



Circuit Protection for Electronics: SiC Devices for ESD and Lightning Strike Defense



Abstract

The rapid adoption of wide-bandgap semiconductors has fundamentally changed how engineers design transient protection for low-voltage electronic systems. Silicon carbide (SiC), long recognized for its high efficiency in power conversion, is now being leveraged for circuit-protection applications that demand exceptional energy absorption, fast switching response, and high-temperature reliability. SiC-based inline and parallel protection devices provide robust defense against electrostatic discharge (ESD) events and lightning-induced transients, ensuring the survivability of mission-critical electronics in aerospace, communications, and embedded environments.

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Introduction

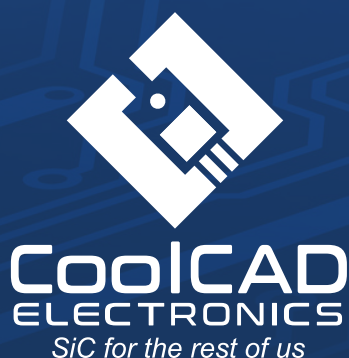
Modern embedded electronics increasingly operate in harsh electrical environments. Aircraft flight-control modules, automotive ECUs, and outdoor telecom equipment must withstand large transient events ranging from microsecond-scale ESD pulses to millisecond lightning surges. Historically, protection has relied on silicon TVS diodes or MOVs; however, these devices exhibit limitations in breakdown voltage, energy absorption, and high-temperature operation. SiC technology, long valued in power electronics for its high breakdown field and thermal conductivity, has now proven equally beneficial for protection applications requiring both speed and durability.



Mechanisms of Transient Suppression

Circuit protection architectures generally fall into two principal categories: inline and line-to-ground configurations. In an inline topology, the protection device is inserted in series between the power or signal source and the load that must be safeguarded. Under normal operating conditions, it behaves as a low-resistance conductor, introducing negligible voltage drop and preserving signal fidelity. When a transient event such as an electrostatic discharge (ESD) pulse or lightning-induced surge occurs, the device instantaneously transitions into a high-impedance state. This shift in conduction restricts current flow through the protected path, effectively damping the transient and preventing the surge from propagating downstream to sensitive components.

In contrast, a line-to-ground configuration operates by shunting excess energy away from the circuit rather than interrupting current flow through it. Components such as transient-voltage suppressor (TVS) diodes are connected in parallel between the protected node and ground. During nominal conditions, these



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devices remain non-conductive, presenting a very high impedance to the line. When the applied voltage surpasses a defined breakdown threshold, they switch sharply into conduction, clamping the voltage to a safe level and directing the surge current harmlessly to ground. Once the transient subsides, the device rapidly returns to its high-impedance state, restoring normal operation.

For low-voltage logic protection, silicon carbide (SiC) inline devices implemented as normally-on, depletion-mode transistors provide a distinct performance advantage over conventional silicon counterparts. With zero gate bias, SiC transistors remain fully conductive under steady-state operation, exhibiting extremely low on-resistance and minimal parasitic capacitance. These properties ensure near-lossless signal transmission and negligible impact on high-speed circuitry. During a transient event, the rapid rise in drain-source voltage modulates the channel, driving the device toward depletion. This intrinsic reaction increases its resistance dynamically, dissipating surge energy along the conduction path and reducing the voltage transmitted to downstream components. Because the transition is a native property of the SiC material system, no external gate drive or control circuitry is required, yielding a self-regulating and inherently fail-safe mechanism.

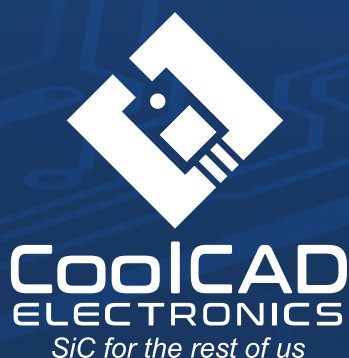
Compared with silicon, SiC protection devices demonstrate markedly higher breakdown voltage, faster response time, and superior thermal conductivity. The wide bandgap of SiC enables operation at higher electric fields, allowing thinner drift layers that reduce series resistance and improve switching speed. Its high thermal conductivity efficiently spreads and dissipates localized heat generated during surge absorption, minimizing thermal runaway and extending device lifetime. These characteristics allow SiC-based protectors to handle larger transient energies, recover more quickly, and maintain stable electrical behavior across extreme temperature ranges.

