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Artículo de Investigación

Evaluación de la confiabilidad en los MOSFET de potencia de SiC y GaN basados en la tecnología emergente de semiconductores Wide Bandgap a partir de una revisión sistemática de la literatura

Reliability assessment in SiC and GaN power MOSFETs based emerging Wide Bandgap semiconductors technology from a systematic literature review

Avaliação da confiabilidade em MOSFETs de potência SiC e GaN baseados na tecnologia emergente de semicondutores Wide Bandgap a partir de uma revisão sistemática da literatura

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Resumen

Los dispositivos de energía de silicio han mejorado en las últimas décadas, pero se están acercando a sus límites de rendimiento impuestos por las propiedades del material. Sin embargo, los materiales emergentes como SiC y GaN están sobresaliendo en tales aplicaciones y han atraído un gran interés en la academia y la industria debido a sus propiedades superiores, para el desarrollo de dispositivos de banda prohibida ancha (WBG), en particular MOSFET de potencia, que serán componentes clave para la próxima generación de electrónica de potencia de alto voltaje y baja pérdida. Ya se encuentran disponibles dispositivos con impresionantes especificaciones nuevas, pero deben demostrar su confiabilidad para ser incorporados a los sistemas. Muchos problemas de inestabilidad deben ser resueltos y analizadas sus causas mediante ensayos de caracterización eléctrica como PBTI y NBTI. Una vez que se determina que los dispositivos no son confiables, se pueden realizar pruebas para comprender las razones según los criterios y las interpretaciones de los métodos de caracterización. Este documento reúne y analiza algunos problemas que pueden ocurrir en GaN y SiC, y los diversos estudios de inestabilidad que son clave para poder prevenir fallas mientras se determina el rango aceptable de condiciones operativas para un dispositivo en particular. Finalmente, se discuten los desafíos tecnológicos, las aplicaciones y las oportunidades de investigación; sabiendo que las aplicaciones futuras, como la automoción, las energías renovables y el espacio, serán más críticas y con mayores requisitos de fiabilidad, por lo que se necesitarán mejores y nuevos métodos de prueba de fiabilidad en sus componentes.

Palabras clave: SiC; GaN; Semiconductores del GBM; BTI, electrónica de potencia; MOSFET 4H-SiC; HEMT.

Abstract

Silicon power devices have improved over the last decades, but they are approaching their performance limits imposed by material properties. However, emerging materials such as SiC and GaN are excelling in such applications and have attracted great interest in academia and industry due to their superior properties, for the development of wide bandgap (WBG) devices, in particu-lar power MOSFETs, which will be key components for the next generation of high-voltage, low-loss power electronics. Devices with impressive new specifications are already available, but they must prove their reliability to be incorporated into systems. Many instability problems must be resolved, and their causes analyzed using electrical characterization tests such as PBTI and NBTI. Once devices are found to be unreliable, tests can be performed to understand the reasons based on the criteria and interpretations of the characterization methods. This paper brings togeth-er and discusses some problems that can happen in GaN and SiC, and the various instability studies that are key to being able to prevent failures while determining the acceptable range of operating conditions for a particular device. Finally, technological challenges, applications and research opportunities are discussed; knowing that future applications such as automotive, renew-able energy, and space will be more critical and with higher reliability requirements, so better and new reliability testing methods will be needed in their components.

Keywords: SiC; GaN; WBG Semiconductors; BTI, Power electronic; 4H-SiC MOSFET; HEMT.

Resumo

Os dispositivos de potência de silício melhoraram nas últimas décadas, mas estão se aproximando dos limites de desempenho impostos pelas propriedades do material. No entanto, materiais emergentes como SiC e GaN estão se destacando em tais aplicações e têm despertado grande interesse na academia e na indústria devido às suas propriedades superiores, para o desenvolvimento de dispositivos de banda larga (WBG), em particular MOSFETs de potência, que serão componentes-chave para a próxima geração de eletrônica de potência de alta tensão e baixa perda. Dispositivos com novas especificações impressionantes já estão disponíveis, mas eles devem provar sua confiabilidade para serem incorporados aos sistemas. Muitos problemas de instabilidade devem ser resolvidos e suas causas analisadas por meio de testes de caracterização elétrica como PBTI e NBTI. Uma vez que os dispositivos não são confiáveis, testes podem ser realizados para entender as razões com base nos critérios e interpretações dos métodos de caracterização. Este artigo reúne e discute alguns problemas que podem ocorrer em GaN e SiC, e os diversos estudos de instabilidade que são fundamentais para evitar falhas ao determinar a faixa aceitável de condições de operação para um determinado dispositivo. Por fim, são discutidos os desafios tecnológicos, aplicações e oportunidades de pesquisa; sabendo que aplicações futuras, como automotiva, energia renovável e espaço, serão mais críticas e com requisitos de confiabilidade mais altos, portanto, métodos de teste de confiabilidade melhores e novos serão necessários em seus componentes.

