

Switching Megawatts with Power Transistors

by Krishna Shenai

Semiconductor silicon revolutionized the computing and communication industries in the last century. With the invention of the semiconductor transistor, miniaturization of electronic systems took place at an unprecedented rate. Today, everyone has access at their fingertips to computing and communication devices capable of delivering multi-megabits of data within seconds, once simply unthinkable. The advent of silicon integrated circuit (IC) technology enabled the information revolution, and information technology (IT) was a prime driver of the 20th century global economic boom.

With the advent of information technology, energy technology has become more critical than ever before.¹ Battery-powered, wireless handheld computing and communication devices are finding applications in every walk of life from the boardroom to the emergency room. However, further miniaturization and performance enhancement of these devices are hindered by battery size and limited storage capacity. At the same time, battery-chargers are inefficient and waste nearly 25% of the electricity used.² Hybrid electric vehicles (HEVs) are becoming cost-effective and popular; and there is growing interest in developing all-electric transportation, especially from the perspective of environmental concerns.³

The electricity transmission and distribution infrastructure is more than 100 years old and is in the midst of the greatest change in its history.⁴ A flexible and robust smart electricity grid is needed that is capable of efficiently integrating distributed renewable energy resources, including solar and wind generators.⁵ At the same time, alternative and more efficient methods of electricity delivery such as direct DC are under development and have the potential for rapid penetration of renewable energy for local utilization.⁶

Fundamentals of Solid-State Energy Conversion

Today, more than 80% of electrons that power electric utility infrastructure and transportation flow through a semiconductor switch that is used to convert one form of electricity into another form. This solid-state energy conversion is widely referred to as “power electronics.” Power electronics constitutes the backbone of electricity transmission, distribution, and processing much like signal electronics is used for

constructing the information highway.^{7,8} Figure 1 illustrates how the load is energized from the power source using a controllable 3-terminal power switch. A voltage source, V_{SUP} , supplies current to the load when the switch is closed by applying a control signal to the switch terminal “C.” Assuming that no stray inductances and capacitances exist in the circuit, all reactive elements present in this circuit arise from the load and the switch. In most power electronic applications, the load is inductive; consequently, both the magnitude ($i_L(t)$) and rate of change of current ($\frac{di_L(t)}{dt}$) in the load are important.

For example, for motor control applications, $i_L(t)$ controls motor speed while $\frac{di_L(t)}{dt}$ determines its torque. In the on-state when supplying power to the load, minimum power must be dissipated in the switch; thus a low switch resistance is desired. For an inductive load, voltage across the switch, $v_{AB}(t)$ rises above the supply voltage, V_{SUP} , because of inductive kick-back; thus the switch breakdown voltage must exceed the voltage overshoot. Typically, at least a 15% safety margin is provided to protect the switch.⁹ In practical circuits, the exact switch voltage rating depends also on the switching and control circuit topologies used.¹⁰ Because of capacitances inherent in a semiconductor switch, the rate of change of voltage across the switch ($\frac{dv_{AB}(t)}{dt}$) can also become a limiting factor on switch reliability. The load current i_L is controlled by the duty ratio “D” of the gate switching signal—a pulse-width-modulated (PWM) control is typically used. The switch capacitances and gate control circuitry mostly determine the amount of overlap between switch voltage and current waveforms during switching, and hence, the switching power loss.

Unipolar Three-Terminal Power Transistor Switch

Several types of silicon power switches are commercially available.¹¹ Single-chip diodes as well as transistors and thyristors rated up to 6.5 kV and hundreds of amps are in use; higher voltage and higher current power modules can be built by series-parallelizing individual silicon chips. The on-state current density, J_{ON} , for a given forward voltage drop, V_F , is higher for a bipolar-mode power switch compared to a unipolar device because of conductivity modulation of the

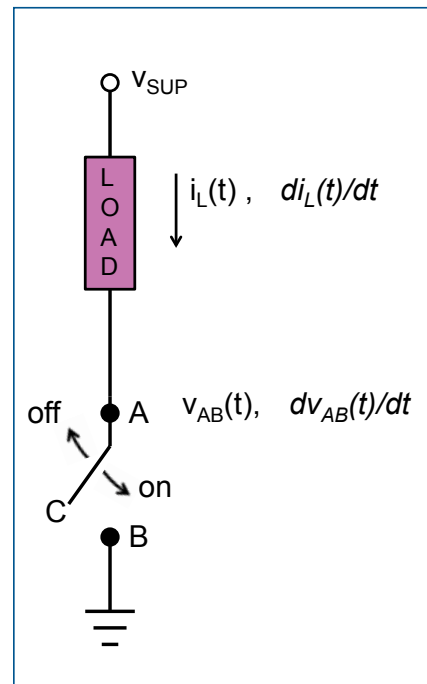


FIG. 1. A simple power electronics switching circuit showing load, switch, control, and voltage and current stresses on the switch.

drift-region of the device. Higher on-state current density leads to smaller chip size for given voltage and current ratings, and hence, lower device cost/watt of power switched. Diodes are two-terminal power switches and do not require a third terminal to control the power flow. Bipolar-mode *pin* diodes as well as unipolar Schottky diodes are used; *pin* diodes are slow to turn off as they suffer from the reverse recovery of minority carrier charge stored in the quasi-neutral portion of the drift-region that supports high voltage in the off-state. However, *pin* diodes offer lower V_F for a given J_{ON} , and hence are, superior to Schottky diodes for higher current and higher voltage applications.

