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# High Single-Event Burnout Resistance 1.2 kV 4H-SiC Schottky Barrier Diode

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**Keywords:** Single Event Immunity, Single Event Effects, Schottky Diode, Silicon Carbide, Device Simulation, Radiation Hardened by Design.

**Abstract:** A 1.2 kV lateral RESURF Schottky diode (TZ-SBD) have been designed from SZ-SBD that can recover from a single-event effect (SEE) in which a heavy ion traverses the device at a linear energy transfer (LET) of 60 MeV·cm²/mg, ESA's standard. Compared to SZ-SBD, TZ-SBD has an additional split in the N-drift region which is usually used to improve the electric field distribution so its breakdown voltage is improved by 9%. During the single events simulations, the maximum temperature is 919 K with reverse voltage (VR) = 1200 V and LET = 60 MeV·cm²/mg, which is much lower then the SiC melting temperature (3100 K) and the chemically unstable temperature of SiC in the presence of metal (1073 K).

## Introduction

Silicon carbide (SiC) power devices are now being widely adopted in a number of applications, including electric vehicles, industrial drives and solar inverters. The common advantage of a SiC inverter is its fast, low loss switching capability when replacing silicon IGBTs, which results in a smaller, lighter power supply. Space agencies and satellite manufacturers alike have a motivation to integrate wide bandgap technologies into their power electronics apparatus. The benefits of a lighter, more efficient power supply are one motivation, given the need to deploy the system to space. However, a second strong motivation in a satellite is the potential to increase the operating temperature of the devices, as current Si-based satellite power supplies have to be mounted on their own radiators, separate from the hot RF travelling wave tubes they serve. Simpler integration, and increased capacity are therefore the potential payoff, if SiC power devices can withstand the challenging radiation environment.

To date, commercial SiC devices have shown excellent total ionizing dose (TID) tolerance that meets ESA's ESCC requirements [1]. However, conventional vertical device topologies, such as those used in SiC MOSFETs, have but high susceptibility to single event effects (SEE), including reverse bias leakage current degradation (SELC) [2,3], and catastrophic single event burnout (SEB) [4,5]. Although several groups of researchers have reported radiation-hardening methods [6,7] to improve SEE tolerance, their local temperatures still exceed 1700 K, which will lead to permanent leakage degradation. The absence of SiC devices that are radiation hard by design (RHBD), means that the use of e.g. an automotive part with significant derating (e.g. use of a 1200V part at 200V) remains the only possibility.

Recently, our group developed a RHBD Schottky barrier diode (SBD), making use of an ideal reduced-surface-field (RESURF) in a lateral topology [8]. It is named as Single-Zone SBD (SZ-SBD) and its practical realizable design can be seen in Figure 1 (without splitting N-drift region).

However, high leakage through the right-most Schottky edge due to the tunneling effect is found on the SZ-SBD. The new lateral RESURF SBD is designed with its two-zone (TZ) splitting the N-drift region into low (Zone 1) and high (Zone 2) doping regions in order to maximize the breakdown voltage by having improved electric field distribution. Although the reduction of the Zone 1 doping leads to an increase in on-state resistance, it suppresses the leakage and ultimately resulted in a device that could recover from a SEE fault. This can be seen in Figures 2 and 3.

This TZ-SBD was optimized in Synopsys Sentaurus TCAD, and shown to recover from after a heavy ion passed through it with energy of 60 MeV·cm²/mg (ESA's ESCC requirements [1]), and while supporting a reverse voltage ($V_R$) of 1200 V.

In this paper, we demonstrate the improvement made by introducing a two-zone designed N-drift region, to form a new TZ variant of the 1.2kV rated 4H-SiC RESURF SBD. We shall discuss the optimization, compare the on- and off-state performances, and the SEE immunity of the new device. Trade-offs in the design are explored that pitch SEE tolerance against fabrication complexity and device efficiency.

