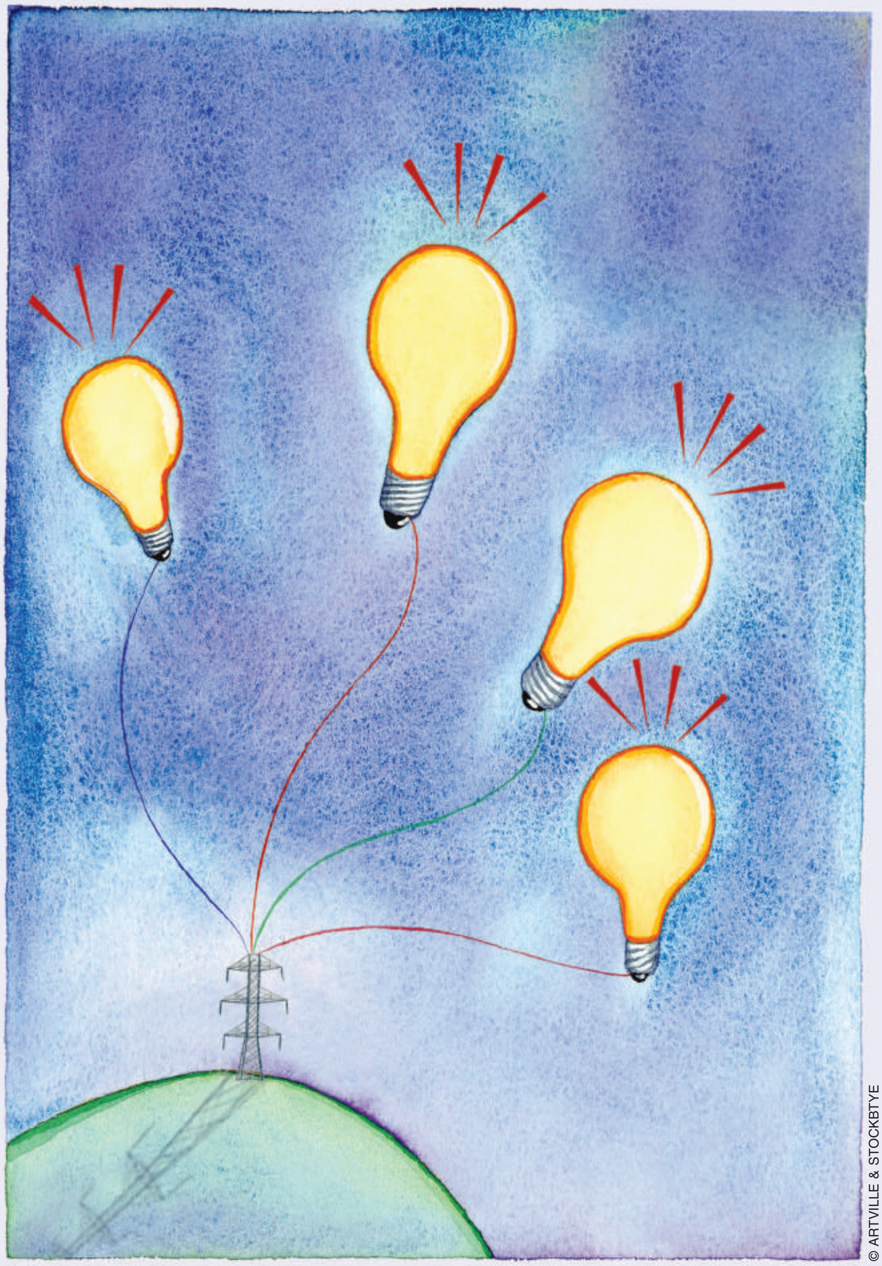
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Smart Grid Technologies

Development of 15-kV SiC IGBTs and Their Impact on Utility Applications

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Although silicon power devices have served the power electronics industry well for more than five decades, silicon-based technology is reaching its physical limits for power handling and switching frequency capability. Although the high-voltage silicon power devices have achieved a very large power handling capability by increasing current handling to more than 1,500 A per device, their voltage capability is typically below 6.5 kV, and their frequency capability is normally below 1 kHz [1]. Also, these silicon power devices normally cannot be used at temperatures higher than 125 °C in power electronic systems [1].

The need for power semiconductor devices with high-voltage, high-frequency, and high-temperature operation capability is growing, especially for advanced power conversion and military applications, and hence the size and weight of the power electronic system are reduced [2], [3]. Silicon power devices are not suitable for

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these applications without costly cooling systems, a large number of parts in parallel or in series, and costly snubbers. Wide-bandgap silicon carbide (SiC) material is the most promising postsilicon alternative to achieve these goals because of its superior properties (e.g., ten times higher breakdown electric field, higher thermal conductivity, and much lower intrinsic carrier concentration when compared with silicon). Since the 1990s, continued improvements in SiC single-crystal wafers have resulted in significant progress toward the development of low-defect, thick-epitaxial SiC materials and high-voltage SiC devices, including the development of 10-kV SiC MOSFETs [4], 3.1-kV gate turnoff (GTO) thyristors [5], 13-kV insulated-gate bipolar transistors (IGBTs) [6], and 4.5-kV SiC emitter turnoff (SiC ETO) thyristors [7].

