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High Power Semiconductor Devices for FACTS: Current State of the Art and Opportunities for Advanced Materials

M.J. Marinella, S. Atcitty, S. DasGupta, R.J. Kaplar, and M.A. Smith

Sandia National Laboratories
PO Box 5800, MS 1084, Albuquerque, NM 87185

Flexible AC Transmission Systems (FACTS) use advanced power electronics to minimize reactive power loss on the grid. Power devices used in FACTS systems must be capable of switching several thousand amps at voltages of 1-10 kV. Traditionally, these systems have relied on silicon thyristors, but recently have also began to incorporate insulated gate bipolar transistors. FACTS systems present an opportunity for emerging SiC and GaN power transistors, which offer major efficiency gains. However, for these advanced materials to be considered for use in high consequence grid level systems like FACTS controllers, excellent reliability must be demonstrated.

Introduction

Rapidly increasing demands for electrical energy and diminishing natural resources in modern times have led to concerns that future electricity needs cannot be met. A number of technological solutions are being publicly proposed to meet this challenge: efficient lighting, improved insulation, and alternative energy sources. However, in 2009 an estimated 6.5% of all electricity generated in the US was lost due to transmission and distribution inefficiency (1). Flexible AC Transmission Systems (FACTS) address this problem by using advanced power electronics to precisely regulate the reactive power on the grid to minimize losses (2).

FACTS utilizes several types of controllers; a few of the major examples are Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSCs), and Unified Power Flow Controllers (UPFCs) (2). At the fundamental level each of them uses a combination of high voltage switches in conjunction with capacitors, inductors, and energy storage devices to control and optimize power on the grid. In the following, we review basic FACTS systems, key properties of power devices used in these systems, and discuss the current state of the art silicon power devices and opportunities for SiC and GaN devices in these systems.

System-Level Considerations

The goal of an electric power grid is to supply reliable power from the generators to industrial and residential customers via a transmission and distribution (T&D) network. Advanced power electronics systems will play a key role in increasing the reliability, security, and flexibility of future power grids by mitigating potential problems (e.g. uneven power flow through the system or “loop flows”), improving transient and dynamic stability, improving frequency regulation, and reducing subsychronous oscillations and dynamic over-voltages and under-voltages across T&D networks. Power electronics controllers currently used in the electric utility system include fault-current limiters, high-voltage direct current (HVDC) converters for DC transmission, flexible AC transmission systems (FACTS) for reactive power (volt-ampere reactive or VAR) control, active filters, solid-state circuit breakers, and solid-state transfer switches. Power conversion systems (PCS) are used in energy storage and distributed generation systems to produce high-quality AC output at desired voltages. Future electric utility systems are envisioned to be highly automated, interactive "smart" grids that can self-adjust to meet the demand for electricity reliably, securely, and economically. Such systems will be highly dependent on power electronics devices and systems, and improvements in both power electronics systems and the devices on which the systems are based will be key components in the development of "smart" grids.

In bulk power transmission systems, power-electronics-based controllers (FACTS controllers) are frequently used to improve the stability of the electric utility system both at transmission and distribution voltage levels. Some lower-power FACTS controller concepts have been applied for end-use applications (i.e., near the customer). These FACTS controllers can also help delay or minimize the need to build more transmission lines and power plants and enable neighboring utilities and regions to economically and reliably exchange power. As the vertically integrated electric utility structure is phased out, centralized control of the bulk power system will no longer be possible. Transmission providers will be forced to seek means of local control to address a number of potential problems such as uneven power flow through the system (loop flows), transient and dynamic instabilities, sub-synchronous oscillations, and dynamic over-voltages and under-voltages. Several FACTS controller topologies have been proposed to mitigate these potential problems, but transmission service providers have been reluctant to use them, usually due to cost and a lack of systematic control. Considerable attention has been given to developing control strategies for a variety of FACTS controllers, including the static synchronous compensator (STATCOM), series STATCOM (SSSC), and the unified power flow controller (UPFC), to mitigate a wide range of potential electric utility issues. As an example, a simplified STATCOM circuit is shown in Fig. 1 below. This figure is used to explain the real and reactive power equations for general STATCOM operation, as an illustration of a typical FACTS controller.