Palavras-chave: SiC; GaN; WBG Semicondutores; BTI, Eletrônica de potência; MOSFET 4H-SiC; HEMT.

Introducción

Currently, the increase in energy demand worldwide is one of the main critical problems affecting our society, and it is even estimated that by 2040 there will be an increase of about 40% of the demand [1]. In this context to efficiently connect power generation sources with the end user, it is important an adequate power management through the efficient application of electronic power control systems [2].

For decades silicon has been the basic semiconductor used for the manufacture of electronic devices, in fact currently about 87% of devices are manufactured in silicon, however there are still unresolved problems due to its high energy consumption when the devices are used in energy transformation systems and critical applications such as: DC/AC converters, inverters, industrial motor drives, power supplies, and others [2, 3], therefore it is necessary to improve the energy efficiency of power devices to reduce overall energy consumption [4]. On the one hand we have that the next generation of power devices present high operating capabilities with respect to voltage, temperature, frequency, and on the other hand ensure better energy efficiency with respect to silicon (see Fig. 1), thus it is important to consider new semiconductors that exceed the physical capabilities of silicon for the manufacture of this new generation of devices.

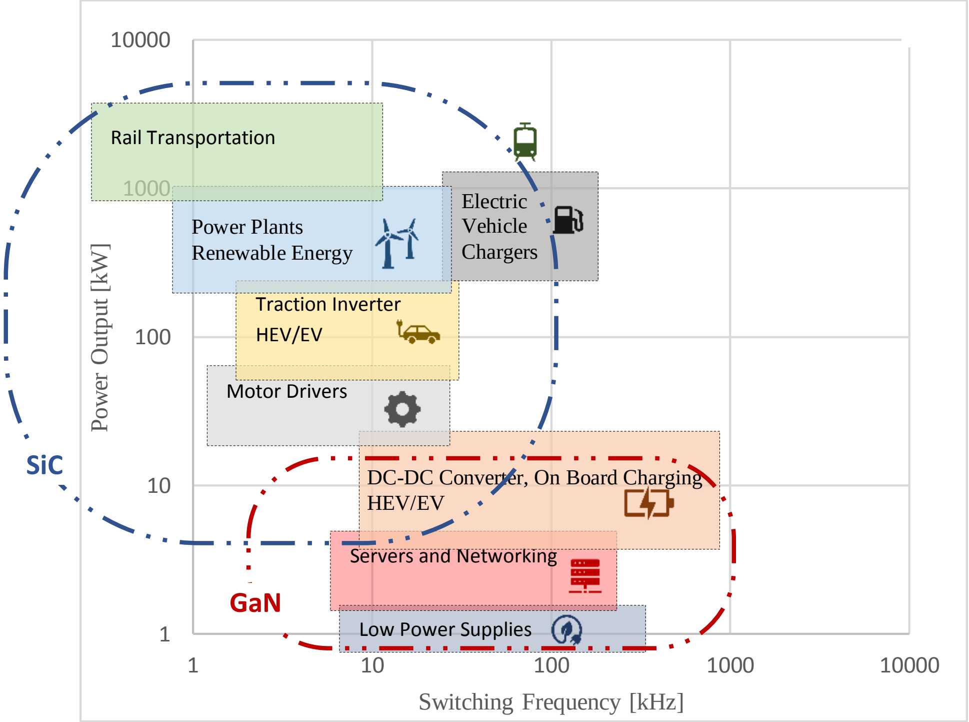

Fig. 1. Applications using SiC and GaN devices.

We can highlight the physical properties of WBG semiconductors, particularly SiC and GaN, which is why they are currently considered materials that will revolutionize power electronics because they can solve problems such as significant power loss due to the ignition resistance R_{ON} and increase the breakdown voltage V_{BD} [5], and others that will be discussed below; taking into account that these are important aspects that must be considered at the time of manufacturing electronic devices.