The combination of low conduction loss, rapid self-activation, and high thermal robustness makes SiC-based inline devices uniquely suited for modern embedded and aerospace systems, where ESD and lightning-strike immunity must be achieved without compromising signal integrity or form-factor constraints.

Device Implementation

Two primary silicon carbide (SiC) device structures are used in transient protection applications, junction field-effect transistors (JFETs) and metal-oxide-semiconductor field-effect transistors (MOSFETs), each offering distinct performance characteristics suited to different protection strategies.

SiC JFET-based protection devices have long been favored for their structural simplicity and rapid switching capability. As depletion-mode devices, they are normally conductive with zero gate bias and transition instantaneously toward cutoff when a transient voltage increases the depletion width at the gate junction. This intrinsic mechanism enables sub-nanosecond response times, ideal for suppressing



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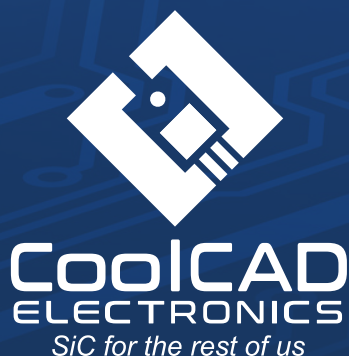
electrostatic discharge (ESD) pulses and other high-frequency transients. JFETs also exhibit excellent ruggedness due to the absence of gate oxide, which eliminates one of the most common failure points in silicon-based counterparts under high electric-field stress. Their high transconductance and low channel resistance allow them to carry significant surge currents while maintaining compact device geometry.

In contrast, SiC MOSFET-based designs have emerged as an attractive alternative due to their streamlined fabrication process and strong electrical performance when configured for depletion-mode operation. The MOSFET architecture provides greater design flexibility through the ability to tailor threshold voltage, oxide thickness, and channel doping to achieve specific protection characteristics. When optimized for normally-on behavior, SiC MOSFETs demonstrate low on-resistance, excellent linearity, and minimal gate leakage, allowing them to serve effectively as inline surge suppressors. Moreover, their smaller parasitic capacitance compared to JFETs reduces signal distortion and improves transient response, particularly in circuits operating with high-frequency or fast-edge signals, conditions typical of ESD or radio-frequency coupling events.

Accelerated stress testing indicates that SiC MOSFETs can match or exceed the reliability of JFET-based protection devices, even under extreme surge and thermal cycling conditions. Improvements in gate oxide quality and interface engineering have mitigated earlier reliability concerns traditionally associated with MOSFET structures. SiC's wide bandgap and high breakdown field further protect the gate dielectric from avalanche-induced degradation, enabling stable performance across repeated transient exposures.

From a manufacturing standpoint, SiC MOSFETs also offer advantages in scalability and process control. Their planar geometry aligns more closely with existing semiconductor fabrication infrastructure, reducing production cost and variability relative to JFETs. This compatibility makes SiC MOSFETs easier to integrate into hybrid modules or multi-chip protection assemblies.





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Ultimately, both device families leverage SiC's intrinsic material strengths, high critical electric field, thermal conductivity, and electron saturation velocity, to deliver exceptional transient suppression performance. JFETs excel in ultrafast, low-capacitance applications demanding extreme speed and simplicity, while MOSFETs combine similar response characteristics with improved manufacturability, design flexibility, and integration potential. The convergence of these advantages positions SiC devices as the foundation for the next generation of high-reliability, high-speed protection architectures in aerospace, automotive, and industrial electronics.