**Simulation Results and Discussion**

Fig. 1 and Table. 1 detail the layout and dimensions of the original SZ design, and the new TZ variant, whereby the electric field distribution is improved by an additional split in N-drift region. The purpose of introducing the two-zone is two fold. First, in the off-state, the high electric field is prevented from reaching the vulnerable Schottky edge, where in the original SZ design it induces high Schottky leakage. Second, the Zone1/Zone2 interface creates an additional electric field peak that improved the breakdown voltage by 8% as shown in Figures 2 &3.

Fig. 3 compares the lateral surface electric field profiles of the SZ-SBD and TZ-SBD at before avalanche, depicting the electric field profiles along a cutline in the drift region, 10 nm below the field oxide. At the off-state, these three electric field peaks are in the drift region under each end of the anode field plate and at the end of the cathode field plate above the field oxide, with values of 3.80, 2.88 and 3.16 MV/cm respectively in SZ-SBD. Schottky leakage immediately increases to $1.62\times10^{-4}$ A/cm$^2$ before the avalanche breakdown.

TZ-SBD, the drift region is split into zone 1 ($1\text{x}10^{16}$ cm$^{-3}$) and zone 2 ($1.5\text{x}10^{17}$ cm$^{-3}$) resulted in an additional spike to improve electric field distribution. From left to right in Fig. 3, the peaks now reach 3.44, 2.87, 2.14 and 2.79 MV/cm. Therefore, the resulting breakdown voltage of the Two-Zone RESURF SBD reaches 2073 V, compared to the original 1887 V.

As a result of the low doped Zone 1, the on-resistance is 3x higher than SZ-SBD, to $4.56\times10^{-2}$ Ω.cm$^2$ for the TZ-SBD, from $9.16\text{x}10^{-3}$ Ω.cm$^2$. Overall, the off-state performance is improved in this Two-Zone RESURF SBD by sacrificing the on-state performance.

Then, a transient simulation was carried out in which a 60 MeV·cm²/mg heavy ion enters the locations with high electric field and passes through the device with a $V_R$ of 1200 V. The initial temperature is set at 300 K. An induced heavy ion enters the TZ-SBD at the left electric field peak (path a)), Zone 1/Zone 2 interface (path b)), and right electric field peak (path c)), and then penetrates through the device vertically at 0.1 ns. The results are recorded from 0 to 1.5 ns as shown in Figure 4. It was found that the most destructive position occurs at the cathode. At the anode, the striking position is closer to the P-pillar, resulting in faster removal of holes.

The SEE responses of SZ- and TZ-SBDs are compared in the worst position path c). At t = 0.1 ns, the heavy ion creates a narrow filament of electron-hole pairs along each ion resulting in an instantaneous increase in current seen in Fig.5. The electrons and holes are swept out via the cathode and P-Pillar respectively. In SZ-SBD, the electric field at the edge of the anode field plate reaches 3.55 MV/cm. This peak subsequently decreases, as electric field peaks in the corners of the anode and the cathode emerge, reaching 3.25, and 4.03 MV/cm respectively at 0.5 ns. At the same time, the temperature of corners increase to 611, and 1103 K. They then undergo thermal runaway, until failing.

In the TZ-SBD, the electrons and holes are swept out via the cathode and P-Pillar so the leakage current starts decreasing at t = 0.2 ns. After t = 1.2 ns, the majority of charge is removed and the current drops away in TZ-SBD. The electric field and depletion region return closer to its steady-state. A final long period follows in which the final excess charge carriers are removed by recombination. The current decreases gradually to its initial value over 1 ms.

The dynamic electric fields of each device are shown in Fig. 6. The TZ-SBD has better SEE immunity as it recovers from the single event, its maximum temperature during the recovery process peaks at 919 K compared to 3100 K for the SZ-SBD.

