Enhancement Mode Gallium Nitride (eGaN™) FET Characteristics under Long Term Stress

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Abstract: *Enhancement mode HEMT transistors built with Gallium-Nitride-on-silicon (eGaN) have been in the commercial marketplace since 2009 as a replacement for silicon power MOSFETs. Superior conductivity and switching characteristics allow designers to greatly reduce system power losses, size, weight, and cost. Military and space applications could benefit from using eGaN FETs, but the parts need to operate reliably under harsh environmental conditions. In this paper we present results demonstrating the stability of these devices at temperature and under radiation exposure.*

Keywords: Gallium nitride; GaN; eGaN; MOSFET; FET; Radiation tolerance; SEE; Gamma radiation; Proton radiation

Introduction:
The basic requirements for power semiconductors are efficiency, reliability, controllability, and cost effectiveness. Recent breakthroughs by Efficient Power Conversion Corporation (EPC) in processing gallium nitride have produced enhancement mode devices (eGaN™) with conductivity and switching speeds much higher than Si power FETs. These improvements enable power converters with higher efficiency and switching frequency, as well as greater input voltage range, leading to simpler, smaller power systems. Ranging in voltage from 40 V to 200 V, and on-state resistance from 4 mΩ to 100 mΩ, this new class of devices has also proved very capable in a high radiation environment.

This paper is divided into four sections. The first discusses the basic eGaN FET structure. The second section shows the result of heavy ion testing with linear energy transfers (LETs) ranging from 28.8 to 87.2 MeV*cm^2/mg. The third section gives pre-and post results for total dose testing up to 500 kRad (Si). The final section discusses the successful multi-thousand hour stress testing under a variety of bias and temperature conditions.

Structure: EPC's eGaN FET process begins with silicon wafers. A thin layer of Aluminum Nitride (AlN) is grown on the silicon to isolate the device structure. On top of the AlN, a thicker layer of highly resistive GaN is grown. This layer provides a foundation on which to build the eGaN FET. Aluminum gallium nitride (AlGaN) is then grown on top of the GaN to form a highly conductive two dimensional electron gas layer (2DEG) immediately underneath [1]. Additional layers are formed to create an enhancement mode gate electrode as well as drain and source electrodes (see Figure 1). This structure is repeated many times to form a power device. Three layers of top metal, isolated from each other by planarized insulators, are then deposited to complete the circuit and bring the terminals to the outside world. The end result is a simple, cost-effective solution for power switching. This device looks and behave similarly to a silicon MOSFET.

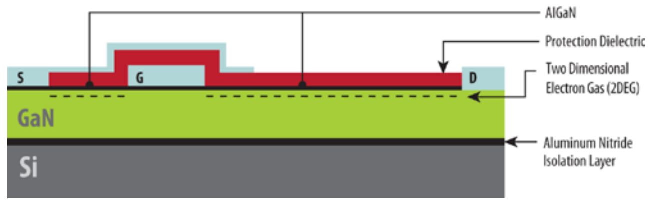

Figure 1. Simplified cross section of an eGaN FET

SEE Testing: Heavy-ion testing of EPC eGaN FETs was performed at the Texas A&M cyclotron in September, 2010 following MIL-STD-750E, METHOD 1080. EPC's entire family of eGaN FET products was tested (See Table 1 for device parameters). EPC1005 (60 V, 7 mΩ), EPC1014 (40 V, 16 mΩ), and EPC1015 (40 V, 4 mΩ) did not exhibit any gate ruptures (SEGR) or drain ruptures (SEB) at the highest LET available. For the remaining part numbers, drain-ruptures were the primary mode of failure and were typically observed as being a gradual transition into failure.

In figure 2 is shown the applied drain-source voltages up to which the parts remained within data sheet limits (dark grey); the voltages up to which the devices exceeded data sheet limits but remained functional (light grey), and the voltage beyond which the devices failed catastrophically (black). In general, the eGaN FETs demonstrated SEE capabilities that exceed similar silicon MOSFETs currently listed on the Qualified Military Listing (QML).

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Table 1: EPC's eGaN FET Electrical Characteristics

Part Number	Package (mm)	Mode Ch	Vds	Vgs	Max. Rdson (mΩ) @5V	Qg @5V	Qgs Typ.	Qgd Typ.	Vth Typ.	Qrr	Id
Single											
EPC1014	LGA 1.7x1.1	EN	40	6	16.0	3.0	1.0	0.6	1.4	0	10
EPC1015	LGA 4.1x1.6	EN	40	6	4.0	11.6	3.8	2.2	1.4	0	33
EPC1009	LGA 1.7x1.1	EN	60	6	30.0	2.4	0.8	0.6	1.4	0	6
EPC1005	LGA 4.1x1.6	EN	60	6	7.0	10.0	3.0	2.5	1.4	0	25
EPC1007	LGA 1.7x1.1	EN	100	6	30.0	2.7	0.8	1.0	1.4	0	6
EPC1001	LGA 4.1x1.6	EN	100	6	7.0	10.5	3.0	3.3	1.4	0	25
EPC1013	LGA 1.7x0.9	EN	150	6	100.0	1.7	0.4	0.7	1.4	0	3
EPC1011	LGA 3.6x1.6	EN	150	6	25.0	6.7	1.5	2.8	1.4	0	12
EPC1012	LGA 1.7x0.9	EN	200	6	100.0	1.9	0.4	0.9	1.4	0	3
EPC1010	LGA 3.6x1.6	EN	200	6	25.0	7.5	1.5	3.5	1.4	0	12