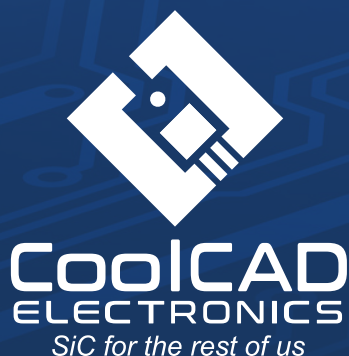


Material Advantages of SiC

Compared with silicon, SiC provides several intrinsic benefits for protection applications:

- High breakdown field ($\sim 3 \text{ MV/cm}$) allows thinner drift regions, yielding lower on-resistance for the same blocking capability.
- High thermal conductivity ($\sim 3.7 \text{ W/cm}\cdot\text{K}$) enables rapid heat spreading and recovery following surge events.
- Wide bandgap (3.26 eV) supports operation at junction temperatures exceeding 200°C .
- Fast carrier mobility and low capacitance minimize response delay during nanosecond-scale events.

The combination of electrical and thermal resilience allows SiC devices to survive repetitive transients that would permanently degrade silicon suppressors.



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ESD and Lightning Strike Qualification

SiC's superior breakdown voltage enables engineers to design simpler, single-stage protection networks that meet these higher waveform levels without stacking multiple components. This advantage becomes critical in modern aircraft and unmanned systems constructed from carbon-fiber composites, which lack the inherent Faraday-cage shielding of metallic fuselages. In such platforms, ESD and lightning currents can directly couple into avionics wiring harnesses, demanding robust line-level protection.

Hybrid Protection Architectures

A common strategy is to combine inline SiC depletion-mode devices with parallel SiC TVS diodes. The inline device initially damps the transient and limits current rise; if voltage continues to climb, the parallel device engages to clamp the residual surge to ground. This staged approach distributes energy dissipation and prevents single-point overstress. Because both components can be fabricated using the same SiC process, integration into compact protection modules is straightforward.

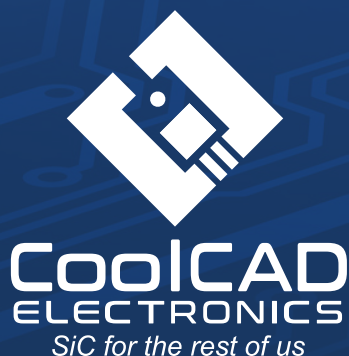
Reliability and Testing

SiC protection devices are evaluated through high-current pulse testing, surge-repetition cycling, and thermal shock. Early studies show negligible parameter shift after hundreds of ESD-class events, confirming SiC's resilience to rapid temperature gradients. The reduced defect density of modern 4H-SiC wafers further minimizes leakage variation between cycles, ensuring consistent clamping thresholds over product lifetime.

Conclusion

The transition from silicon-to-silicon carbide (SiC) represents a major advancement in protecting low-voltage electronics operating in high-stress environments. Traditional silicon suppressors are increasingly limited by their breakdown strength, temperature tolerance, and response speed. SiC overcomes these barriers through its wide bandgap, high breakdown field, and superior thermal conductivity, allowing protection devices to handle higher voltages, dissipate more energy, and recover faster after transient events.

