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Targeted Ion Radiation of AlGaN/GaN High Electron Mobility Transistors

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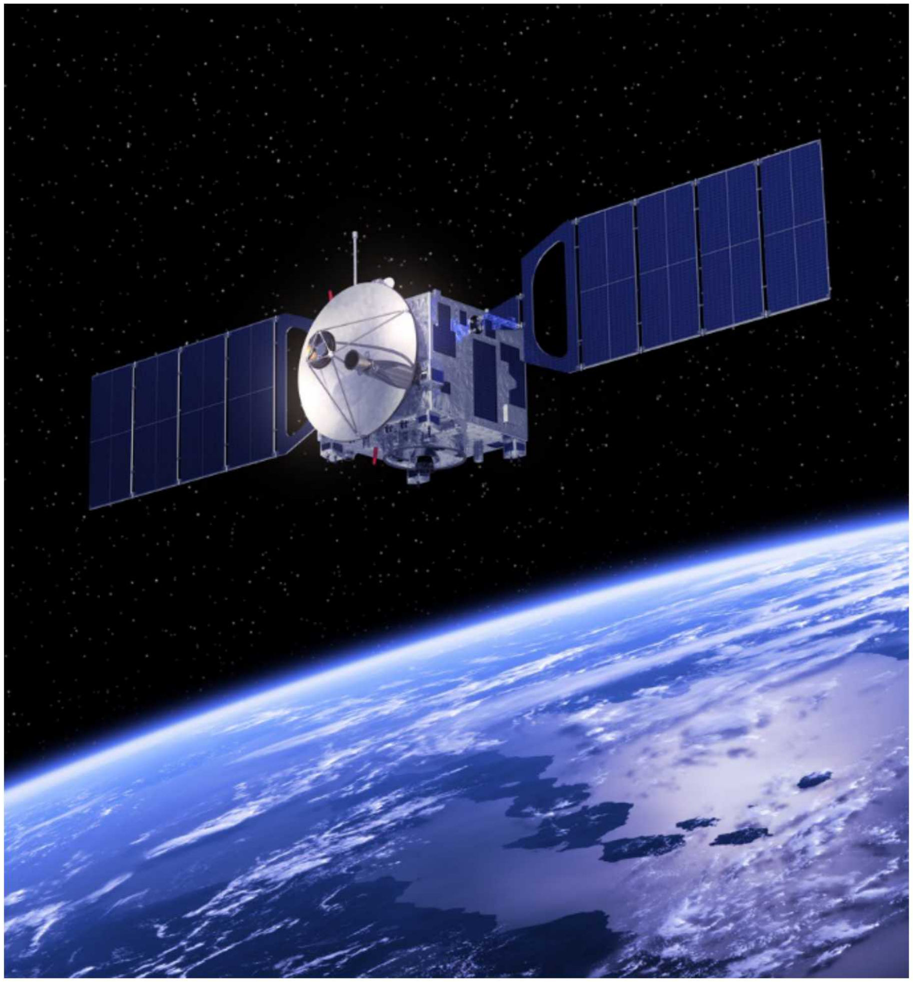
[a] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Overview

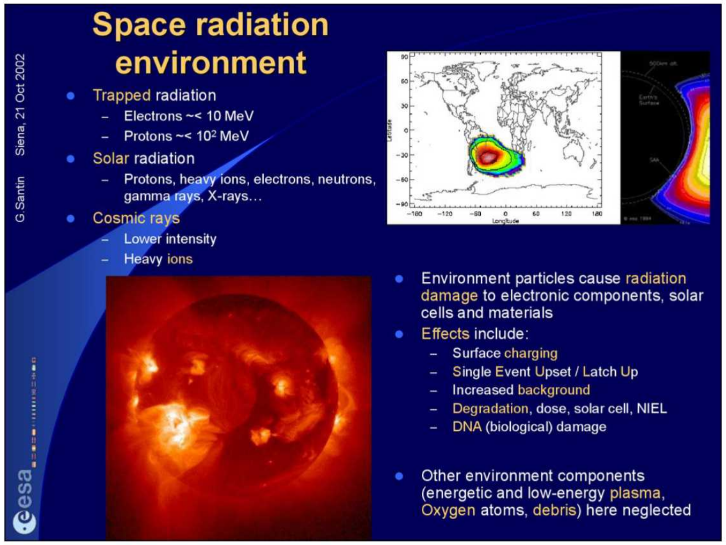
- Motivation
- AlGaN/GaN HEMT
- Experiment Details
- Results
- Conclusion



https://compoundsemiconductor.net/article/102949/UMS_GaN_HEMT_process_qualified_for_space

