Exploiting the high temperature promise of **SiC**

Replace silicon diodes and transistors with those made from SiC and the operating temperature of power electronics can soar to such an extent that bulky thermal management systems are no longer needed. The upshot: Squeezing grid-scale renewable energy inverters, downhole electronics and aerospace engines and actuators into far smaller spaces, says **Ranbir Singh of GeneSiC**.

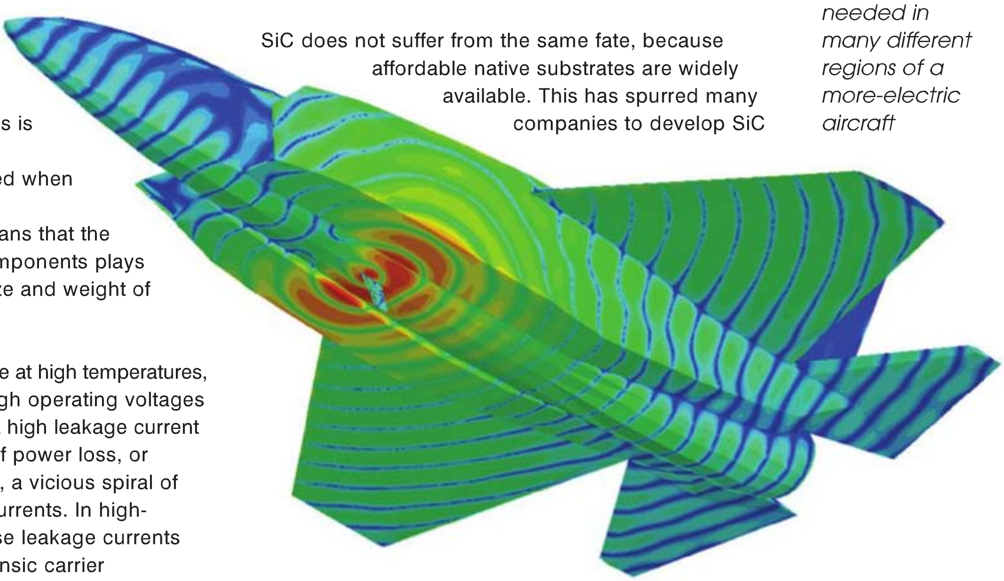
Engineers searching for ever-increasing stealth in fighter jets, greater fuel-efficiency in airliners and vehicles, and compactness in grid scale solar inverters are united in one ambition: To throw out liquid-cooling loops, because this trims the size, weight, volume and cost of the electronic systems.

In all these applications, consumption and generation of electrical power occurs at different voltages and currents. For example, solar panels generate a low-voltage DC output, but this must be transformed into a high-voltage AC output before it is fed into the grid. This conversion process takes place in electronics circuits built from power semiconductors and passive components, such as inductors and capacitors. Electrical conversion is not 100 percent efficient, with losses converted into heat, which must be managed to ensure that these systems function optimally. Often, the thermal management apparatus is bigger than the circuits – and this difference is even more pronounced when the entire circuit operates in a high temperature environment. This means that the temperature tolerance of these components plays a critical role in determining the size and weight of these systems.

