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SEE Testing On GaN FETs—Interpreting Results For Space Power Applications

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The space and high-reliability industry have been looking at new wide-bandgap devices such as gallium nitride (GaN) and silicon carbide (SiC) in power applications. These devices provide many advantages over traditional silicon such as higher breakdown voltages, lower on-resistance ($R_{DS(ON)}$) and extremely low gate charge (Q_G). These benefits allow power management solutions to achieve higher efficiencies in a smaller PCB footprint.

However, there is an added benefit, especially from GaN devices, that make them attractive to the space market—studies have shown that these devices are inherently radiation hard to total ionizing dose (TID). Still, their performance with respect to single event effects (SEE) requires further investigation.

After going over the advantages of GaN, this article will discuss the SEE testing performed on three power GaN FET devices (40 V, 100 V and 200 V) from Renesas Electronics. The tests described here were performed to determine the susceptibility of these devices to single-event burnout due to a heavy ion-induced increase in leakage current.

After presenting the test results, a method is proposed for a worst-case analysis of the increase in I_{DSS} (leakage current on the drain) due to SEE. This approach to WCA considers the impact of I_{DSS} increase under practical operating conditions for applications with low earth and geostationary orbits. The latter represent many of the high-reliability, long-life missions in space applications.

Advantages Of GaN FETs

Compared to silicon, the separation between the drain and source can be a factor of 10 smaller for a given breakdown voltage. This translates to a much smaller channel width in GaN for the same $R_{DS(ON)}$ in silicon. This reduces the size of the die which also reduces parasitics like output capacitance and layout inductance. The lower $R_{DS(ON)}$ provides lower conduction losses while the lower output capacitance and layout inductance results in lower switching losses. Fig. 1 shows the efficiency boost of a GaN FET compared to a MOSFET with the same $R_{DS(ON)}$ and breakdown voltage.

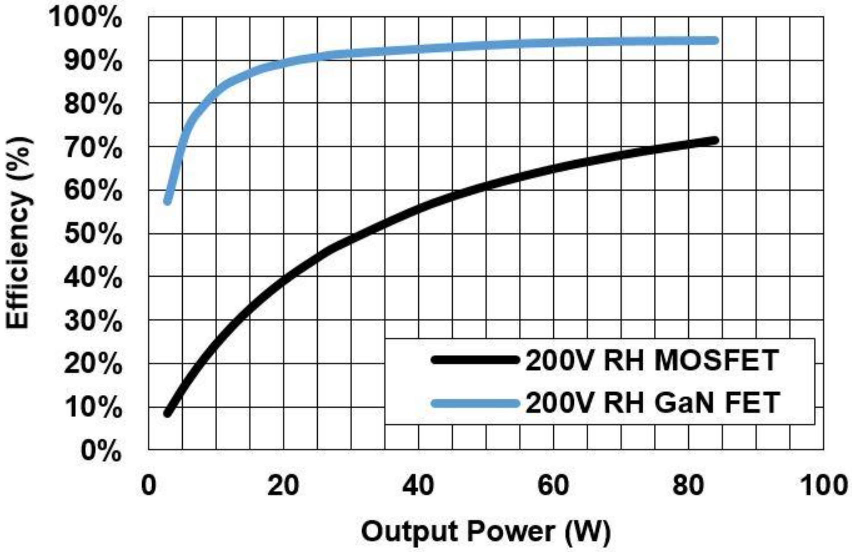

Fig. 1. Efficiency comparison between a 200-V rad hard GaN FET and a comparable MOSFET in a half-bridge power stage (100 V to 28 V).

Another benefit is that GaN FETs do not have a parasitic p-n diode which means they do not have any reverse recovery. Reverse recovery leads to longer dead times in power supplies to recover the diode charge, which vary with temperature, current and diode conduction time. However, GaN does conduct in the reverse direction through the main channel. While this voltage drop is larger than a diode, the loss can be minimized by using a dead time between 5 and 15 nanoseconds in a half-bridge configuration.

SEE Test Setup

Three different devices were chosen for this test—40-V, 100-V and 200-V GaN-on-silicon FETs. These GaN FETs come with rad hard assurance (RHA) testing for total ionizing dose (TID) but their performance under heavy ions needs to be determined.