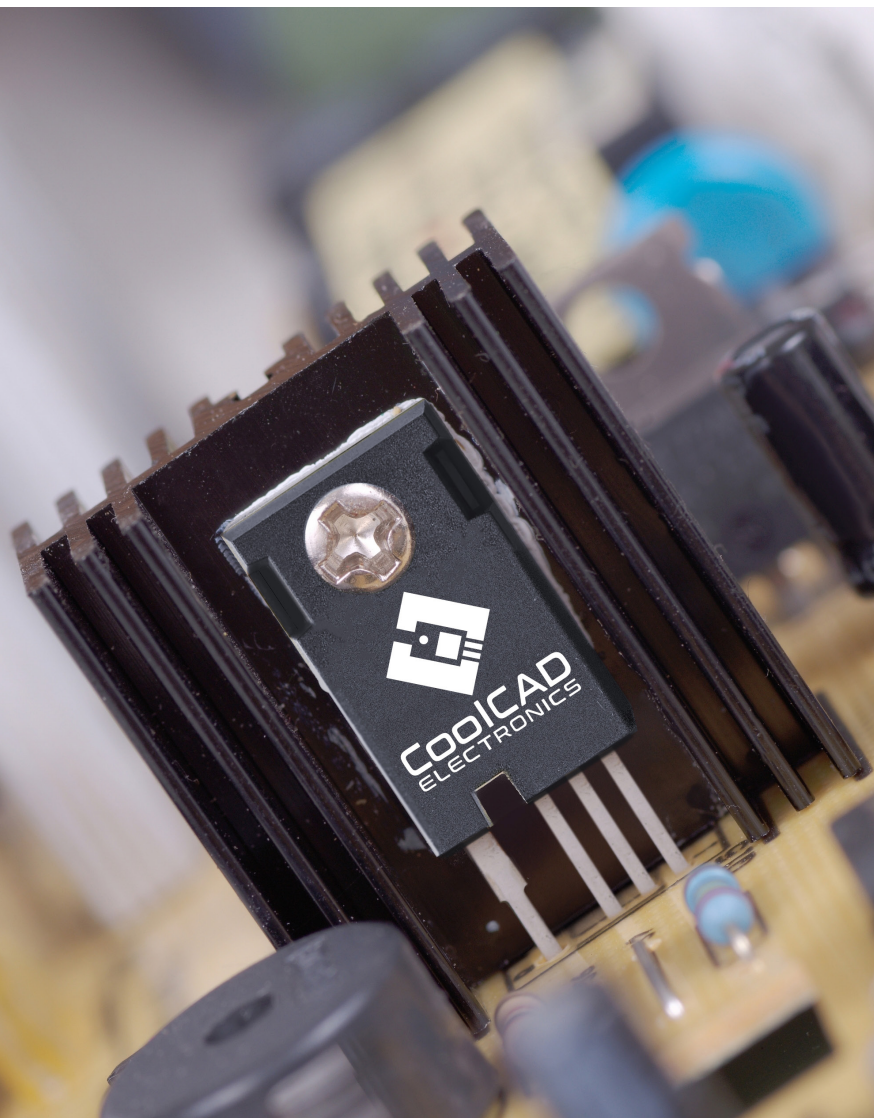
SiC's combination of high thermal conductivity and wide bandgap enables compact device structures that maintain low on-resistance and stable operation beyond 200°C. These properties allow SiC devices to survive repetitive ESD and lightning transients without degradation, performance that conventional silicon diodes or MOVs cannot match. Inline depletion-mode SiC transistors and parallel SiC TVS diodes respond intrinsically to voltage surges, providing fast, self-regulating protection without the need for external control circuitry.

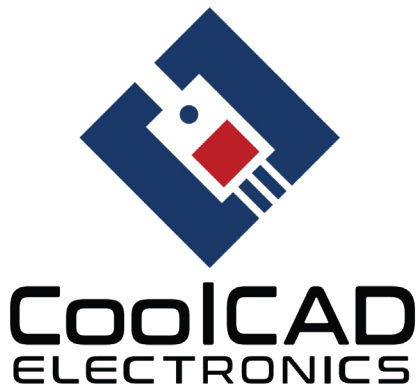


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At the system level, SiC extends protection reliability across aerospace, automotive, and industrial platforms where thermal extremes, vibration, and surge exposure are unavoidable. The high-speed response and low parasitic capacitance of SiC devices preserve signal integrity even in dense, high-frequency electronic systems. Modern 4H-SiC fabrication processes also support both JFET and MOSFET architectures, making integration into hybrid modules and compact protection assemblies practical and cost-effective.

In short, SiC brings wide-bandgap performance advantages to the domain of circuit protection. Its speed, durability, and temperature resilience provide engineers with a dependable foundation for next-generation designs, ensuring that critical systems remain operational even under severe electrical and environmental stress.





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About CoolCAD

CoolCAD Electronics is a leader in the development and fabrication of SiC-based power devices and high-temperature semiconductor electronics for aerospace, automotive, defense, geothermal development, green energy production, industrial furnace control, water purification, and oil and gas extraction. The CoolCAD team possesses a unique combination of expertise in electronics, semiconductor physics, fabrication, and design. They also excel at integrated and board-level circuit development and manufacturing. They have published 100s of research papers in professional scientific and engineering journals, and have multiple patents on their key discoveries in the area of wide bandgap SiC electronics.

To learn more about CoolCAD visit coolcadelectronics.com