Motivation

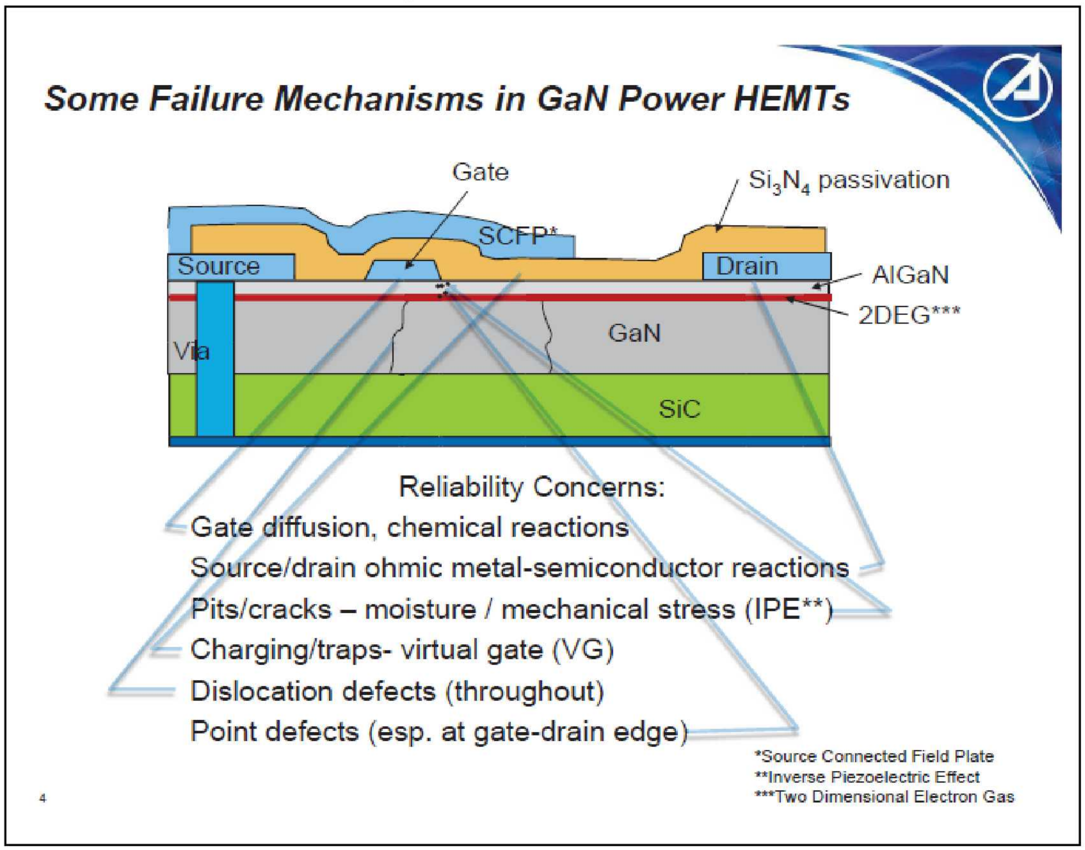
- Reliability predictions often use (in Si and GaAs technology) the constant temperature Accelerated Life Testing (Arrhenius Relationship)
  - Inadequate for GaN HEMT technology failure mechanisms and/or failure modes
- Multiple failure mechanism makes GaN HEMT qualification challenging
- Seeking refined qualification protocol in areas including
  - Radiation
  - Intrinsic Reliability



G. Santin, et al. *New Geant4 based simulation tools for space and radiation shielding and effect analysis Slide 2. 8th Topical Seminar on Innovation Particles and Detectors. 21-24 October 2002. Siena Italy.*

AlGaN/GaN HEMT

- High Electron Mobility Transistors (HEMT) were first created with GaAs
- AlGaN/GaN HEMT failure mechanisms are located in nearly the same location and each type of failure mechanism has different effect on device performance



Slide 4 from The Aerospace Corporation presentation "Space Qualification of GaN HEMTs – Guidance Document Announcement" at the 20 June 2018 NASA NEPP meeting by John Scarpulla and Caroline Gee [1]

AlGaN/GaN HEMT Failure Mechanisms

- Inverse piezoelectric effect – changing the electric field at the interface which allows inversion due to the HEMT structure
- Hot carrier – particularly hot electrons which are caused when high electric fields create high energy electrons that can cause damage near the interface
- New trap generation -
- Contact degradation

AlGaN/GaN HEMT attributes

- GaN technology has performed well in radiation environments [2]
- Recent interest has coupled radiation with different performance states (on, off, semi-on) producing differing degradation [3]
- Additional coupling of radiation effects with long term reliability analysis has also been explored [4]

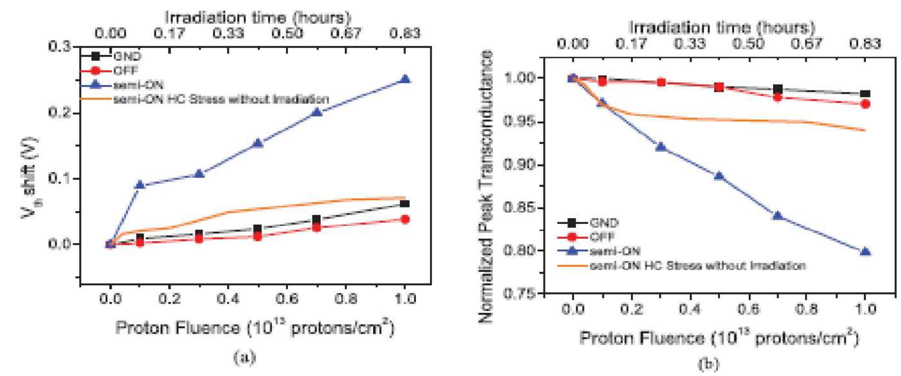
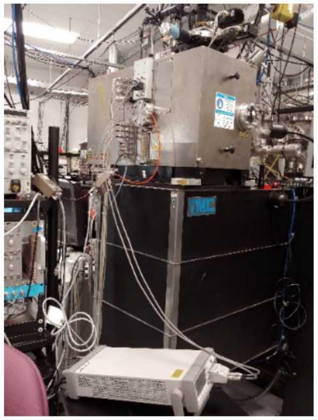


Fig. 3. (a) V_{TH} shift and (b) normalized peak transconductance for GaN/AlGaN HEMTs as a function of proton fluence, for $V_{ds} = 25$ V and $V_g = -2$ V. $V_{ds} = 5$ V during measurement. The hot carrier stress data (no irradiation) are from Fig. 2.

Chen et al. Effects of applied bias and high field stress on the radiation response of AlGaN/GaN HEMTs. IEEE Transacations of Nuclear Science. Vol 62. No 6. December 2015.