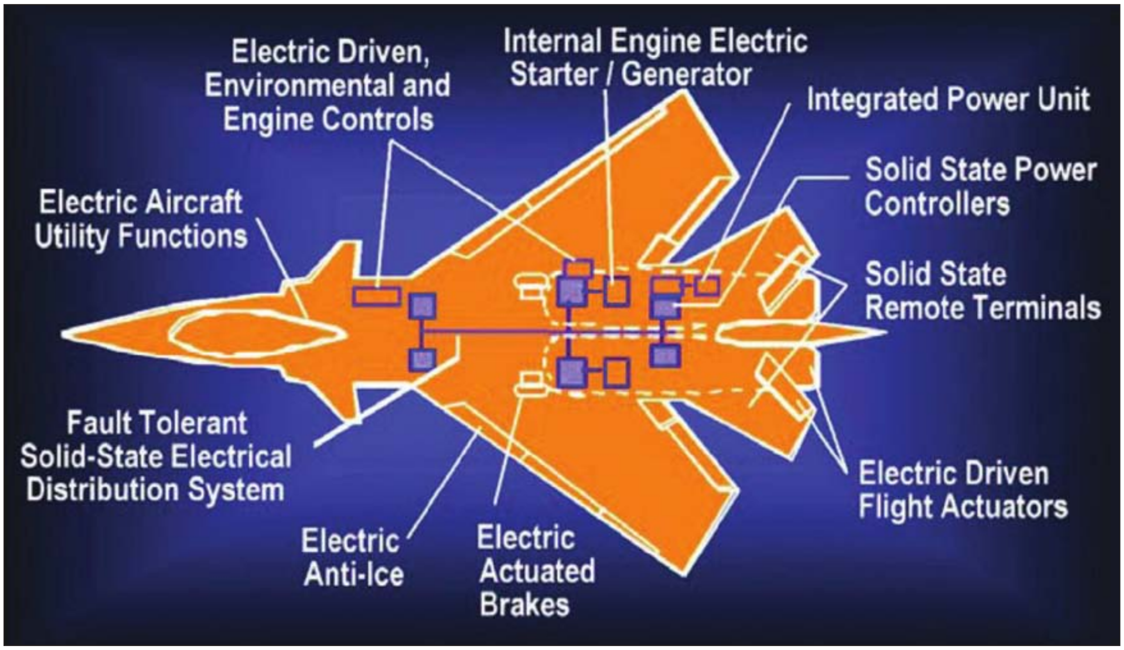
When power semiconductors operate at high temperatures, increases in leakage currents at high operating voltages tend to limit system performance. A high leakage current can result in unacceptable levels of power loss, or device failures by thermal runaway, a vicious spiral of over-heating and higher leakage currents. In high-voltage-blocking pn junctions, these leakage currents are directly proportional to the intrinsic carrier concentration in the semiconductor. This concentration is several orders of magnitude lower in GaN and SiC than it is in silicon, which is why these wide bandgap materials hold tremendous promise for making high-temperature devices with incredibly low leakage currents.

Ideally, GaN power devices would be built on a native substrate. However, GaN substrates are very pricey, so foreign substrates such as sapphire, SiC and silicon must be used instead. Although this trims costs, hetero-epitaxial growth creates high levels of crystal defects, which are to blame for the high leakage currents in devices biased to high voltages. As operating temperatures increase, this leakage current grows exponentially, preventing GaN devices from operating at reasonably high junction temperatures.

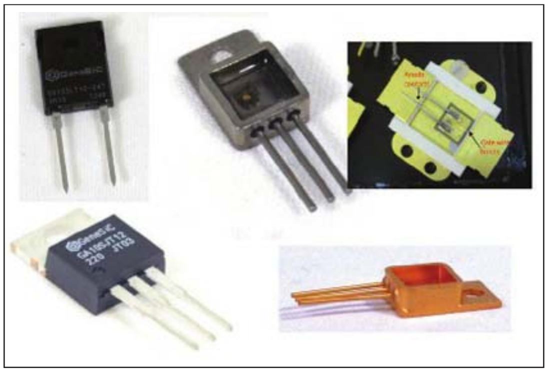
SiC does not suffer from the same fate, because affordable native substrates are widely available. This has spurred many companies to develop SiC



Power electronics is needed in many different regions of a more-electric aircraft



High temperature surfaces on modern aircraft severely burden the electronics required to operate them



GeneSiC offers various packages for its SiC power devices

devices, with attention focused on the development of Schottky barrier diodes. In these devices, leakage currents are governed by design and fabrication processes, rather than the intrinsic properties of the pn junction. Consequently, there is a tremendous variation in the high-temperature performance of Schottky diodes made by different manufacturers.

Slashing leakage currents

At GeneSiC Semiconductor of Dulles, Virginia, we have developed high-temperature Schottky barrier diodes that exhibit the lowest increase in leakage current as the operating temperature is ramped up (see Figure 1). This unprecedented performance stems from our superior designs and processes, including unique expertise in designing, fabricating and characterizing devices at high temperature and high voltages (see Figure 2).