A three-terminal semiconductor power switch is preferred as it offers improved flexibility in the control of the load power profile. Silicon power transistors and thyristors are used as 3-terminal controllable power switches. A silicon double-diffused MOSFET (DMOS) structure with a hexagonal cell layout—known as “HEXFET”—is widely used for power conversion below 1,000 volts and 100 amps as it offers the highest cell packing density with improved ruggedness.¹² In a power MOSFET device, an insulated gate structure

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provides adequate input and output isolation; it also minimizes the input control power required. Further improvement in electrical conductivity for a given die size is achieved by using trench-gate power MOSFETs and super-junction power MOSFETs. Figure 2a is the cross-section of a vertical trench-gate silicon power MOSFET structure along with various parasitic resistances, capacitances and bipolar junction transistors; Fig. 2b illustrates the equivalent circuit of the power MOSFET structure where the parasitic bipolar junction transistor can also be activated as a *pin* diode under certain adverse switching conditions. In circuit applications, it is important to optimize the electrical conductivity while suppressing deleterious effects from parasitic circuit elements. Hence, the parasitic bipolar junction transistor and body junction diode in Fig. 2b must be suppressed; this places important device and process design constraints, as well as limits on the maximum power-handling capability of the switch.

Bipolar Three-Terminal Power Transistor Switch

A bipolar-mode silicon power transistor, such as the insulated-gate bipolar transistor (IGBT), is used for higher voltage (> 600 volts) applications as it provides superior conductivity performance compared to even super-junction power MOSFETs.¹¹ Figure 3a is cross-section of a vertical trench-gate silicon power IGBT structure along with various intrinsic parasitic elements; Fig. 3b illustrates the corresponding equivalent circuit for the switch. In the *n*-channel IGBT structure shown in Fig. 3a, the *pnp* bipolar junction transistor is turned on by electron current injected through the transistor base by creating the *n*-type MOS channel under the gate electrode when a positive voltage is applied to the collector electrode with respect to the emitter. The bipolar junction transistor is turned-off when the *n*-channel is removed. However, IGBT suffers from minority carrier charge storage, and hence, is much slower when turning off compared to a power MOSFET. It can be seen that IGBT contains an intrinsic thyristor structure, and

care must be taken to avoid thyristor latch-up under both static and dynamic power switching conditions. A maximum on-state current density, J_{ON} , and output voltage slew rate, $\left(\frac{dv_{CE}(t)}{dt}\right)$ are typically specified to avoid thyristor latch-up.

Three-Terminal MOS-Controlled Thyristor (MCT) Power Switch

The highest electrical conductivity for a power semiconductor switch is obtained from a thyristor device. However, past attempts to develop a silicon MOS-controlled thyristor (MCT)¹³ device had limited success because of design and process complexities and poor turn-off characteristics. Figure 4 illustrates the schematic cross-section of a *p*-channel MCT unit cell—a silicon power switch with a potential for switching the highest power density for a given chip area. In this device, the *p*-channel MOSFET triggers the thyristor turn-on process by injecting holes into the drift-region, and the *n*-channel MOSFET diverts the electron current to initiate its turn-off. To obtain the desired

