Heavy Ion Testing of Commercial GaN Transistors in the Radio Frequency Spectrum

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Abstract—Commercial gallium nitride (GaN) high-electron mobility transistors (HEMTs) are tested in the radio frequency (RF) spectrum at heavy ion facilities to explore space environment stresses on these emerging technologies. Findings indicate that gate leakage degradation is a key parameter to consider when selecting devices. Variations in the manufacturing process may drive product selection for use in harsh environments.

Fig. 1: GaN HEMT structure. Figure adapted from [1].

I. INTRODUCTION

RECENT interest in gallium nitride (GaN) devices for radiation environments has prompted consideration for use in space systems [1] and [2]. The majority of the studies, however, focus on direct current (DC) measurements with limited RF testing being reported. Efforts to explore the DC and RF response in a radiation environment as a baseline characterization for space-based applications are underway. The focus of the experiments is to first, characterize the RF response and second, characterize the gate and drain current degradations seen in [3] and [4]. Data relating to this effort are presented in this paper.

The devices tested are all high-electron mobility transistors (HEMTs). A sample GaN HEMT device structure is shown in figure 1. These are majority carrier devices with a thin AlGaIn layer for electron generation. Table 1 shows the rated power, test conditions, and test facility of the tested devices.

II. EXPERIMENTAL DETAILS

The devices were tested at one of two heavy ion facilities, Lawrence Berkeley National Laboratory or Texas A&M University's cyclotron. This section describes the test setups for each facility and the equipment used.

TABLE I
COMMERCIAL HEMT DEVICE CHARACTERISTICS

Vendor	Rated Power	Test Frequency	Facility
A	30W	DC, 2.14 GHz	LBNL
A	120W	DC, 2.14 GHz	LBNL
B	100W	DC, L1	LBNL
C	35W	DC, 3.2 GHz	LBNL
D	25W	DC, 3.5 GHz	TAMU

A. Lawrence Berkeley National Laboratory

The testing conducted at the Lawrence Berkeley National Laboratory (LBNL) included a series of experiments developed to explore leakage currents and RF characteristics of multiple high- and low-power commercial devices. The tests used 5.8 MeV neon (Ne), 38.96 MeV krypton (Kr), 53.03 MeV silver (Ag), and 58.78 MeV xenon (Xe). The tests involved a series of exposures to a fluence of 1×10^7 ions/cm² under operational bias conditions. The irradiations are done in 1 milliTorr (mT) vacuum.

Testing was done to observe leakage in the device under test (DUT) during RF drive. A secondary outcome of this test was to capture transients generated by ions. RF measurements were performed with continuous wave carrier signals using the test setup and equipment shown in Fig. 2 and Table 2. Manufacturer demonstration boards were used to interface the amplifiers to the test equipment to ensure proper matching. Boards were attached to heat sinks and a cold plate to keep the amplifier baseplate at 22°C and manage thermal dissipation during test.

The remainder of the LBNL testing was done under DC conditions to further explore the conditions of the leakage current. The schematic for the DC test configuration is the same as used for the RF testing, as seen in Fig. 2. Again, manufacturer demonstration boards were used.

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Fig. 2: RF test setup used for heavy-ion experiments at the LBNL facility. Details of equipment used are listed in Table 2. “Cave 4” and the accompanying dotted line indicate the portion of the experiment that was in the test chamber at LBNL.

TABLE 2

TEST EQUIPMENT USED FOR RF HEAVY ION EXPERIMENTS SHOWN IN FIG. 2

Test Equipment	Model
RF Signal Generator	18 Slot NI PXIe 153869D-01L
RF Signal Analyzer	Varian VZL69641K1 or Minicircuits TVA-11-422
Pre-Amplifiers	(2) Agilent 423B, (1) Wiltron 75N50B, (1) Nardi 4503A
Power Meter	Minicircuits PWR-4RMS
(4x) Detectors (not shown)	Tektronix MSO70404C
Oscilloscope	Keithley 2200-72-1
Gate Power Supply	BK Precision XLM10014
Drain Power Supply	

B. Texas A&M

The testing conducted at Texas A&M University (TAMU) includes a series of experiments developed to explore leakage issues identified during a previous experiment at the same facility [5]. The tests primarily use 2955 MeV gold (Au), but also 2715 MeV tantalum (Ta), 2475 MeV holmium (Ho), 2115 MeV praseodymium (Pr), 1935 xenon (Xe), and 1635 silver (Ag). The tests involve a series of exposures to a fluence of 2×10^7 ions/cm² under varying bias conditions. The irradiations are done in air.