**Summary**

The existing radiation-hardened SiC devices still have a maximum temperature exceeding 1700 K at the metal/semiconductor interface. Our group has introduced new topologies in order to limit the internal temperature increase. Via Synopsys Sentaurus TCAD simulations, results show that both developed radiation-hardened 1200 V SiC RESURF SBD meet the ESCC requirements of the ESA [1]. A fully optimized 1.2kV RESURF layout has shown single event immunity, by improving dynamic electric field distribution and providing an escape route for both the electrons and holes generated. A low doped Zone 1 prevents the Schottky leakage leads to an improvement in the reverse characteristics in this double zone design, but sacrifices its on-state performance.

The maximum temperature is 919 K with reverse bias (VR) = 1200 V and linear energy transfer (LET) = MeV·cm²/mg, below the SiC melting temperature (3100 K).


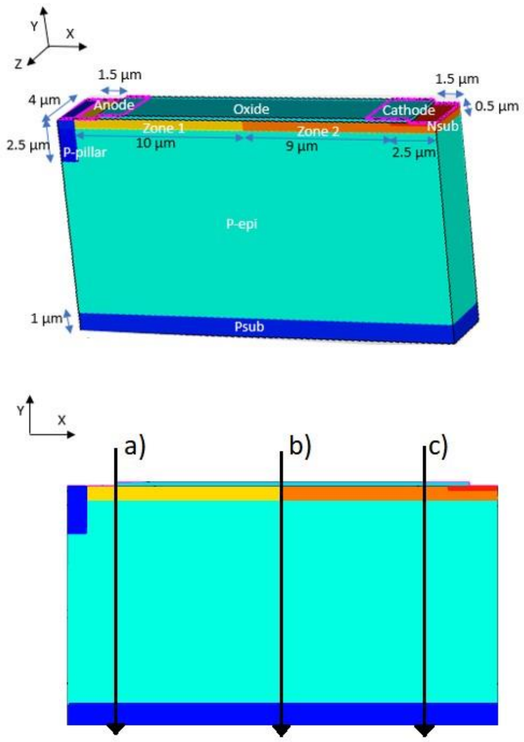


**Fig. 1.** The 2D &3D layouts of lateral RESURF SBD (x, y & z: width, depth & thickness) and heavy ion paths.

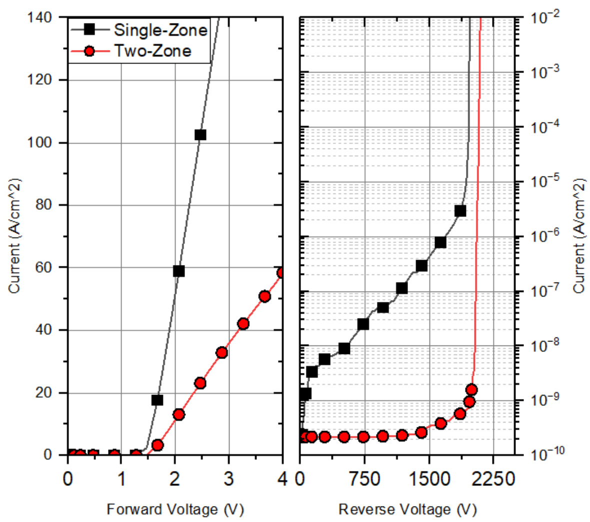


**Fig. 2.** The forward and reverse characteristics of the TZ- and TZPR-SBD; (Right) The recovery processes of the TZ- and TZPR-SBD with VR = 1200 V, LET = 60 MeV·cm²/mg.

