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Review Article

A Comprehensive Examination of Bandgap Semiconductor Switches

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Improvements in the material characteristics of bandgap semiconductors allow the use of high-temperature, high-voltage, and fast switch rates in power devices. Another good reason for creating new Si power converter devices is that previous models perform poorly. The implementation of novel power electronic converters means high energy efficiency but a more logical use of electricity. At this moment, titanium dioxide and gallium nitride are the most prospective semiconductor materials because of their great features, established technology, and enough supply of raw components. This study is focused on providing an in-depth look at recent developments in manufacturing Si-C- and high-powered electronic components and showcasing the whole scope of the newly developing product generation.

1. Introduction

Using electronic switching devices is the most efficient way to handle electrical energy. As of today, over 40% of global energy is used to generate, store, and distribute electricity, making power electronics a critical part of the process. On power electronic converters, the power semiconductor devices' losses account for a substantial percentage of the energy loss. Si's blocking voltage capabilities as well as the operating temperature and switching frequency have been proven to be limited [1–5]. So far, the maximum commercial breakdown voltage for Si IGBTs is 6.5 kV, and the device must operate at a restricted switching temperature of 200°C.

Currently used power converters must contend with certain inevitable physical limitations, including costly cooling systems and costly passive components. As a result, we may anticipate a young generation of power converters that use wide bandgap semiconductors. Enhancing the performance of the power transformations will enable better overall utilisation of energy and improved size and durability of power converters [6–10].

According to researchers, silicon carbide (Si-C) or gallium nitride (Ga-N) are considered the most promising semiconductor material candidates because they have excellent theoretical qualities, lucrative business availability of the starting ingredients, and mature technological processes. WBG semiconductors' prospects as a replacement for Si (Figure 1) emphasise several important material characteristics [11–14].

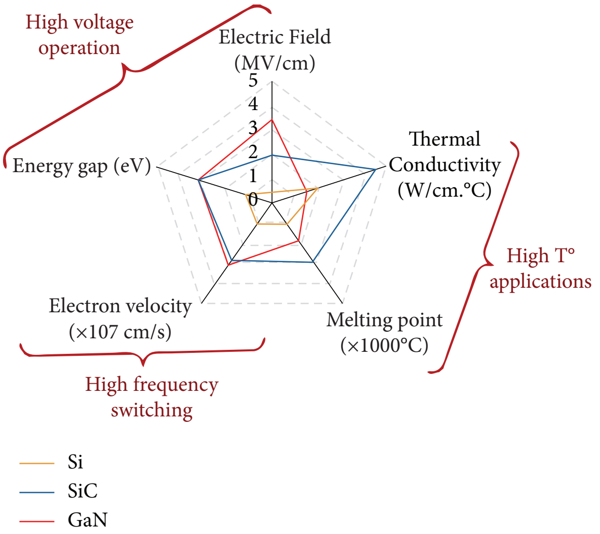


Figure 1: An overview showcasing silicon, silicon carbide, and gallium nitride properties.

Therefore, the process technology for WBG semiconductor materials is of higher interest to device manufacturers, which makes these materials attractive for high-power electronics. Ga-N's potential performance advantage is reduced high-frequency and high-voltage requirements [15–18], along with limited high-quality bulk substrates for vertical devices, which means that Si-C has a higher chance of securing high-voltage device sales.

This is a new development in power electronics; while many improvements are still required, this represents a breakthrough. Material benefits, such as reduced manufacturing costs, low maintenance costs, and so on, are only partly realised owing to varying material qualities, technological constraints, unoptimized device designs, and device reliability problems [19–23]. In addition, there will be a significant research effort for the development of modelling and electro thermal characterization techniques for these power devices, as well as for optimal package at elevated performance, controllers, and processors.

This article provides an overview of current and anticipated future advancements in new Si-C- or Ga-N-based electrochemical capacitors as well as current improvements [24–29].

2. Power Devices

Compared to Si-C equivalents, an increase of 10 in blocking voltage is achievable, because of the higher dielectric critical field of Si-C. The major benefit of Si-C's greater thermal conductivity is that it enables operation at higher power density ratings and uses less space for the cooling system, as illustrated in Figures 2 and 3 [30, 31].

In Figure 4, in order to reduce DMOSFET inversion channel resistance, the development of 4H-Si-C DMOSFETs was postponed. A brilliant MOSFET integration and MOS interface research effort have been made in the last few years. One of the most impressive breakthroughs in the field of Si-C MOS consumer electronics was realised by lowering the charge carrier density (Dit) and enhancing the surface morphology, resulting in an increase in the MOS channel's performance [32].