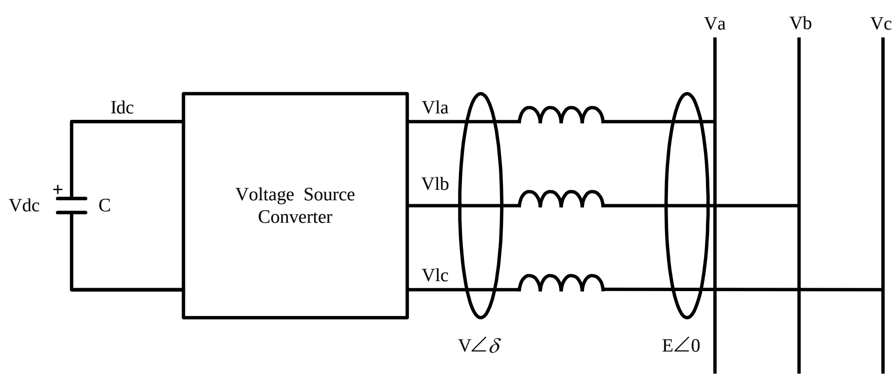

Figure 1. Schematic diagram of STATCOM.

Fig. 1 includes a DC-link capacitor (C) that provides the voltage required by the voltage-source converter. Although the figure only shows a DC-link capacitor, energy storage technologies (such as batteries) which are DC in nature may be attached in parallel to the capacitor to provide additional power and voltage support. The power electronics-based converter (in this case a voltage-source converter) converts DC power into AC power to be used by the utility at the load. The electric utility load is represented by a 3-phase voltage output (V_{la}, V_{lb}, and V_{lc}) and a 3-phase current output (I_{la}, I_{lb}, and I_{lc}). The leakage reactance is represented by X. V_a, V_b, and V_c are the 3-phase voltages at the electric utility interface. The voltage-source converter output voltage is also represented by voltage magnitude (V) and angle (δ). Similarly, the electric utility voltage at the interface is represented by voltage magnitude (E) with its reference angle set at zero. The real power (P) and reactive power (Q) delivered by the voltage-source converter to the electric utility interface are given by the following equations:

$$P(\text{Watts}) = \text{VE} \sin(\delta) / X \qquad [1]$$

$$Q(\text{VAR}) = [V^2 - VE \cos(\delta)] / X \qquad [2]$$

Equation [1] indicates that real power (P) is a function of the AC voltage magnitudes (V and E) and the phase angle (δ) between the voltages. Given that the voltage magnitudes can only be allowed to vary within a rather narrow band (e.g. ±5%), the real power is primarily a function of the phase angle. Therefore, the real power output of the converter can be controlled by adjusting the phase angle of the inverter with respect to the grid voltage. Equation [2] shows that the reactive power (Q) is strongly dependent on the voltage magnitude, particularly for small values of δ. Thus ideally, increasing V causes the converter to increase reactive power output. There are two methods for controlling reactive power: directly and indirectly. In direct control, the inverter output V is adjusted, usually by keeping δ close to zero to reduce real power flow into and out of the converter. In indirect control, reactive power is absorbed from or injected into the electric utility by controlling the DC-link capacitor voltage (V_{DC}).

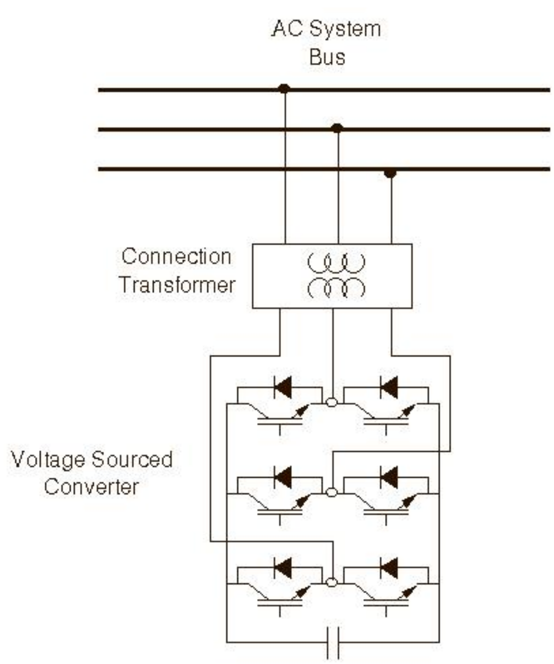

Figure 2. Schematic diagram of voltage-source converter, showing the utilization of power semiconductor devices as switching elements.

