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Radiation and Thermal Cycling Effects on EPC1001 Gallium Nitride Power Transistors

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Abstract

Electronics designed for use in NASA space missions are required to work efficiently and reliably under harsh environment conditions. These include radiation, extreme temperatures, and thermal cycling, to name a few. Information pertaining to performance of electronic parts and systems under hostile environments is very scarce, especially for new devices. Such data is very critical so that proper design is implemented in order to ensure mission success and to mitigate risks associated with exposure of on-board systems to the operational environment. In this work, newly-developed enhancement-mode field effect transistors (FET) based on gallium nitride (GaN) technology were exposed to various particles of ionizing radiation and to long-term thermal cycling over a wide temperature range. Data obtained on control (un-irradiated) and irradiated samples of these power transistors are presented and the results are discussed.

Background

Radiation and extreme temperature exposures, which are typically encountered in space exploration missions and deep space planetary applications, are a major concern for the operation and reliability of power system electronics. Current spacecraft utilize various forms of structural shielding to provide protection for on-board circuits from damaging radiation, and make use of some thermal control elements to ensure adequate temperature for proper operation of electronic systems. Many benefits would be realized if the electronics could function properly without the need of radiation shielding or heating/cooling accessories. These benefits include increased efficiency, improved reliability, and decreased system development and launch costs.

Semiconductor devices based on wide band-gap materials, such as gallium nitride (GaN), are becoming more readily available as the enabling technologies begin to mature. Increased availability is largely due to advancement in the manufacturing process by maximizing yield and reducing defects at the wafer level, to the ability to grow GaN structures on silicon substrates, and to reduced production cost. The low on-resistance of wide band-gap materials allows the development of a new generation of transistor devices that switch faster and with greatly reduced losses. The combined higher switching speed and efficiency of these transistors, for example, allows the operation of DC/DC converters at very high frequencies, thereby reducing weight, saving board space, and conserving power.

In comparison to other semiconductor materials, GaN is of particular interest for use in radiation environment due to its high ionic bond strength and large crystal density. These properties suggest that GaN may exhibit greater radiation hardness than other comparable compound semiconductors and will suffer less from the influence of interstitial impurities [1]. In addition, the wide band-gap structure of GaN-based power devices offers great benefits when compared with those made of silicon (Si). Some of these advantages include high breakdown voltage, higher power and current densities, low on-resistance, higher switching frequency, and high operating temperatures. Table I lists a comparison of properties of silicon and gallium nitride semiconductor materials [2]. By being able to withstand large voltages with small leakage currents and fast switching speeds, GaN devices show great promise for use in advanced power electronic circuitry.

Table I. Properties of silicon and gallium nitride semiconductor materials [2].

Property	Si	GaN
Band-gap, E_g (eV at 300K)	1.12	3.4
Critical electric field, E_c (V/cm)	2.5×10^5	3×10^6
Thermal conductivity, (W/cm.K at 300K)	1.5	1.3
Saturated electron drift velocity, v_{sat} (cm/s)	1×10^7	2.5×10^7
Electron Mobility, μ_e (cm^2/Vs)	1350	1000 - 2000
Hole Mobility, μ_h (cm^2/Vs)	480	30
Dielectric constant	11.9	9.5

Scope of Work

A newly-developed GaN enhancement-mode field effect transistor, type EPC1001, was selected for performance evaluation after exposure to radiation and long-term thermal cycling. These first-generation devices, which were produced by Efficient Power Conversion (EPC) Corporation, are based on GaN grown on Si wafers using standard CMOS (complimentary metal-oxide-semiconductor) manufacturing processes [3]. The exceptional high electron mobility of GaN and low temperature coefficient allows these devices to have very low drain-source on-resistance ($R_{DS(ON)}$). In addition, the lateral device structure and majority carrier diode provide exceptionally low gate charge (Q_G) and zero source-drain recovery charge (Q_{RR}); resulting in very high switching frequency capability [3]. Such features enable these GaN devices to compete with Si power MOSFETs (metal-oxide-semiconductor FET) in applications such as point-of-load converters, DC/DC converters, and hard switching and high frequency circuits. These new devices are supplied in a passivated die form with solder bumps, as shown in Figure 1.



Figure 1. EPC transistor structure with solder bumps

A total of eight samples of EPC1001 GaN FETs were used in this work. Table II lists some of the manufacturer’s specifications for this device. The experimental work involved exposing some of the devices to different particles of ionizing radiation, followed then by subjecting these and un-irradiated samples to long-term thermal cycling. Four of these parts were control (un-irradiated), one exposed to gold-ion (Au) radiation, and the remaining three to xenon ions (Xe). The radiation exposure procedure adhered to the test guidelines reported in [4]. Parts were serialized (if not already done), with controls marked prominently to distinguish them from test samples, and exposures were performed at ambient laboratory temperature. Since the packages from EPC were atypical, the DUTS had to be remounted in a dead-bug configuration for ion exposure and testing with the ATE. Devices were verified to be functional after mounting on the test carrier. Table III lists more information on conditions of the radiation exposure.

Table II. Manufacturer’s specifications of test parts [3].

Part #	EPC1001
Drain-Source Voltage, V_{DS} (V)	100
Gate Threshold Voltage, V_{TH} (V)	0.7 - 2.5
Drain Current, I_D (A)	25
Drain-Source On Resistance, $R_{DS(ON)}$ (m Ω)	5.6 - 7.0
Operating Temperature, T_C ($^{\circ}$ C)	-40 to +125

Table III. Listing of EPC1001 parts and radiation conditions.

# of Parts	Device Label	Condition	Ion	Energy (MeV)	LET (MeV.cm²/gm)	Range (μm)	Dose (rad)
1	K7063	Irradiated	Au	2342	84.7	122.9	22718
1	K7064	Irradiated	Xe	1569	98.8	124.5	8301
1	K7044	Irradiated	Xe	1569	50.9	124.5	7886
1	K7065	Irradiated	Xe	1569	98.8	124.5	15838
4	K7068-K7071	Control (un-irradiated)					

The thermal cycling test, which was carried out in a Suns Systems Environmental Chamber, consisted of the following conditions, with a profile as depicted in Figure 2.

- Total # of cycles: 1000
- Temperature rate of change: 10 $^{\circ}$ C/min
- Temperature range: -55 $^{\circ}$ C to +125 $^{\circ}$ C
- Soak time at extreme temperatures: 10 min

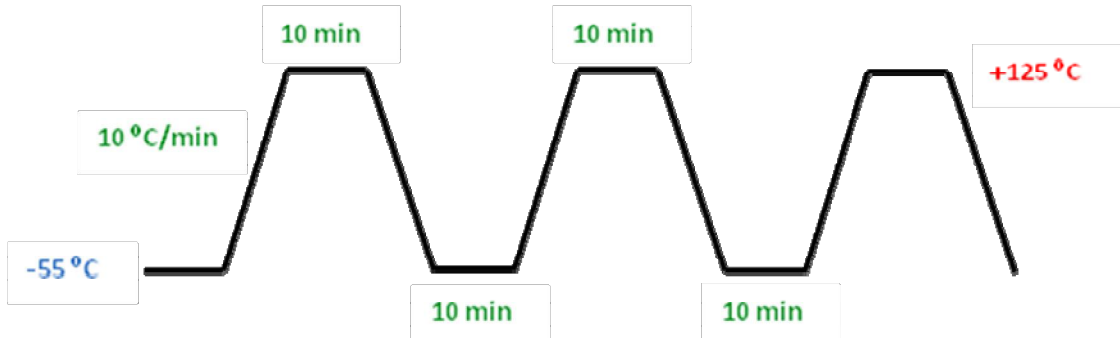


Figure 2. Profile of thermal cycling

Device parametric evaluation, which included voltage/current characteristic curves, voltage threshold level, and drain-source on-resistance, was performed before, during, and after radiation exposure and also thermal cycling. These measurements involved the use of a Sony/Tektronix 370A Curve Tracer and several Keithley 238 Source-Measure Units.