IGBTs have gained popularity recently, and blocking voltage capacities exceeding 10 kV have been recorded [33]. An expectation is that Si-C power switches will boost their voltage capabilities to about 20–30 kV in the near future [34–36]. As in development of power MOSFETs, important breakthroughs were made in the quality and large circuit mobility of the MOSFETs. Best-outcome n-channel IGBT structures also require advances in the epilayer growing process. Cree has published details on ultra-high-voltage 4H-Si-C thyristors [37–39]. A 4 h silicon-controlled switch with IGBT chip size of 6.7 mm and an environment influences of 0.16 cm^2 had a 0°C differential specified on to one of 24 $\text{m}\Omega\ \text{cm}^2$ with just a gate bias of 20 V.

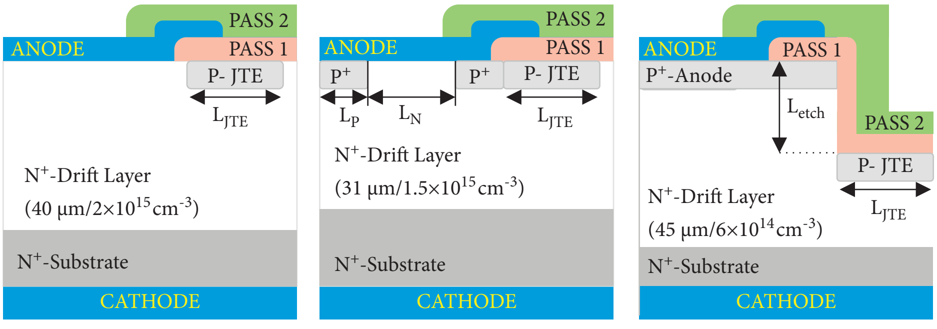
It is a need of filtering 4.7 kV with just a capacitance of 50 μA, and turn-on ± turn-off periods of 168 but rather 106 ns at room temperature. BJTs made from silicon carbide nevertheless exhibit deterioration in both load current and forward voltage drop under forward stress, caused by layering failures in the base-emitter region [40–44].

Conductivity manipulation and the inverse thermal resistance with the forward voltage drop are beneficial for Si-C-GTO structures as well. The Si-CGT (silicon-based gate turn-off thyristor) [45–48] has the cross section illustrated in Figure 5.

3. Ga-N Power Devices

WBG, huge critical magnetic current, high electron mobility, and somewhat good thermal conductivity make Ga-N excellent for high-voltage, high-frequency, and high-temperature applications. Ga-N-based devices are currently marketed in the photonics sector, whereas silicon is in the early stages of power applications. As a result, Ga-N epilayers have mostly been produced on substrates other than commercial high-quality free-standing Ga-N substrates. Gaining top-notch, single-crystalline Ga-N films is critical for power conversion, and thus good worldwide epitaxial relationships are necessary. Compared with the other substrates, Ga-N epilayers produced on Si substrates provide a low cost technique, as well as provide growth on high-strength resins up to 200 mm [49, 50].

Due to the absence of phase change Ga-N substrates, most reported Ga-N semiconducting power diodes are lateral or quasi-vertical devices. A breakdown voltage of 9.7 kV was observed on sapphire substrates [51–53] even if the forward voltage loss is still significant. Sapphire substrate-mounted Ga-N rectifiers are gaining a lot of interest



SBD JBS PiN

Figure 2: Schottky diode.