As with the LBNL tests, testing was done to observe leakage in the DUT during RF drive. A secondary outcome of this test was to capture transients generated by ions. RF measurements were performed with a continuous wave 3.5 GHz carrier signal using the test setup and equipment shown in Fig. 3 and Table 3. The manufacturer’s demonstration board was used to interface the amplifiers to the test equipment to ensure proper matching. The board was attached to a heat sink to manage thermal dissipation during test.

Prior to irradiation, DC drift measurements were taken with the Vendor D device in pinch-off ($V_g = -4.5V$ and $V_d = 28V$) for 45 minutes. The unirradiated drift is minimal ($\sim 10 \mu A$) compared to the leakage currents generated during irradiation ($\sim 100s$ of μA).

The remainder of the TAMU testing was done under DC conditions to further explore the conditions of the leakage current. A schematic for the DC test configuration is shown in Fig. 4. Again, the manufacturer’s demonstration board was used for the device fixture.

Fig. 3: RF test setup used for heavy-ion experiments at the TAMU facility. Details of equipment used are listed in Table 3.

TABLE 3

TEST EQUIPMENT USED FOR RF HEAVY ION EXPERIMENTS SHOWN IN FIG. 3

Test Equipment	Model
Signal Generator	HP 83623B
Pre-Amplifier	Ophir 5162
Power Meter	HP EPM-442A
(2x) Power Sensors (not shown)	(2x) HP ECP-E26A
Oscilloscope	Tektronix MSO72004C
Source Meter	Keithley 2410
Power Supply	TDK Lambda Gen150-10
Digital Multimeter	HP 3458A

Fig. 4: DC test setup for TAMU testing.

III. EXPERIMENTAL RESULTS

During the RF tests, previously unirradiated 100W+ and 25-35W rated devices from 4 commercial manufacturers were biased at their recommended (pre-radiation) quiescent conditions as shown in Table 4. The devices were operated at frequencies of 1.57542, 2.14, 3.2, and 3.5 GHz with varying levels of RF power output.

At LBNL, parts were exposed up to six times to a fluence of 1.0×10^7 ions/cm² each time (once each to Ne, Kr, and Ag, and up to three times to Xe). At TAMU, the devices were subjected to Au exposures five times successively to a fluence of 2.0×10^7 ions/cm² each.

Operating characteristics were monitored prior to, during and after each exposure. This time between exposures (typically <60s) has been removed from each dataset. No efforts were taking during exposures to maintain the manufacturer’s recommended quiescent currents. That is, the drain current is allowed to change with exposure to radiation.

TABLE 4
DC CONDITIONS OF DEVICES USED FOR RF HEAVY ION EXPERIMENTS

Vendor	I_{DS}	V_{DS}	V_{GS}	Peak Power
A	130 mA	28 V	-3.0 V	36.4 dBm
A	440 mA	48 V	-2.9 V	38.8 dBm
B	500 mA	50 V	-2.6V	49.5 dBm
C	500 mA	28 V	-2.4 V	42.5 dBm
D	250 mA	28 V	-2.5 V	40.0 dBm

A. Gate Current Results

Figures 5-10 show gate current results with respect to accumulated exposure time. In general gate current increased during exposures for the devices with varying levels of annealing. Figures 6 and 7 show results for two previously unirradiated devices from Vendor B, described as “DUT1” and “DUT2”. These devices exhibit significantly different annealing responses. These differences could be due to variability in the manufacturing process, but additional testing is needed to draw significant conclusions. The gate current responses for the low power devices from Vendors A and C are shown in Figs. 8 and 9, respectively.