Test Results

Radiation Effects

Heavy ion testing of the newly available GaN FETs from EPC was conducted at TAM. Four of the EPC1001 were tested for general radiation response from gold and xenon ions. Overall, the devices showed radiation degradation commensurate with breakdown in isolation oxides, and similar testing by EPC and Microsemi agrees with these data. These devices were the first production generation of the device, called Gen1. The effects of Au-radiation at various dose levels on the gate and drain currents of device K7063 are shown in Figure 3, while Figures 4 through 6 show the influence of Xe-radiation on the characteristics of the EPC1001 parts at 60 degrees tilt, 60 degrees roll, and normal incidence for device K7064, K7065, and K7044, respectively.. Full results are described in [5].

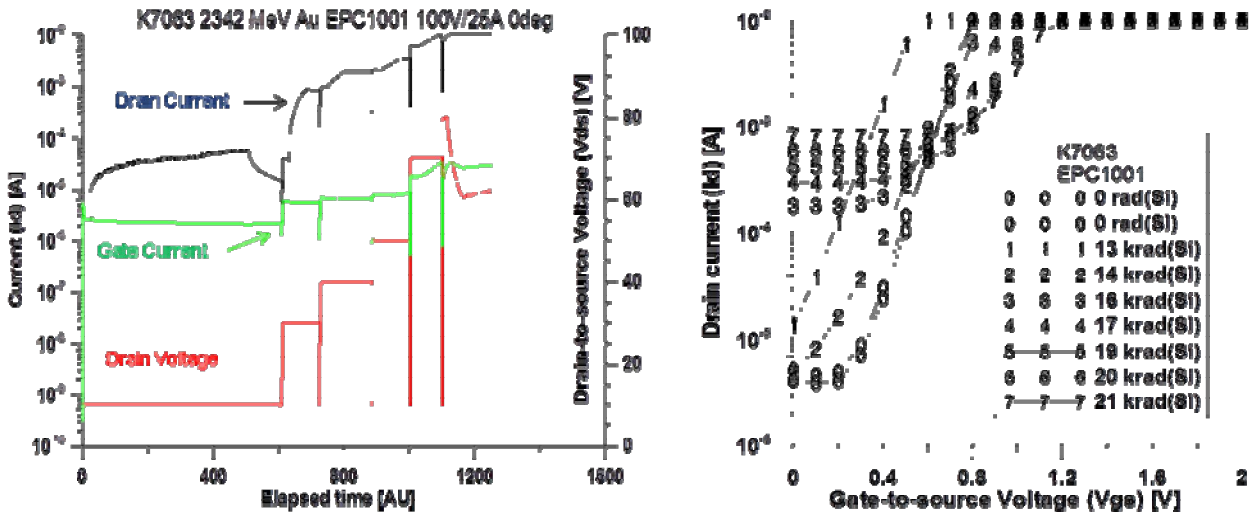


Figure 3. Effects of Au-radiation on characteristics of device K7063

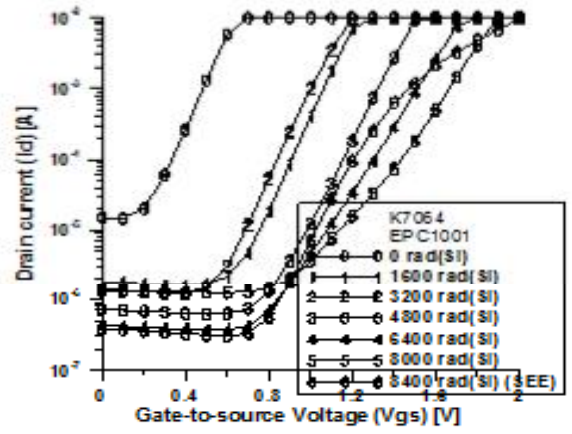
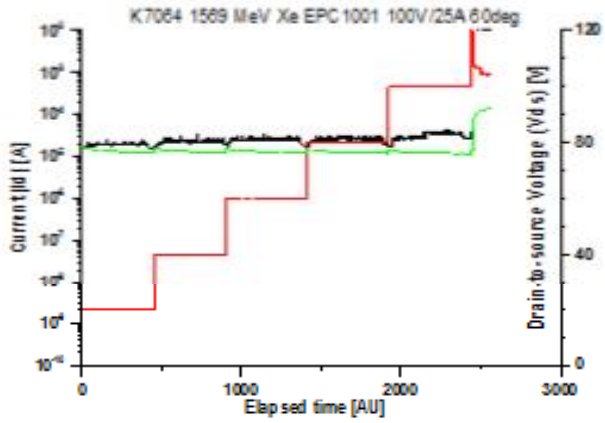


Figure 4. Effects of Xe-radiation on characteristics of device K7064

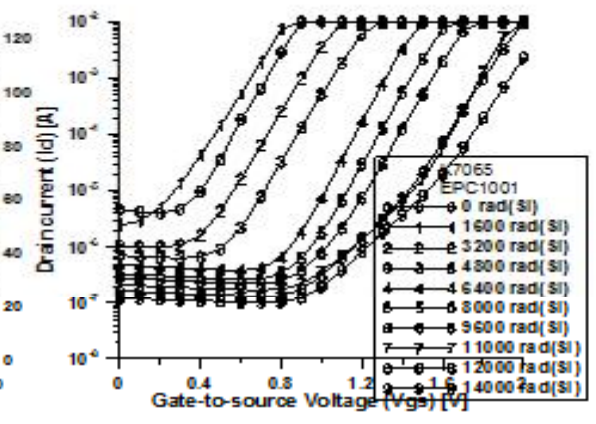
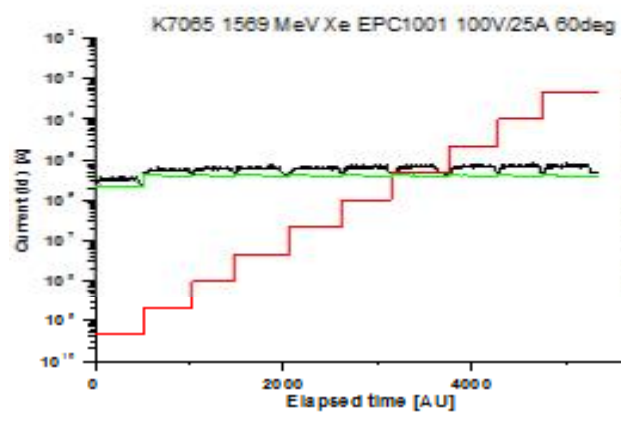