WBG Semiconductors

Table 1 shows important physical properties of SiC and GaN. These properties provide the devices with a considerable increase in performance in terms of frequency, power, radiation, and high noise immunity. Additionally, these physical parameters shown are important for determining the characteristics and performance during device fabrication. The potential advantages over silicon provide research opportunities as well as challenges [6].

Table 1. Physical properties of semiconductor materials.

Property	Si	3C-Si	4H-SiC	GaN
Band Gap (eV)	1.12	2.2	3.2	3.4
Breakdown field E_B (MV/cm)	0.25	1.2	3	4
Electron mobility μ (cm^2/Vs)	1350	900	800	1300
Saturation velocity v_s (10^7 cm/s)	1	2	2	3
Thermal conductivity k (W/cm °K)	1.5	4.9	4.9	1.3
Dielectric constant ε	11.8	9.6	9.7	9.5

The higher GAP compared to silicon, results in a lower carrier concentration, in technical terms this allows to reduce the leakage current and provides the possibility to operate at higher temperatures at the same time with a high thermal conductivity. The use of these emerging materials in the manufacture of electronic devices allows to reduce costs and weight involved in the implementation of a cooling and dissipation system, respectively.

Another important aspect to be considered is the high critical electric field that allows these materials to be good candidates for the fabrication of power devices required in demanding and critical applications. Therefore, the same breakdown voltage can be achieved with a reduction in the thickness of the active layer of the device, which allows reducing the R_ON turn-on resistance and conduction losses. Finally, these devices show higher RF switching capability due to better saturation speed with respect to silicon, this feature is very useful in high mobility HEMTS transistors [7].

SiC devices

Due to its physical characteristics, this material has been used for the manufacture of high voltage power devices, and it is a technology that has been under development for twenty years; for example, Schottky diodes have been commercially available since 2001.

Currently, research is focused on the fabrication of field effect transistors based on the metal-oxide-semiconductor structure [8], likewise to date 4H-MOSFETs devices have been commercialized with operating voltages ranging from 600 to 1700 V, with R_DSON turn-on resistances in the range of 80 to 52 mΩ at a temperature T=25 °C [9, 10].

Both mentioned devices have allowed to significantly reduce the power losses in different electrical power conversion systems [11]; since in a typical power conversion system, a switching circuit essentially consisting of a transistor and a diode is used to regulate and control the energy supplied to the load [7].

GaN devices

Likewise, GaN has excellent physical properties such as high critical electric field, high saturation velocity, which is why it has also been used for the fabrication of power devices since it guarantees a low ignition resistance combined with a high breakdown voltage [12, 13]. Initially, we could assume that GaN offers better performance than SiC with respect to its electrical characteristics, however being a relatively new technology, GaN has problems in device processing, such as low crystal and substrate quality [14].

An important advantage to highlight is that GaN technology offers the possibility of using alloys with heterostructures. The AlGaN/GaN heterostructure is a two-dimensional structure that offers important characteristics such as high carrier density and excellent mobility, so it is used in the manufacture of high mobility transistors operating above GHz and power densities at W/mm levels. These devices are very useful in the fabrication of inverters and converters for renewable energy and electric vehicle applications [15, 16].

Methodology

This work corresponds to documentary research that makes use of many documents analyzed by means of a Systematic Literature Review (SLR). This method allows to deepen and broaden the knowledge related to the reliability of SiC and GaN devices. These documents (articles, books, and chapters) were obtained from relevant scientific databases such as SCOPUS, Science Direct and IEEE Xplore. In addition, an analytical method was used to examine each manuscript and then sort them separately according to the topic of interest to be addressed. Some web pages with relevant information were also reviewed.

Subsequently, the inductive method was applied to analyze particular cases of reliability testing in WBG devices based on already proven procedures and techniques. The instruments and techniques reviewed in this study are validated by many researchers in several research works, some examples will be detailed in the section referred to Silicon Carbide and Gallium Nitride based MOSFETs. Additional observations and proposals will be addressed in the Discussion section.