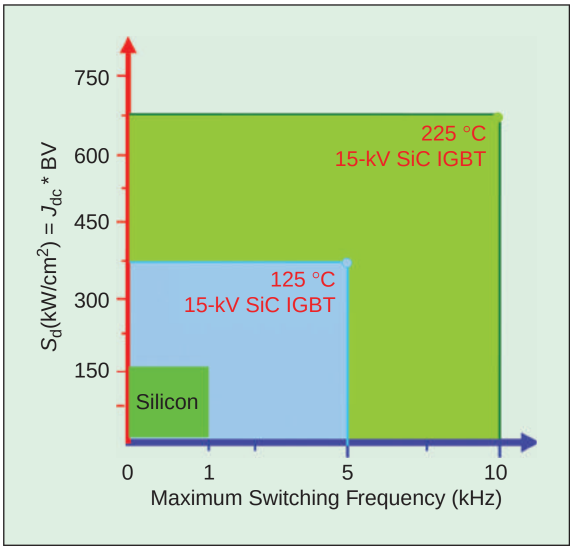

FIGURE 1 – Calculated 15-kV SiC IGBT power versus frequency capability.

Among those high-voltage SiC devices under development (and not commercially available), the on-state resistance of the SiC MOSFETs increases significantly as their blocking voltage and operation junction temperature increase; this makes it unacceptable for applications where high dc supply voltages (≥15 kV) are used. For high-voltage power devices capable of 15–25-kV blocking, SiC IGBT technology becomes attractive because of its superior on-state characteristic, fast switching speed, and excellent safe operating area (SOA). Figure 1 shows the calculated capability of the 15-kV SiC n-channel IGBT in