Figure 5. Effects of Xe-radiation on characteristics of device K7065

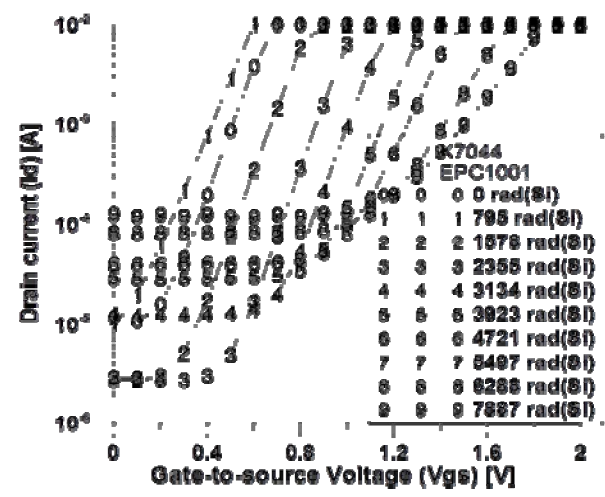
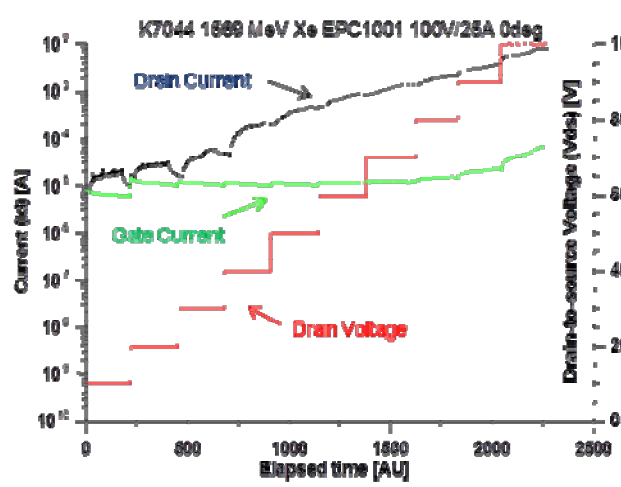


Figure 6. Effects of Xe-radiation on characteristics of device K7044

Thermal Cycling Effects

The room temperature characteristic I/V curves of all eight (four control and four irradiated) EPC1001 GaN FETs at various stages of the thermal cycling activity are shown in Figures 7 through 14.

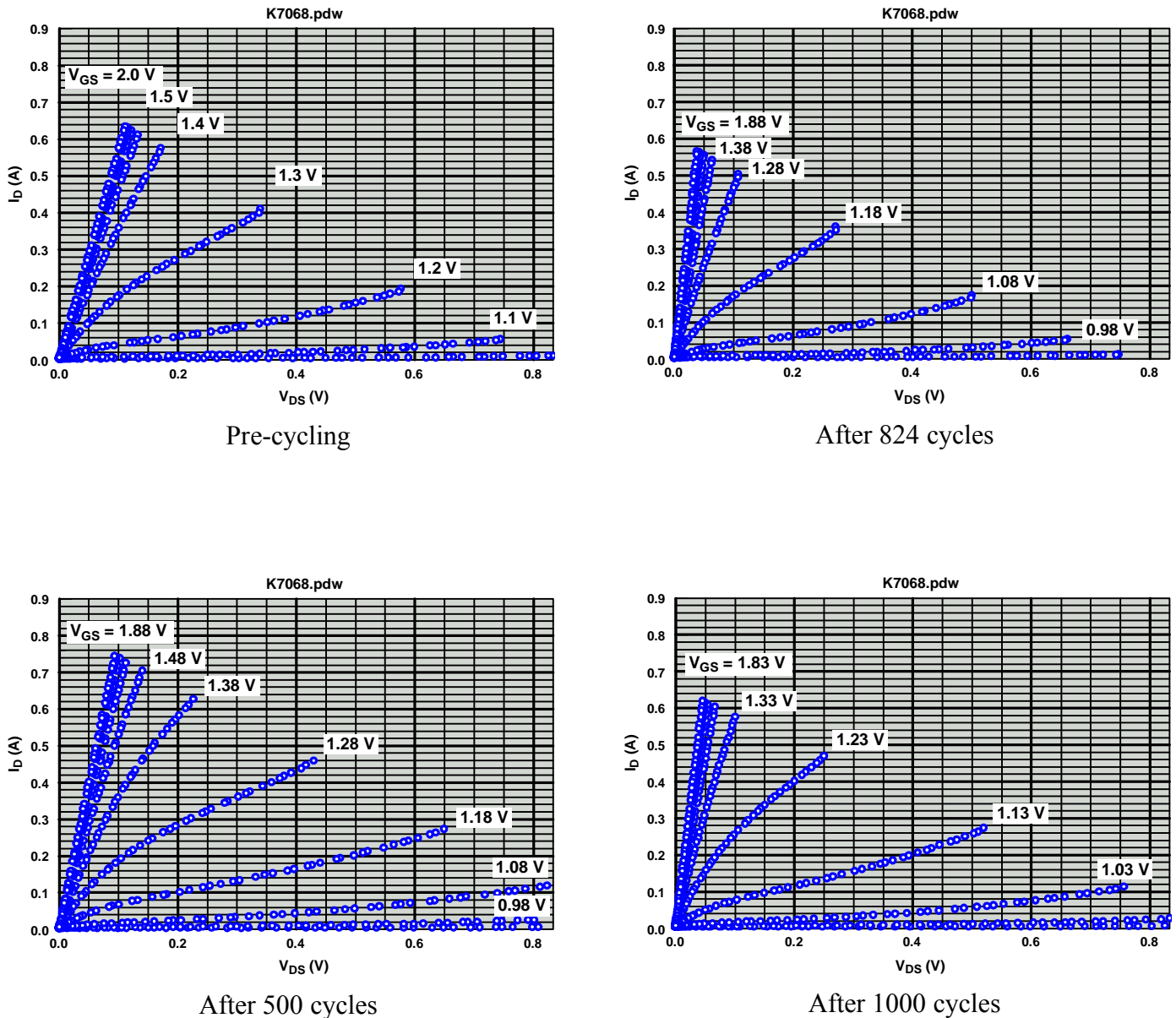
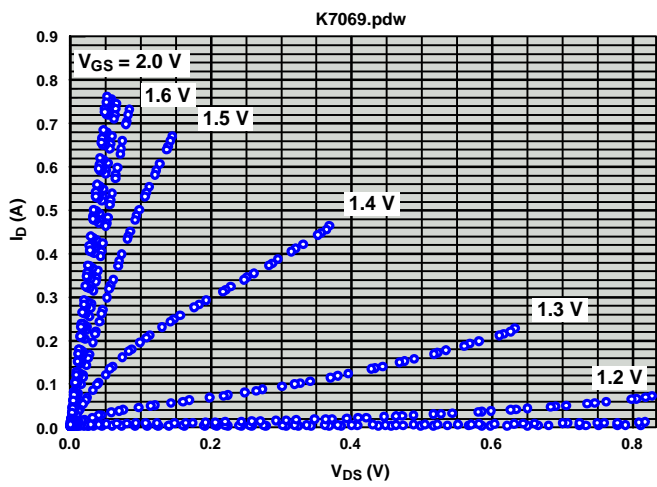
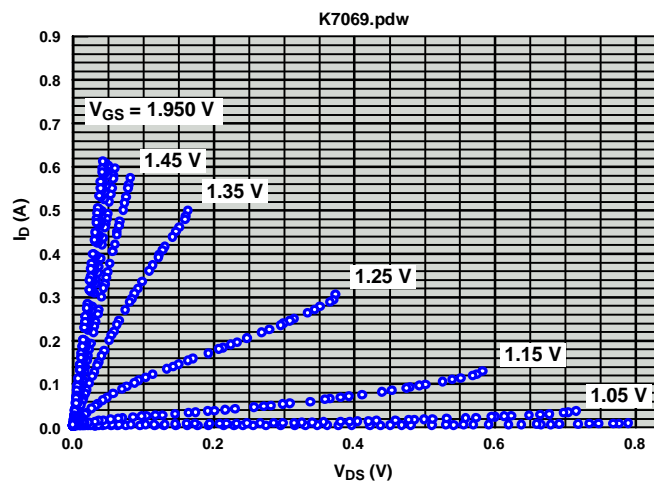