**Table I.** Dimensions of the TZ-SBD and TZPR-SBD.

| Device Variant | Region | Properties | | |
|---|---|---|---|---|
| | | Width (μm) | Depth (μm) | Doping ($cm^{-3}$) |
| Common Values | P-epi | 23 | 11 | $1\times10^{15}$ |
| | Ncath | 5 | 0.2 | $1\times10^{19}$ |
| | P+ pillar | 1 | 2.5 | $1\times10^{19}$ |
| | Oxide | 16.5 | 0.2 | - |
| SZ-SBD | Zone 1 | 9.35 | 0.5 | $7\times10^{16}$ |
| | Zone 2 | 7.65 | 0.5 | $7\times10^{16}$ |
| TZ-SBD | Zone 1 | 9.35 | 0.5 | $1\times10^{16}$ |
| | Zone 2 | 7.65 | 0.5 | $1.5\times10^{17}$ |

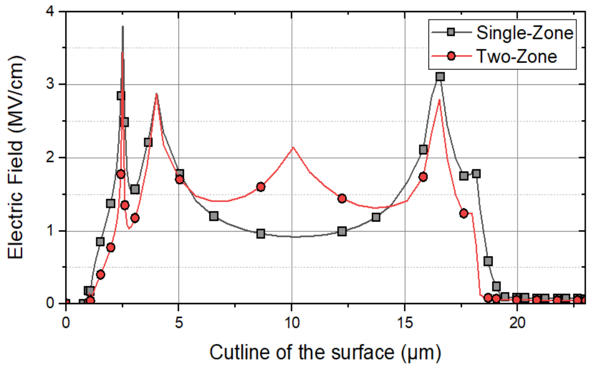


**Fig. 3.** The lateral surface electric field profiles of the TZ- and TZPR-SBDs, along a cutline in the drift region 10 nm below field oxide.

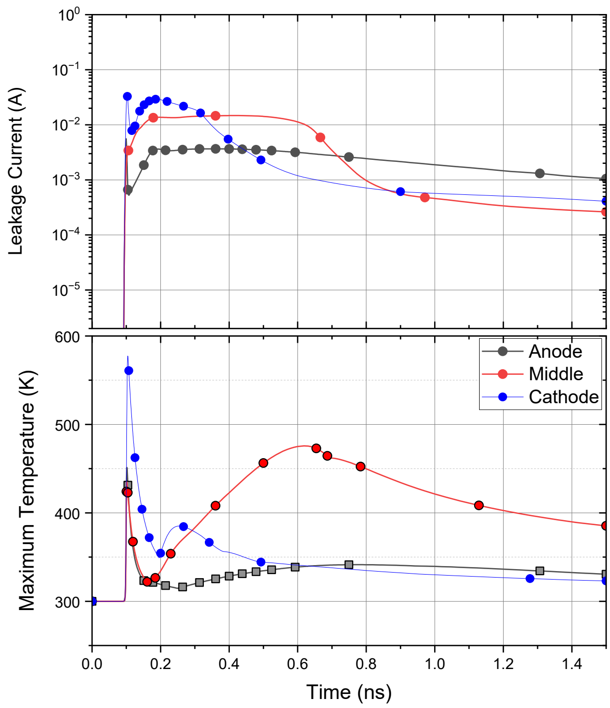


**Fig. 4**. The SEE recovery processes of the TZ-SBD under heavy ion paths (Anode: a); Middle: b); Cathode: c)) with VR = 1200 V, LET = 60 MeV·cm²/mg.