Our device development begins with two-dimensional device design using finite element analysis. Once we have determined the device's architecture with a fundamental physics-based simulation, this is translated into layout designs using a sub-micron mask. These layouts are carefully matched with fabrication techniques. We have unique, world-leading expertise in the specialized nature of fabrication techniques such as: Sidewall etches, double-level, high-temperature metallizations; and implementing involute gate designs. The wafers that we fabricated are tested up to extremely high temperatures using high-temperature chucks. Wafers are diced into individual devices and put into prototype packages for evaluation and optimisation for high temperature operation.

These diodes can be used in power-conversion circuits alongside three-terminal transistors that have the role of

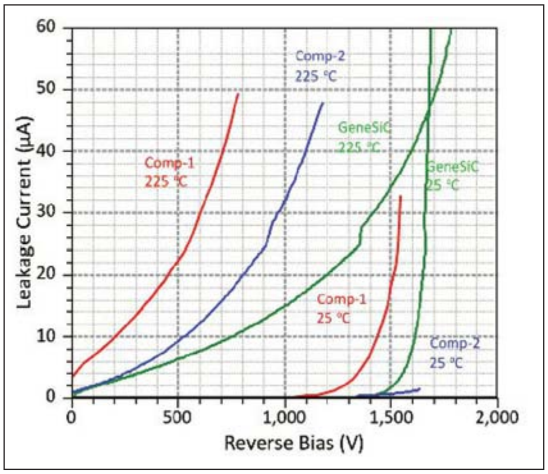


Figure 1: Leakage current comparison for three 1200 V SiC Schottky rectifier technologies at room temperature and elevated temperatures shows the least increase in leakage for GeneSiC's rectifiers

a switch. When the transistor is in its ‘off’ state it blocks high voltages, and in its ‘on’ state it delivers high currents with low power losses.

The SiC community has devoted significant effort to the development of SiC power MOSFETs. However, the improvement in high temperature performance of SiC MOSFETs is marginal over a silicon equivalent. That’s because the high-temperature limit for operation is determined by the interface between SiO_2 and SiC, rather than the level of current leakage from the pn junction. The conduction band offset between SiO_2 and SiC is quite small, resulting in the degradation of the MOS interface at relatively low temperatures. As a result, as of today, the junction temperature of the only commercially available SiC MOSFE is rated up to a just 125 °C.

To address this weakness and allow this class of transistors to fulfil its full potential, we have developed a high-temperature SiC switch: The ‘Super’ Junction Transistor (SJT). The hallmark of this gate-oxide free, normally-off, majority carrier device is its incredibly high current gain, which can exceed 88. It also has many other virtues, including a ‘square’ reverse-biased safe operating area, which allows extremely rugged operation in typical inductive motor and actuator drive applications.

What’s more, the temperature co-efficient of on-resistance for this transistor is slightly positive, which is desirable for paralleling multiple devices for high-current configurations; ‘turn-on’ and ‘turn-off’ times are less than 20 ns; operating temperature can exceed 250 °C; and the SJT features a low ‘on-state’ voltage drop and high-current operation, thanks to the absence of a channel region and a near-zero drain-source offset voltage.

Our SJTs combine a near-theoretical breakdown voltage with a temperature-independent, low-reverse-leakage current up to 325 °C. In addition, our SJT displays a distinct lack of a quasi-saturation region, and is notable for the merging of the different gate current I-V curves in the saturation region. The implication of these two features is a lack of charge storage in the drift region of the transistors – this distinguishes it from a ‘bipolar’ silicon BJT. The resulting benefit is temperature-independent, fast-switching transients. The low, on-state voltage drop stems from appropriate metallization schemes and an optimised epilayer design.

The switching performance of our 4 mm^2 and 16 mm^2 SiC SJTs have been evaluated by pairing them with an inductive load and our ‘free-wheeling’ 1200 V/ 7 A and 1200 V/30 A SiC Schottky diodes. To drive the SJTs, we used a commercially available IGBT gate driver with an output voltage swing from -8 V to 15 V. For the 4 mm^2 SJTs, a 100 nF dynamic capacitor connected in parallel with the gate resistor can generate high initial dynamic gate currents of 4.5 A and -1 A during turn-on and turn-off switching, respectively. During the turn-on pulse, a constant gate current of 0.52 A was maintained. These large initial dynamic gate currents rapidly charge and discharge the device input capacitance, yielding faster switching performance. We recorded temperature-independent, ultra-low drain current rise and fall times of just 12 ns and 13 ns, respectively, for switching 8 A and 800 V by the 4 mm^2 SJT (see Figure 3).