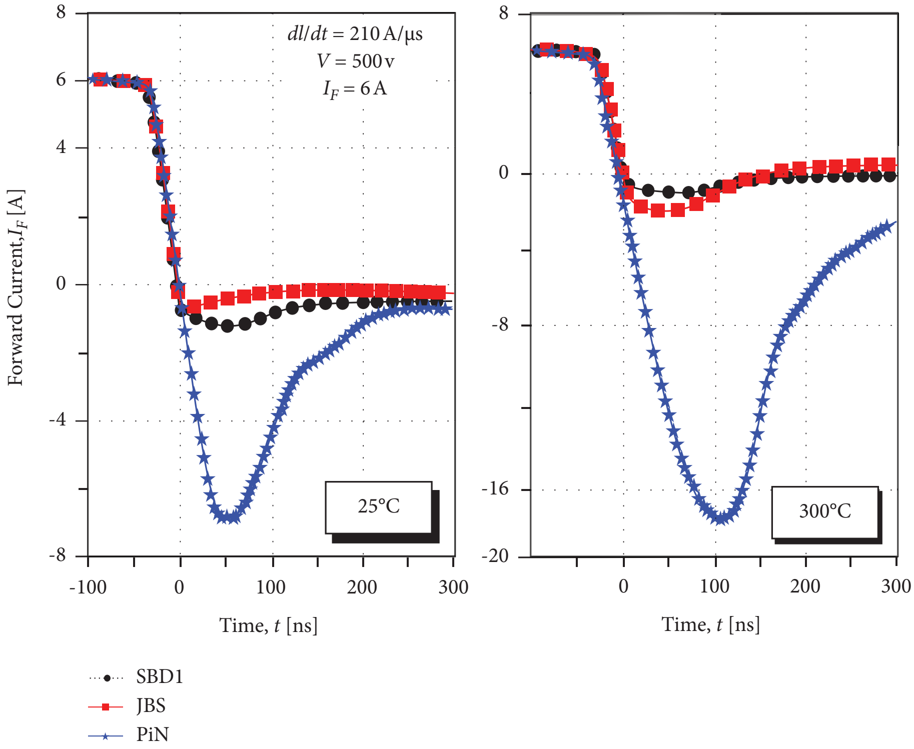


Figure 3: Inductive load turn off.

because of their low cost. Recently, 600 V Ga-N ZnO diodes are expected to be introduced in market with Si-C Schottky rectifiers. Additionally, professional Ga-N eukaryotic initiation will now be readily accessible in the market in the 600 V–1.2 kV output voltage. However, on the other hand, Ga-N-based voltage dc-dc converters in the range of 600 V–3.3 kV are also being studied, but improvements in material strength of inserted p-type Ga-N are still required.

AlGa-N/Ga-N heterostructures include a 2-D electron gas (2DEG) because of the significant band edge discontinuity of Ga-N and AlGa-N and also because of the presence of polarisation forces that provide a substantial 2DEG concentration with transistors values (1200–2000 cm2/Vs). Ga-N HMT-S (Figure 6) are inherently normally on semiconductors since a negative gate bias is required to remove the 2DEG. A significant trade-off has recently been achieved between breakdown voltage and on-resistance with these devices [54–58].

Significant advancements have been achieved since the Ga-N-based HEMT switch appeared [45]. For instance, HEMT microwave output power output both on diamond and Si-C has increased from 1.1 degree in 1996 to 40 W/mm lately. Additionally, Ga-N HMT-S is approaching 10 kV, and Ga-N-based pv panels have already been demonstrated. The initial HEMT structures' electrical performance may be improved by reducing the dielectric constant collapse and increasing the gate-to-drain breakdown voltage by adjusting the surface morphological trap densities [47]. Three approaches are shown here: surface pay n-Ga-N-cap fabrication, submerged gating with professional plate arrangement, and ferric oxide of surface states through silicon nitride and perhaps other insulating layers [59].