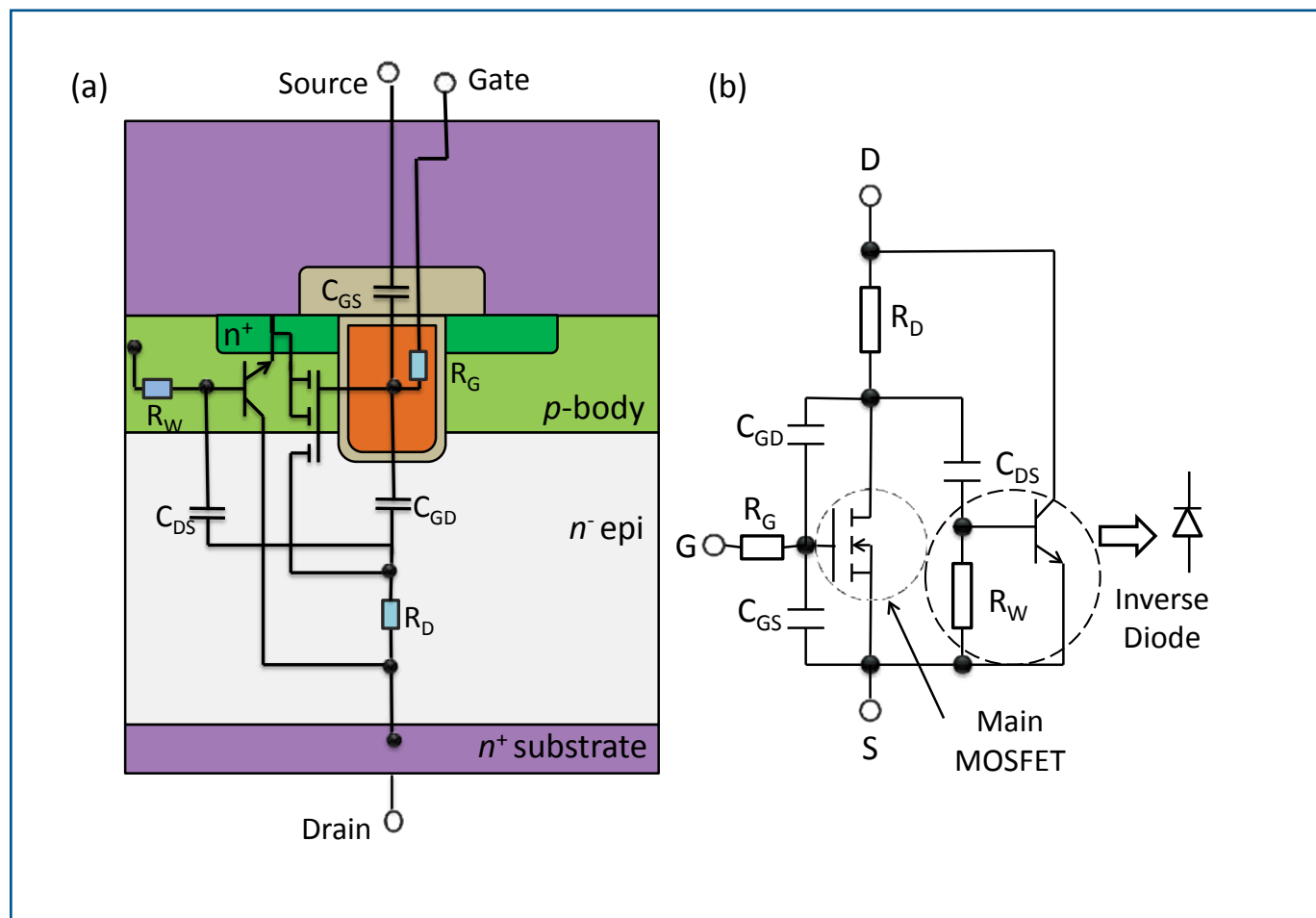


FIG. 2. (a) Cross-section and (b) equivalent circuit of a trench-gate power MOSFET.

current rating, millions of such unit cells are connected in parallel. However, during turn-off, only a very small portion of the stored electron charge can be removed through the n -channel. Thus, plasma constriction takes place as shown in Fig. 4b.

Wide Bandgap (WBG) Semiconductor Power Devices

This phenomenon results in current filamentation and turn-off failure in the silicon MCT. This limits the usage of silicon MCTs to moderate power levels; hence, MCTs are often not preferred to IGBTs with simple construction. This important structural limitation in MCT must be eliminated in order to further advance high-power switching in semiconductors. For more than two decades, wide energy bandgap semiconductors, especially silicon carbide (SiC) and gallium nitride (GaN), have been touted as preferred semiconductors for developing compact, high-power, and high-temperature electronics systems because of their superior electrical and thermal characteristics

compared to the semiconductor silicon.¹⁴ Power Schottky barrier diodes (SBDs) rated up to 1,700V/25A; power MOSFETs rated up to 1,200V/33A; and, power JFETs rated up to 1,700V/4A—all fabricated on 4H-SiC material—are now commercially available. These devices are increasingly used in computer/telecom power supplies, motor control, and electric utility applications. Lateral GaN power switching transistors rated up to 200V are sampled by select customers and are being evaluated for point-of-load (POL) DC-DC power converter applications. Although the on-state conduction performance of the current state-of-the-art commercial GaN and SiC power-switching devices is superior to similarly rated silicon power switches, much is desired in terms of improved power switching performance, reduced manufacturing cost, and improved ruggedness. With reduced cost and improved field reliability, the current GaN and SiC power-switch market has the potential to be easily expanded by two orders of magnitude. In order to accomplish this objective, GaN and SiC power module costs must be significantly reduced, and devices must be avalanche- and dv/dt -

rated for $T_{JMAX} > 200^{\circ}\text{C}$, where T_{JMAX} is the maximum junction operating temperature.