Discussions

Having analyzed the main potentialities of WBG semiconductors, particularly SiC and GaN, this section will discuss the problems they present due to the immaturity of the technology, which are related to crystal quality and device processing. It is important to discuss these problems because they define the electrical behavior and reliability of the devices, therefore a significant development of these technologies must wait, and research efforts should be focused on improving aspects such as crystal quality, charge transport and problems related to device processing based on electrical characterization tests [17, 18].

Mobility analysis of 4H-SiC MOSFETs

Currently, devices fabricated in SiC are expected to operate with breakdown voltages up to 10 Kv. However, there are technological problems that mainly affect MOSFETs [19, 20] related to the low inversion of the channel mobility, and according to experimental studies, the mentioned effect is present in devices operating below 1.2 Kv [5], the authors of this work report evidence that the mobility directly affects the R_{ON} of the devices. It can be determined that the low mobility values measured in the oxide (SiO_2) of the MOS structure are attributed to the high density of traps at the D_{it} interface caused by semiconductor defects (intrinsic material defects at the SiC/SiO_2 interface, SiO_2 or carbon atoms) located near the conduction band. Thus, the high presence of electric charge at the interface reduces the mobility, especially in the inversion layer; the effect caused is attributed to Coulomb scattering [21, 22].

The effective mobility of the 4H- SiC MOSFET has been evaluated as a function of the difference between gate and threshold voltage (V_G - V_T) applied for different gate oxide chemical processes [3, 23]. Each evaluated MOSFET reports a maximum mobility prior to entering triode mode, these different maximum values reached by each MOSFET makes us understand that this parameter varies quite a lot according to the specific gate oxide chemical process (see Fig. 2); for example, there is an increase of the maximum mobility when applied to SiO_2, which means untreated or dry, nitriding processes [3, 23].

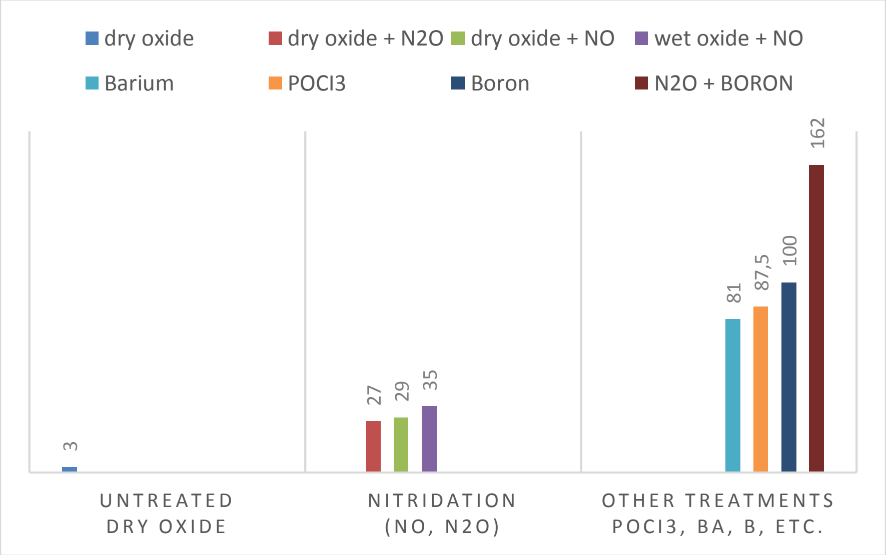

Fig. 2. Maximum mobility (cm^2 V^{-1} s^{-1}) achieved by each MOSFET when entering triode mode.

As an alternative to nitriding processes, several studies report that gate oxide doping by introducing different elements increases the channel mobility [24, 25], such procedures achieved an increase of mobility up to about 150 cm^2 V^{-1} s^{-1}. However, this approach is not applicable for the fabrication of real devices because large amounts of mobile carriers in the gate oxide present serious problems in the electrical behavior of the device, mainly in threshold voltage and drain current variation.

Therefore, most of the studies suggest only the application of nitriding processes to gate oxide because it has been experimentally determined on real devices that the threshold voltage V_T shows some stability when operating under room temperature conditions, although for elevated temperatures it shows undesired behavior [26]. Furthermore, the variation of the threshold voltage when devices operate under adverse temperature conditions is estimated to be due to energetic activation mechanism involving defects present in the gate oxide. Analyses of temperature dependence studies report similar activation energies in the range from 1.04 to 1.14 eV, which vary slightly according to the type of oxide processing [24, 25, 27].