Figure 5: Gate current remains approximately constant during exposures for Vendor A high-power device. Exposures are, from left to right, Ne, Kr, Ag,
<gap>, Xe2, and Xe3. The gap in data is for a run, Xe1 in which data was not recorded for this device. The Xe3 data are taken with bias conditions intended to observe any high-power effects.

Figure 6: Gate current increases during exposures with minimal recovery for Vendor B’s DUT1 high-power device. Exposures are, from left to right, Ne, Kr, Ag, Xe1, Xe2, and Xe3

Figure 7: Gate current increases during exposures with near full recovery for DUT2 from Vendor B. Exposures are, from left to right, Ne, Kr, Ag, Xe1, Xe2, and Xe3.

Figure 8: Gate current increases with higher LET exposure with minimal annealing for Vendor A low power device. Exposures are, from left to right, Ne, Ag, Xe2, and Xe3.

Figure 9: Gate current stays the same with each exposure for high power Vendor C device. Exposures are, from left to right, Ne, Kr, Ag, Xe₁, Xe₂, and Xe₃.

In order to observe changes in leakage currents across repeated heavy ion exposures, two Vendor D DUTs were irradiated with gold in ten successive exposures to fluences up to 2×10^7 atoms/cm² with a 5 minute rest period following each irradiation. The devices were biased in pinch-off ($V_g = -5$ V and $V_d = 28$ V) during both irradiation and rest periods. Gate and drain current sweeps were done before each irradiation and at the conclusion of the experiment. A single data point ($V_g = -4.9$ V, $V_d = 28$ V) is recorded from each current sweep and plotted in Figure 11 with respect to the accumulated fluence of the devices. In this figure, solid icons represent data from S/N 5; unfilled icons represent data from S/N 6 from Vendor D. This data point was chosen because it was the lowest gate bias in which a complete data set was available for each DUT.

Results for drain current testing are not shown in this paper. The trends for drain current closely follow the patterns of the saturated power results shown in the following section.

Figure 10: Gate current magnitude increases with each exposure with minimal annealing. Breaks indicate separate exposures to Au. Each exposure is to a fluence of 2.0×10^7 ions/cm².

Figure 11: The magnitude of gate and drain leakage currents of the Vendor D device type at gate voltage -4.9 V and drain voltage 28 V before each irradiation and at the conclusion of the test.

B. Power Saturation Results

During this series of exposures, P_{SAT} slightly decreased during runs, with some annealing between runs (see Figures 12-15). Since there appear to be no major decreases in P_{SAT} , this can be explained by increases in the junction temperature while the devices warm up. As can be seen in the experimental setup section for LBNL above, we also were able to record RF output transients. Note that the Xe₃ data in Figure 12 is inconsistent with the general trend of the rest of the data. This is due to a tweak to the test setup to test the device in a power-stressed condition.

Figure 12: RF P_{SAT} current decreases during exposures with minimal recovery for Vendor A high-power device. Exposures are, from left to right, Ne, Kr, Ag, <gap>, Xe₂, and Xe₃. The gap in data is for a run, Xe₁ in which data was not recorded for this device. The Xe₃ data are taken with bias conditions intended to observe any high-power effects.

During this series of exposures for Vendor D, no changes in P_{SAT} were observed. As mentioned in the experimental setup section above, there was an attempt to trigger on RF output transients, but with no success. This could be due to the matching network, or simply because there were no transients during test. The frequency spectrum was measured for the final three exposures, but no anomalous behavior was observed.

IV. DISCUSSION

It is clear that degradation of leakage current is a concern for these devices. However, the magnitude of the leakage degradation depends on the vendor. For example, the high-power device type from Vendor A showed little degradation, while DUTs from Vendor D show significant degradation. This difference could be due to differences in facilities, ion energies, ion weights, test conditions, burn-in status, or several other factors.