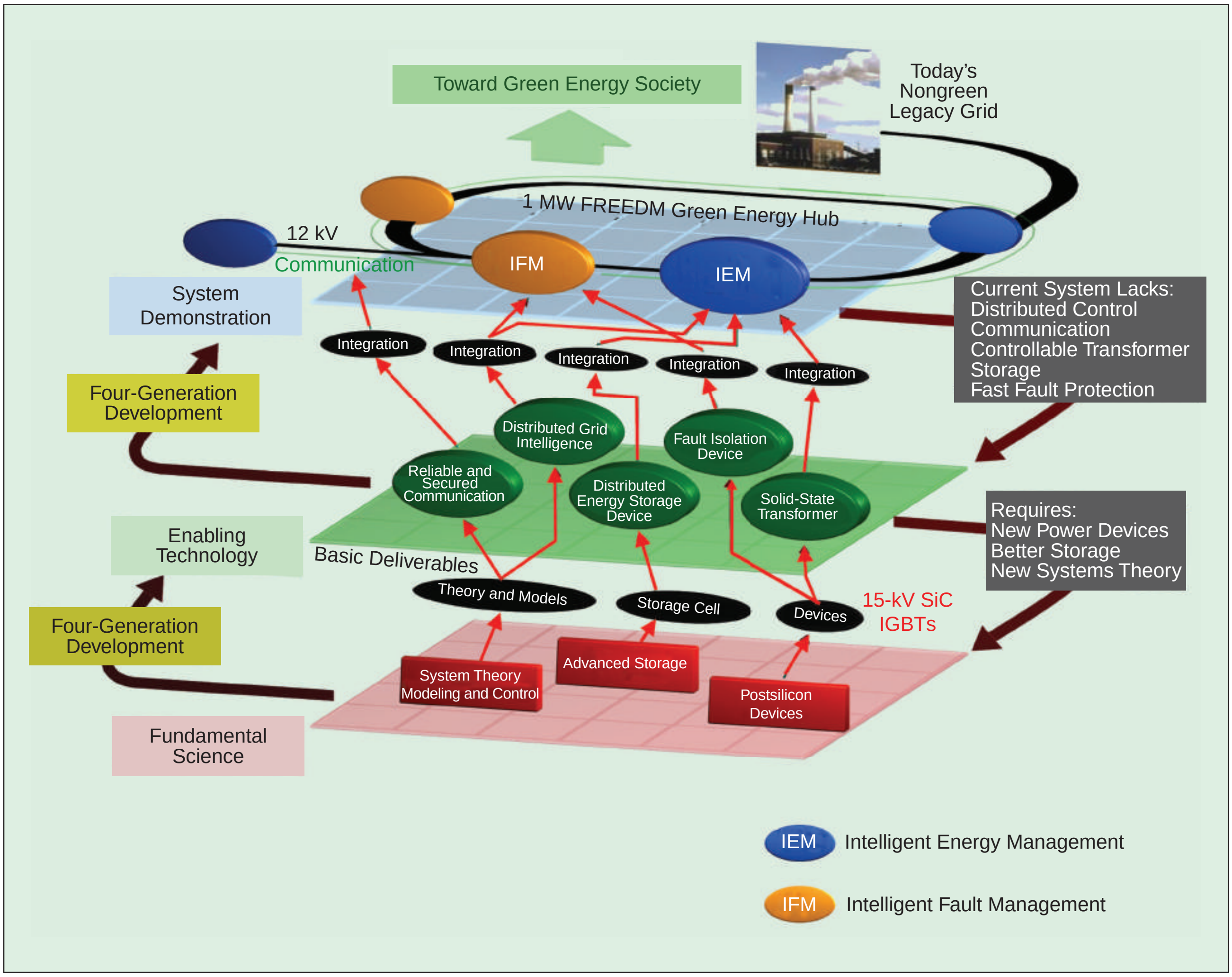

FIGURE 2 – Proposed FREEDM System ERC Research Program.

SiC IGBT technology becomes attractive because of its superior on-state characteristic, fast switching speed, and excellent safe operating area.

terms of power handling capability and switching frequency. The power density handling capability (S_d) of switching devices is expressed as the multiplication of their normal operating current density (J_{dc}) and blocking voltage (BV). Because of the immature material growth technology that limits the maximum size of the device, today's SiC power devices are manufactured in smaller die sizes than comparable silicon devices. However, based strictly on the material properties and loss calculations [8], SiC power devices can potentially handle three times more power and can switch several times faster than comparably rated silicon devices. The self-heating induced by their larger power losses at higher frequency operation results in their higher junction operating temperature (around 225 °C), so their power handling and frequency capability are increased in high operation junction temperature.

The emerging high-voltage SiC IGBTs with their high-frequency, high-temperature capability will have a great impact on high-power utility applications. First, several application concepts that were previously considered impractical have become feasible. One example is the solid-state transformer (SST) concept to replace the traditional 60-Hz distribution transformer. Although the SST has many advantages such as light weight, small size, and unity power factor, the development of SST has made no progress up to now because of the limitation of the switching frequency in the silicon power semiconductor devices. With the development of the 15-kV class SiC IGBTs capable of 5-kHz switching frequency, the SST may become a reality, just like what had happened in the power supply industry in the 1970s and 1980s, when switching mode power supply (SMPS) had become the norm for power conversion instead of the 60-Hz transformer. Second, it will drive a potentially dramatic change on the existing power electronics-based utility applications, especially for flexible ac transmission system (FACTS) devices. For example, traditional high-voltage static synchronous compensators (STATCOMs) [9] depend on multilevel topologies or series connection of devices to endure high-voltage pressure. With the help of high-voltage SiC IGBTs, the structure of STATCOM can be dramatically simplified. At the same time, the power qualities are also improved because of much higher switching frequencies. Transformerless STATCOM may become a reality for effective application in renewable energy integration such as wind farm and solar farm.

The need for renewable energy technologies, energy storage technologies, and smart grid technologies has grown in recent years. As a new National Science Foundation (NSF) Generation-III Engineering Research Center (ERC) established in 2008, the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center is developing the fundamental and enabling technologies necessary for a new and paradigm-shifting power grid infrastructure, the FREEDM System [10]. Figure 2 shows an application example of 15-kV SiC IGBTs in a 1-MW FREEDM System Green Energy Hub, to be constructed at North Carolina State University's Centennial Campus. The 15-kV SiC IGBTs will be used in the revolutionary SST technology to replace the 60-Hz transformer and the distributed control for the FREEDM system. They will also be used as the fault isolation devices (FIDs) to

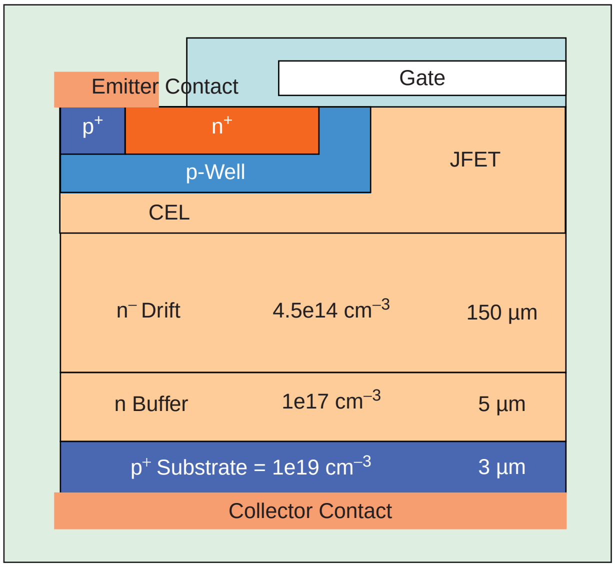

FIGURE 3 – Schematic structure of 15-kV SiC IGBT.