Reliability Analysis of 4H-SiC MOSFETs

In the following, the reliability of some SiO_2 and SiO_2/SiC related electrical parameters of 4H-SiC MOSFETs are discussed with respect to PBTI and NBTI analysis [28] that determine the time evolution of parametric degradation of MOSFETs. The device is stressed to achieve an accelerated aging condition but avoiding high voltages to prevent oxide breakdown. It is possible to monitor the degradation of the device parameters through the data obtained from the V_G - I_D characteristic curves measured before and after BTI application, the source drain voltage V_{DS} is biased with values close to zero to keep the electric field in the channel as constant as possible and to be able to monitor the linear drain current $I_{D\text{-}LIN}$ [14, 18, 29].

Each laboratory contributing to the scientific literature reports some independence in the characterization methods to know the degradation level of the SiC MOSFETs according to their researchers' criteria. However, the base model to evaluate the degradation of electrical parameters is the BTI, and the applied stress values (temperature and voltage) are below or close to their nominal operating values [8, 9, 16, 28].

A rather interesting BTI procedure is reported in [30], which can be discussed and somewhat adopted in further research. This procedure consists of three phases: initial stabilization, stress, and recovery. Regarding the first phase a negative gate voltage between -1V to -5 V is applied for 5000 seconds, in this way the virgin device is stabilized by releasing possible stored charge, furthermore such procedure is performed after each application of stress, so the device reaches a reference state for subsequent experiments.

During the stress phase the device is biased with positive gate voltages ranging from 6V to 20V, temperatures below 160 °C, and high voltages are avoided to prevent oxide breakdown. The stress is interrupted at logarithmic time intervals and the V_G and I_D values of the characteristic curve are measured, to immediately calculate the threshold voltage variation ΔV_T. Data from these experiments have shown that the threshold voltage variation is larger when V_G is increased regardless of temperature.

After each stress phase the recovery phase is evaluated by applying a negative gate voltage between 0V and -2V to the device for 1000 seconds, from the reported measurements it can be determined that ΔV_T tends to zero during this time (see Fig. 3).

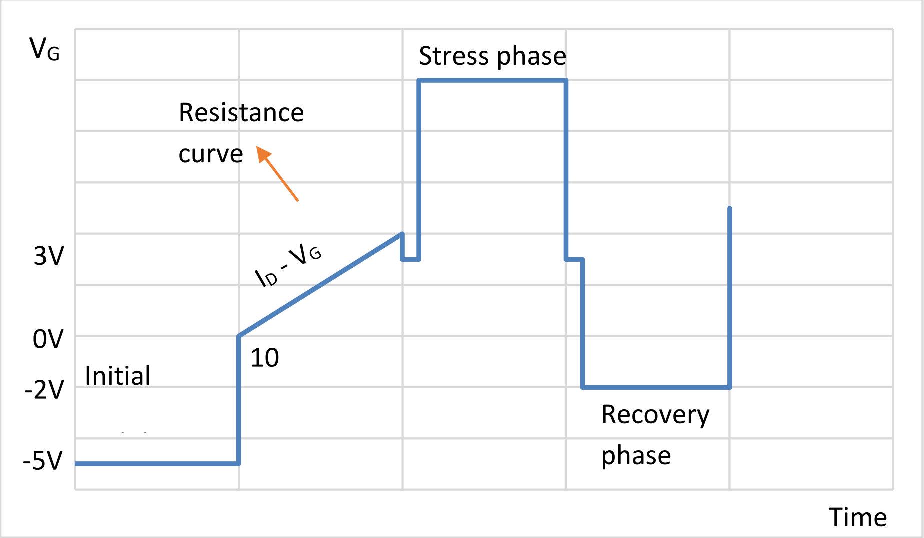

Fig. 3. Stabilization – Stress – Recovery cycle (SSR cycle)

By analyzing the results of this process and seeing that the stress conditions imposed by these researchers do not cause permanent damage to the device and the experiment obeys the electron capture and emission processes, we suggest this method with certain modifications under technical and scientific criteria, and according to the resources of each laboratory for further research.

On the other hand, the work [31] applies a slightly different method but reports in the same way the effect of threshold voltage variation with respect to BTI. Measurements have been performed at device and wafer level on 1200V 4H-SiC MOSFETs. The base electrical characterization method is Measurement - Stress - Measurement (MSM) (see Fig. 4), also the threshold voltage is analyzed before and after BTI application where the temperature varies in the range of 25°C up to 190 °C for different stress times. So, it is another good option to consider for research on this topic.