Figure 5 is a plot of the specific on-state resistance (R_{sp}) vs. avalanche breakdown voltage (V_{BD}) of commercial silicon and 4H-SiC power semiconductor devices; GaN power transistors are not considered since they are not yet used for high-volume commercial applications. The theoretical, specific, on-resistance limits for various semiconductors are calculated from the well-known formula, first proposed by Shenai et al.¹⁴:

$$R_{sp} = \frac{4V_{BD}^2}{\epsilon_s \mu_n E_c^3} \quad (1)$$

where V_{BD} is the avalanche breakdown voltage, ϵ_s is the semiconductor permittivity, μ_n is the drift-region electron mobility, and E_c is the critical electric field strength of the semiconductor material at avalanche breakdown. Note that the low-voltage, silicon power MOSFET performance first reported by Shenai¹⁵ essentially provided the framework for silicon technology optimization. The measured on-resistance data for commercial silicon power devices clearly indicates the need for bipolar-mode

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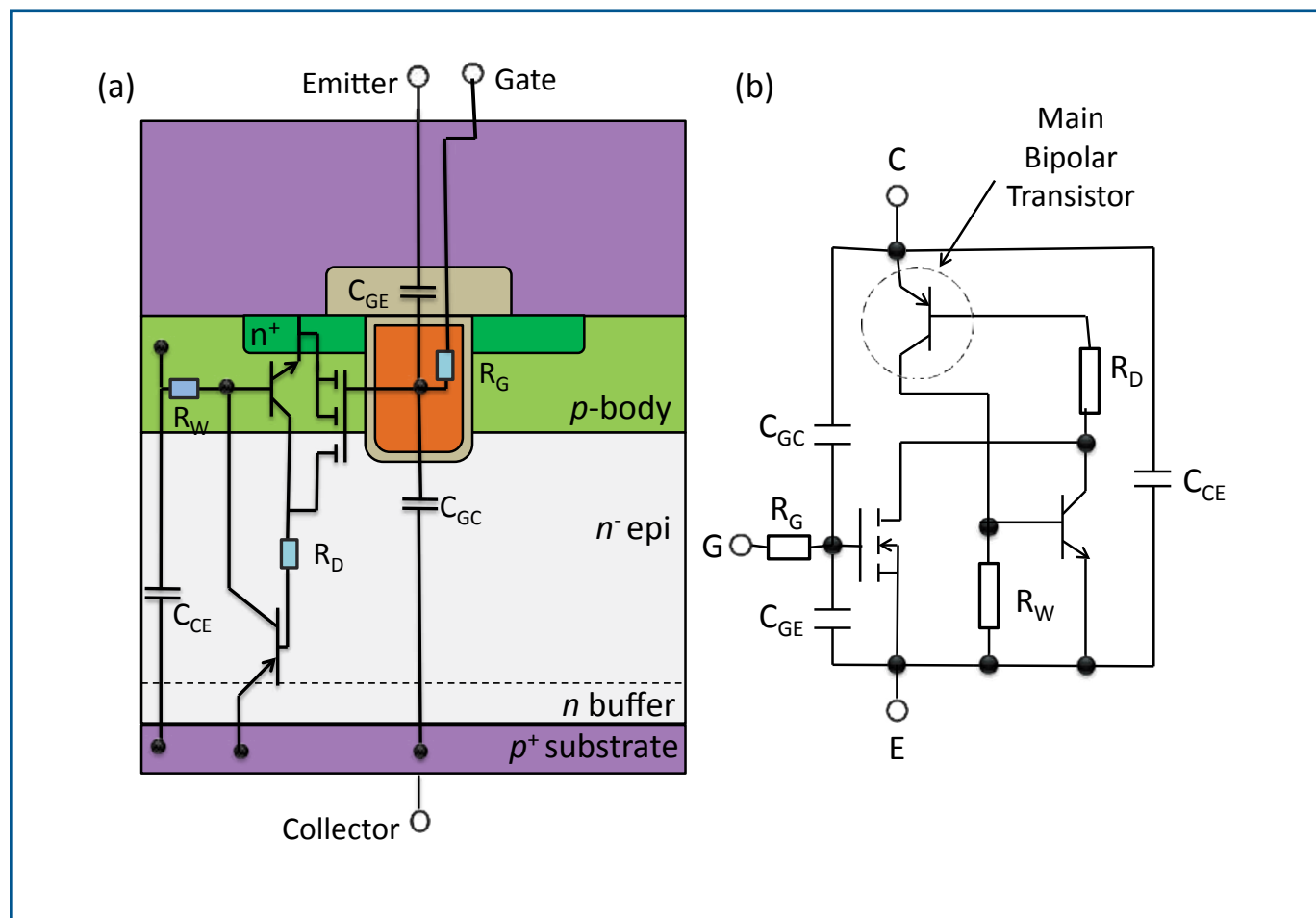


FIG. 3. (a) Cross-section and (b) equivalent circuit of a trench-gate power IGBT.

power devices, especially for optimum high-voltage and high-power applications with thyristor device showing the highest electrical conductivity. For SiC, on-resistance data for commercial 4H-SiC Schottky barrier diodes (SBDs) are shown as 4H-SiC power MOSFETs but are yet to find acceptance in high-volume applications. Clearly, 4H-SiC power Schottky barrier diodes (SBDs) are de-rated by almost a factor of 2 compared to their true avalanche breakdown capability. This feature is likely due to a high density of defects in the drift-region of the device which prevents them from operating close to the critical electric field, E_c for avalanche breakdown.