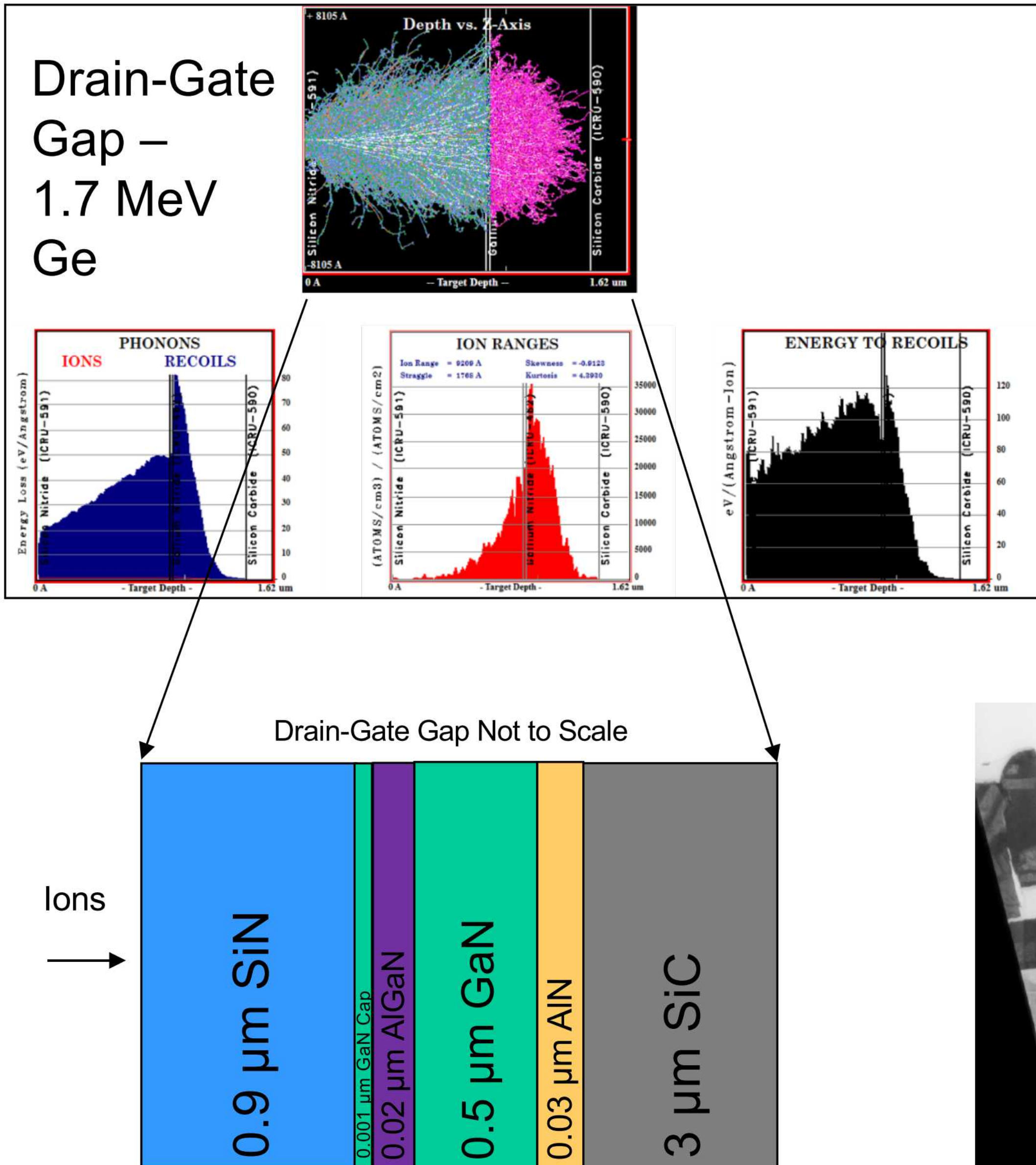
Experimental Details

- Goal: Determine if location vulnerable to stress testing is also vulnerable to heavy-ion irradiation; how does the vulnerability differ with different bias conditions?
- Sandia Ion Beam Laboratory
  - HVE 6 MV Tandem
  - MicroOne – microbeam with a spot size of ~1 micron
  - 1.7 MeV Germanium ion
- Targeted between gate and drain at different bias conditions while under irradiation to determine if location was susceptible to irradiation and if bias affects device performance