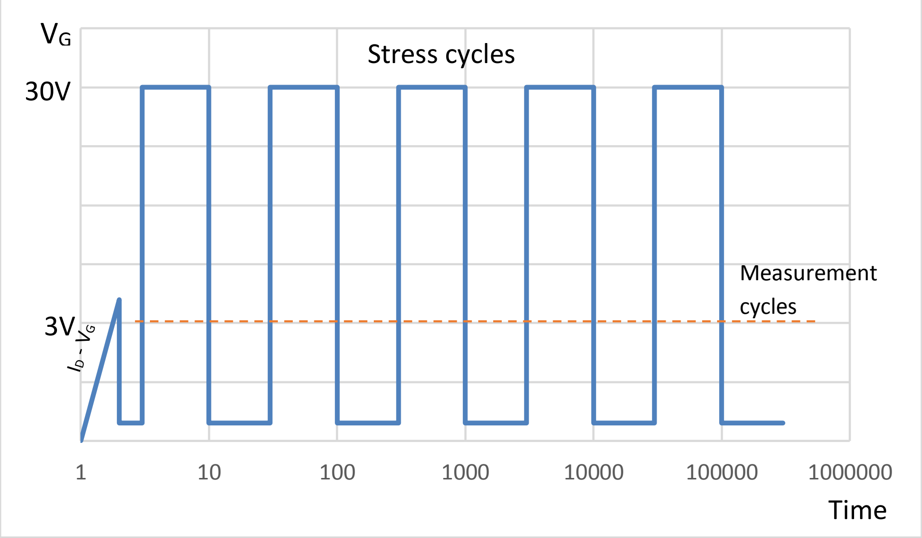

Fig. 4. Measure -Stress- Measure (MSM) test pattern.

To determine the threshold voltage shift, slow and fast measurements are performed according to the effects of BTI stress. Regarding the fast measurements it has been possible to determine that the threshold voltage shift is due to trapped and released charge carriers (trapping/detrapping) at the SiO_2 and SiO_2/SiC interface. The values of interest can be obtained using the ultra-fast Keithley 4200 SCS semiconductor analyzer, which allows us to apply a stress voltage and measure the I-V characteristic curve during the stress interruption, the total stress time generally applied is 100000 seconds with 10 interruptions per decade. Similarly, regarding slow measurements it is feasible to use Keysight B1505 semiconductor analyzer, devices can be stressed by gate voltages up to 35V, temperature variation range is from 25°C to 190 °C, in situ threshold voltage recovery is shown during measurement.

With these experiments it can be shown that the variation of threshold voltage ΔV_T decreases with increasing temperature, suggesting that the recovery V_T is activated by temperature in both types of measurements. Furthermore, when variations in stress (voltage and temperature) are presented by fast measurements it allows us to observe more significant changes of the threshold voltage compared to slow measurements, this effect is attributed to the large defect recovery with the slow measurement.

Mobility analysis of GaN MOSFETs

Unlike SiC, the scientific literature reports less information on this subject, however, it is important to say that the characterization methods would technically be the same. We will briefly discuss the information reviewed.

One problem in channel mobility and reliability that has been investigated in GaN-MOSFETs with embedded gates is etch damage to the GaN and impurity in the gate insulator known as traps. These traps cause the threshold voltage to shift below the gate voltage. Improving the fabrication process of the gate structure helps the channel mobility and threshold voltage stability. Two gate structure processes in GaN-MOSFETs known as recessed normally off are reported in [32]. The first treats the surface to eliminate damage caused by recess etching, while the other anneals the gate insulator to drastically reduce impurities.

A fabrication process to eliminate etch damage by a surface heat treatment technique under NH_3 environment can be reviewed in [33], it also reduces the traps by additional annealing. The result is an effective process for etch damage removal and impurity reduction. Characterization testing of these devices is essential to ensure that these fabrication processes are effective, developing suitable characterization processes are the current challenges.

Reliability Analysis of GaN devices

A very important parameter to characterize is the threshold voltage shift of the GaN MOSFET in PBTI tests. The threshold voltage shift factor is one way to understand this characteristic since it is to find the direct relationship with environmental conditions such as temperature.