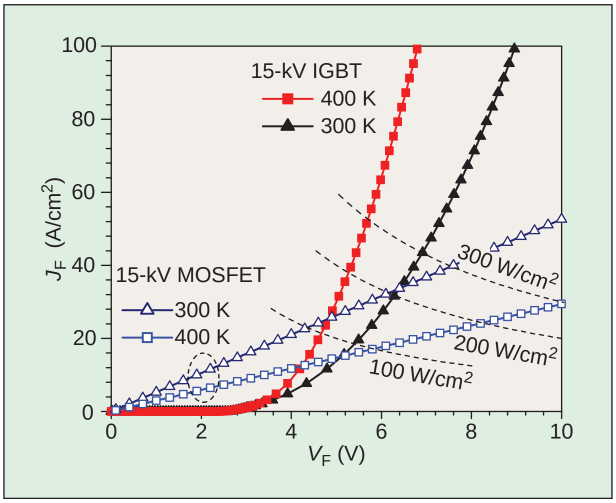

FIGURE 4 – Simulated forward *J-V* curve of 15-kV SiC IGBT and MOSFET.

achieve rapidly isolating faults during fault conditions in the FREEDM system.

Because of the promising nature of postsilicon devices, the SiC IGBTs (that are under development) become suitable for these applications because of their low loss, fast switching speed, rugged switching capability, and high temperature capability. In this article, the design and optimization of 15-kV n-channel SiC IGBTs are carried out, and the revolutionary impact of the SiC IGBT to utility applications is discussed in the example of SST applications.

Design and Optimization of 15-kV SiC IGBT

Figure 3 shows a designed half-cell schematic cross section of a 15-kV 4H-SiC n-channel IGBT. The epitaxial layers will be grown on 4H-SiC n^+ substrate. A 3-µm thick, 1×10^{19} cm^{-3} doped p^+ emitter layer will be the first epitaxial layer. The following n-type bottom buffer layer (field stopper) was 5-µm thick, with a doping concentration of 1×10^{17} cm^{-3} to prevent field punchthrough while achieving a good tradeoff performance. The n^- drift layer for the IGBT is chosen to be 150 µm thick and doped at 4.5×10^{14} cm^{-3} to block 15 kV. A 3-µm thick heavily doped n-type current enhancement layer (CEL) will then be grown on top of the drift layer to reduce the resistance of the JFET region and enhance the conductivity modulation of the drift layer in the conduction state. After the epigrowth of 4H-SiC, the n^+ substrate will be removed by chemical mechanical polishing (CMP). The p-well will be implanted to a depth of 0.5 µm with aluminum. The p^+-well and n^+-well contact will be selectively implanted with nitrogen and aluminum, respectively. The channel length will be 0.7 µm defined by e-beam photography. The width of the JFET region between the two p-well regions in a unit cell will be 5 µm. The gate oxide thickness will be around 500 Å. Subsequently, a 5,000-nm polysilicon layer will be degenerately doped to form the gate electrode and patterned by reactive ion etching (RIE) dry etching. Al/Ni contacts will be deposited as the p-type ohmic metal and Ni as the n-type ohmic metal for the emitter. A Ni backside contact will then be deposited as the collector. Thick aluminum and gold overlayers will be deposited on the front and back sides, respectively.

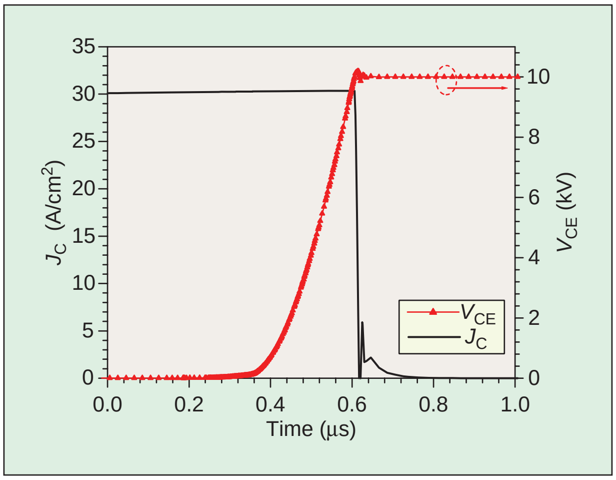

FIGURE 5 – Simulated switching waveform of a 15-kV SiC IGBT.