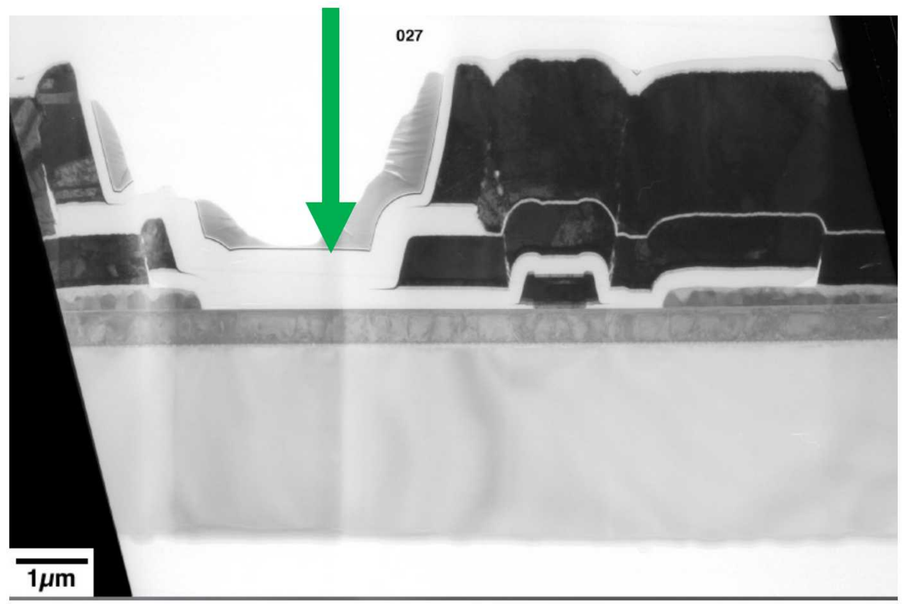


Experimental Setup at Sandia Ion Beam Laboratory

SRIM/TRIM Calculation



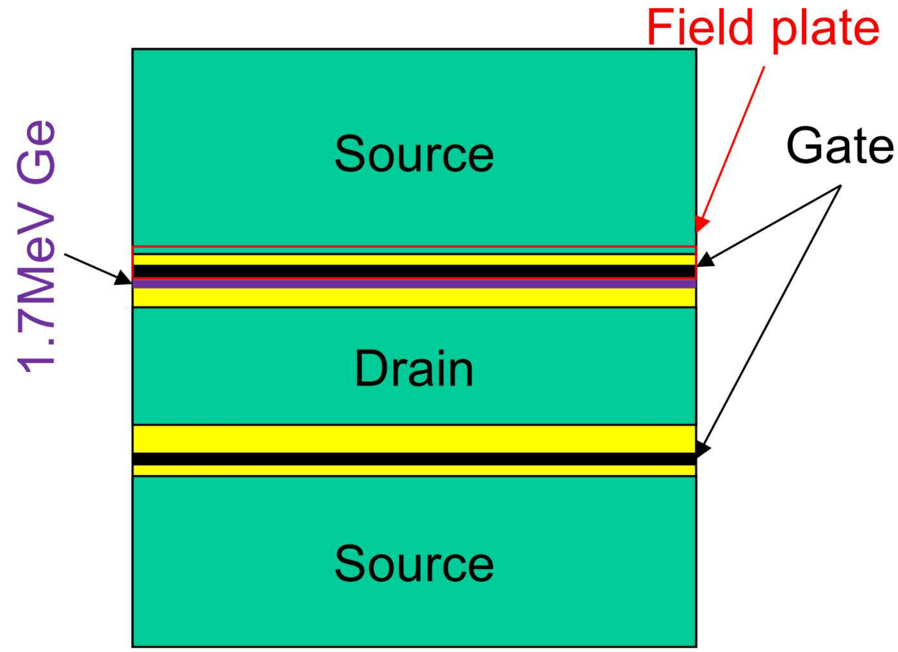
Top view of device



Cross section of device

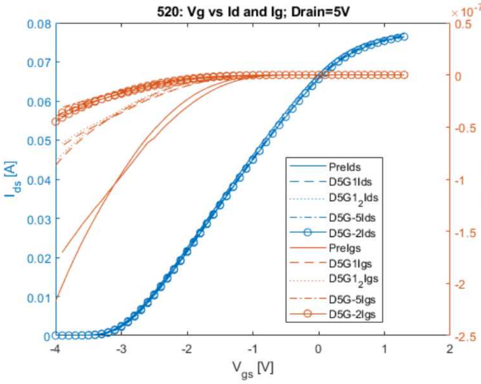
Experimental Details

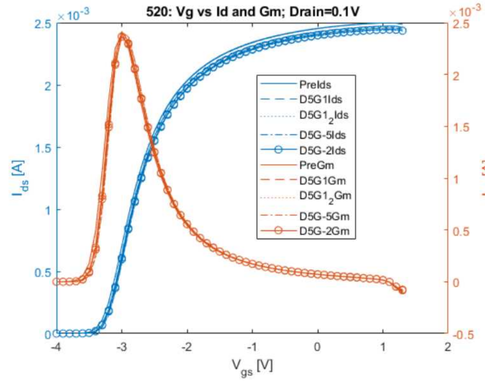
- Pre – Irradiation Measurement
- AlGaN/GaN HEMT held at a constant stress (off, on, or semi-on) while targeted 1.7MeV Ge ions at the drain side of the gate edge
- Insitu measurement of the stress/irradiation shows how the gate and drain current changes as irradiation and stress time increases
- Insitu measurement of control part was stressed in off, on and semi-on state without radiation
- Post-Irradiation Measurements

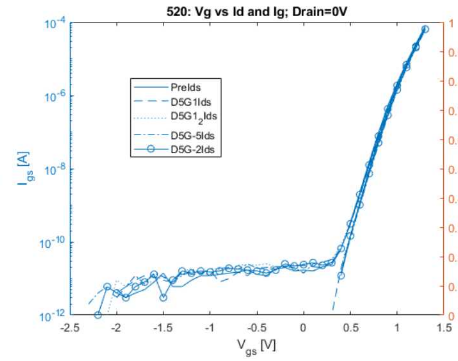


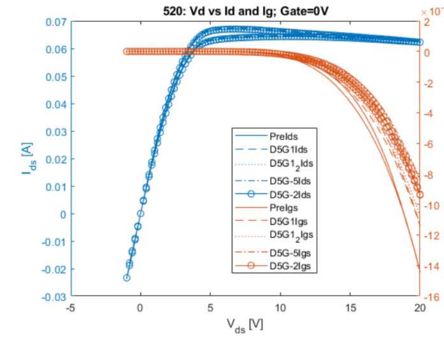
Device Vth = -3.1V	OFF Drain = 5V Gate = -5V	ON Drain = 5V Gate = 1V	SEMI ON Drain = 5V Gate = -2V
2655-0002 (502)			X
2655-0003 (503)	X		
2655-0006 (506)		X	
2655-0007 (507)			X
2655-0010 (510)	X		
2655-0011 (511)		X	
2655-0012 (512)			X
2655-0013 (513)		X	
2655-0017 (517)	X		
2655-0025 (525)			X

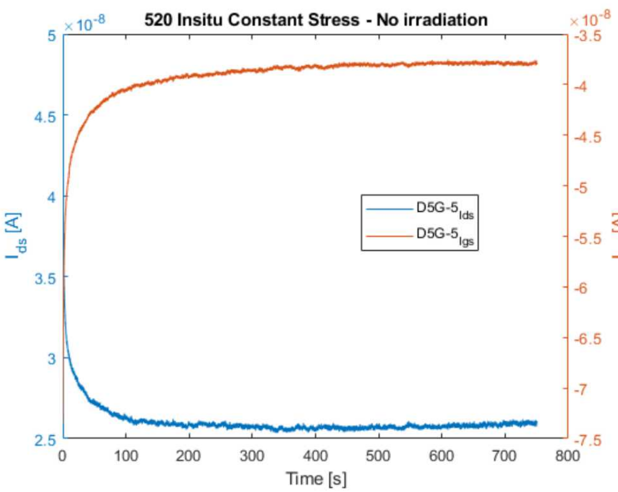
Results – Stress only (No irradiation)

