Silicon Carbide Thyristors usher in the Smart Grid Revolution

These devices offer near-theoretical, on-state blocking voltage and switching performance

Global demand for high-efficiency, green energy technologies and products has placed new challenges on the electrical grid, on efficient exploitation of renewable energy resources, and on electric-based solutions for ship systems. All of these applications require ultra-high-voltage power devices (to reduce energy loss) with high-frequency ratings (to reduce system size, weight, and volume).

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Annually, over $2 trillion of electricity is processed through the U.S. electric grid. Thus, even relatively small improvements in system efficiency represent tremendous economic and environmental benefits. By increasing power electronics efficiency, advanced interconnection technologies widen the practical end use of fuel cells, photovoltaics, wind power, batteries, superconducting magnetic storage, adjustable speed drives, and efficient power supplies. It is well recognized that silicon-based semiconductors have inherent limitations that reduce their suitability for use in utility-scale applications. Power electronics applications including static transfer switches, dynamic voltage restorers, static VAR compensators (SVCs), high-voltage direct current (HVDC) transmission, and flexible alternate current transmission systems (FACTS) will become economically feasible. Some of these applications require voltage-blocking capabilities in the tens and hundreds of kV, and thousands of amperes.

Figure 1 shows the future vision by Electric Power Research Institute (EPRI, San Jose CA) for applications of Thyristors in Smart Grids.

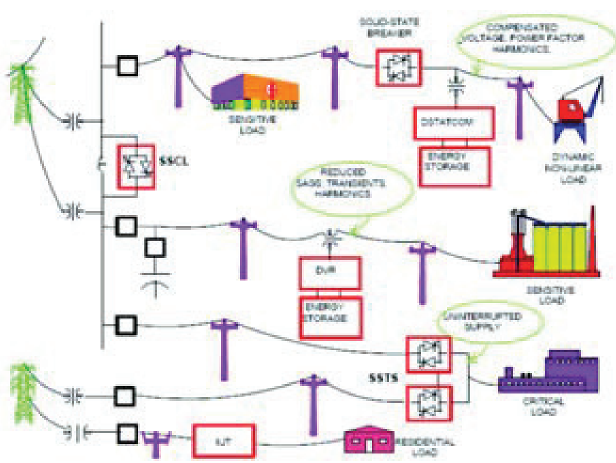

Figure 1: Solid-state current limiters, energy storage elements and solid-state breakers play a critical role in future vision of Smart Grid power electronics based technologies.

According to this futuristic vision, the growth in the generation of electrical energy, increased penetration of distributed resources, and increased interconnection of the networks will lead to higher incidence of faults. The growth in capacity requires replacing existing circuit breakers with higher fault-current ratings results has a significant impact on cost and down time.

Utility-Scale Power Semiconductor Devices

All utility-scale 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 (GTO s) 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., pulse-width modulation-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 voltage blocking capability and a higher junction temperature (greater than 100oC). Presently, the three challenges power conversion elements face are thermal management of semiconductor losses generated during system operation;

large stacks of high-voltage devices required to be usable in >4.16 kV line voltages; and slow speed (<4 kHz) prevents widespread use of pulse width modulators (PWM) circuits to maintain power quality.

Recently, new, wide-band-gap materials such as silicon carbide (SiC) have become attractive alternatives to silicon for semiconductor switches. These materials offer the potential for higher switching speeds, a higher breakdown voltage, lower switching losses, and a higher junction temperature than traditional silicon-based switches. SiC-based diodes are coming on the market now and switching devices with increased capabilities are currently being developed. Higher voltages and higher operating temperatures pose numerous development challenges which must be resolved before commercial systems can be built. These devices offer all of the advantages of SiC-based devices as well as improved voltage standoff capability, increased operational flexibility, and higher current carrying capability than traditional silicon-based devices.

SiC-based Thyristors offer 10X higher voltage, 100X faster switching frequencies and higher-temperature operation compared with conventional Silicon-based Thyristors. Targeted research applications include general-purpose medium-voltage power conversion (MVDC), grid-tied solar inverters, wind-power inverters, pulsed power, weapon systems, ignition control, and trigger control. Ultra-high-voltage (>10 kV) SiC device technology will play a revolutionary role in the next-generation utility grid. SiC-based Thyristors also offer the best chance of early adoption due to their similarities to conventional power grid elements. Deploying these power semiconductor technologies could provide as much as a 25–30% reduction in electricity consumption through increased efficiencies in the delivery of electrical power.