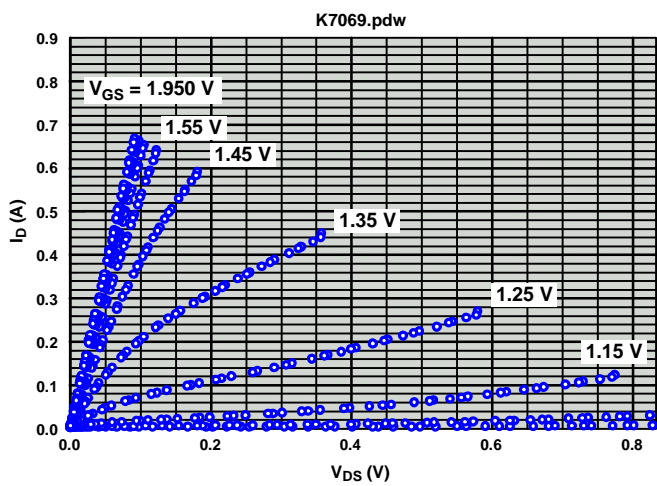
Figure 7. I/V curves of control device K7068 at various stages of thermal cycling



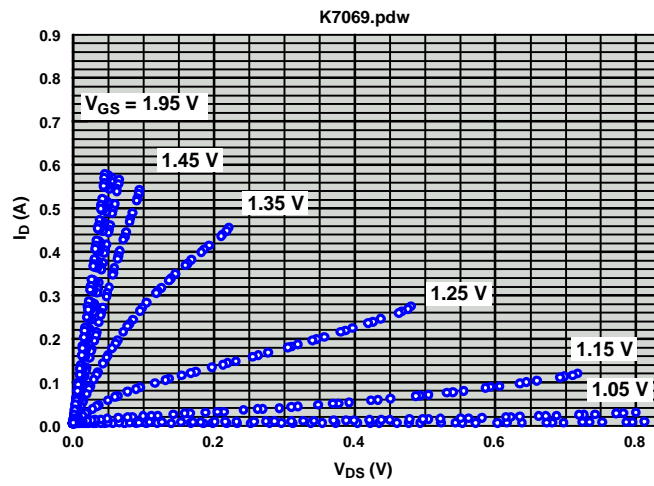
Pre-cycling



After 824 cycles

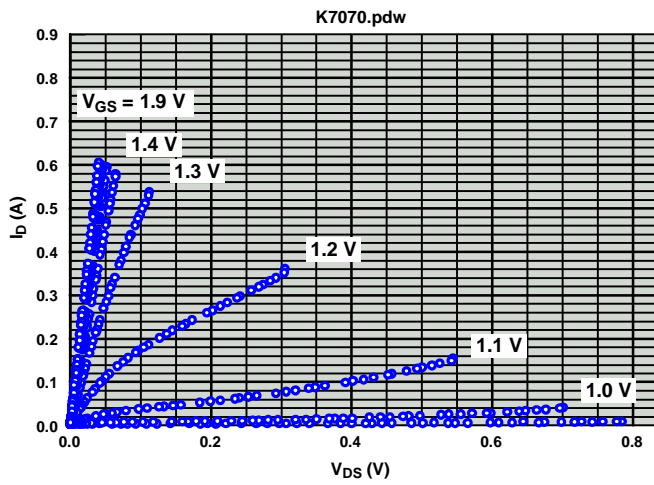


After 500 cycles

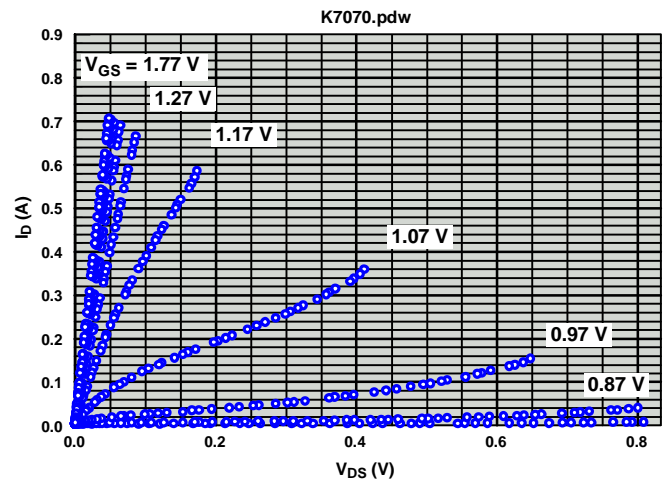


After 1000 cycles

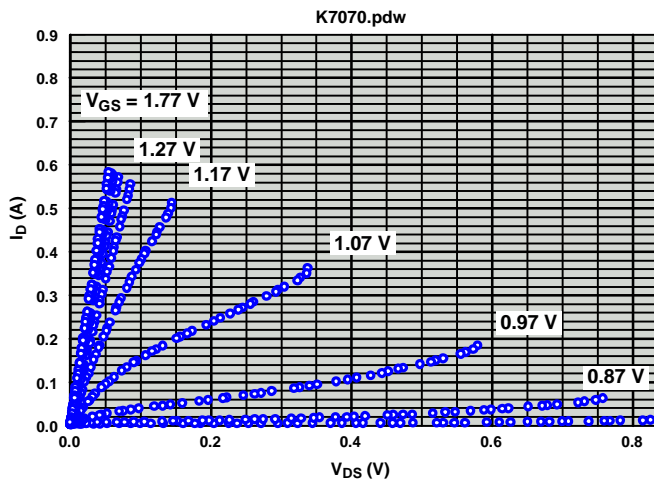
Figure 8. I/V curves of control device K7069 at various stages of thermal cycling