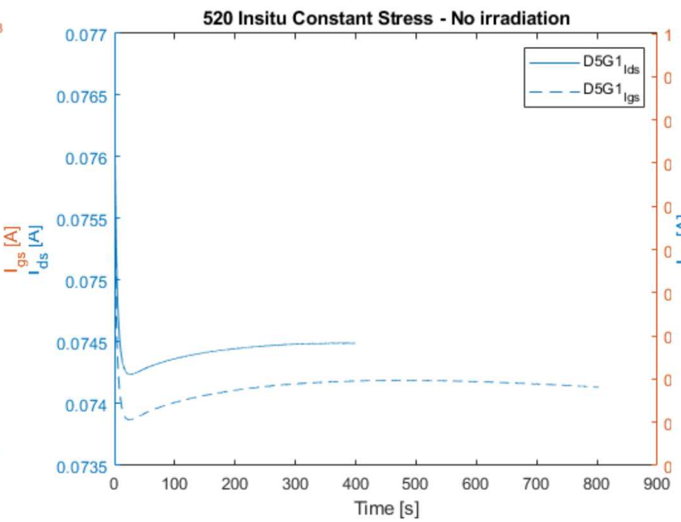


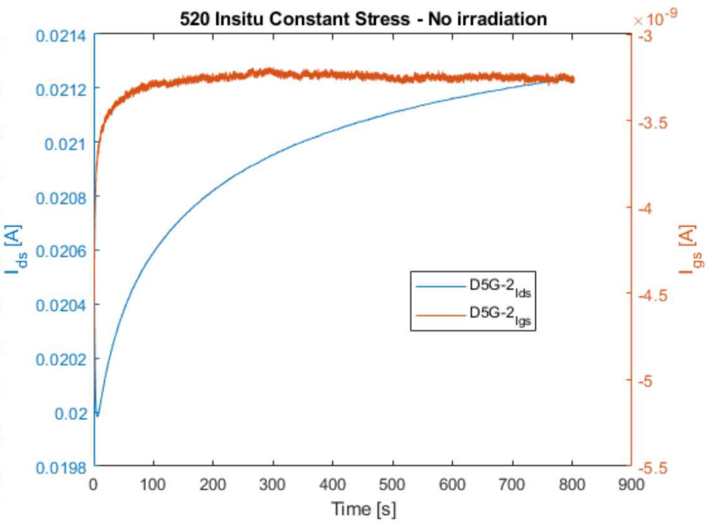




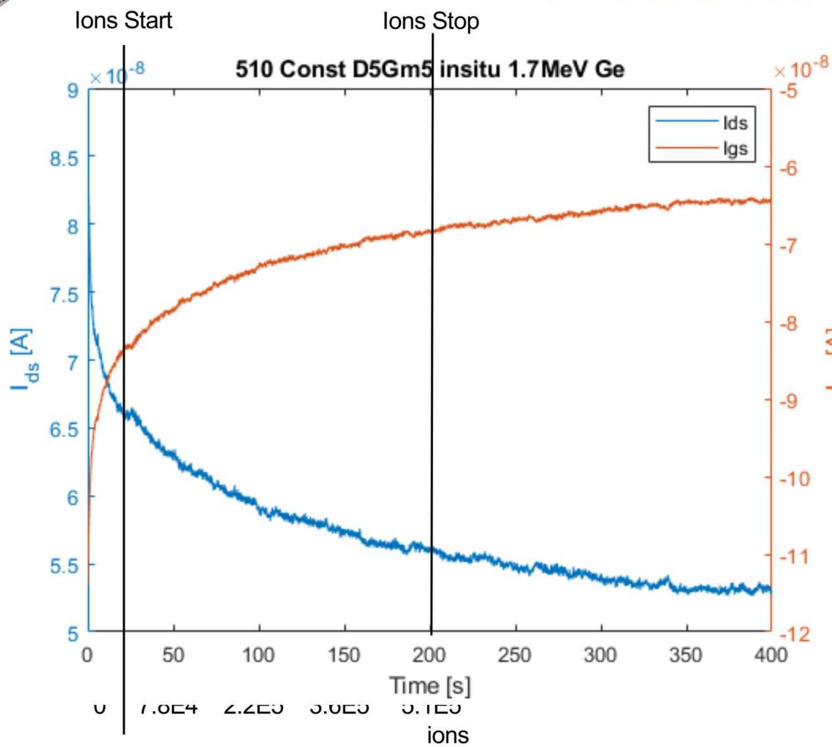


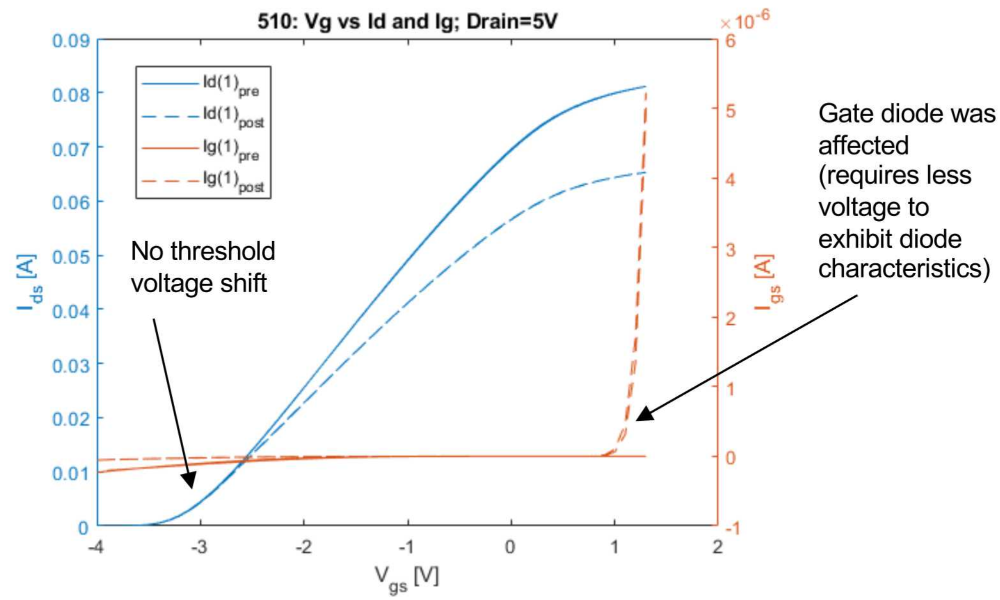


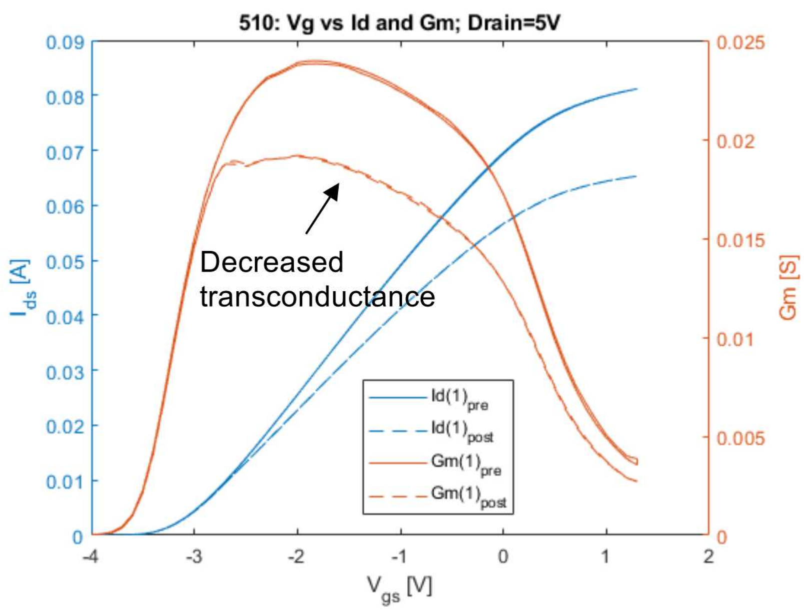


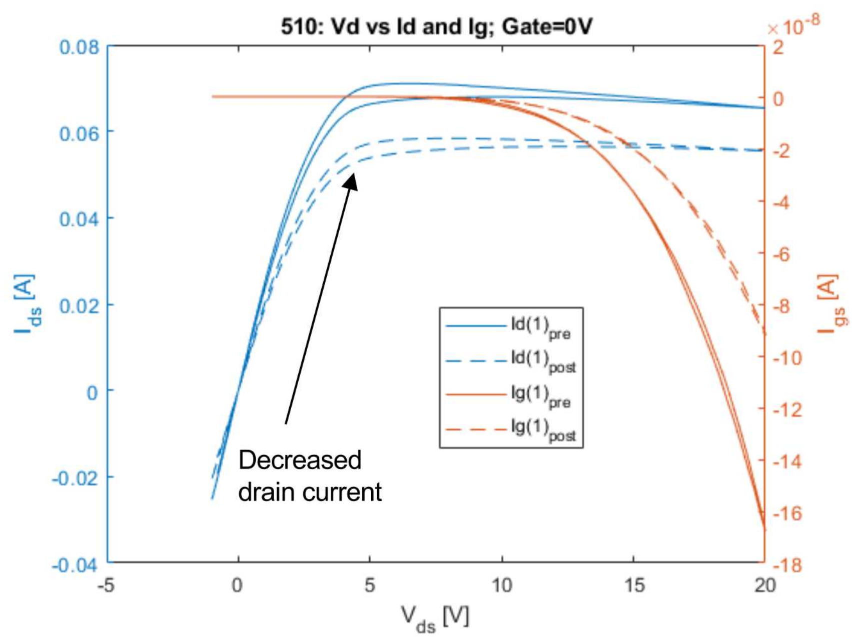


Results – Off State

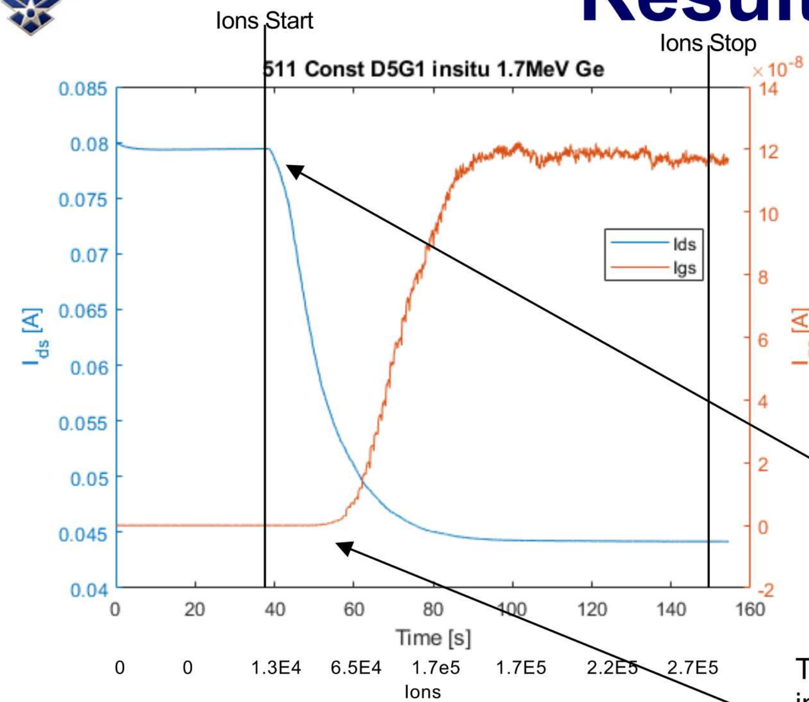