The voltage-source converter is the heart of the STATCOM. It, in turn relies upon power semiconductor devices to perform the necessary switching functions. A schematic of a STACOM highlighting the internal circuitry inside the voltage-source converter is shown in Fig. 2.

Note the presence of the six power semiconductor switches inside the voltage-source converter, which are controlled using a pulse-width modulation (PWM) scheme; switching frequencies for modern FACTS controllers are typically less than 5 kHz. In this example, these switches are composed of insulated gate bipolar transistors (IGBTs) and diodes. The properties of these switches (e.g. voltage and current ratings, switching speed, and switching loss) determine the properties of the voltage-source converter. The properties of the power semiconductor devices are discussed in the next section.

Key Power Device Properties for FACTS Applications

As described above, FACTS systems are implemented using semiconductor power devices. The high currents and voltages required by FACTS controllers, and high consequences associated with failure of components of the power grid create unique requirements for these devices. These requirements are highlighted in the following subsections.

Breakdown Voltage and Specific On-Resistance

Individual device breakdown voltages in FACTS controllers range from 1 kV to 10 kV (and higher in some cases). Clearly, having a high breakdown voltage is one of the most critical parameters of semiconductor devices used in FACTS systems. Breakdown in both bipolar (i.e. *p-i-n* diodes) and unipolar (i.e. MOSFETs) power devices is generally caused by avalanching. When a large reverse bias is applied across a p-n junction, carriers are generated as a result of the high energy collisions, and this process is exponentially dependent on electric field. The electric field at which avalanche breakdown occurs depends inversely on the doping level, and also depends on the material. For a given doping level, 4H-SiC has a breakdown voltage over 100 times greater than Si (3).

Designing unipolar power devices is a tradeoff between a high blocking voltage V_{BD} and a low specific on-resistance R_{on}. The physical reason for this is illustrated in Fig. 3. Consider the left side of Fig. 3, which illustrates the *p-i-n* diode structure that forms the drain of a unipolar power MOSFET. The drain blocking voltage must be dropped mostly across the lightly doped region of this structure. To the right of the *p-i-n* structure, the electric field ε_C is plotted versus distance. For a given material (e.g. Si), there is a maximum electric field which, if exceeded, will result in avalanche breakdown. Further, the breakdown voltage of the entire structure, V_{BD}, is given by the area under the field versus distance curve. Thus, the design constraint is defined: the distance *d* must be thick enough that the desired V_{BD} can be achieved without exceeding ε_C. However, increasing this thickness adds to the series resistance of the device. In a unipolar power device, the ideal relationship between R_{on} and V_{BD} is given by (3):

$$R_{on} = \frac{4V_{BD}^2}{\epsilon_S \mu \varepsilon_C^3} \qquad (3)$$

where μ is the mobility. The ε_C^3 term in the denominator gives insight as to why there is enormous interest in replacing unipolar transistors made from silicon ($\varepsilon_C \approx 0.3$ MV/cm) with those using SiC ($\varepsilon_C \approx 2.0$ MV/cm) or GaN ($\varepsilon_C \approx 3.3$ MV/cm). The theoretical improvement in R_{on} attained with SiC and GaN is on the order of 100 better than silicon for a given V_{BD}.

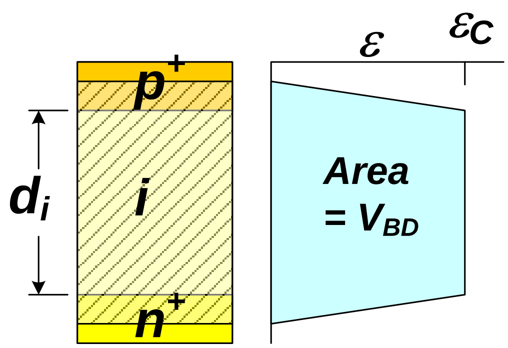

Figure 3. (left) Physical depiction of a reverse-biased p-i-n diode and (right) corresponding electric field versus position plot. Courtesy D.K. Schroder.