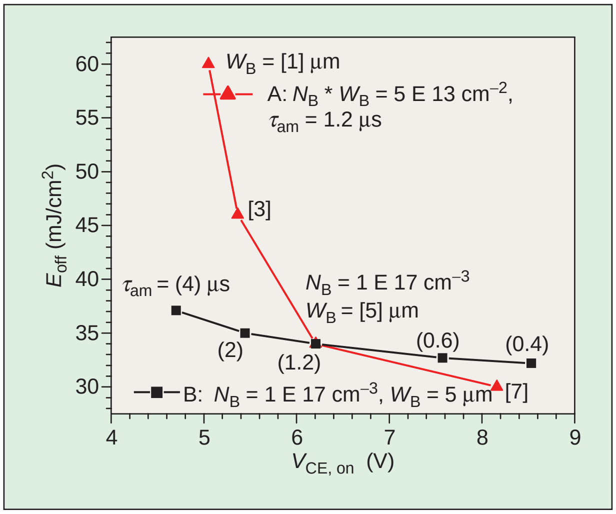

FIGURE 6 – Simulated tradeoff curve of a 15-kV SiC IGBT.

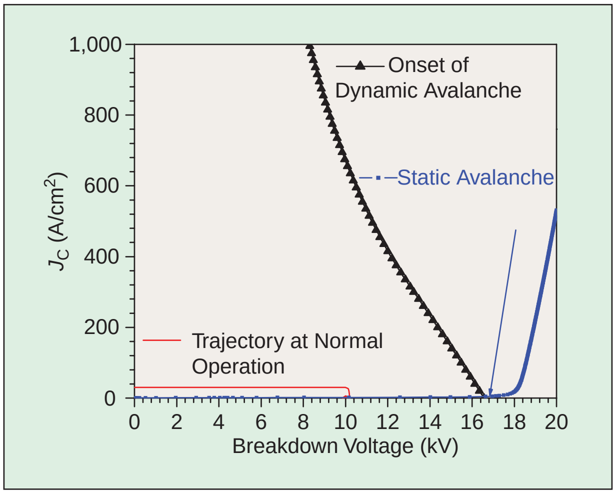

FIGURE 7 – Static avalanche breakdown, onset of avalanche breakdown of a 15-kV SiC IGBT, and its comparison with a typical turnoff current–voltage trajectory curve.

Figure 4 shows the simulated forward $I-V$ curve of the 15-kV SiC IGBT and MOSFET at elevated temperatures. The simulation study shows that the 15-kV SiC IGBT can achieve a forward voltage drop of 6.2 V at a collector current density of 30 A/cm^2 and room temperature with a carrier ambipolar lifetime of 1.2 µs in the drift layer and a forward voltage drop of 5 V at 400 K. Compared to the 15-kV SiC MOSFET, the SiC IGBT shows superior conduction characteristics, especially at high temperature and high current density.

The turnoff characteristics of the SiC IGBT are simulated in a clamped inductive load circuit with a load current of 30 A for a 1-cm^2 device, a dc-link voltage of 10 kV, and an external gate resistor of 5 Ω. Figure 5 shows the simulated switching waveform of the SiC IGBT. The turnoff time of the SiC IGBT is 360 ns with a dV/dt of 48 kV/µs and a di/dt

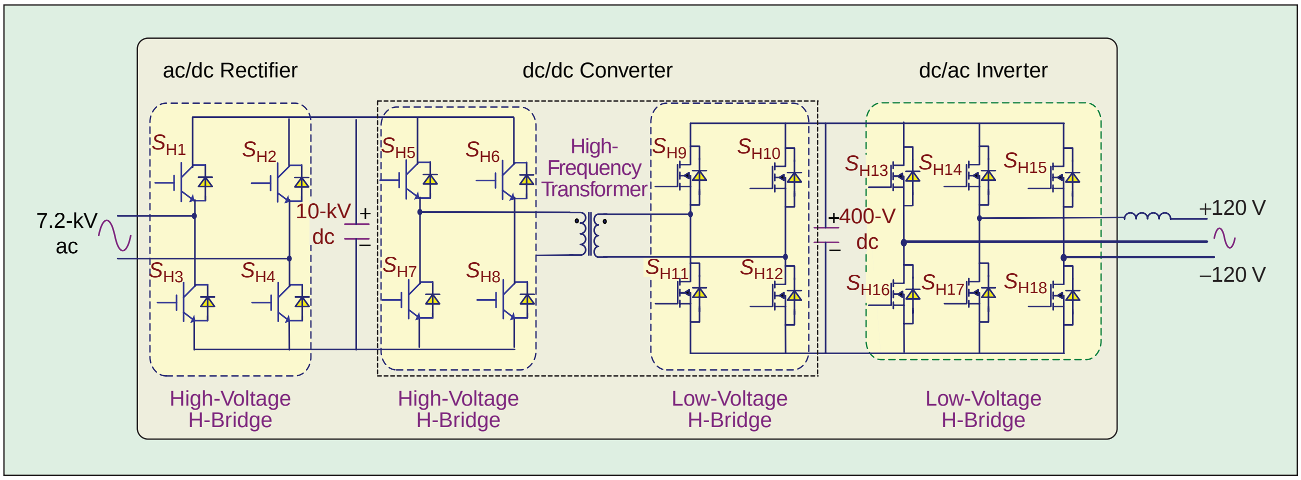

FIGURE 8 – The proposed baseline topology for a single-phase 10 kVA SST used in a distribution power system.