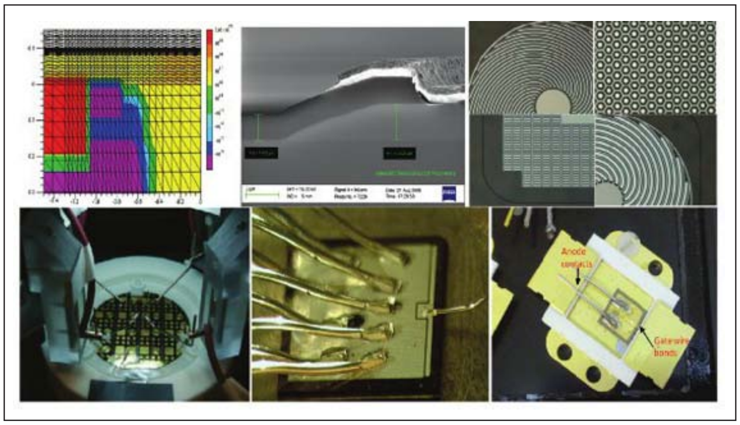


Figure 2. GeneSiC’s expertise includes – from left to right (a) two-dimensional device design through computer intensive finite element simulations; (b) Precise sub-micron controlled SiC reactive ion etching; (c) Complex integration of designs to fabrication tools and techniques; (d) high temperature/high voltage on-wafer testing and characterization; (e) die attach and wire bonding; and (f) final high temperature optimized packaged products

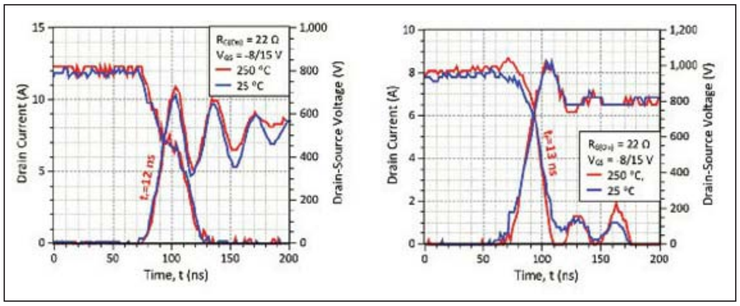


Figure 3: (Left, a) Turn-On and (Right, b) Turn-off drain current and voltage transients recorded for switching 800 V and 8 A through a 4 mm^2 SiC SJT. There is no difference in switching speed between 25 °C and 250 °C, due to the unipolar nature of the SJT device design

A realistic assessment of the performance of our SiC transistors and diodes demands a comparison with state-of-the-art silicon devices deployed in real circuits. To do this, we procured three best-in-class 1200 V silicon IGBTs: A NPT1 ‘non-punch-through’ IGBT, which is rated up to 125 °C and 1200 V; a ‘non-punch-through’ variant rated up to 150 °C and 1200 V, the NPT2; and a trench field stop (TFS) IGBT rated up to 150 °C and 1200 V. All three IGBTs were pre-packaged with silicon fast recovery diodes in anti-parallel configuration. These efforts revealed that the SiC combination excels over a wide temperature range (see Figure 4). In comparison, when silicon IGBTs are pushed beyond 175 °C their leakage current rockets.

We have also investigated the switching performance of SJTs and silicon IGBTs using an inductively clamped, double-pulse switching setup. This involves using our 1200 V/ 7A Schottky diode and silicon IGBT co-packs as free-wheeling diodes in the switching test circuit. Gate and source terminals of the silicon IGBT co-pack were tied together (V_{GS} = 0 V) to prevent IGBT conduction during dynamic testing. Measurements demonstrated the superiority of SiC devices over a wide temperatures range (see Figure 5). At up to 250 °C, the SiC SJTs displayed temperature-independent drain-current rise and fall times as short as 12 ns and 14 ns, respectively, for switching at 800 V and 7 A. These ultra-short switching times enabled the pair of SiC devices to deliver switching losses that are lower than the all-silicon configurations and those based on a silicon IGBT and a SiC free-wheeling diode.