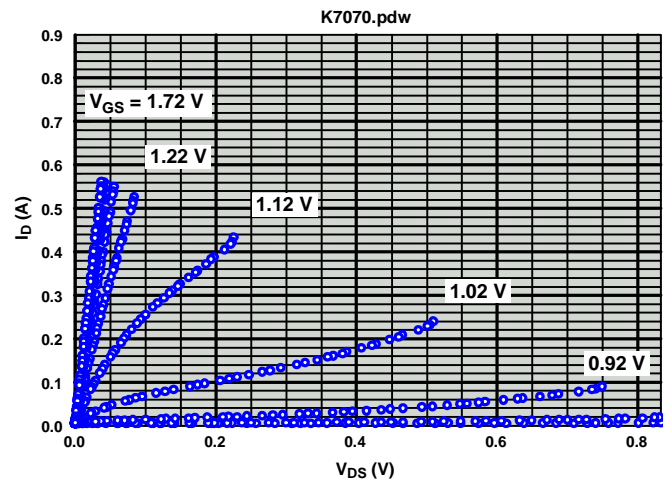
Pre-cycling



After 824 cycles

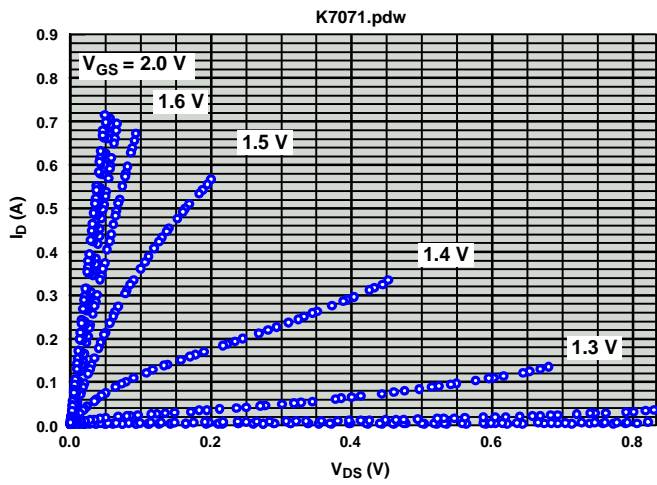


After 500 cycles

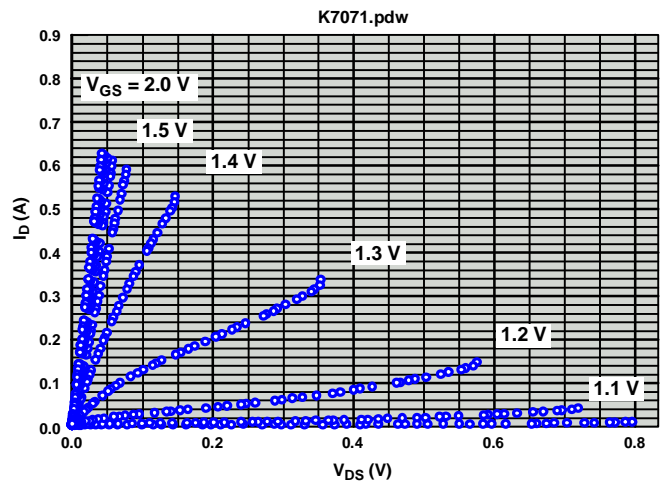


After 1000 cycles

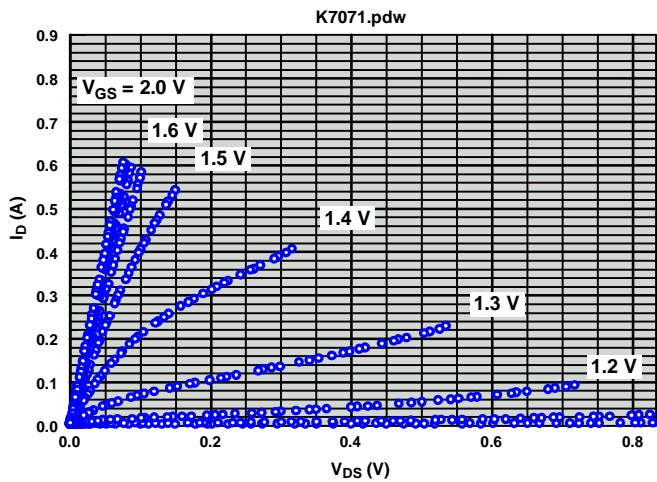
Figure 9. I/V curves of control device K7070 at various stages of thermal cycling



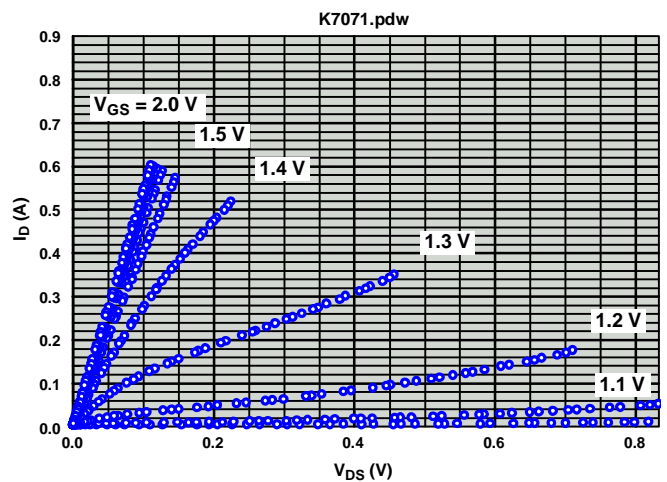
Pre-cycling



After 824 cycles

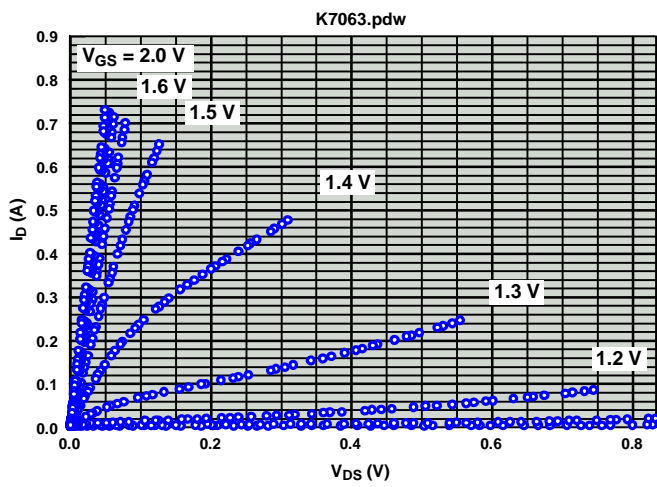


After 500 cycles

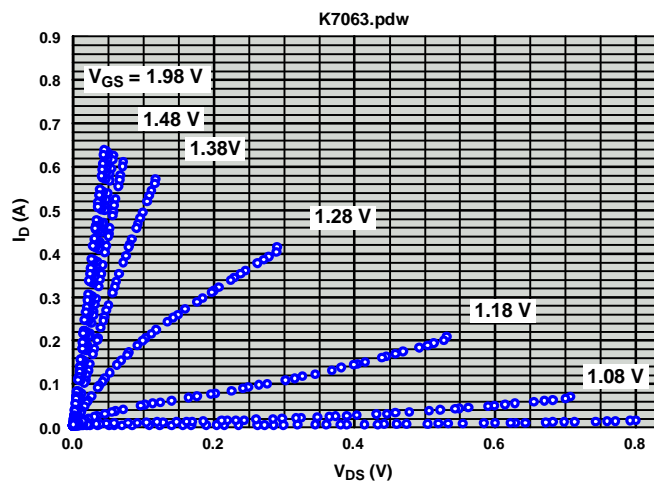


After 1000 cycles

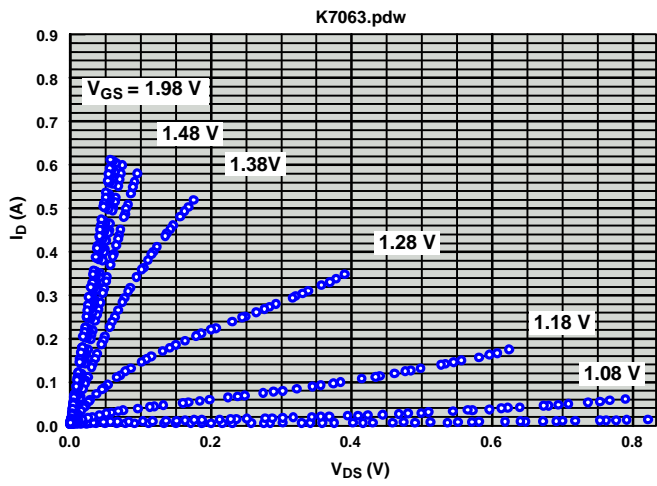
Figure 10. I/V curves of control device K7071 at various stages of thermal cycling