The objective of the SEE testing was to characterize the behavior of I_{DSS} (two-terminal blocking current) while the device is exposed to heavy ions. The primary concern was single event burnout (SEB) typified by a sudden large increase in I_{DSS} during irradiation. The secondary concern was the gradual increase in I_{DSS} with exposure to irradiation. The testing is intended to provide a safe operating area (SOA) for SEB and to quantify the rate of gradual increase of I_{DSS} with fluence, V_{DSS} and linear energy transfer (LET).

To make the devices accessible for ion radiation, the flip chip devices were mounted with the solder bumps exposed away from the pc board (PCB). The connections from the device to the PCB were made by soldering fine wires from the bumps to the board. The parts were wired in a two-terminal configuration with the drain biased against the gate, source, and substrate. For each of the GaN FET tests, the DUT's I_{DSS} was logged at the irradiation V_{DSS} of 60%, 80% and 100% of the V_{DS} rating for 30 seconds before, during and after exposure to the beam.

Test Results

For each GaN FET, the minimum I_{DSS} before irradiation was subtracted from the maximum I_{DSS} after irradiation to establish the I_{DSS} delta for each run. The change in microamps was then divided by 2.5 to yield an I_{DSS} rise per 1x10^6 ions/cm^2. Tables 1, 2 and 3 summarize the I_{DSS} deltas for the 100-V, 200-V and 40-V devices, respectively.

The 100-V GaN FET DUTs did exhibit gradual growth of I_{DSS} with LETs of 60 and 86 MeV•cm^2/mg but not at LETs of 28 and 43 MeV•cm^2/mg. The greatest rise in I_{DSS} (5.88 μA per 1x10^6 ions/cm^2) was recorded at the most extreme of conditions (V_{DS} = 100 V and LET = 86 MeV•cm^2/mg).

Table 1. ΔI_{DSS} of the 100-V ISL70023SEH at V_{DSS} and LET per irradiation with 1x10^6 ions/cm^2.*

	ΔI_{DSS} (μA)											
	V_{DSS} = 60 V				V_{DSS} = 80 V				V_{DSS} = 100 V			
LET (MeV•cm^2/mg)	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4
28	0.08	0.09	0.08	-0.09	-0.56	-0.28	-0.33	-0.22	-0.14	-0.08	0.32	-0.06
43	0.06	-0.23	0.07	0.24	-0.11	-0.30	0.12	-0.20	0.23	-0.12	0.03	0.20
60	1.18	-0.17	1.20	1.32	-0.21	0.54	-0.05	-0.04	1.72	1.94	1.17	0.78
86	1.16	1.57	3.06	2.85	3.73	4.17	4.63	2.78	3.15	3.07	1.46	5.88

*Rows highlighted in yellow indicate a significant change in I_{DSS}.

The 200-V GaN FET DUTs did exhibit gradual growth of I_{DSS} with an LET at or above 43 MeV•cm^2/mg. The numbers in Table 2 show that there was no significant change in I_{DSS} with an LET of 28 MeV•cm^2/mg. The rows highlighted in yellow indicate a significant increase in I_{DSS} while the four DUTs highlighted in red indicate catastrophic failures (SEB). The greatest rise in I_{DSS} (32.37 μA per 1x10^6 ions/cm^2) was recorded at a V_{DS} = 160 V and LET = 86 MeV•cm^2/mg.

Table 2. ΔI_{DSS} of the 200-V ISL70024SEH at V_{DSS} and LET per irradiation with 1x10^6 ions/cm^2.*

	ΔI_{DSS} (μA)											
	V_{DSS} = 120 V				V_{DSS} = 160 V				V_{DSS} = 200 V			
LET (MeV•cm^2/mg)	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4
28	0.14	-0.19	-0.47	0.02	0.12	-0.02	0.04	0.28	0.16	-0.06	-0.07	0.05
43	2.00	0.27	0.61	0.50	0.86	0.59	0.89	0.86	2.50	6.70	2.91	3.70
60	1.24	5.08	2.71	7.40	3.14	2.45	2.56	2.61	7.11	9.52	10.45	15.26
86	7.30	8.87	8.61	6.78	14.51	32.37	28.14	11.73	SEB	SEB	SEB	SEB

*Rows highlighted in yellow indicate a significant change in I_{DSS}.