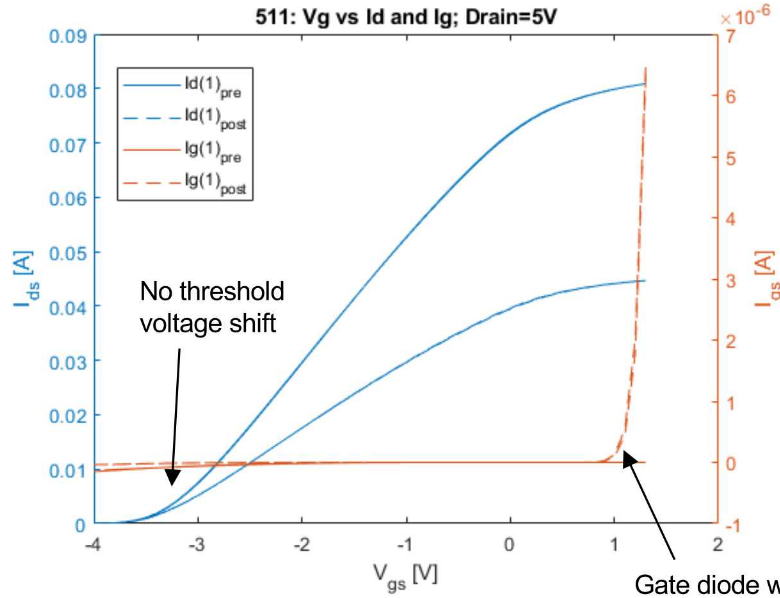


Results – On State

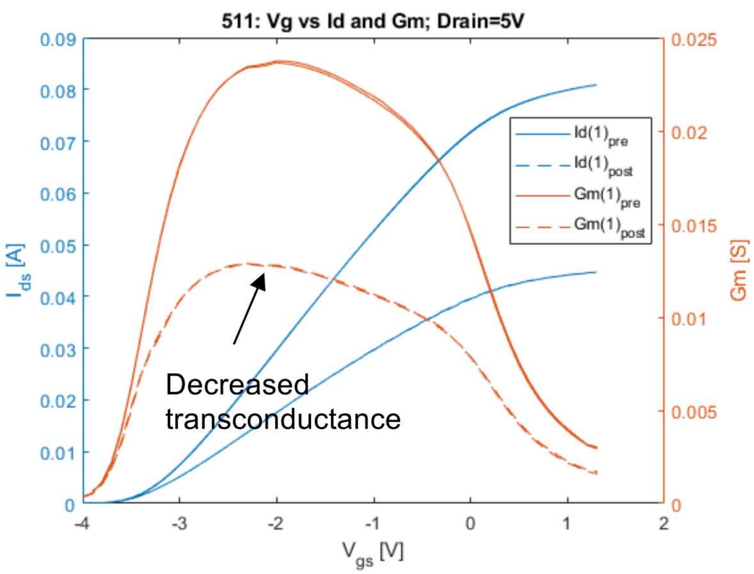


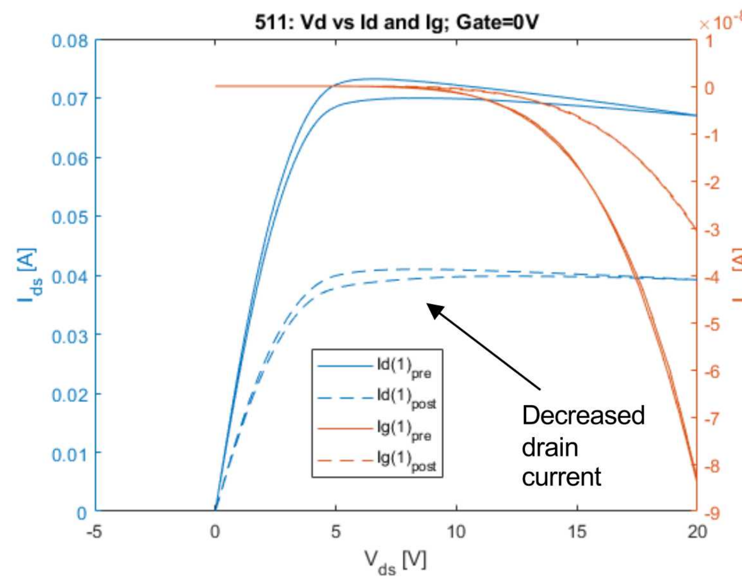
The drain current immediately decreased rapidly due to the ion strikes in the on-state

The gate current does not immediately increase due to ion strikes in the on state (~5×10[4] ions strike)