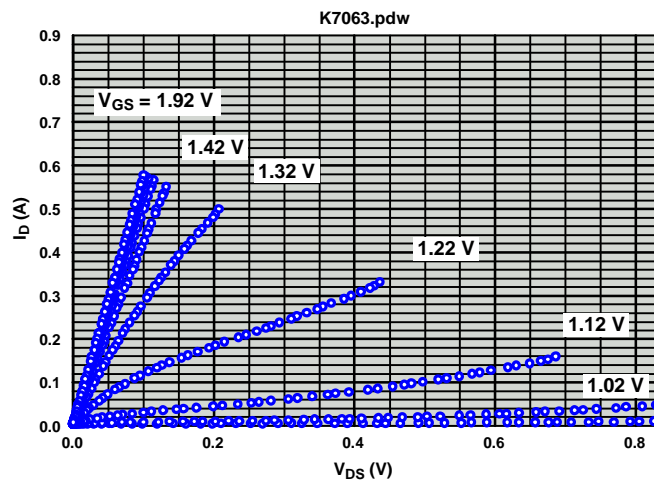
Pre-cycling



After 824 cycles

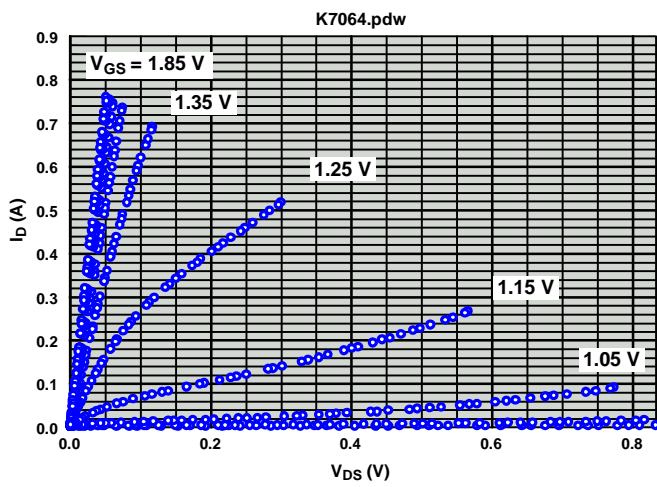


After 500 cycles

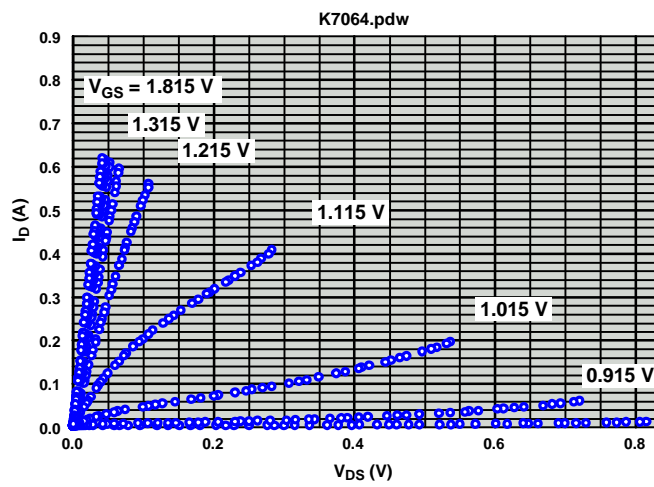


After 1000 cycles

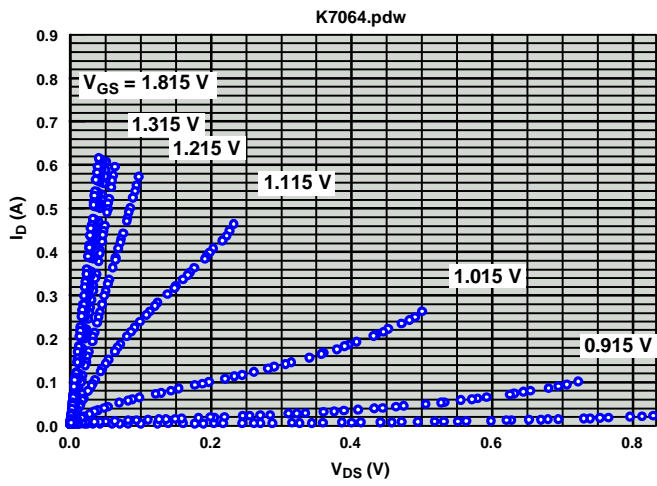
Figure 11. I/V curves of Au-irradiated device K7063 at various stages of thermal cycling



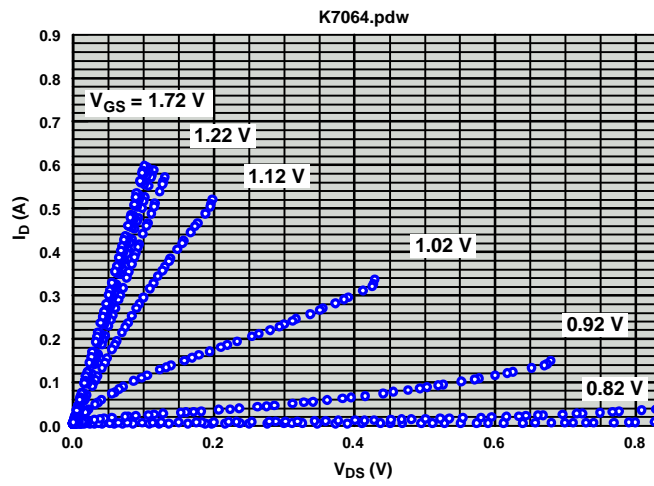
Pre-cycling



After 824 cycles

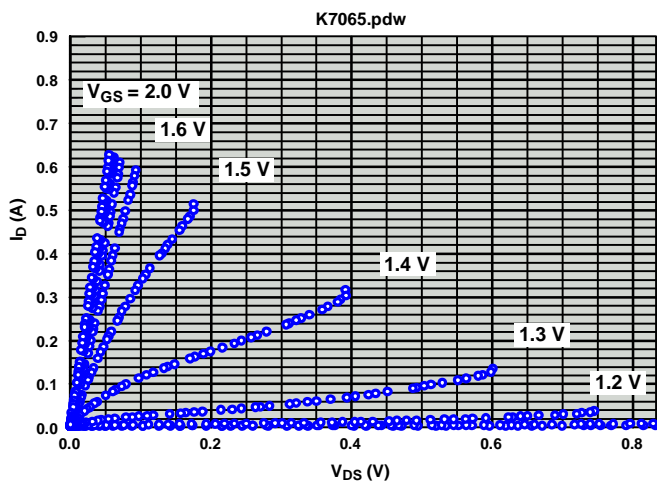


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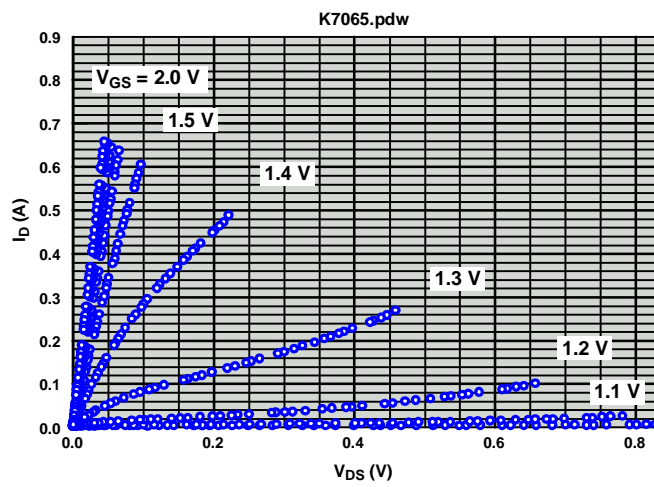