The 40-V GaN FET DUTs did exhibit gradual growth of I_{DSS} with an LET at 60 and 86 MeV•cm^2/mg with a V_{DSS} of 40 V. The not-highlighted cells in Table 3 show conditions where there was no significant change in I_{DSS}. The rows highlighted in yellow indicate a significant increase in I_{DSS}. The greatest rise in I_{DSS} (8.97 μA per 1x10^6 ions/cm^2) was recorded at a V_{DS} = 40 V and an LET = 86 MeV•cm^2/mg.

Table 3. ΔI_{DSS} of the 40-V ISL70020SEH ΔI_{DSS} (μA) at V_{DSS} and LET per irradiation with 1x10^6 ions/cm^2.*

	ΔI_{DSS} (μA)											
	V_{DSS} = 24 V				V_{DSS} = 32 V				V_{DSS} = 40 V			
LET (MeV•cm^2/mg)	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4	DUT 1	DUT 2	DUT 3	DUT 4
28	-0.30	-0.26	-0.28	0.11	-0.61	-0.76	-0.96	-0.73	-0.34	-0.82	-0.49	-0.59
43	-0.46	-0.80	-0.36	-0.40	-0.45	-0.49	-0.24	0.04	-0.12	-0.06	-0.10	0.11
60	-0.21	0.29	-0.39	-0.38	-0.14	-0.23	0.03	-0.06	0.10	0.04	-0.72	0.40
86	-0.13	-0.30	-0.08	-0.09	4.76	5.36	2.32	1.92	5.48	8.97	1.97	5.97

*Rows highlighted in yellow indicate a significant change in I_{DSS}.

Worst-Case Analysis Of Results And Conclusion

All the GaN FETs tested exhibited some increase in I_{DSS} under certain conditions of V_{DSS} and LET. Arguably, of the three devices that were tested, some fared better than others with regard to the drain leakage increase under heavy ions. However, it is important to put the I_{DSS} current increase in the perspective of a typical mission in the geosynchronous orbit (GEO). Using the data gathered on the GaN FETs alongside the parameters for a GEO mission in the single event simulation program CREME96, it is possible to show that the increase in I_{DSS} for a typical GEO mission is inconsequential.

Fig. 2 shows a CREME96 spectrum file generated for a satellite in GEO with all species of heavy ion particles from atomic number 2 through 92 with a minimum energy value of 0.1 MeV/nuc. Assumptions included solar minimum conditions for worst-case cosmic flux through 100 mils of aluminum shielding.

The integral flux in Fig. 2 is in terms of the number of particles incident in a solid angle about a line normal to a small area on the surface of a sphere. The LET on the x axis is in MeV•cm^2/g. The colored lines on the plot represent the flux of particles at a given LET.

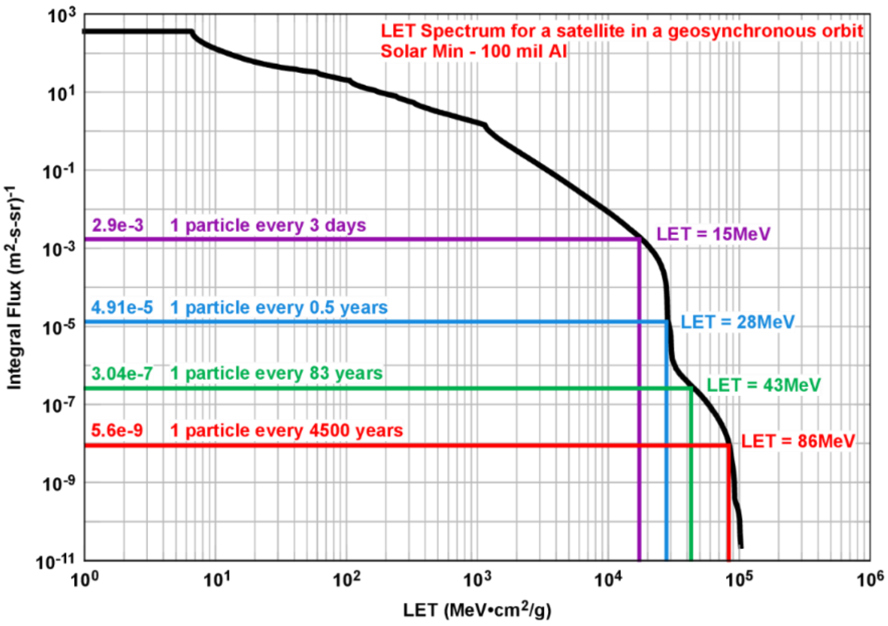

Fig. 2. CREME96 LET spectrum for a satellite in GEO assuming solar minimum conditions and 100 mils of Al shielding.