Switching Speed and Losses

Switching losses and maximum switching speeds are another important property of power devices used in FACTS controllers that require consideration. These controllers require devices to switch at frequencies of 50 to several thousand Hz for pulse PWM converters. The term *dv/dt* generally refers to the time it takes for a device to switch from a high-current, low-voltage (on) state to a low-current, high-voltage state, known as turn-off time. Conversely, the term *di/dt* refers to the time it takes for the current to rise (turn-on time). The *dv/dt* and *di/dt* capabilities of a power device determines the switching losses, which are the practical limiter of switching speeds. In general, an attractive feature of unipolar power devices is that the maximum switching speeds are much greater and the switching losses much lower than those for bipolar devices due to the fact that bipolar switching speed depends on the electron-hole recombination time.

Fast unipolar switching speeds are the main reason that power MOSFETs are used for applications that require frequencies above 100 kHz, whereas bipolar thyristors and IGBTs have prohibitively high switching losses at these frequencies. There are advantages to higher frequencies for FACTS systems. For example, higher frequencies provide a high control bandwidth (or faster response) and smaller passive filter requirements (capacitors and inductors). However, with higher frequencies the thermal management becomes a challenge due to the switching losses. Thus, if unipolar SiC or GaN transistors were available to operate at the high voltages and currents required by FACTS controllers, their lower switching losses would provide a distinct advantage for PWM applications.

Maximum Current Rating

A unique requirement of FACTS controllers and other grid-level applications of power electronics (such as HVDC) are operating currents of hundreds to thousands of amps. Currently, silicon thyristors are available capable of 5000 A in a single device and silicon IGBTs are available with static operating currents as high as 2000 A. Wide bandgap power devices are not yet available with the current ratings necessary for FACTS, although they are under development.

Safe Operating Area and Thermal Considerations

The safe operating area (SOA) of a power semiconductor device is a current-voltage domain within which the device can operate without damaging or destroying itself. In general, this limit is time-dependent and very high current-voltage combinations (known as short circuit operation) can be safely reached for short durations, generally less than 100 μs. Figure 4 gives a generic descriptive plot of the SOA of a power MOSFET, with labels for specific limits. As discussed above, the maximum current at low V_{DS} is typically limited by the R_{on} whereas the high V_{DS}, low I_D limit is due to avalanche breakdown in the drain-body *p-i-n* diode. The short-circuit limit is dictated by the ability of the device to dissipate heat, which is why the static limit can be greatly exceeded for a very short time period. Finally, there are packing related limits, such as the resistance of the bond wire and the ability of the package to dissipate heat. All materials limits of the SOA are greatly increased for SiC and GaN due to both the high breakdown electric fields and excellent thermal conductivity of these materials compared to silicon.

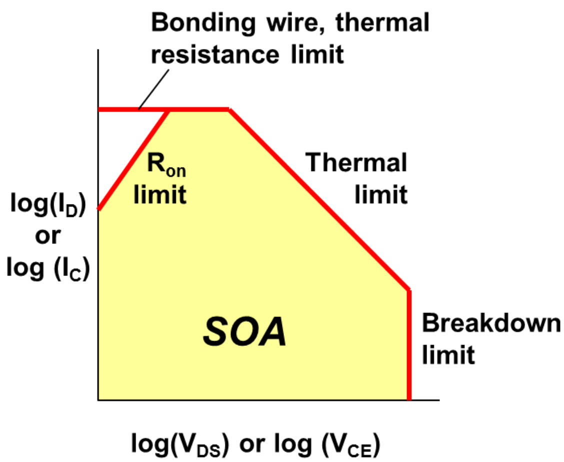

Figure 4. Descriptive plot of the safe operating area (SOA) for a power MOSFET. Courtesy D.K. Schroder.

Reliability

FACTS controllers are a part of the power grid and therefore a single failed device can potentially affect thousands to hundreds of thousands of customers. Non-catastrophic power device failures can cause inefficient or erroneous operation. Clearly, reliability is of paramount importance for power devices used in FACTS, which is why engineers involved in the design and implementation of these systems are reluctant to move to new technologies without assurance that reliability will not suffer. For this reason, Sandia National Laboratories has undertaken a major effort to evaluate the reliability of SiC and GaN power devices to examine and assure their reliability for grid level applications such as FACTS and HVDC.