of 2.1 kA/μs. Its turnoff energy loss density is 34 mJ/cm^2, which enables it 5 kHz switching applications with conventional thermal management.

The development of the SST has made no progress up to now because of the limitation of the switching frequency in the silicon power semiconductor devices.

One of the ideas to improve the tradeoff relationship between the forward voltage drop and turnoff loss of the SiC IGBT is a reduction of the drift layer thickness with the punchthrough structure. The bottom buffer layer (field stopper) shown in Figure 3 is used in the designed 15-kV SiC IGBT. Numerical two-dimensional (2-D) simulations were conducted to investigate the effects of the doping concentration (N_B) and thickness (W_B) of the buffer layer. The curve A in Figure 6 shows the tradeoff curve between the forward voltage drop at 30 A/cm^2 and turnoff energy loss in the 15-kV SiC IGBT at room temperature. When the carrier lifetime in the drift layer is 1.2 μs and the charge density ($N_B \cdot W_B$) in the buffer layer is 5×10^{13} cm^{-2}, the turnoff energy of the IGBT decreases and the forward voltage drop increases with the increase of the buffer layer thickness (W_B). A buffer layer with a 5-μm thickness and 1×10^{17} cm^{-3} doping concentration can achieve a good tradeoff performance at a 5 kHz switching frequency and 0.5 duty cycle.

The extent of the conductivity modulation in the drift layer and the current gain of the internal p-n-p transistor of the SiC IGBT are governed by the ambipolar lifetime of the carriers in the drift layer. So another idea to improve the tradeoff relationship between the forward voltage drop and turnoff loss of the SiC IGBT is to adjust the carrier lifetime in the n$^-$ drift layer of the SiC IGBT. Cree's thick epitaxial growth routinely produces material with a carrier lifetime in the 300 ns to 2 μs range [11]–[14]. The effect of the carrier lifetime in the drift region to the tradeoff performance of the 15-kV SiC IGBT was investigated with numerical 2-D simulations. The curve B in

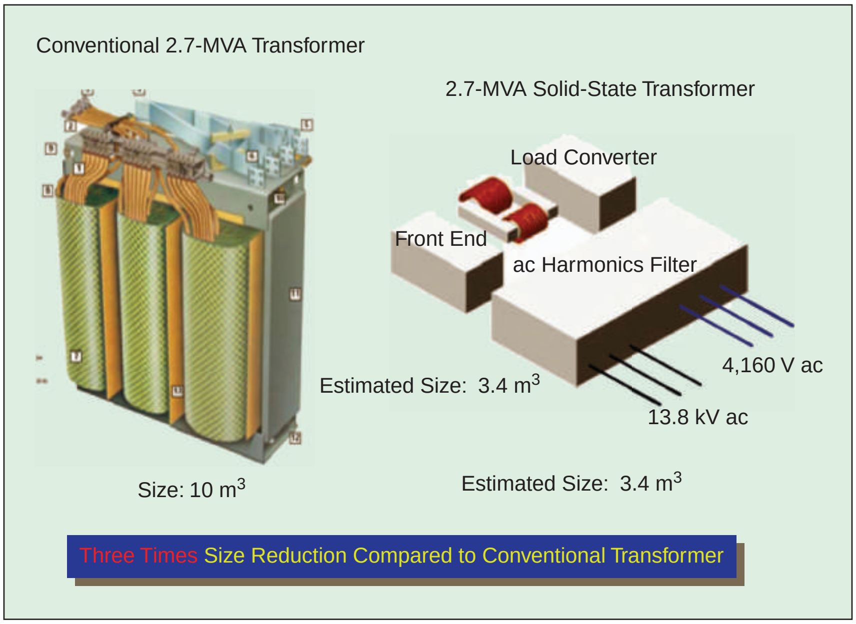

FIGURE 9 – Computer-aided design (CAD) drawing of a 2.7-MVA SST showing three times size reduction compared with a traditional 60-Hz transformer.