After 1000 cycles

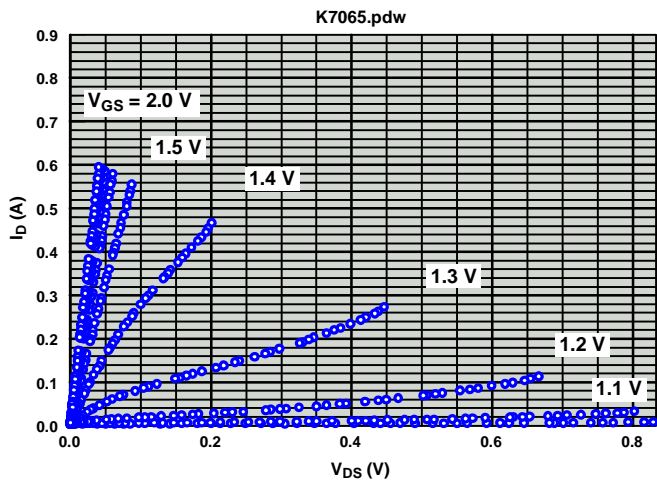
Figure 12. I/V curves of Xe-irradiated device K7064 at various stages of thermal cycling



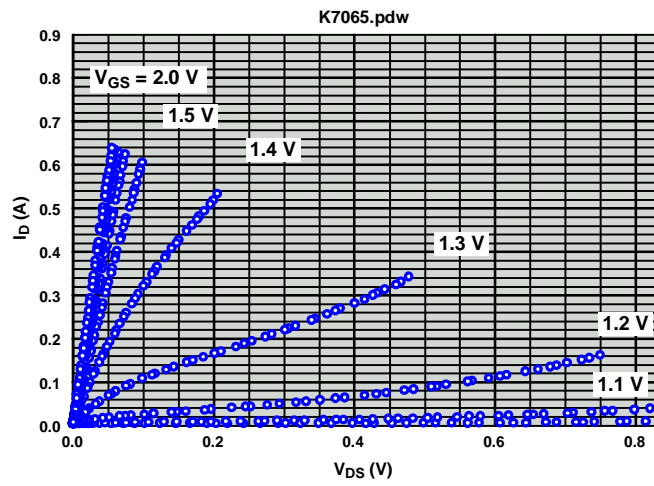
Pre-cycling



After 824 cycles

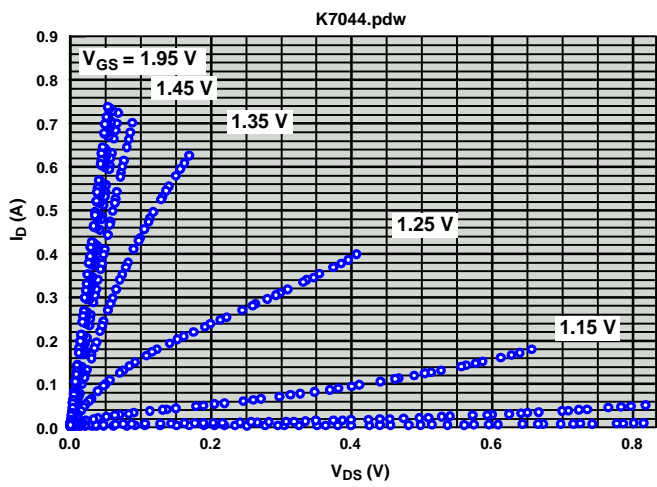


After 500 cycles

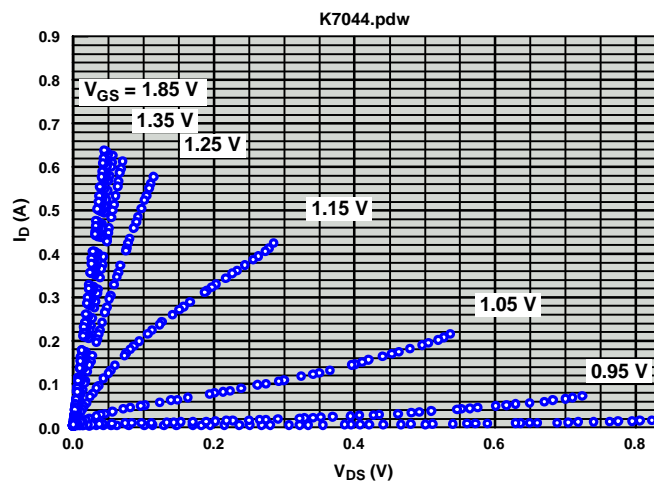


After 1000 cycles

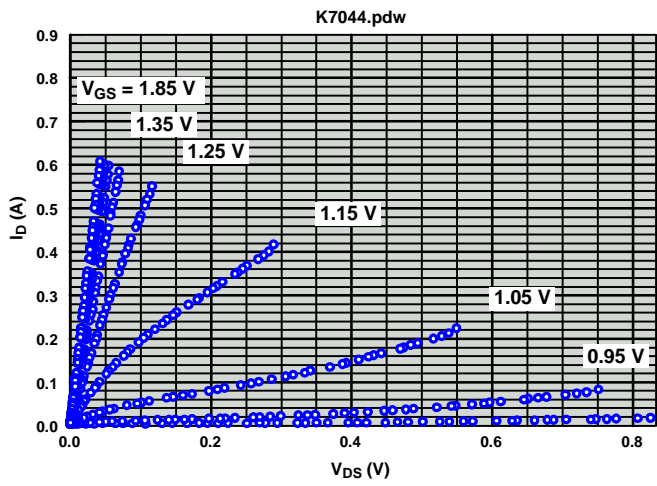
Figure 13. I/V curves of Xe-irradiated device K7065 at various stages of thermal cycling



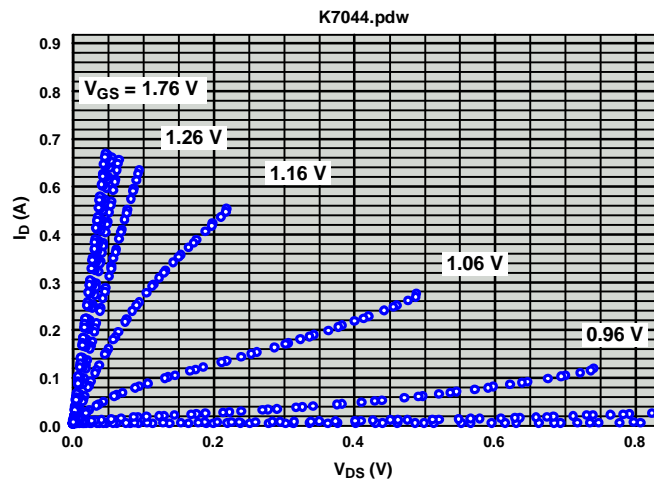
Pre-cycling



After 824 cycles



After 500 cycles



After 1000 cycles

Figure 14. I/V curves of Xe-irradiated device K7044 at various stages of thermal cycling

Examination of the thermal cycling data presented in Figures 7 through 14 of all the EPC1001 GaN FETs reveals the following observations:

- All eight GaN transistors (4 control and 4 irradiated parts) remained functional after 1000 cycles between $-55\text{ }^{\circ}\text{C}$ & $+125\text{ }^{\circ}\text{C}$ as none underwent any catastrophic damage
- Thermal cycling seemed to introduce slight, but inconsistent, variation in the I-V characteristic curves of all samples; possibly due to lack of thermal conditioning of produced devices
- The threshold voltage, V_{TH} , of tested devices experienced an initial decrease with cycling but seemed to level off after exposure to about 130 cycles; probably due to thermal annealing
- While the control samples exhibited profound variation in their drain-source on-resistance, $R_{\text{DS(ON)}}$, with cycling as their values fluctuated between 70 and $200\text{ m}\Omega$; the irradiated devices were more stable as the $R_{\text{DS(ON)}}$ of all four parts remained at the $70\text{ m}\Omega$ level throughout the cycling

These induced changes in the V_{TH} and the $R_{\text{DS(ON)}}$ properties of these GaN FETs due to the thermal cycling are illustrated in Figures 15 and 16, respectively.