Current State of the Art of Power Devices in FACTS Systems

The vast majority of power electronics systems in use today rely on silicon-based semiconductor switches to perform their functions. Indeed, for over five decades, silicon-based semiconductors have been the power device of choice for most, if not all, high-power applications. In particular, silicon-based insulated-gate bipolar transistors (IGBTs) and gate turn-off thyristors (GTOs) have been the dominant semiconductor switches for high-power applications, and technology improvements over the last several decades have resulted in consistently higher power levels for these devices. Nevertheless, silicon-based semiconductors have inherent limitations that reduce their suitability for use in utility-scale applications. These limitations include a low voltage-blocking capability, low switching speeds, and a limited junction operating temperature. Although switch-mode power supplies (e.g., PWM based converters), which feature greater control capability and provide better conversion efficiency, have been developed in the last two decades and have changed the way power is converted in many high-power applications, utility-scale applications would directly benefit from the development of semiconductor switches with higher (greater than 20 kV) voltage blocking capability and a higher (greater than 150 ºC) junction temperature.

The silicon thyristor has been the most important power device for traditional FACTS controllers due to its high blocking voltage and low impedance "on" state. The thyristor is a triple junction (*pnpn*) device that usually has three terminals: anode, cathode, and gate. The device is used as a switch that achieves a low-impedance forward-bias on-state by pulsing the gate. In a standard thyristor, the off-state is restored only by reversal of the anode-to-cathode voltage or decay of the forward conduction current below the holding value. The gate-turn-off (GTO) thyristor ceases forward bias conduction with a reverse polarity gate pulse. The main advantage of GTOs over thyristors are higher switching speeds as well as the ability to turn off the current without reversing the anode-to-cathode voltage. Modern silicon thyristors are capable of on-state conduction of up to 5000 A and reverse blocking of up to 8000 V. Since the thyristor is a bipolar device, the on-state impedance remains low even when designed to withstand a large blocking voltage. The major drawback of the thyristor is the long, high-energy switching time. Fig. 5 shows and example of a modern silicon-based power thyristor module designed for grid level applications.

Figure 5. High-voltage silicon thyristor module co-developed by Sandia National Labs.

Figure 6. Packaged ABB HiPak 6.5kV Insulated-gate bipolar transistor (4).

The Si Insulated-Gate Bipolar Transistor (IGBT) is a hybrid device that combines desirable properties of bipolar and MOS devices (3). Since it is a bipolar device, the on-state resistance is low, while MOS gate control provides a high gate input impedance and provides controlled turn-off capability. However, like all bipolar devices, the switching speed is limited. The other disadvantage of the IGBT is a high voltage drop (one junction drop in series with resistive drop across the blocking layer) which increases power dissipation. Modern commercial FACTS controllers often make use of IGBTs rather than GTO thyristors at moderate switching speeds (greater than several hundred Hz) due to their enhanced safe operating area and higher short circuit tolerance, and because they do not require “snubber” circuits (5). The two junction structure makes it somewhat less suitable for achieving high breakdown voltages than the three junction thyristor – and the highest voltage rating on IGBTs is 6.5 kV with a peak current of 750 A (4). Commercial device with currents up to 3600 A are in production, although these have breakdown voltages of only 1700 V (6). As with the MOSFET, the there are benefits to of SiC over than silicon in IGBT performance, including lower switching losses and greater thermal management. However, reliability problems concerning the gate oxide and SiC/SiO_2 interface are critical issues that must be resolved before SiC IGBTs become a reality. 12 kV SiC IGBT prototypes have current densities nearly as high as the SiC GTO (7). However, the junction voltage drop is considerably higher (~3V) due to the wide bandgap of SiC, and the switching losses are about 1.5 times SiC MOSFETs of similar ratings and sizes.