Figure 2: GeneSiC recently introduced 6.5kV-class Silicon Carbide Thyristors to researchers investigating utility-scale power conversion circuits.

The utilization of a single-chip packaged ultra-fast, high-temperature 6.5 kV SiC GTO Thyristor module will revolutionize electricity delivery, renewable energy integration, and energy storage technology. GeneSiC recently introduced world's first commercially available, high-voltage, high-frequency, high-current, high-temperature, single-chip devices with ratings exceeding 6.5 kV, 200 kHz (pulsed), 80 A, and 200oC, as shown in Figure 2. As compared to other commercial SiC devices—which comprise of only two terminal rectifiers—these devices offer much higher (3–4X) blocking voltages and current/voltage control capability. As compared to Silicon Thyristors, SiC Thyristors offer much higher switching speeds (100–1000X) and higher temperature operation (up to 300oC, versus 125oC). These advantages result in exceptionally high usability and efficiencies in next-generation power circuits.

Design of Silicon Carbide (SiC) Thyristors

SiC Thyristors control large amounts of electrical power (Voltage, Current) through high- frequency switching of high voltages, currents at high temperatures. SiC is a novel, wide bandgap material which offers the realization of semiconductor devices that can offer an order of magnitude higher rating as compared to silicon. However, the design and fabrication techniques required to fully exploit this important material system is extremely challenging.

As shown in Figure 3, SiC Thyristors are three-terminal, bipolar-mode devices (as compared to uncontrolled two-terminal, unipolar devices such as diodes) that use diffusion physics of operation relying on minority carrier transportation during on-state operation. Minority carrier transportation allows much lower on-state voltage for >3 kV power devices as compared to unipolar power devices. In contrast to commercially available SiC unipolar Schottky diodes, three terminal devices like SiC Thyristors are critical towards actively controlling electrical power.

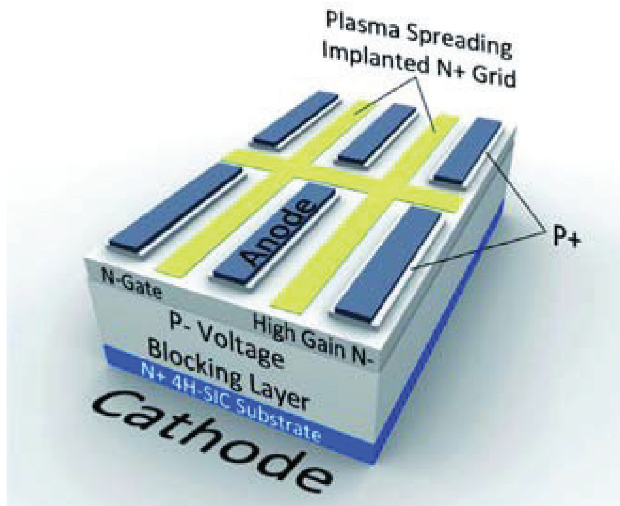

Figure 3: SiC npnp Thyristors have their three electrical terminals–Anode and Gate regions on top, and Cathode contact at the bottom. Various SiC layers and their doping types from the top are P+ Anode layer, N-type Gate layer, P- blocking layer, and the N+ Cathode layer. The rated voltage is supported between with n-Gate/p-blocking layers, so that the p-blocking layer doping and thickness primarily determines the breakdown voltage of the device.

When no current flows through the gate-anode junction, the device blocks a high voltage in both the forward and the reverse bias. To turn the device on, a trigger current flows through the Anode-Gate junction, thereby activating the inherent Anode-Gate-P-based transistor. This gate current is amplified to supply the gate current to the other inherent N-Gate/P Blocking and N-Cathode transistor. This leads to a turn-on of both inherent transistors by a regenerative action. A Thyristor conducts a large current between the Anode and Cathode terminals with little forward voltage drop in this condition.

