, including GaN and SiC performed by the measurement circuit described in Fig. 2(b).

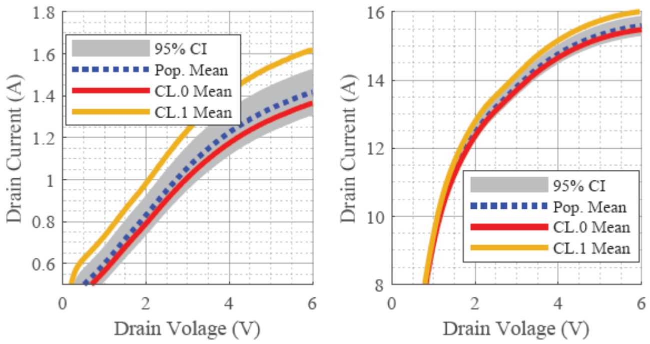
IV. DATA PROCESSING TECHNIQUES

With the extensive data generated from characterization tests, advanced processing techniques are pivotal. To process the time-series feature of the dataset to numerical data type, the sample time-series mean across the entire measurement period was calculated for each frequency test condition for each transistor device. Then the Euclidean distance to the sample population measurement mean was determined across the measurement size. The principal component analysis (PCA) algorithm was used for dimensional reduction between the feature dimensions. The PCA minimizes the mean squared distance between the dataset and the projected hyperplanes with the maximum variance. Such a transformation allows reduction of dimensional to d dimensions, defined by the first *d* principal components [7]. In this study, the first two principal components were used to project the dataset to the 2D plane while preserving a large part of the dataset's variance.

Lacking prior knowledge or a relevant dataset for the devices requires identification of groups with similar features. An unsupervised clustering technique can be used to enable grouping of the data points based on similar instances [8]. In this paper, the K-Means algorithm was used to train and cluster the data samples of the PCA derived *d*-dimensional



(a)



(b)

Fig. 5 – K-means clustering results based on: (a) the clustering results with k=2 along the PCA1 and PCA2 dimensions, and (b) The comparison of the sample mean of Cluster 0 (CL.0) and Cluster 1 (CL.1) to the population mean with 90% CI.

The optimal centroids are selected based on the rate of the inertia drop at the inflexion point called the "elbow". Fig. 5(a) illustrates k = 2 clustering of the dataset on the 2D plane of the first 2 principal components. It can be observed that there are two distinctly identified cluster groups: Cluster 0 and Cluster 1, near the identified centroids.

With the separation of the dataset into two clusters, analyzing each cluster's dataset and its mean electrical specifications to the overall device population mean characteristics can be performed. Fig. 5(b) demonstrates the ML clustering performance on a selected electrical characteristic. The figure visualizes the clusters performance compared to the population mean along with the 90% CI of the output characteristic at V_{GS}=2V. The average sub-population mean categorized as Cluster 0 (CL.0) is realized to be closer to the overall sample population than the average sub-population mean categorized as Cluster 1 (CL.1). Moreover, the samples in CL.0 are within the 95% CI of the population statistics.

V. CONCLUSION AND FUTURE WORK

The proposed characterization of semiconductor devices is important for ensuring their reliability and applicability, especially in applications where failure has significant repercussions. This paper has highlighted the importance of both static and dynamic characterization techniques in providing a comprehensive understanding of device performance. Moreover, the role of advanced data processing, particularly through machine learning, emerges as a critical factor in deciphering the vast amounts of data generated during characterization, paving the way for more informed decisions in device design and application. As the field of semiconductor technology continues to evolve, the methodologies and techniques for device characterization are becoming critical, which underscores the need for continuous research and development in this dynamic domain.

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