Figure 6 shows the simulated turnoff energy loss versus forward voltage drop of the 15-kV SiC IGBT with various drift layer carrier lifetime and a 5 μm thick, 1×10^{17} cm^{-3} doped buffer layer. The simulations indicate that the SiC IGBT with a long drift layer carrier lifetime is superior to that with a short drift layer carrier lifetime for the tradeoff between the forward voltage drop and turnoff loss. Because the current gain of the internal p-n-p transistor is dominated by the heavily doped buffer layer for the IGBT with low injection efficiency from the lowly ionized p$^+$ emitter,

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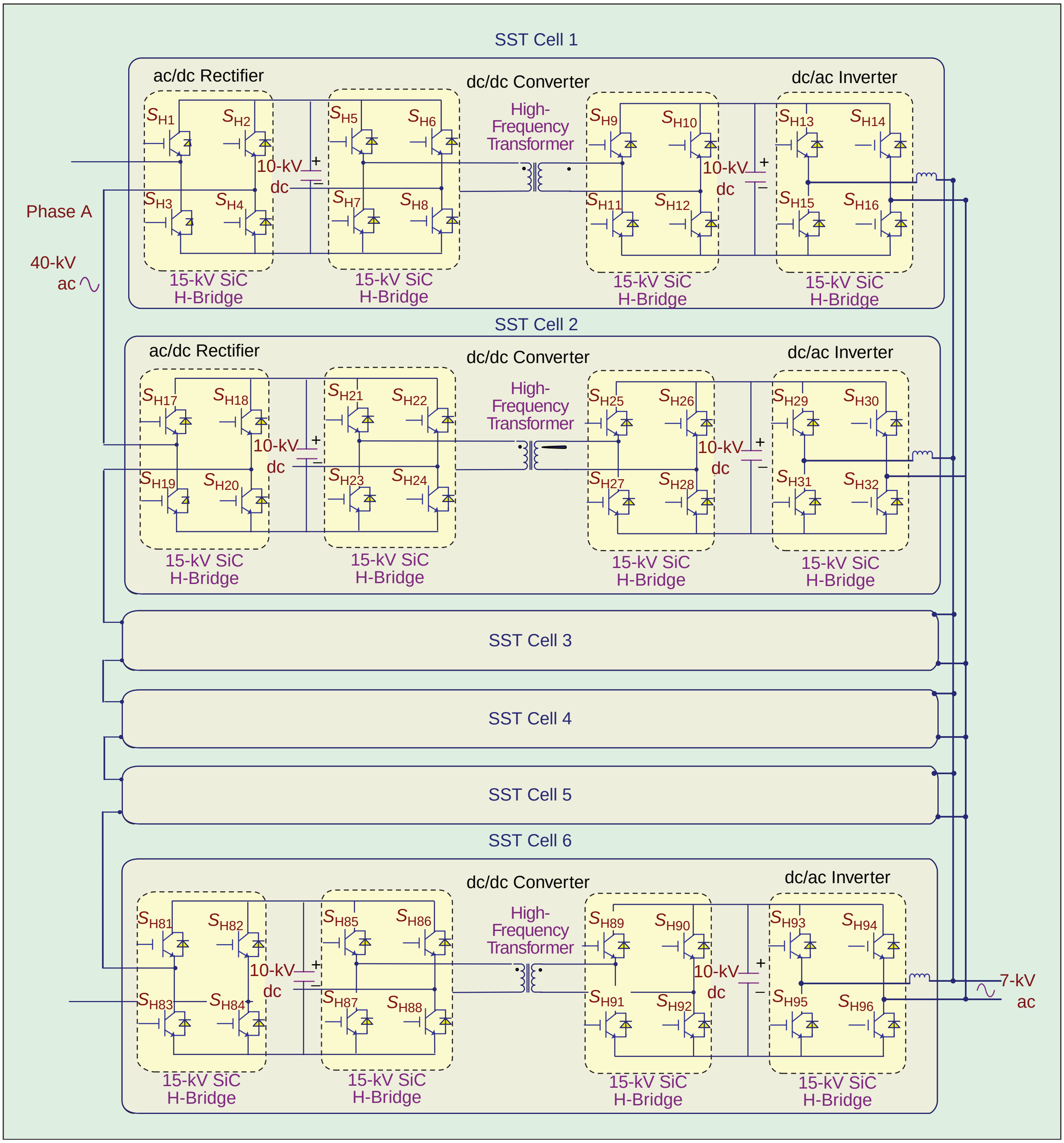

FIGURE 10 – Possible 69-kV/12-kV substation-class SST topology based on series-connected modular 15 kVA SST cells (only single phase shown).

> **A lower-voltage cell can be used to reach a higher-voltage level in a power transmission system.**

some recombination current exits in the buffer layer of the lower lifetime device, but the net effect on the device tradeoff performance is small. Therefore, the carrier lifetime increase of the 4H-SiC epitaxial layer with the improvement of the 4H-SiC epigrowth technology can further improve the frequency capability (>5 kHz) of 15-kV SiC IGBTs.