Opportunities for High Power SiC and GaN Power Devices in FACTS Systems

The motivation of using wide-bandgap materials for grid-level applications comes from their high immunity to electric field induced generation – a precursor to most device breakdown mechanisms (i.e. avalanching). The resistance to carrier generation at high electric fields can be used to achieve better R_{on} and smaller parasitic capacitances, as described above. The result of this is high switching speeds (or lower switching losses for a given frequency) which improve the waveform quality and response time of the system to voltage fluctuations. This greatly reduces filtering requirements, which for FACTS are generally costly, bulky and have large cooling requirements. In addition to this, both SiC and GaN have excellent thermal conductivity – which allows them to handle much higher current densities than Si – and achieve the same voltage and current handling capabilities for smaller die sizes. Thus, wide-bandgap based switches have the potential to greatly reduce the system footprint and cost, and to increase system efficiency.

However, before power devices which use post-silicon materials are implemented in FACTS systems, the operational reliability of these devices must be sufficiently proven. For example, kV SiC MOSFETs will not be considered for use in FACTS systems until issues like bias temperature instability are fully understood and eliminated. In the following subsections, we detail the potential benefit of wide bandgap diodes, thyristors, and field effect transistors in FACTS applications.

SiC Diodes

SiC Schottky barrier diodes or metal–semiconductor diodes are attractive for low switching losses. Unlike the *p-i-n* diode, the Schottky diode does not require the removal of injected minority carriers during turn-off, and so it turns off very rapidly. Although Schottky diodes are desirable because of their low switching loss, it is not feasible to build high voltage Schottky diodes in silicon. This is because of the relatively low barrier heights between common metals and silicon. The bandgap of silicon is 1.12 eV and the barrier heights of metal contacts to silicon are typically less than 0.5 eV. Under large reverse bias, the barrier is further reduced by Schottky barrier lowering – which results in large reverse currents under high blocking voltages. This is not the case with SiC where Schottky barrier heights can be as high as 1.5 eV (8). SiC Schottky diodes have been commercially available for a decade; current products have voltage ratings as high as 1.7 kV (9) while device prototypes at much higher voltages have been reported (8).

SiC Thyristors

The suitability of the thyristor architecture for achieving extreme breakdown voltage and current handling capability, coupled with the possibility of achieving high switching speeds (relative to silicon thyristors and GTOs) due to extremely low minority-carrier density, makes the SiC GTO a potential candidate for a FACTS switch. Prototype devices with breakdown voltage of 10 kV and current handling capability of 140 A/cm^2 (7) have been demonstrated. The biggest challenge to SiC GTOs achieving simultaneous high-voltage and high-current capability is the development of SiC wafers of large enough area with low defect densities. While single thyristors on Si wafers of 100 mm diameter are in commercial production, the die size in commercially available SiC power devices is currently about 7.5 mm. An improvement in die radius by a factor of 3 could potentially bring SiC GTOs within the domain of operation for FACTS switches.

Wide-Bandgap Field-Effect Transistors

Unipolar wide bandgap power transistors such as the MOSFET provide very low switching losses and are thus an attractive replacement for GTOs, especially at higher switching frequencies. Since on-state conduction is not due to minority-carrier injection, turn-off transients are suppressed and higher switching frequency may be obtained.

Recent advances in high voltage SiC MOSFETs and GaN high electron mobility transistors (HEMTs) are of particular interest to the FACTS community. Figure 7 plots the theoretical relationship between R_{on} and breakdown voltage for Si, SiC, and GaN transistors, as well as some experimental results (10).

SiC MOSFET. The native oxide of SiC is SiO_2 (as is the case for Si) which is an excellent insulator that is particularly useful in creating a field-effect transistor. SiC MOSFETs are now commercially available with a blocking voltage of 1200 V, maximum DC current capability of 33 A, and R_{on} of 80 mΩ. In addition, SiC is inherently more capable of handling higher temperatures that Si, although the reliability of the SiO_2 insulator on SiC is an open question. Indeed, the greatest challenge in SiC MOSFET development has been the poor SiC/SiO_2 interface quality. When operated under high gate electric field operation and high temperatures, this has led to large threshold voltage instabilities (11), (12). In FACTS controllers, even though MOSFETs are operated as switches, threshold voltage shifts can cause inefficient and unstable operation. The extremely high current operation of FACTS switches would necessitate thermal management capabilities much higher than the state-of-the-art device, which starts to show significant threshold voltage instability above junction temperatures of 175 °C due to electrons tunneling into oxide traps (13). However, the motivation for developing SiC MOSFETs of higher breakdown voltage and current rating comes from its very low switching losses. SiC MOSFET prototype devices with 12 kV breakdown voltage show a factor of ~18 improvement over the Si IGBT in terms of power dissipation at both 500 Hz and 5 kHz operation at 5kV (7).