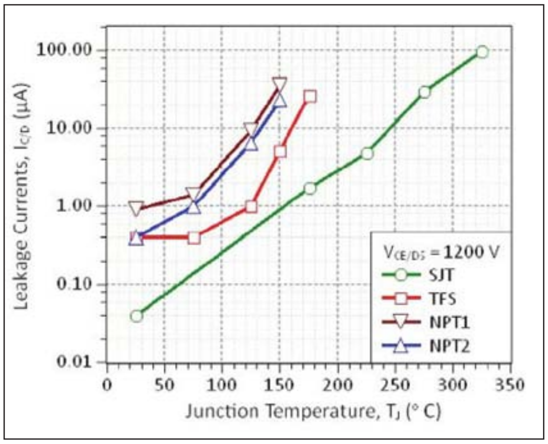


Figure 4: Comparison of leakage currents of SiC SJT and silicon IGBTs as a function of temperature

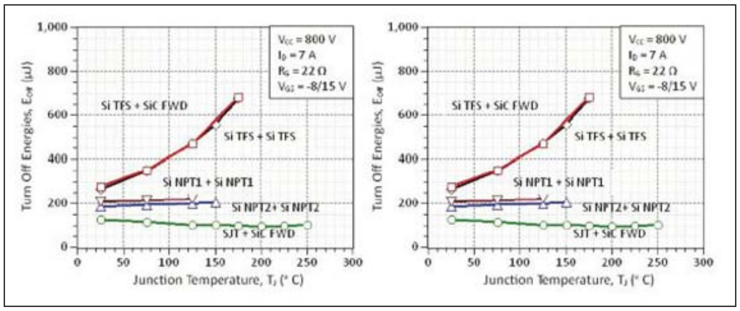


Figure 5: Comparisons of 'turn-off' and 'turn-on' switching energies for SiC SJT and silicon IGBTs at various operating temperatures. "Si TFS + SiC FWD" represents a silicon trench field stop IGBT as the device under test (DUT) and the SiC Schottky diode as free-wheeling diode. In the case of "Si TFS + Si TFS", the silicon TFS IGBT is the DUT, and the silicon TFS IGBT co-pack is the free-wheeling diode. A commercially available IGBT gate driver with an output voltage swing from -8 V to 15 V is used for driving all the devices. While driving the SiC SJT, a 100 nF dynamic capacitor connected in parallel with the gate resistor generated high initial dynamic gate currents of 4.5 A and -1 A during turn-on and turn-off switching, respectively, while maintaining a constant gate current of 0.52 A during its turn-on pulse. These large initial dynamic gate currents charge/discharge the device input capacitance rapidly, yielding a faster switching performance. The testing process also involved a 1 µF charging capacitor, a 150 µH inductor, 22 Ω gate resistor and a supply voltage of 800 V

It is possible to determine the contributions to the power loss of all these devices by considering dynamic and static characteristics for a 100 kHz switching frequency (see Figure 6). At 250 °C, the gate drive, conduction and switching losses of the SJT are 5.25 W, 26.65 W and 20 W, respectively. Note that although the gate driver loss of the SJT is higher than that of the silicon IGBT, its contribution to the overall losses is insignificant. These measurements also take into account the higher conduction losses of the SJT operating at 250 °C.

The measurements show that it is possible to trim overall switching losses by more than 30 percent by simply replacing a silicon fast-recovery epitaxial diode with a SiC Schottky diode for the free-wheeling diode. However, when an all-SiC line-up is employed in the place of silicon IGBTs and pin diodes, power loss reduction is cut by more than 50 percent. These tremendous energy savings show that SiC is well on the way to unlocking its potential at high temperatures.

We are now allowing key potential customers to evaluate the performance of our SJTs and high-temperature Schottky barriers for themselves, while we simultaneously validate our products. These products will expand our portfolio, which also includes SiC Schottky barrier diodes with a more conventional operating range and SiC thyristors.

Figure 6: Overall loss comparison of SJT and silicon IGBTs at their maximum operating temperature. The results are given for a 100 kHz switching frequency