Gate Bias Dependence in PBTI Test. Threshold voltage changes are typical for MOSFETs. Certain authors [34] have developed tests showing the gate bias dependencies of the Id-Vg characteristic in the PBTI test measured under various gate bias conditions: Vg = +15V, Vg = +20V, and Vg = +25V. The Id-Vg characteristics were measured under the condition of drain voltage of + 1V and stress time of t = 0 s and t = 1000 s. These values may change depending on future experiments to be performed, according to criteria, requirements, and resources. Results can be obtained for the Id-Vg characteristic because the curves shift to the positive bias direction with increasing stress time.

Photoirradiation Capacitance-Voltage Measurement of MOS Capacitor. The objective of this experiment is to focus on charge behavior in the gate dielectric of a capacitor device based in GaN. An experiment applying threshold voltage shift occurred because of utilizing stress bias (+15 V) to an anode electrode for 500 seconds, CV measurements were made while irradiating light to MOS capacitor. The wavelength was modified from 700 nm to 380 nm with a 10 nm steps to excite any electron traps in SiO2 from a shallow level. As a result of this experiment, the threshold voltage shift was caused by electron traps in the dielectric of the SiO2 gate. The experiment under these criteria can demonstrate that the presence of electron traps in the SiO2 gate dielectric causes threshold voltage changes [34].

Reliability Model for GaN Power FET. Reliability studies have been performed on E-GaN FET power devices. On the one hand dedicated circuits have been designed to accelerate various degradation mechanisms such as Ring Oscillators (RO) [35]; And on the one hand test such Rds of GaN FET (EPC2038) and Gamma irradiation experiment in high power [36]. According to our analysis of the literature, these tests are recommended for application in these types of devices.

Reliability test for GaN HEMT devices. The problems and improvements of GaN Mosfet devices have been discussed. Table 1 is a summary of the different stress tests to which the devices are subjected to obtain reliability results, based on a statistical analysis of GaN HEMT device failures.

Table 2. Table captions should be placed above the tables.

Test	Features	Type
HTOL (High Temperature Operating Life)	Is used to determine the effects of bias and temperature stress conditions on solid-state devices over long periods of time. Requires the application of a high temperature and voltage stress on the semiconductor devices, for small sample size, to evaluate the lifetime and failure rate of the larger population [37].	Life tests
EOL (end-of-life tests)	These tests are competent in stimulating and precipitating semiconductor device and packaging failures. The goal is to precipitate failures in an accelerated manner compared to use requirements [38].	Life tests
HTRB stress (High Temperature Reverse Bias)	Presenting similar degradation signatures over a longer stress period [39].	Life tests
OCT (Optical coherence tomography)	It is used for high resolution and non-destructive measurements of semiconductor optical devices [40].	Optical test

These reliability studies are based on the statistical analysis of the failures that the devices present after the different stress tests. The following Table 3. shows the different analysis alternatives. There are different statistical methods to interpret the results of the measurements made in the reliability tests, but according to the literature review, the most used are: MTTF (Mean Time to Failure) and FIT (Failure in Time).

Table 3. Table captions should be placed above the tables.

Statistical Method	Features
MTTF (Mean Time to Failure)	It is a basic measure of reliability for non-repairable systems. MTTF is a value that is meant to be the average over a long period of time and a large number of units. It is also considered as the average time expected until the first failure of a device [41].
MTBF (Mean Time Between Failures)	It is the average time between each occurrence of a specific stop due to failure (or breakdown) of a process. Technically, MTBF should be used only for a repairable item. However, MTBF is commonly used for both repairable and non-repairable items [41].
FIT (Failure in Time)	Reports the number of expected failures per billion hours of device operation. This term is used particularly in the semiconductor industry, but it is also used by component manufacturers. FIT can be quantified in several ways: 1 million devices per 1000 hours or 1000 devices per 1 million hours each, and other combinations. The FIT and Confidence Limits (CL) are often provided together [41].

In general, the conventional statistical method of the Weibull curve is used to measure the MTTF (Mean Time to Failure) failure rate [38]. This parameter is difficult to obtain, since most failures occur during the "early or infant failure rate", due to the lack of maturity of the technology and the small number of devices available.