Using the green line as an example for an LET of 43 MeV•cm^2/mg (note the conversion required to go from g to mg), which was the lowest LET that resulted in an increase in I_{DSS}, we get a resulting flux of particles of 3.04 x 10^{-7} particles/m^2-s-sr or 3.04 x 10^{-11} particles/cm^2-s-sr.

To determine the particle fluence at an energy of 43 MeV•cm^2/mg we can use the following equation:

$$Fluence = Flux * Time \tag{1}$$

$$= (3.04x10^{-11}\,\frac{particles}{cm^2{-}s{-}sr}) * (3600\,\frac{s}{hr}) * (24\,\frac{hrs}{day}) * (365.25\,\frac{days}{year})$$

$$= 9.59x10^{-4}\,\frac{particles}{cm^2{-}yr{-}sr}$$

As the number calculated in the third line of equation 1 is for a sphere and the area of interest is a 1-cm^2 area on that sphere (which overestimates the area of the die), we need to multiply by 4π sr (solid angle of the entire sphere) to remove steradian from the units. Doing so gives us the amount of time to encounter one particle:

$$Time\ to\ encounter\ 1\ particle = \left(9.59x10^{-4}\ \frac{particles}{cm^2\!-\!yr\!-\!sr} * 4\pi\ sr\right)^{-1} \quad (2)$$

$$= 82.98\ \frac{yrs \bullet cm^2}{particle} \approx 83\ \frac{yrs \bullet cm^2}{particle}$$

From equation 2, we can approximate that, on average, the electronics in a satellite in GEO would see a particle with ≥43 MeV•cm^2/mg every 83 years. Following equations 1 and 2 for an LET of 86 we can approximate that the electronics would see a particle with ≥86 MeV•cm^2/mg once every 4500 years. While these energetic ions can have major impacts on electronics from a single event latch-up (SEL) standpoint—and SELs have not been observed in GaN FETs—they are insignificant for a cumulative event, like current increase.

To get the current increase shown in Tables 1 through 3, it would take 292 million years to encounter 1 x 10^6 ions that have an LET ≥60 MeV•cm^2/mg. Consequently, to encounter 1 x 10^6 ions with an LET ≥86 MeV•cm^2/mg, it would take 4 billion years. As shown in Table 4, the worst-case current increase is in the picoamps range (or less) for any of the ions that caused an increase in I_{DSS} for a typical 20-year GEO mission.

Table 4. GaN FET I_{DSS} increase after 20 years at 1 x 10^6 ions/cm^2 for different values of LET in MeV•cm^2/mg.

Part Type	V_{DSS} (V)	Current increase in amps			
		LET = 28	LET = 43	LET = 60	LET = 86
ISL70020SEH	40	3.19 x 10^{-11}	2.89 x 10^{-14}	4.93 x 10^{-14}	4.00 x 10^{-14}
ISL70023SEH	100	1.25 x 10^{-11}	5.54 x 10^{-14}	1.33 x 10^{-13}	2.62 x 10^{-13}
ISL70024SEH	160	1.09 x 10^{-11}	2.14 x 10^{-13}	2.15 x 10^{-13}	1.45 x 10^{-13}
	200	6.23 x 10^{-12}	1.61 x 10^{-12}	1.05 x 10^{-12}	SEB

While the data from the SEE testing of the ISL70020SEH, ISL70023SEH and ISL70024SEH showed evidence of an increase in I_{DSS} at energies above 43 MeV•cm^2/mg, the scarcity of ions at this energy in geosynchronous orbit make the actual increase in I_{DSS} for a 20-year mission inconsequential.

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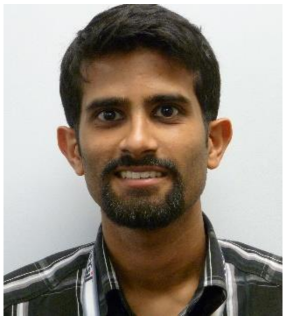
About The Author



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For more on rad hard power components and power converters, see How2Power's special section on Space Power.