Preliminary information subject to change

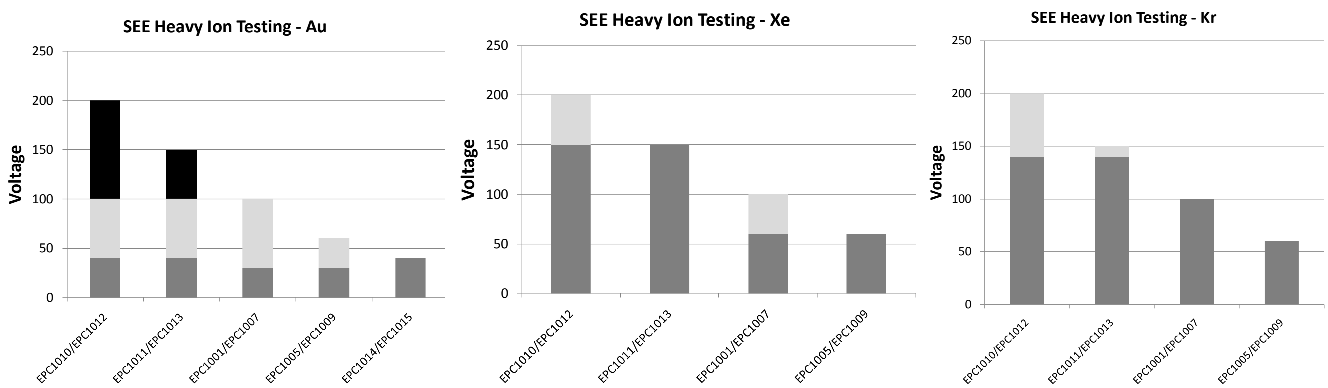

Figure 2. SEE Results for Au, Kr, and Xe bombardment. Dark grey bars represent the voltage range within which devices remained inside data sheet limits. Light grey bars represent the range where devices continued to function but drain-source leakage exceeded data sheet. Black bars represent regions where devices catastrophically failed

Total Dose Testing: Utilizing the "Gamma Cave" at the University of Massachusetts, Lowell, six EPC1014 (40 V, 4 mΩ) were subjected to a total gamma dose of 500 kRads (Si) at a dose rate of 96 Rads (Si)/sec. A ^{60}Co source was used and all testing was according to MIL-STD-750, Method 1019. Two different test conditions were used. The first test condition biased the drain-source at 80% of rated $V_{DS(MAX)}$ (32 V in the case of the EPC1014). The second test condition biased the gate-source at 5 V. Table 2 shows the pre and post electrical characteristics of these devices. Very little change is seen in any of the characteristics under either bias condition.

With 32 V from drain to source during irradiation, the threshold voltage (V_{TH}) changed less than 18% percent; $R_{DS(ON)}$ changed less than 8 percent, and all parameters remained well within the data sheet limits. With 5 V from gate to source during irradiation, the threshold voltage (V_{TH}) changed less than 4 percent; $R_{DS(ON)}$ changed less than 3 percent, and all parameters again remained well within the data sheet limits.

Whereas we can't quantify how long the parts will last in a given orbit since that depends on factors such as the placement of the part within the payload and within the spacecraft (This can make an order of magnitude to the dose rate), we can make relative comparisons. The problem designers run into with silicon MOSFETs is that they must choose between radiation tolerance and electrical performance. Commercial MOSFETs have thick gate oxides and trap a lot of charge, resulting in large shifts in the threshold voltage and eventual failure at relatively low total-dose. Meanwhile, the rad-hard MOSFETs available have on-resistance and device capacitance several times higher than their commercial counterparts, leading to either low efficiency or large size (due to the low switching frequency). Now we have a new capability; eGaN FETs, with electrical performance superior to the cutting edge Si MOSFETs, and radiation tolerance at least as high as the best rad-hard power MOSFETs available. These eGaN FETs bring a combination of electrical and radiation performance that cannot be matched.

Additional radiation testing is ongoing using different part numbers, different bias conditions, and different dose rates. These results will be reported in a later publication and are expected to reinforce the conclusion that eGaN FETs are resistant to very high doses of radiation.