For GaN, theoretical limit lines for both lateral high-electron mobility transistors (HEMTs) as well as vertical GaN power transistors based on bulk material conduction are shown. As the mobility of electrons in a two-dimensional electron gas (2 DEG) is much higher than in a MOS channel or in the bulk semiconductor, the theoretical on-resistance limit for lateral GaN power transistor based on 2 DEG is much lower than a vertical GaN MOS power transistor. However, lateral power devices are known to be susceptible to surface breakdown and are not easily scalable to higher voltages and higher currents; hence, lateral GaN power transistors are expected to find only limited applications below 600 volts. Figure 6 illustrates the electric field distribution in vertical and lateral silicon power MOSFETs at breakdown.¹¹ From optimum performance and reliability considerations, bulk avalanche breakdown is desired. Hence, vertical GaN power devices with bulk avalanche breakdown are needed for high-voltage and high-current applications.

Safe Operating Area (SOA) of a Power Semiconductor Switch

An important measure of power electronics switching is the safe operating area (SOA) of a power semiconductor switch.¹⁶ The SOA of a power semiconductor device refers to voltage and current limits within which the device can be safely switched. The SOA deviates from the rectangular shape due to thermal heating as shown in Fig. 7; the loss of SOA occurs when power dissipation is at its maximum and is a function of switching frequency and duty ratio. Provided bond wires and die-to-package interface remain intact, and assuming isothermal die boundary conditions, it is well-known that “hot spots” occur locally during power switching and can lead to current filamentation and local “burn outs” as dictated by the Poynting vector.^{17,18} Maximum power dissipation occurs within the drift-region of the device as the electric field is high. The challenge is