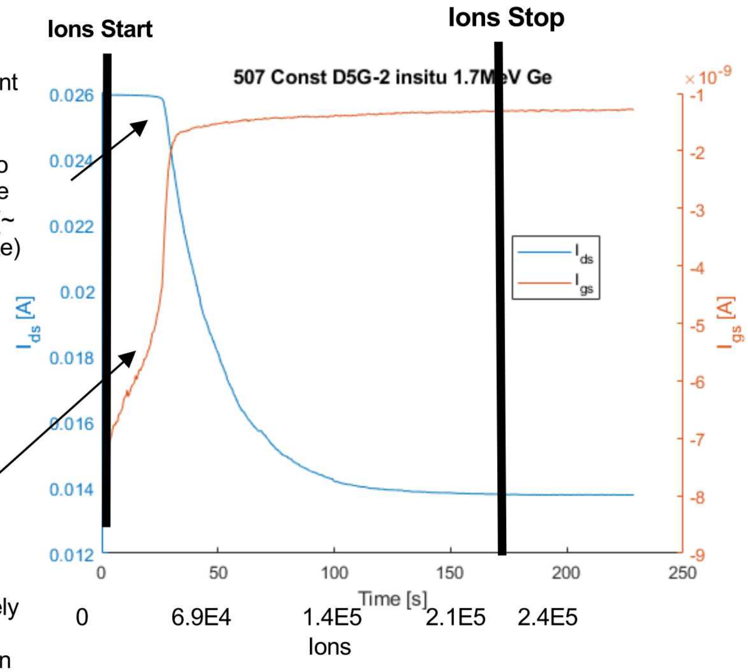
Gate diode was affected (requires less voltage to exhibit diode characteristics)



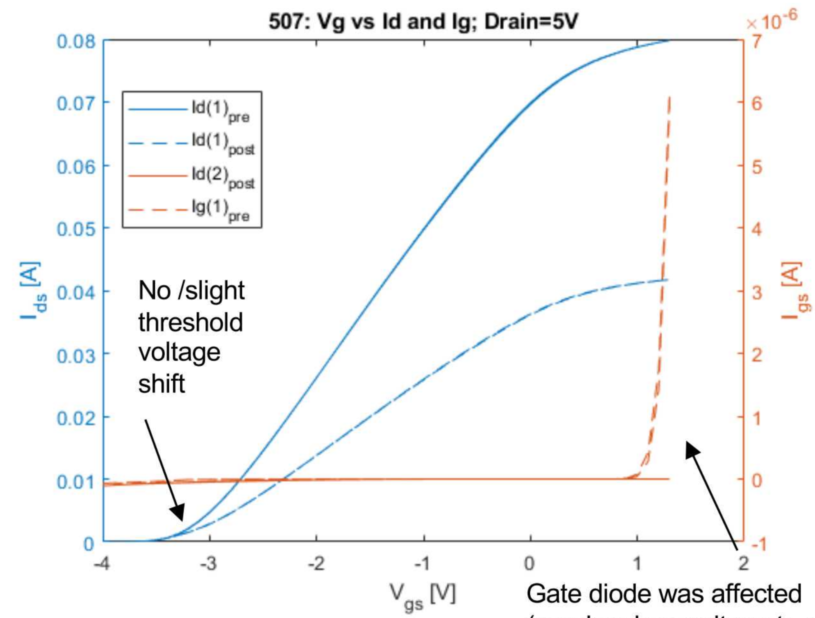


Results – Semi-On State

The drain current does not immediately decrease due to ion strikes in the semi-on state (~ 5×10[4] ions strike)