The robust turnoff capability of the SiC IGBTs is required in their applications in power electronic systems. The dynamic avalanche breakdown (or avalanche injection) is the basic failure mechanism of the IGBT during its turnoff transient [15]. Using the empirical parameters of 4H-SiC [16], the onset of dynamic avalanche breakdown voltage of the 15-kV SiC is calculated [17] and plotted in Figure 7. The power density at the onset dynamic avalanche point of the SiC IGBT is about 7 MW/cm^2, which is more than 20 times larger than the theoretical value of high-voltage Si devices [18]. The comparison of the onset of dynamic avalanche breakdown and the turnoff $I - V$ trajectory curve (Figure 5) in a normal operation condition indicates that the SiC IGBT has robust turnoff capability. Combining the advantage of the low loss and fast switching speed, the rugged turnoff capability of the SiC IGBTs makes them suitable for high-voltage power electronic applications.

15-kV SiC IGBT-Based SST

The SST is not only a transformer but also a fault current limiter, a reactive power compensator, and a sag restorer. These advantages make SST very promising in future power systems. Figure 8 shows the proposed baseline topology for a single-phase 10 kVA SST used in the FREEDM system. It includes three stages of power conversion. The first stage is an ac/dc rectifier that converts 7-kV single-phase ac to 10-kV dc. The second stage is a high-frequency (5–10 kHz) dc-dc converter that converts 10 kV dc to 400 V dc. It consists of a high-voltage H-bridge unit, a low-voltage H-bridge unit, and a high-frequency transformer between them. Soft-switching techniques can be used to increase the switching frequency of the SiC IGBTs and dc-dc converter. The third stage is a voltage source inverter (VSI) that inverts 400-V dc to 60 Hz, ±120 V ac. The 15-kV/2-A SiC IGBTs will be used in the ac/dc rectifier and primary stage of the dc/dc converter.

The key of the SST is to achieve size and weight reduction of conventional transformers by increasing the dc-dc converter operation frequency so that the size and weight of passive components can be greatly reduced. To compare the size and the weight with the traditional transformer, a proposed 2.7-MVA SST using the 10-kV SiC MOSFET technology is shown in Figure 9 [2]. Today's 2.7-MVA transformer weighs more than six tons and uses a large amount of copper. Literature indicates that a three times reduction in size and weight of transformers is possible [2]. Moreover, SST is potentially more attractive since the SST uses much less copper, whose cost keeps increasing. The high-power SST for industry customers using higher current, high-voltage SiC IGBTs is feasible with the maturation of SiC epitaxial growth technology.

A lower-voltage cell can be used to reach a higher-voltage level in a power transmission system. Figure 10 shows a single phase of the possible 69-kV/12-kV substation-class SST topology, which is based on series-connected modular 15-kV SST cell. For input stage of the SST, it is a cascade multilevel rectifier. This topology avoids the series connection of power semiconductor devices and is easy for modular design. The input voltage sharing can be preliminarily solved by swapping the switching patterns for input stages. Moreover, additional balancing control will be added to balance the dc capacitor voltages in input stages.

In the earlier proposed SiC-based SST, our preliminary, nonoptimized design indicates that an efficiency greater than 90% is achievable. To compete with traditional transformer, higher efficiency (97%) is required. Advanced technology on topology, core of transformer, and soft switching will be used to increase the efficiency of the SST.

Conclusions

It is likely that future power generation and distribution will involve a lot of distributed renewable energy resources and power grids. Both power generation and storage interconnect to the grid or microgrid, via a new power distribution infrastructure or energy Internet. The energy Internet will have bidirectional energy flow control capability, allowing it to provide key plug-and-play features and isolate the system from faults on the user side. The need for advanced power semiconductor devices with high-voltage, high-frequency, and high-temperature operation capability is required for the energy Internet.

The Si IGBTs have been widely used in the medium-voltage traction motor drives and traditional power distribution systems. As the most promising postsilicon device, the SiC IGBTs can break the silicon theoretical limits because of the superior properties of SiC material. Our numerical study shows that the 15-kV SiC IGBTs have much lower loss, faster switching speed, and more rugged turnoff capability than Si counterparts. Therefore, the high-voltage SiC IGBTs are promising technology for the future power electronic applications.

Biographies

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B. Jayant Baliga is an internationally renowned scientist, author of 15 books, and more than 500 publications, and has been granted 120 U.S. patents. Among his inventions, the most widely commercialized device is the IGBT, which is extensively used around the globe for consumer, industrial, transportation, and medical applications. He has received numerous IEEE awards including the 1999 Lamme Medal and is a member of the National Academy of Engineering. He has 25 years of experience with the design of silicon and SiC IGBTs. He is a Fellow of the IEEE.

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