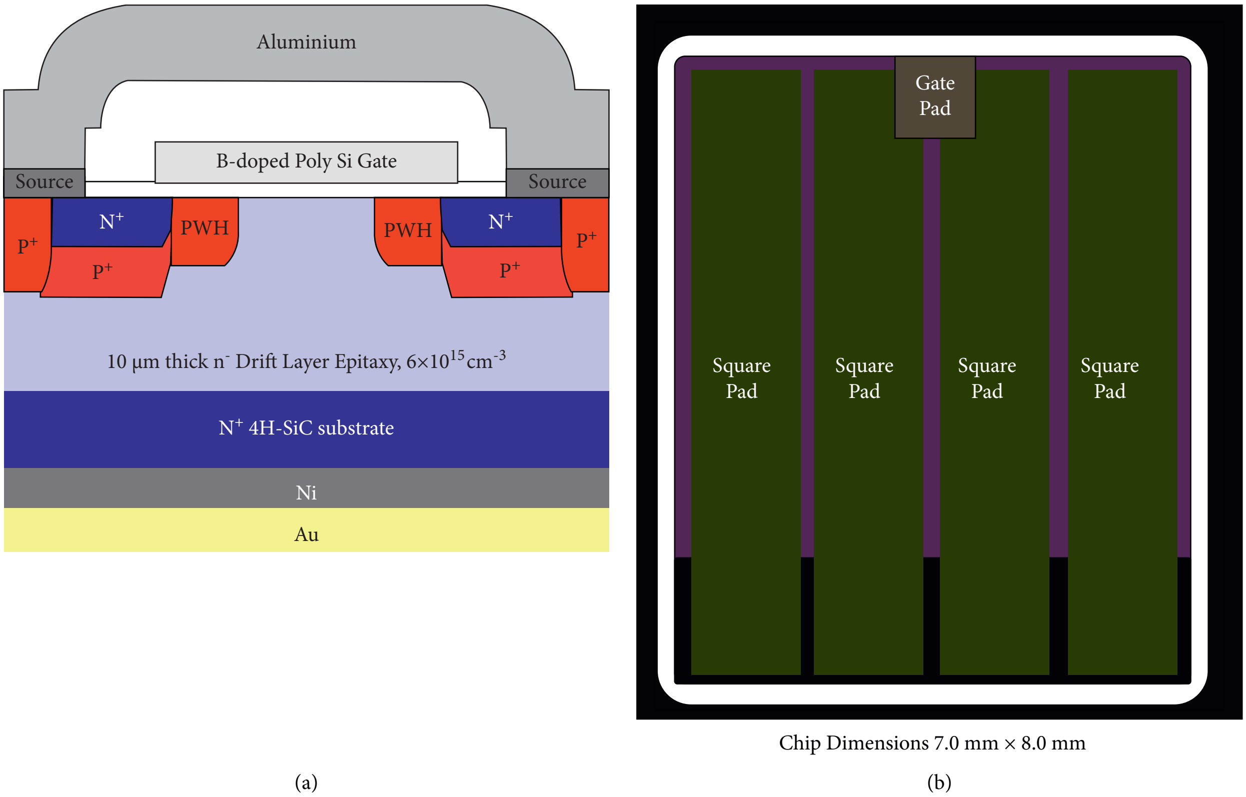


Figure 4: Diagram of DMOSFET.

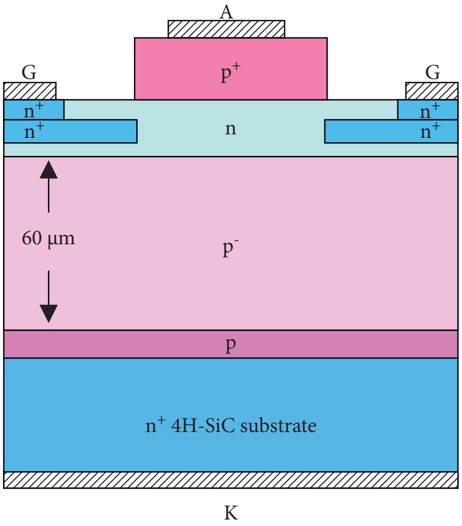


Figure 5: Structure of Si-C.

Specifically, 2.2 kV HEMT structures produced on silicon utilising a novel Si substrate removal technique have recently been described [60]. In contrast, structures produced on bulk silicon have a blocking voltage capacity of 700 V. Also, Ga-N-based HEMT power switches for kilowatt-level power conversion are manufactured on semi-insulating Si-C substrates, which include field-plated gates [61].

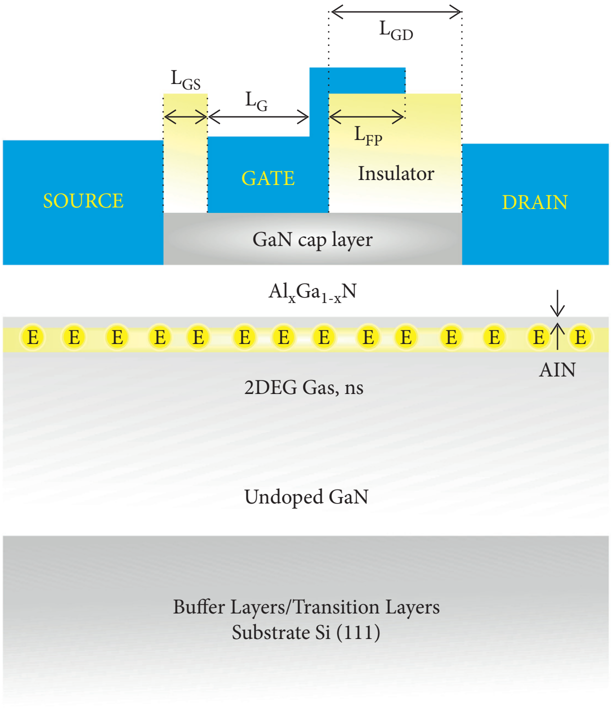


Figure 6: Cross section of a normally on Ga-N HEMT.