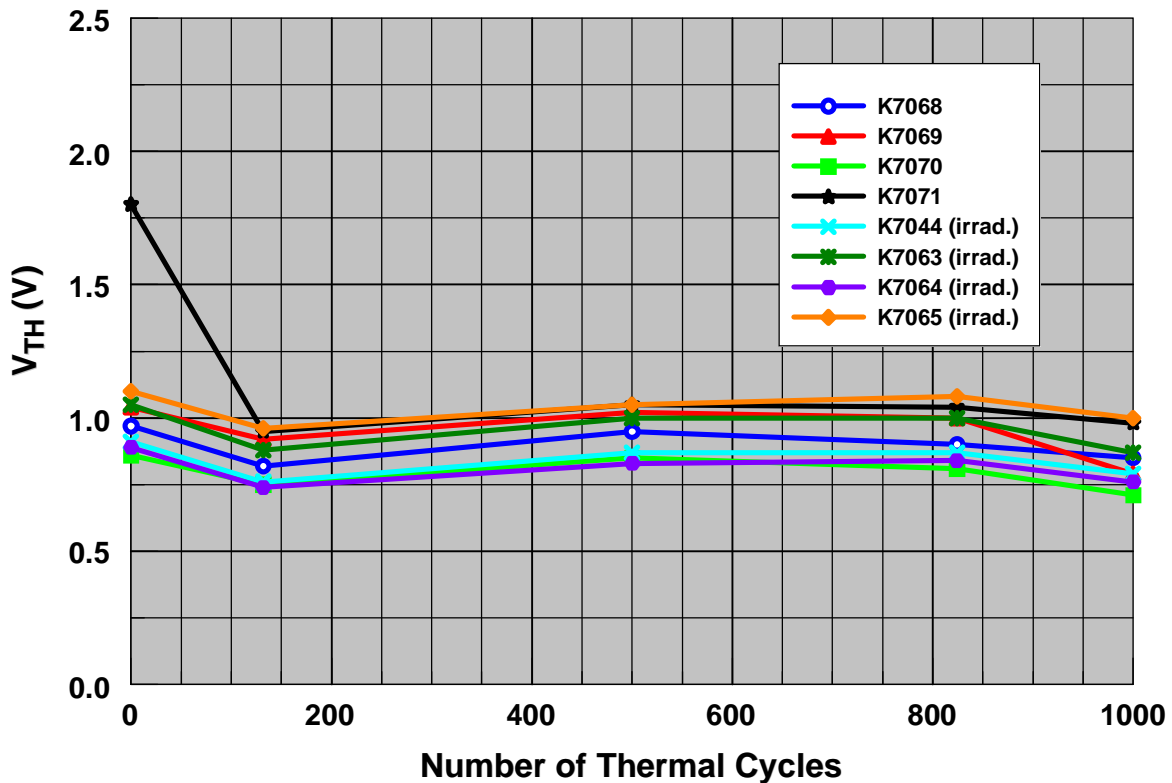


Figure 15. Variation in the threshold voltage of EPC1001 GaN FETs with thermal cycling

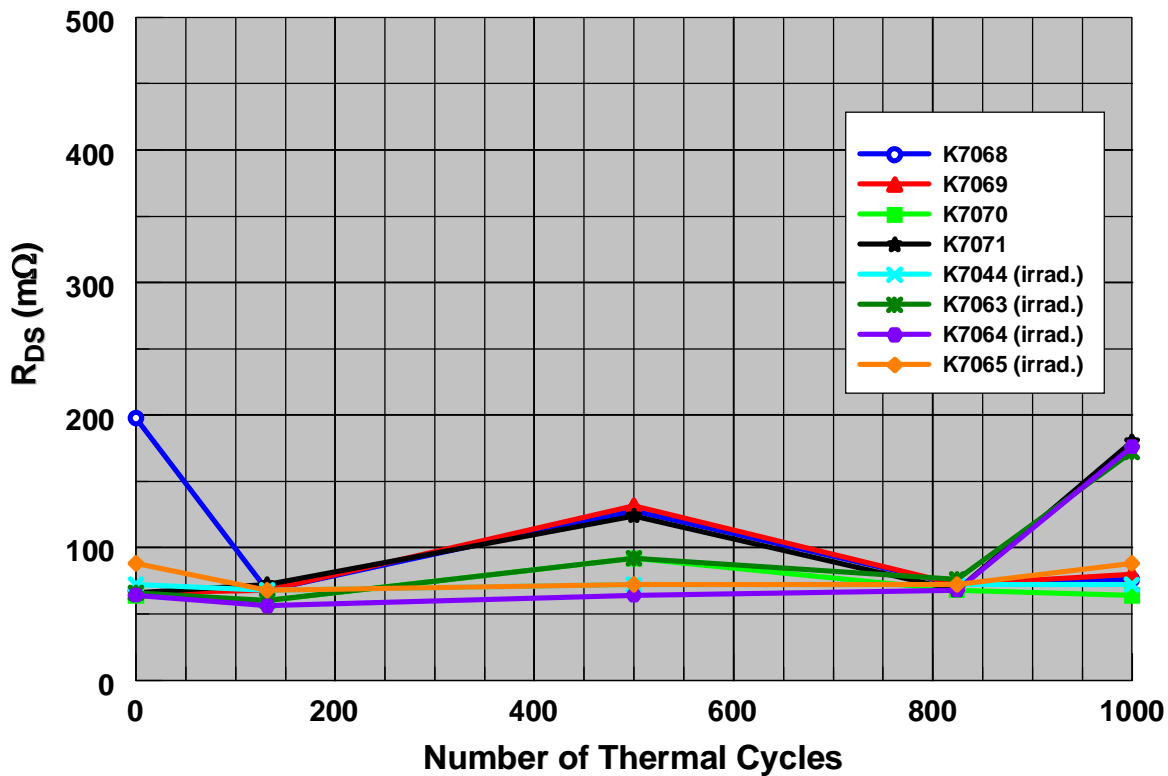


Figure 16. Variation in drain-source on-resistance with thermal cycling

Conclusions

Electronic modules and power circuits designed for use on many of NASA space missions are required to be efficient, reliable, and capable of operation in harsh environments. Some of these environmental stresses that are encountered in a typical deep space mission include high levels of radiation and also thermal cycling. The performance of newly-developed GaN enhancement-mode field effect transistors, type EPC1001, was evaluated after exposure to radiation and long-term thermal cycling. Some parts were initially exposed to different particles of ionizing radiation, followed then by subjecting them and also un-irradiated samples to long-term thermal cycling. In general, the irradiated devices showed radiation degradation commensurate with breakdown in isolation oxides. As far as thermal cycling is concerned, none of the devices underwent any catastrophic damage, although slight variation in their I/V switching characteristics was observed. Efforts are currently underway to repeat these investigations on an improved version, i.e. second generation, of these new GaN power FETs.

References

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