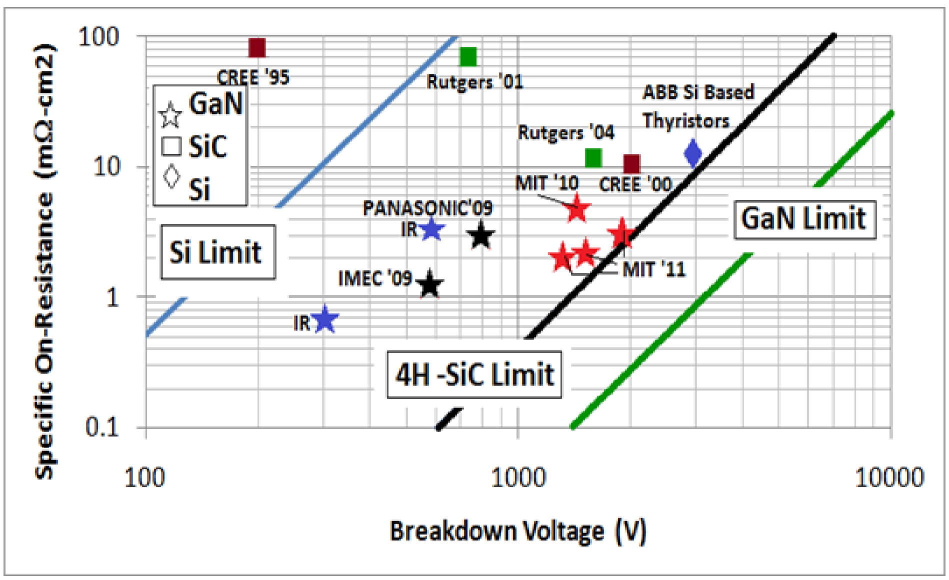

Figure 7. Relationship between specific on-resistance and breakdown voltage for unipolar power transistors.

GaN HEMT. The difficulties encountered in achieving high interface quality in the SiC MOS system has led to efforts to develop the GaN HEMT into a high-power, high temperature device. The wide bandgap properties of GaN are complemented by the ease of achieving low on-resistance in a HEMT due to the spatial separation of carriers from their donors in the entire conductive path from source to drain, as well as the HEMT's depletion-mode operation.

Recently, GaN devices have been fabricated out of epitaxial layers grown on Si substrates. In addition to the economic advantage of growing the devices on inexpensive and abundant Si wafers, the possibility exists of developing a completely Si-compatible process. However, high electric fields extending into the Si substrate have limited the maximum achievable breakdown voltage (14). Post-process removal of the Si and subsequent bonding to a wafer of insulating material (such as AlN) can greatly increase the breakdown voltage as well as improve thermal management issues (13). GaN HEMTs with approximately 1.5 kV breakdown voltage and DC current capability of 12 A, exhibiting R_{on} of 0.1 to 0.2 mΩ, have recently been fabricated (10). This demonstrates the prospect of developing high-voltage devices with extraordinarily low switching losses. The major roadblock for the GaN HEMT, much like the SiC technology, lies in growing epitaxial GaN layers of sufficiently large area and low defect density to give the devices the current-handling capability required for FACTS switches.

Conclusion

FACTS controllers presents a unique opportunity for emerging SiC and GaN power devices, especially the SiC MOSFET and GaN HEMT. If reliable transistors can be developed from these wide-bandgap materials that operate at the necessary current and voltage levels for FACTS controllers, a major energy savings can be achieved due to the lower on resistances and reduced switching losses. Further, SiC and GaN devices can operate at high temperatures, which reduce cooling requirements. However, before being considered for these high-consequence grid level systems it must be conclusively proven that these devices can be operated reliably for decades.

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