High-power Vendor B DUTs were not consistent in response under identical test conditions, with one showing little annealing (Fig. 7) and the other showing significant annealing (Fig. 8). This implies that the manufacturing process may not be stable.

Some conclusions can be drawn based on these data. First, the leakage current increases with the weight of the incident ion (see Appendix A for a note on LET and stopping power in GaN). Second, leakage current varies from vendor-to-vendor and DUT-to-DUT. This implies that vendors must be carefully evaluated for process maturity and suitability for the intended application.

In conclusion, these studies emphasize the need for consistent test processes for analysis of devices. Small variations in test setups, particularly in the RF spectrum make large differences in test results. There is a need to standardize test procedures in the radiation effects community.

V. APPENDIX A

The following is a brief discussion on the interaction of heavy ions with GaN to set the theoretical expectation of energy transfer and deposition. The passage of the heavy ion through the DUT material produces ionization which is related to the energy deposition per unit track length. There are two commonly used measures of this energy deposition: stopping power and LET. Stopping power is simply the energy deposition per unit track length in convenient units of MeV/um. Linear energy transfer (LET) is the stopping power normalized to the density of the DUT target material. LET has convenient units of MeV/mg/cm².

The measure of the amount of ionization produced by heavy ion tracks is the number of electron-hole pairs produced in the material per unit volume. These extra electron-hole pairs can be collected as extra current or as charge on the node of a capacitor. Other heavy ion effects include the disruption of the bonding of atoms at material interfaces, the production of dangling bonds. These interface states can become leakage paths.

Heavy ion testing of devices and circuits is performed for basic physics research and also for assessing the suitability of the components for a particular application environment, perhaps a space environment such as earth orbit or interplanetary mission. The parameters in the test matrix include the DUT electrical inputs and the parameters of the beam. Beam parameters include ion mass and ion energy and ion angle of incidence. Reference [6] has a broad scope of tutorial material and references regarding the setup and

Figure 13: RF P_{SAT} current decreases during exposures with minimal recovery for Vendor B (DUT1) high-power device. Exposures are, from left to right, Ne, Kr, Ag, Xe₁, Xe₂, and Xe₃.

Figure 14: RF P_{SAT} current decreases during with minimal recovery for Vendor A low-power device. Exposures are, from left to right, Ne, Ag, Xe₂, and Xe₃.

Figure 15: RF P_{SAT} current decreases during exposures with minimal recovery for Vendor C low-power device. Exposures are, from left to right, Ne, Kr, Ag, Xe₁, Xe₂, and Xe₃.

performance of heavy ion experiments for hardness assurance testing.

For a particular DUT target material and a particular heavy ion beam, the energy deposition per unit length in the material is ion energy-dependent. Figure A1 below shows the energy dependence of the LET for the ions used in this study. The maximum LET occurs for a particular target material and ion at an energy called the “Bragg peak.” A given LET in the material can be achieved for the same ion with two different energies, one above and one below the Bragg peak.

Figure A1: LET vs. ion energy for ions on a GaN target material.

Except for very specialized applications, the energy of the ion should be chosen to be above the Bragg peak. For ion energies much below the Bragg peak, the ion track starts becoming non-straight-line, described statistically as “straggling.” The straight line ion paths are optimum because a straight line ion path allows for uniform distribution of energy per unit volume in the material. When there is significant straggling, the energy deposition in the DUT becomes non-uniform. Interpreting test results and comparing data among different experiments becomes difficult when the energy deposition is non-uniform. Another reason to avoid using beam energies below the Bragg peak is that the experiment becomes more sensitive to the details of the thickness and composition of the device overlayers, such as tungsten vias and gold field plates. These high-Z materials introduce much uncertainty in the beam properties because of

straggling. The straggling might possibly make the results vendor-dependent in a way that the experimenter did not intend, if the different vendors use different materials as overlayers. Such is the case for the 5.8 MeV beam of 20-Ne ions in this test matrix. The Ne ion energy is low enough that straggling dominates and the true flux and LET on the active layer are not well defined. Therefore, while some effect is seen with the neon ion irradiation, the results should be interpreted with this note in mind.

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