To turn the device off, the Gate-Anode junction is reverse biased for a short period of time by the application of an external current pulse. When a sufficient loss of minority base current occurs through the gate terminal of the pnp transistor, it turns off and stops supplying gate current to the npn transistor as well. Hence, the npn transistor also turns off. The device is capable of supporting a large anode-Cathode voltage under this condition. A high-performance thyristor developed here offers withdrawal of the gate charge more effective through stringent design of the Gate-anode layout design, The gate contact must surround the anode region everywhere and must be closely spaced. The developed thyristor provides highly inter-digitated Gate-anode patterns, like the involute patterns, as shown in Figure 4. Additionally, it has an implanted n+ type region below the gate contact of the device. this makes the extraction of gate charge from the pnp transistor more eff ective during the turn-off of the device, thereby requiring a smaller gate current requirement for both turn-on and turn-off .

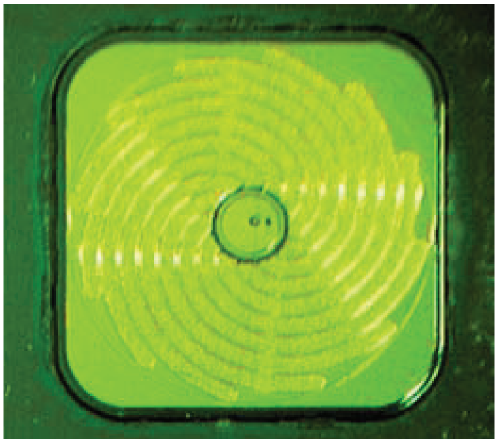

Figure 4: Various Anode-Gate inter-digitations patterns of the Thyristor structure were explored during the development of these Thyristors. An involute pattern shown here was found to provide the best switching performance. In this chip structure, a central Gate terminal provides trigger currents to turn on this Thyristor by flowing the impressed gate current through equidistant Anode-Gate fingers.

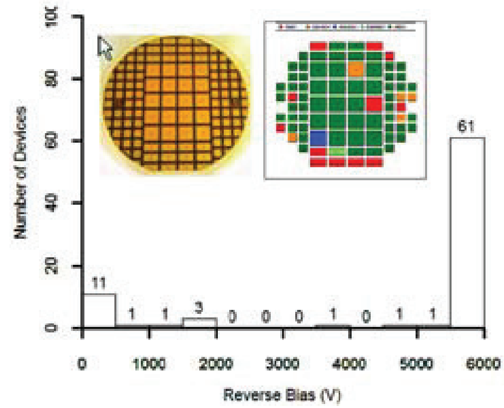

Figure 5b: Histogram of forward blocking voltages measured on all devices from a 3" SiC wafer. A photograph of the wafer is shown as an inset.

Operation of SiC Thyristors

SiC Thyristors developed by GeneSiC were turned on by increasing the Gate current in 10 mA steps until the device latched on, while keeping the VAK bias fixed at 5 V. A very low Von of 3.8 V and a differential specific on-resistance of 2.55 m?-cm2 at 100 A/cm2 was measured on the 4.1x 4.1 mm Thyristors, indicating a high-level of conductivity modulation of the p- drift region and the achievement of low contact resistances, especially for the p+ Anode contacts. Some devices were found to block voltages in excess of 8.1 kV (an example curve is shown in Figure 5 (a)). This represents > 84% of the theoretical (unipolar) breakdown voltage of 9700 V for the p- epilayer used for fabrication. This result was made possible by the optimized edge termination and passivation schemes utilized for fabricating these Thyristors. A histogram of forward blocking voltages measured on all devices from a 3 inch wafer is shown in Figure 5 (b). It was found that 85% of all 8.1x8.1 mm devices blocked voltages in excess of 6 kV. After packaging the Thyristors, high-current (up to 50 A) measurements were performed at in the 25-200oC temperature range.

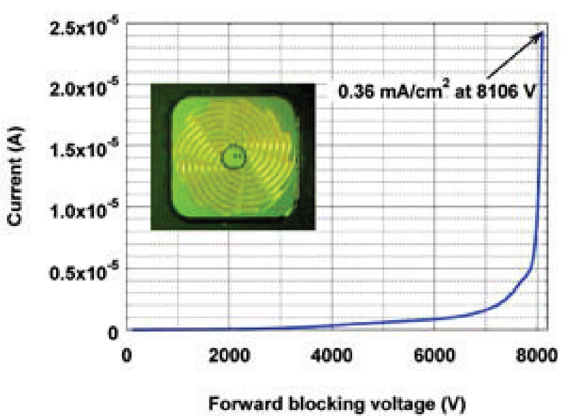

Figure 5a: Forward blocking voltage measured on a representative 4.1x4.1 mm involute GTO Thyristor