It is also possible to develop mathematical models from the measurements made in the different failure tests, studying the time evolution of magnitudes such as transconductance, drain saturation current, pinch-off voltage, gate leakage current and voltage. gate bias, etc. The results obtained will be directly related to the maturity of the technology.

Bias temperature stress tests pattern for SiC and GaN

In this literature review study, we have found quite reliable tests that can be replicated in future electrical characterization investigations for the analysis of threshold voltage instability with respect to temperature variation and voltage stress (BTI) in different commercial n-channel SiC and GaN devices from different manufacturers, since their results are very reliable and have been compared with similar investigations that have coincided in their results and interpretations. In addition, these tests are less complicated, but quite reliable, giving us the assurance of obtaining valid results.

These stress measurements are generally performed on an Agilent B1500A semiconductor analyzer, the temperature variation for the experiments is set from -50 to 150 °C, source drain voltage tending to zero V_{DS}=0.01V, stress gate voltage $V_{G\text{-}Stress}$=25V. This experiment can demonstrate the relationship that exists in the threshold voltage variation with respect to temperature variation, which means that it follows the same trend with respect to measurements in other tests and on other devices regardless of the manufacturer. The same happens with respect to the recovery measurements obtained experimentally when $V_{G\text{-}Recovery}$=5V after the application of $V_{G\text{-}Stress}$=25V in 100 seconds (see Fig. 5). Different BTI studies for SiC and GaN n-channel MOSFETs have been discussed and it is concluded that the trend with respect to temperature variation shows the same behavior with respect to BTI application, independently of the applied characterization method or test pattern [42, 43], so we can rely on this characterization test.

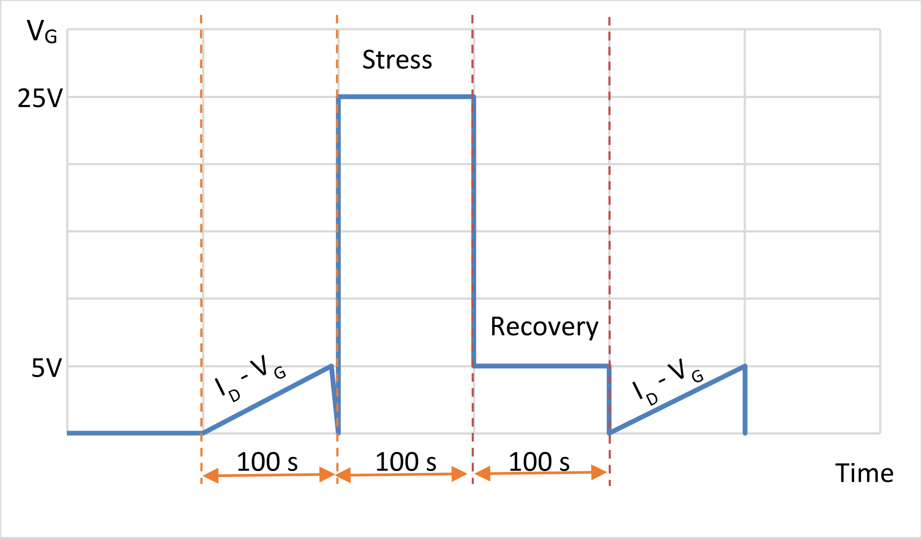

Fig. 5. Bias temperature stress tests pattern.

Conclusions

Wide bandgap (WBG) semiconductors, such as silicon carbide (4H-SiC) and gallium nitride (GaN), are the materials of the future in power electronics because they guarantee higher energy efficiency in power conversion than silicon devices; and they are already commercialized, but there are still many problems to be solved to fully exploit the wide potential of these materials, so reliability testing plays a crucial role.

It is important to analyze the instability factors in SiC and GaN devices, using tests such as PBTI, NBTI to determine if there is instability in their electrical parameters. Once the devices are found to be unreliable, tests can be performed to understand the reasons why, based on criteria and interpretations of characterization methods.

The tests discussed in this paper focus on the reliability analysis of SiC and GaN devices. The industrial and energy sector benefits from the implementation of these devices, therefore, knowing their electrical characteristics is very important and of great impact in these sectors and academia.

GaN devices are much more resistant to radiation such as gamma radiation, according to some of the test results discussed. However, there is still insufficient information, and this represents a research opportunity and challenges for academia and for the industry that manufactures these devices and that which implements them in their applications.

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