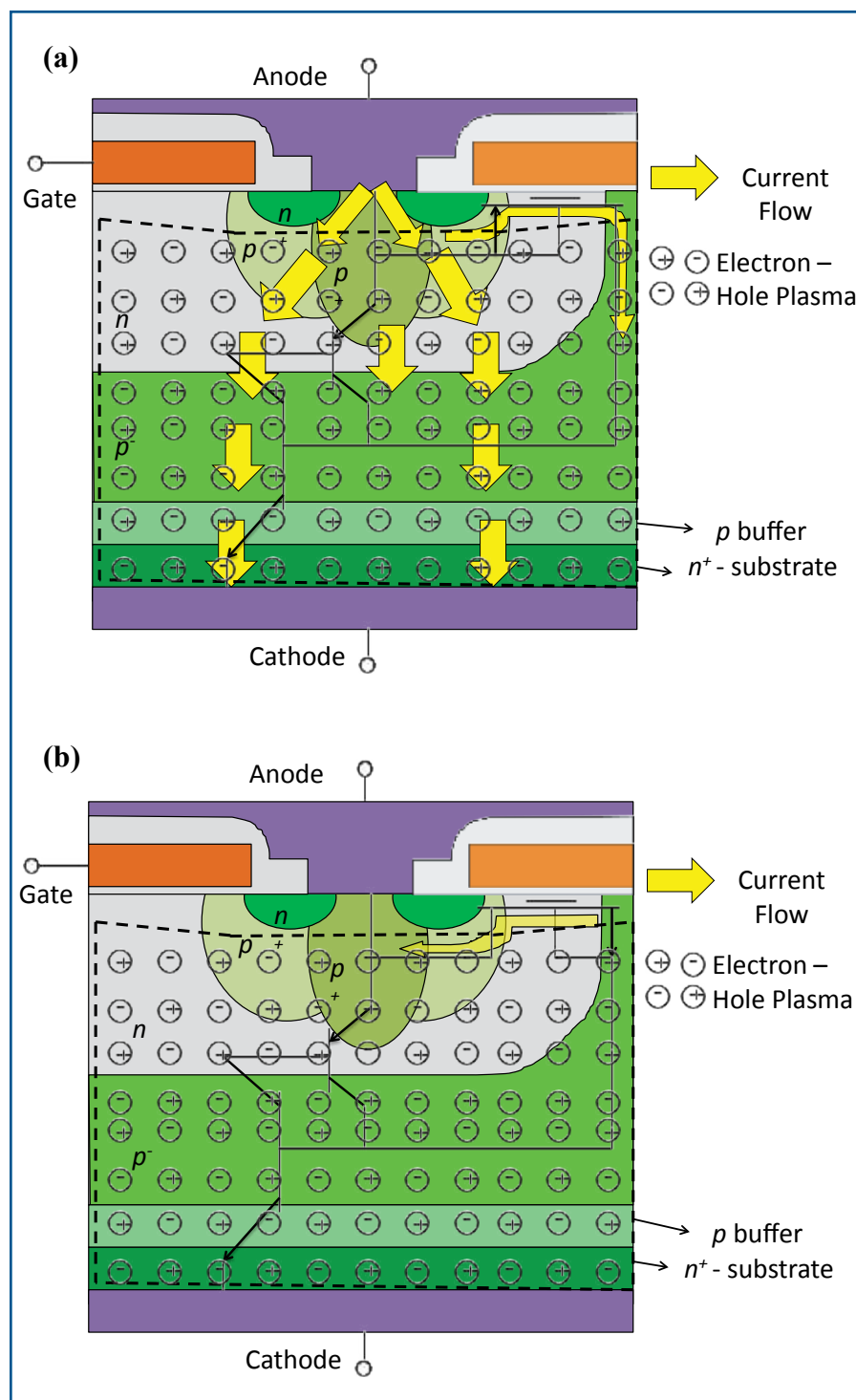


FIG. 4. Schematic cross-sections of the MCT to illustrate charge dynamics during (a) turn-on and (b) turn-off.

then to rapidly remove heat away from the drift-region; the thermal time constant must be small (typically less than a microsecond), and hence, the substrate must be thinned down so that the cooling surface is brought close to the drift-region of the device. As shown in Fig. 7, the SOA of GaN power device is smaller than that of a SiC power device primarily due to its lower thermal conductivity. Because of direct energy bandgap of GaN, the minority carrier

lifetime is small; conductivity modulation of the drift-region is difficult; and thus bipolar-mode power devices are not possible, at least in the near future. Therefore, for higher voltage (above 1,000 volts) and higher current (above 100 amps), vertical SiC power devices hold the greatest promise.

A high density of crystal defects present in the drift-region of the device ultimately limits performance, cost, and reliability of the power semiconductor device. For

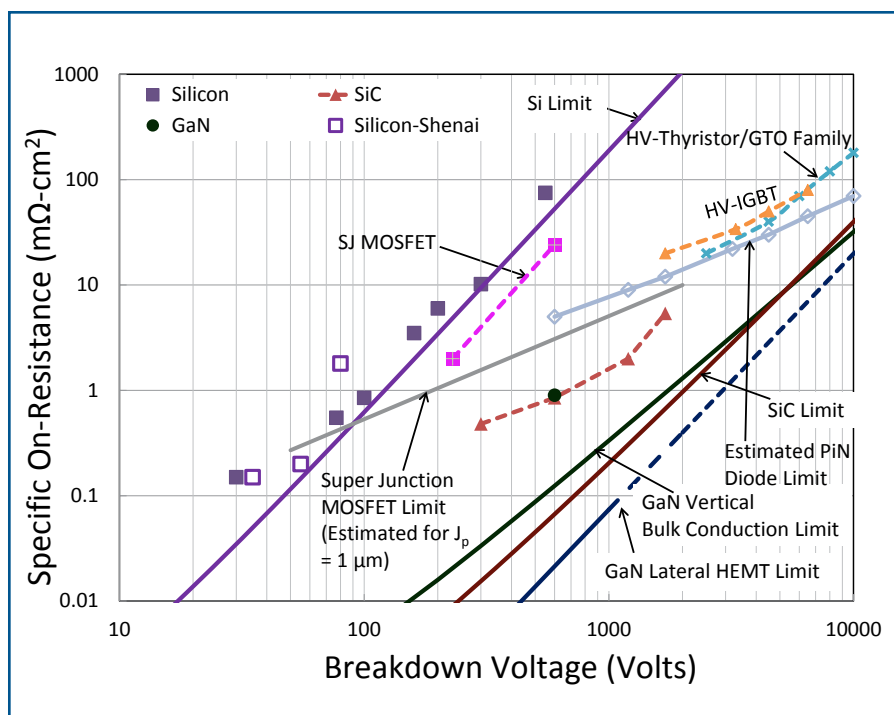


FIG. 5. Specific on-state resistance vs. avalanche breakdown voltage for commercial devices with material limits.

example, experimental results accumulated over the past two decades by researchers around the world clearly suggest that non-micropipe defects present in the bulk and epitaxial SiC material cause severe degradation in the performance and reliability of SiC power devices.^{19,22} More recently, it is becoming increasingly clear that SiC crystal defects also limit the voltage and current ratings and severely hinder the development of cost-effective, energy-efficient, and reliable SiC-based power electronics systems. Under high electric field and charge injection conditions, these other crystal defect sites lead to enhanced leakage, enhanced generation of local micro plasma,²³ and cause degradation in forward current conduction of *pin* diodes.²⁰ To this day, these defects remain present in commercial SiC wafers/epilayers to a density where their presence (and undesirable effects) must be accounted for in the manufacture of SiC commercial power devices. Before the impact of such devices on reliability was fully appreciated, early commercial deployment of high-voltage SiC power Schottky barrier diodes (SBDs) in high-