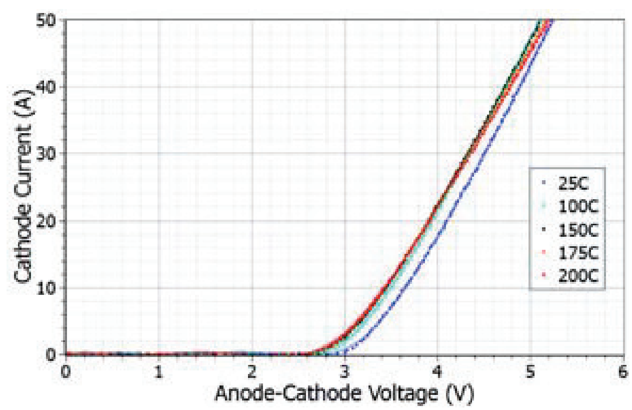

Figure 6: High-current I-V measurement performed on a packaged 8 kV SiC Thyristor.

Forward I-V measurements performed at different temperatures on a 4.1 x 4.1 mm packaged Thyristor are shown in Figure 6. The on-state measurements were performed by ramping the Anode-Cathode bias and the triggering the device into its on-state by the application of Gate current. The built-in voltage decreases slightly with increasing temperature, whereas the on-resistance shows a gradual increase with temperature.

SiC Thyristors are used to switch very high voltages and very high currents. Figure 7 shows the Anode-Cathode Voltage, Anode-Current and Gate-Current pulse waveforms of a SiC Thyristor turning off 16 A of anode current in a unity-gain turn-off condition. Here, the entire anode current is extracted from the gate terminal to turn-off the Thyristor. Initially, the Thyristor is blocking a VAK of 2000 V, following which it is triggered to its on-state by applying a gate current pulse of 2.4 A. For turning off the device, the anode current is switched off using an external MOSFET and the entire anode current is commutated to the gate electrode and the Thyristor turns off like an open-base npn transistor. It can be seen that a unity gain turn-off condition is established here (IG = IAK). The total turn-off time was measured to be 1.5 ìs. The entire turn-on and turn-off transient takes less than 4 ìsec, indicating that the device is capable of a pulsed switching frequency of >250 kHz.

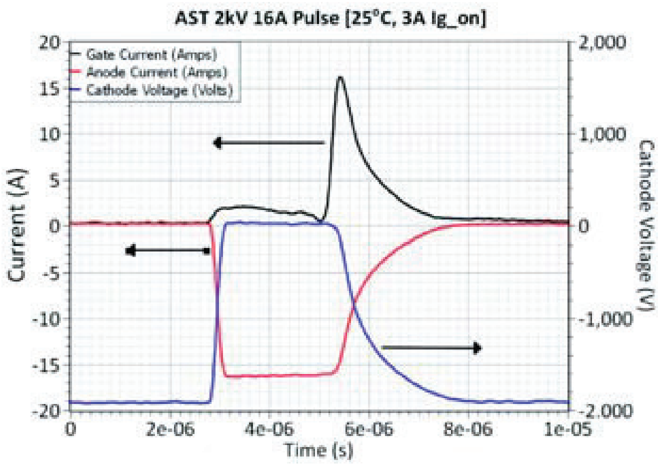

Figure 7: A Silicon Carbide Thyristor being switched under a unity-gain turn-off condition. In this plot, the SiC Thyristor undergoes a switching between 2000 V and 16 Amperes of current.

Conclusions

Although bipolar devices in Silicon Thyristors have been known previously, bipolar devices in Silicon Carbide have been demonstrated to operate in somewhat unexpected performance levels (e.g., 1000X lower minority carrier charge; lower temperature-dependence). These new modes of operation were verified and optimized upon by GeneSiC researchers through this commercial offering. These commercial devices offer near-theoretical, on-state blocking voltage and switching performance as compared to anything that has ever been demonstrated before, even in a laboratory.

Silicon Carbide Thyristors not only improves on the competition, but it is a revolutionary step towards power electronic system integration. GeneSiC's Thyristors offer unique and pioneering performance advantages as compared to any competing technologies. In the near future, power semiconductor switches applicable towards power conversion tied to the power grid are likely to be SiC-based Thyristors due to their high-voltage capability, high-temperature capability, and fast switching speeds.

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