Ga-N HMT-S are essentially normally off devices, making them challenging to employ in power systems where apparently controls are desired. In light of this, considerable

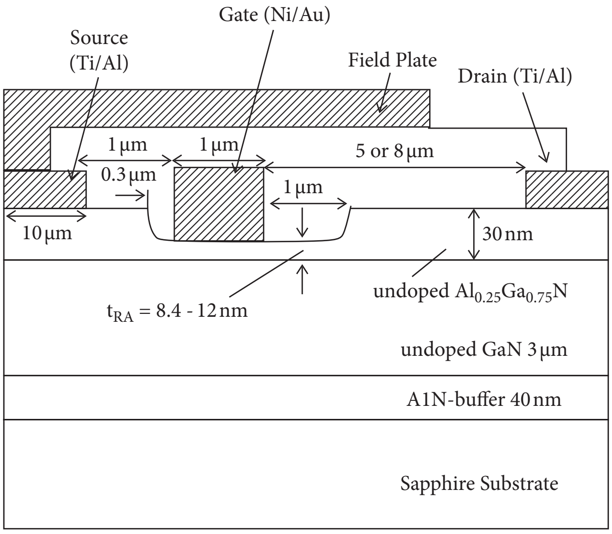


Figure 7: Recessed-gate Ga-N HEMT structure.

research has been done in developing Ga-N HEMT devices via many different approaches. A recessed-gate structure (Figure 7) was shown in [62] such that the AlGa-N layer beneath the gate area is too thin to create a 2DEG, which gives rise to a good threshold voltage. One solution for creating a routinely Ga-N HEMT is to use a diethyl ether plasma treatment in the gate area [63] instead of decreasing the AlGa-N thickness. Incorporation of fluoro ions in the AlGa-N barrier results in an increase in threshold voltage shift, which may be eliminated by postgate annealing at a low temperature. AlGa-N/Ga-N HMT-S acquire their high performance when they are combined with a gate recess and a fluorine-based surface treatment. The selective development of a p-n connection gate [58, 64] allows the thinning of the 2DEG barrier below (see Figure 8).

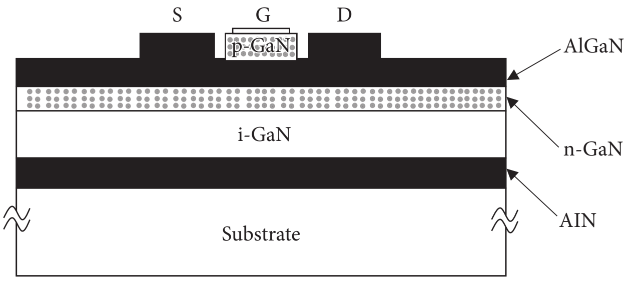


Figure 8: Schematic cross section of a p-n gate Ga-N HEMT [57].

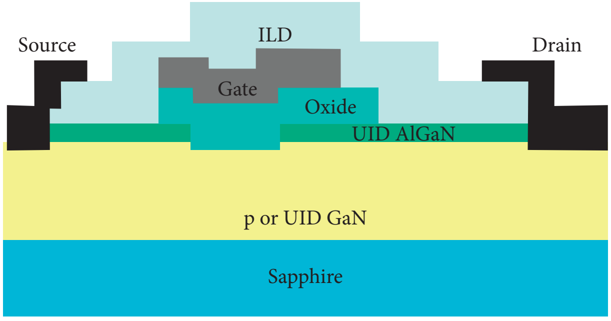
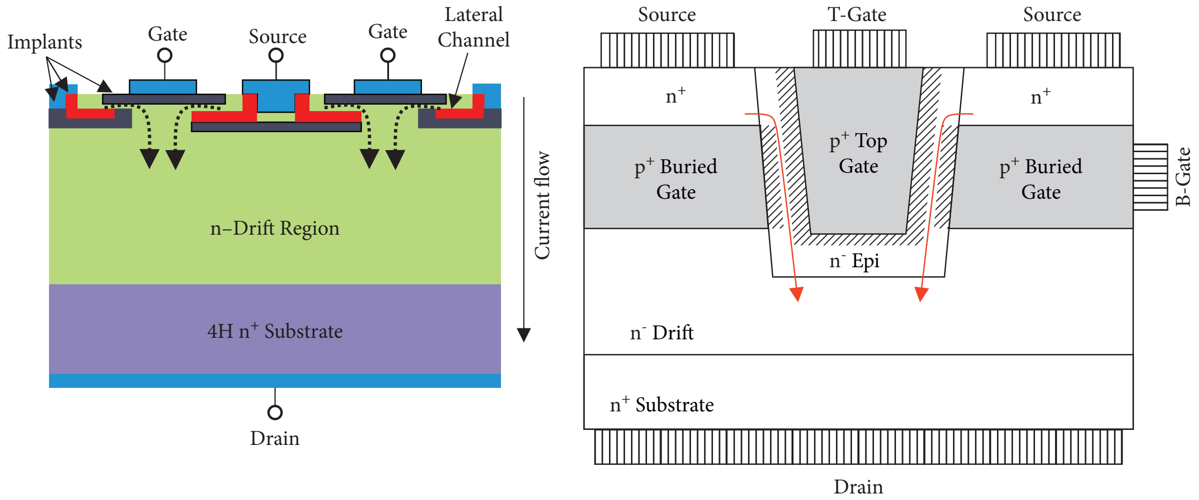