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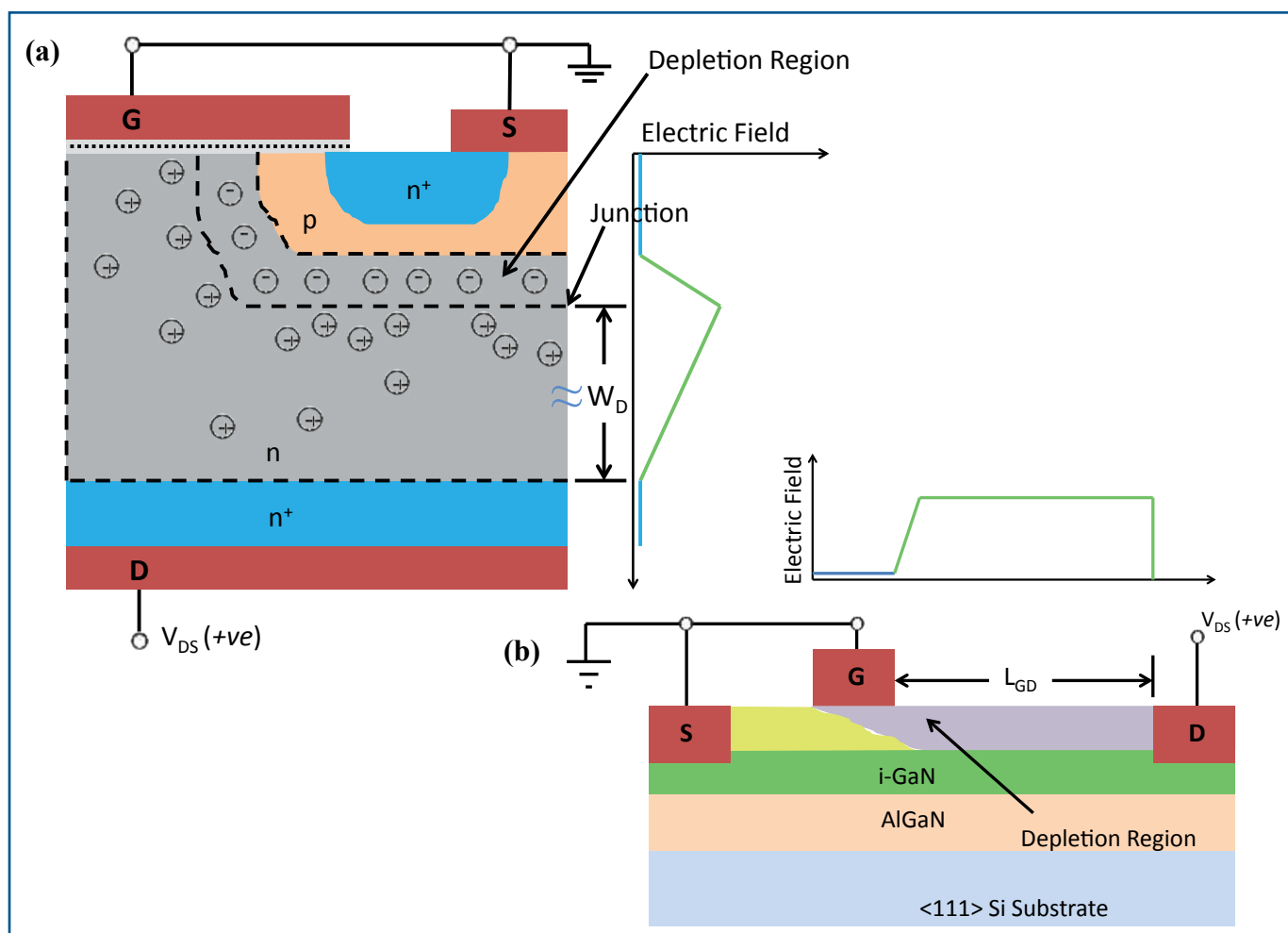


FIG. 6. Cross-section and electric field distribution at breakdown for (a) vertical power MOSFET and (b) lateral GaN HEMT.

density, computer/telecom power supplies resulted in repeated field-returns. This type of device failure has been attributed to dv/dt -related premature breakdown caused by excessive charge generation in the space charge region of a reverse-biased, high-voltage SiC power SBD with dislocations.²⁴ The problem becomes particularly acute with increased dv/dt stress, especially at elevated temperatures. Commercialization of SiC power *pin* diodes has effectively been prevented for over a decade due to unreliable device degradation traced to basal plane dislocation (BPD) glide in the SiC crystal in the forward on-state.²⁵