Table 2. Pre and post irradiation data shows little change after 500 kRad (Si)

EPC1014	Test	IGSSr	IGSSf	IDSS	IDSS	VTH	RDON	VDSON
	Bias1	5.00 V	5.00 V	32.0 V	40.0 V	2.00mA	5.00 A	500 mA
	Bias2						5.00 V	0.00 V
	Min					700.0m		
kRAD	Max	500.0uA	2.000mA	100.0uA	100.0uA	2.500 V	16.00mR	1.800 V
0k VDS	1	12.60u	38.87u	29.91u	29.06u	1.624	14.18m	2.304
	2	13.23u	58.39u	26.26u	27.16u	1.583	14.64m	2.283
	3	11.27u	34.95u	31.80u	30.24u	1.552	13.83m	2.254
0k VGS	4	11.35u	27.85u	31.42u	30.63u	1.487	13.68m	2.227
	5	11.49u	27.90u	30.04u	29.69u	1.548	13.54m	2.251
	6	12.47u	23.76u	30.29u	29.55u	1.606	13.81m	2.302
Group D	Min					700.0m V		
Limit	Max	500.0uA	2.000mA	100.0uA	100.0uA	2.500 V	16.00mR	1.800 V
500k VDS	1	5.119u	24.95u	10.58u	11.93u	1.714	14.71m	2.401
	2	4.698u	46.89u	8.679u	11.07u	1.868	15.83m	2.449
	3	3.860u	28.35u	8.187u	10.75u	1.879	14.55m	2.386
500k VGS	4	9.059u	22.15u	33.16u	30.80u	1.482	13.47m	2.252
	5	6.500u	32.39u	22.82u	23.51u	1.611	13.58m	2.243
	6	11.61u	19.52u	35.05u	35.64u	1.568	13.41m	2.292

Long Term Reliability Testing: The key reliability considerations for power transistors include: (a) device stability in the on-state when the FET is fully enhanced with voltage applied to the gate; (b) device stability in the off-state when the FET is in voltage blocking mode withstanding up to its rated drain-source voltage; and (c) device stability in switching operation. Device stability is impacted by device design, packaging technology, and operating environment. Good reliability results have previously been reported for depletion mode GaN FETs for RF [2,3] applications and power switching applications [4].

EPC's eGaN FET reliability test results are summarized in Table 3, in which the type of test, stress conditions, part numbers, sample size, stress hours, and number of fails are listed. JEDEC standards were followed where applicable. Even very high levels of environmental stress applied to hundreds of parts generated no failures thus demonstrating the basic capability of the technology and the product to survive over many years in terrestrial or space environments.

Table 3. Reliability test results for eGaN FETs

Stress Test	Test Condition	Part Number	Sample Size	# of fails 1000HR	# of fails 3000HR
HTRB	100Vds, 125°C	EPC1001	45	0	-
HTRB	40Vds, 125°C	EPC1014	50	0	-
HTRB	200Vds, 125°C	EPC1012	50	0	-
HTRB	200Vds, 125°C	EPC1010 with underfill	50	0	-
HTRB	200Vds, 150°C	EPC1010	50	0	0
Stress Test	**Test Condition**	**Part Number**	**Sample Size**	**# of fails 1000HR**	**3000HR**
HTGB 5V	5Vgs, 125°C	EPC1001	45	0	0
HTGB 5.4V	5.4Vgs, 125°C	EPC1001	45	0	0
HTGB 5V	5 Vgs, 150°C	EPC1010	45	0	-
HTGB -5V	-5Vgs, 125°C	EPC1001	50	0	-
Stress Test	**Test Condition**	**Part Number**	**Sample Size**	**# of fails 1000cys**	
TC	-40C to 125°C	EPC1001	45	0	-
TC	-40C to 125°C	EPC1014	50	0	-
TC	-40C to 125°C	EPC1012	45	0	-
TC	-40C to 125°C	EPC1012 with underfill	45	0	-
Stress Test	**Test Condition**	**Part Number**	**Sample Size**	**# of fails 1000HR**	
THB	85°C/85RH, 40Vds	EPC1014	45	0	-
THB	85°C/85RH, 40Vds	EPC1015	45	0	-
THB	85°C/85RH, 100Vds	EPC1010	25	0	-
THB	85°C/85RH, 100Vds	EPC1010 with underfill	25	0	-
Stress Test	**Test Condition**	**Part Number**	**Sample Size**	**# of fails 168HR**	
MSL1	85°C/85RH, 168HR	EPC1001	50	0	-
Stress Test	**Test Condition**	**Part Number**	**Sample Size**	**# of fails 1200HR**	
Power Supply Life Test	10A, 250 kHz, 30°C	EPC1001	10	0	-

Conclusions:

EPC's eGaN FETs have been tested under heavy ion bombardment, gamma irradiation, and various environmental stress factors. These devices demonstrate their ability to be used in the most stringent of environmental as well as radiation environments and exceed the capabilities of silicon power MOSFETs.

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