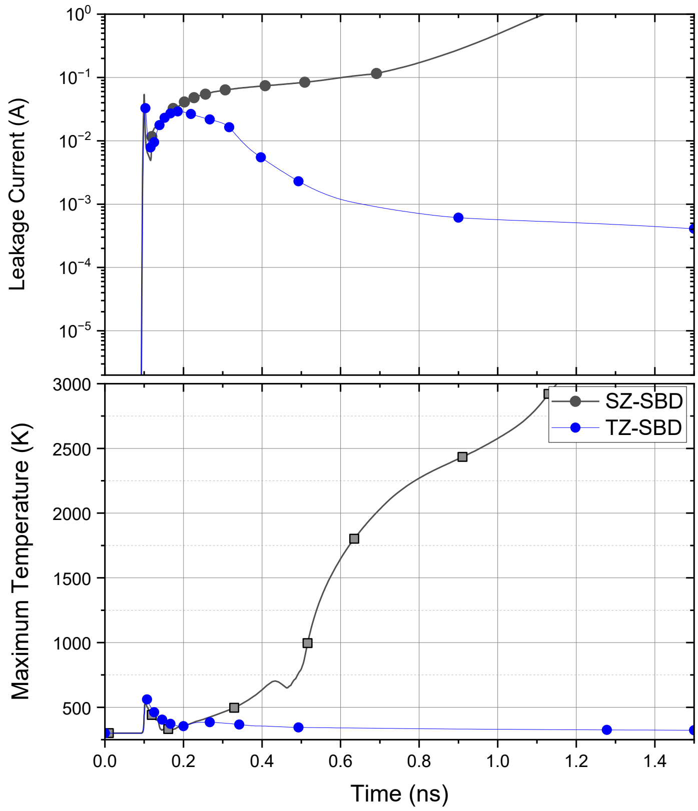


**Fig. 5.** The SEE responses of the SZ-SBD and TZ-SBD under heavy ion path c) with VR = 1200 V, LET = 60 MeV·cm²/mg.

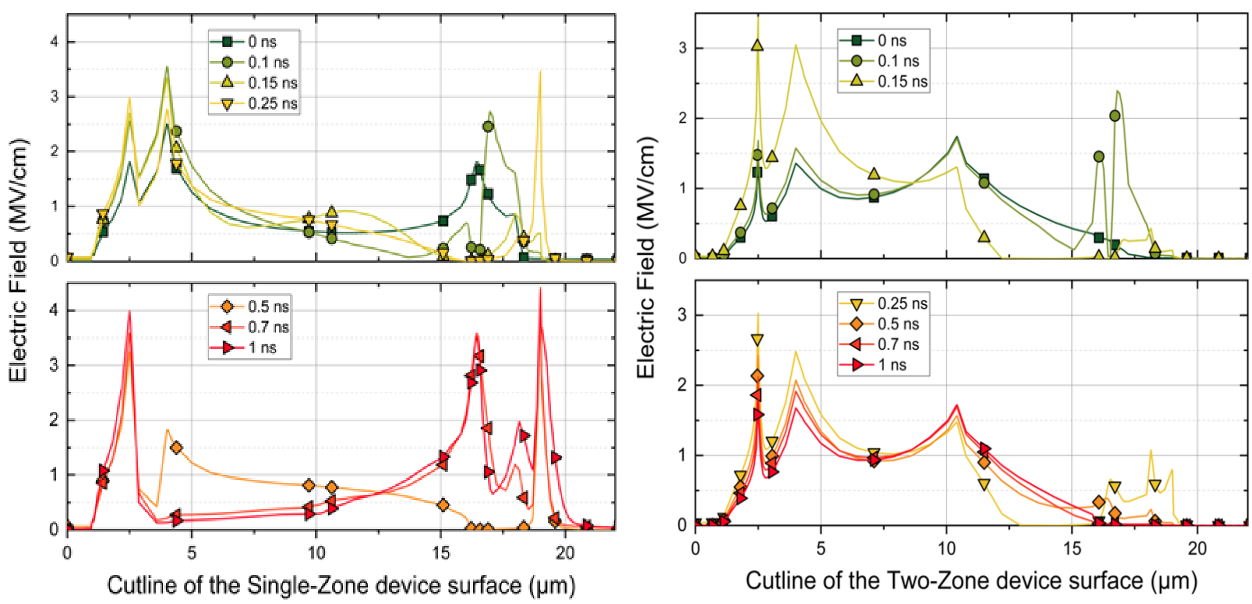


**Fig. 6.** Dynamic electric field profiles of the SZ-SBD (left) and TZ-SBD (right) during the heavy ion event (VR = 1200 V, LET = 60 MeV·cm2/mg). Profiles taken along a cutline 10 nm below the SiC surface, in the N-drift region.

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