Table I lists various defects and their densities in the epitaxial layers grown on current state-of-the-art 4H-SiC material. While there has been a concerted effort in industry for over 25 years to reduce the defect density in the SiC material, the progress has been very slow. For example, in the last decade or so, while micropipes have been effectively eliminated, the threading screw dislocation (TSD) density has only been reduced from 10^4 per cm^2 to about 10^3 per cm^2 . Similarly, while basal plane dislocation (BPD) densities have been reduced from 10^4 - 10^5 per cm^2 to about just a few hundred per cm^2 , there has been no more progress on reduction in the densities of threading edge dislocations (TEDs) that remain at even higher densities.^{26,27} Thus it is very important to note that all commercial SiC power devices contain an abundance of non-micropipe dislocation defects. These dislocation defects have proven more difficult to observe in part because they have less immediately obvious negative impact on SiC device performance than micropipes, but are likely to cause severe field-reliability problems. The exact role of non-micropipe dislocations on device performance, wafer manufacturing yield, and field-reliability of 4H-SiC power devices is currently being investigated.

Summary and Discussion

It has been clear for nearly two decades that silicon power switching technology had reached material limits; wide bandgap semiconductors were touted as the “next” breakthrough materials. Among these, silicon carbide (SiC) and gallium nitride (GaN) are the most promising semiconductors for electrical power switching. Although there has been significant investment and research in the past two decades, progress in developing low-cost and reliable SiC and GaN power devices has been slow. Unlike silicon, both SiC and GaN materials contain high density of crystal defects in the drift-region of a power semiconductor switch; these defects are primarily caused by defects in the substrate material used for growing the epitaxial layers that support the high

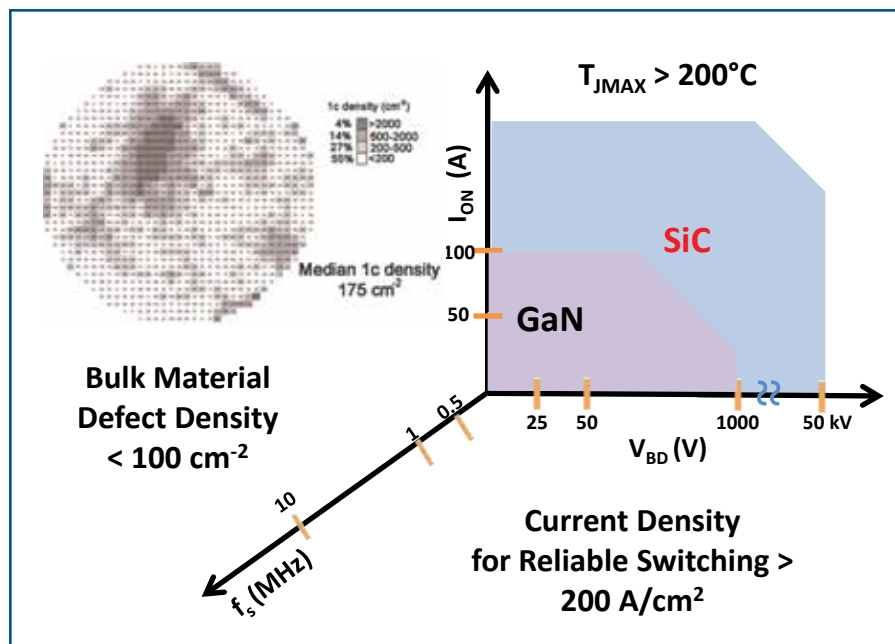


FIG. 7. Typical defect density in the current state-of-the-art 4H-SiC wafers, and projected safe-operating-area (SOA) limits for GaN and SiC power devices.

Table I. Summary of defects in the current state-of-the-art 4H-SiC epitaxial layers.

Main defect in epilayer	Impacts on device performance	Current status of commercial 50 micron 4H-SiC epilayer
BPD	Increase in the forward voltage drift	~200 cm^{-2}
IGSF	Breakdown voltage reduction and leakage current increase	~2 cm^{-2}
TSD	Breakdown voltage reduction	~3000 cm^{-2}
Growth pit	Non-smooth surface. Some pits may be associated with TSDs.	<10 cm^{-2}
Carrot defect	Increase in reverse leakage current	~2 cm^{-2}
Defects generated during epi growth	Breakdown voltage reduction and leakage current increase	unknown

voltage. A paradigm shift in the bulk crystal growth of both SiC and GaN materials that leads to a dramatic reduction in the density of bulk crystal defects is needed. In order to impact such a philosophical change, a “reliability-driven” material technology must be pursued as it is guaranteed to lead to the lowest die cost with high manufacturing yield. What is needed is a systematic correlation of drift-region defect density to the current density that can be reliably switched for a given breakdown voltage rating in order to guarantee certain prescribed mean-time-between-failures (MTBF) of power converter under actual field-operating conditions. This requires paradigm shift in the current method of technology development and manufacturing.

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