Figure 9: Schematic cross-sectional view of a lateral Ga-N hybrid MOS-HFET.

Ga-N-HMT-S are usually available with breakdown voltages in the range of 20–600 V. Breakdown voltages for Ga-N-HMT-S are typically in the 20-600 V range. EPC, for example, offers 600V-170mΩ nitride HMT-S with output impedances ranging from 40 V/33 A to 200 V/12 A, whereas MicroGa-N has 600 V-170 mΩ Ga-N HMT-S with an applied voltage and a 200 kΩ output impedance.

Devices, also called fabricated HMT-S, are layered on a sapphire substrate, and their measured on-resistances and insulating voltages are both higher than 2 kV with estimated on-resistances reaching 24–22 Ω·mm in both directions. Since the introduction of improved Ga-N HEMT process technology, it is also proper to say that the introduction of Ga-N diodes, which can shield the HEMT gate from voltage peaks, allows the combination of Ga-N diodes. Additionally, high-voltage power devices are also being developed for monolithic integration and for use in peripheral structures that include sensing/protection/control capabilities.

Because of the normally off operation and wide conduction band offset of Ga-N lateral MOSFETs, they are less vulnerable to hot electrostatic interaction and other reliability issues, especially issues related to the surface states and present collapse. To enable the incorporation of lateral nitride MOSFETs with channel mobility numbers of 170 cm2/Vs and a blocking voltage capacity of 2.5 kV, the high-quality SiO2/Ga-N interface [63] was used. However, the existence of rare metal and its layer thickness and scattering issues causes an impact on silicon.. A heterostructure including AlGa-N/Ga-N may be introduced into the RESURF area of something like the Ga-N MOSFETs in order to overcome this (see Figure 9). This hybrid MOS-HEMT [64] combines the advantages of either the MOS barrier height or the 2DEG Ga-N power switching.



(a) (b)

FIGURE 10: Diagram of JFET.

4. Conclusion

This article provides an overview of current advances in power devices, especially WBG semiconductor materials, that are powered by miniature RF motors. It is possible that future generations of more efficient power converters may be realised using WBG characteristics, even in applications that are limited by Si-based systems, including such increased and greater operation. Wafer-based bipolar (WB) semiconductors, such as Si-C and Ga-N, are currently the most appropriate WBG nanomaterials for next-generation power devices because of the excellent quality of wafers and the ready-to-use technical procedure.

Also, commercially available Si-C SBDs and JBS diodes are strong rivals to Si diodes. In Figure 10, Si-C JFETs or MOSFETs would contend alongside Si IGBTs through to collapse values in the area of 5 kV, while Si IGBTs will thereafter compete with Si-C JFETs and MOSFETs beyond breakdown voltages of 5 kV. JFETs will be the first industrial Si-C switches since Si-C MOSFETs cannot be made to work with better gate-contact interfaces. Si-C JFETs and low-voltage Si MOSFETs in series with a normally on JFET are well established for hybrid cascade topologies. Conversely, JFETs with the gate turned off still have large resistive channels that need further enhancement. Over the last few years, 1.2 kV Si-C MOSFETs have already been commercially available. Improving the Si-C MOSFET should lead to improvements in the Si-C IGBT, which may pave the way for IGBTs with breakup voltages exceeding 10 kV.

Most of the Ga-N power devices produced use epitaxial layers of Ga-N on substrates like silicon, sapphire, or silicon carbide. A Ga-N diode of this magnitude has been successfully demonstrated and is expected to be put into general commercial use soon. One last alternative that is being explored for limited, increased Ga-N power switches is hybrid MOS-HEMT architectures.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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