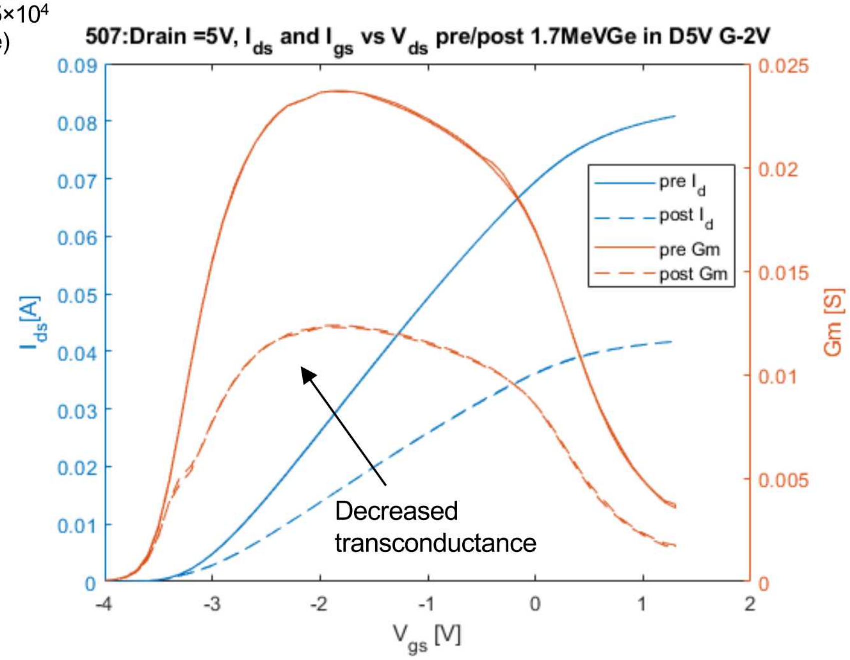


The gate current does not immediately decrease due to ion strikes in the semi-on state (~ 5×10[4] ions strike)

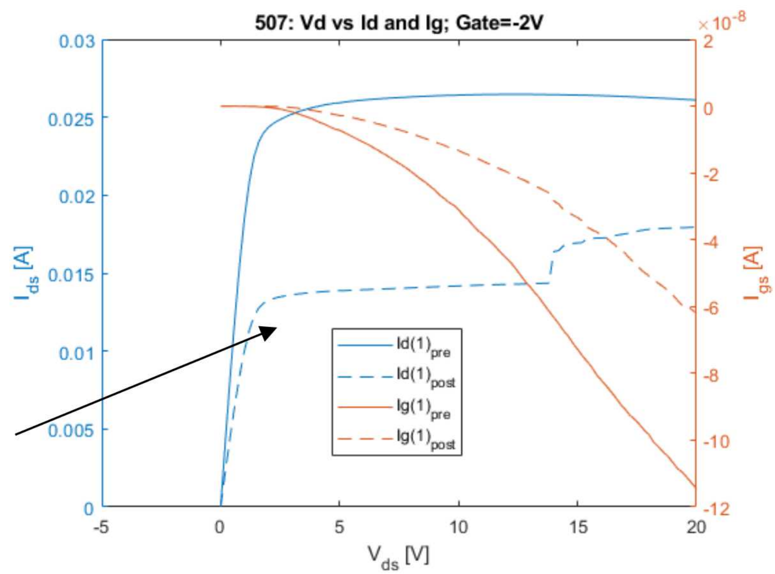


No /slight threshold voltage shift

Gate diode was affected (requires less voltage to exhibit diode characteristics)



Decreased transconductance

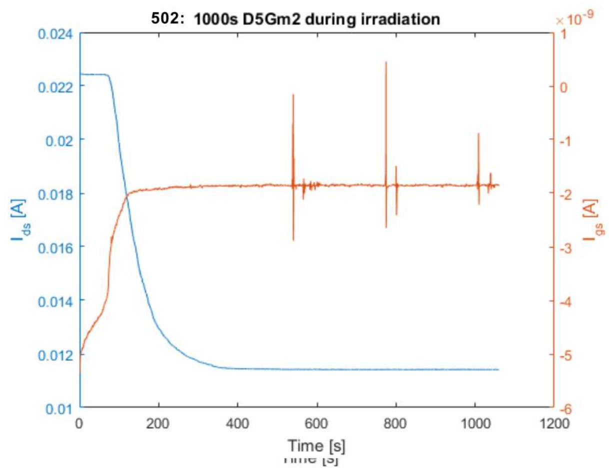


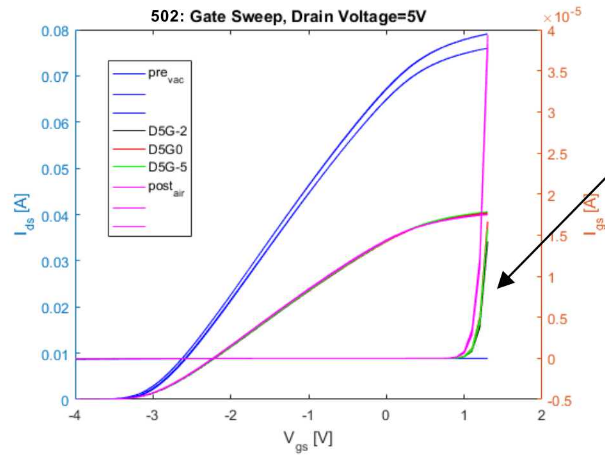
Decreased drain current

Distribution A

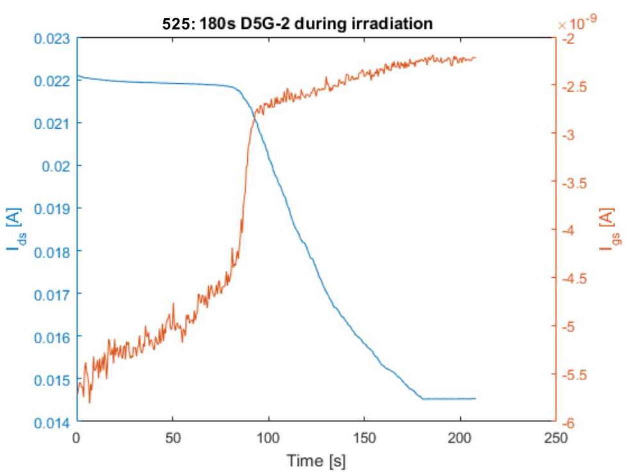
Recoverable

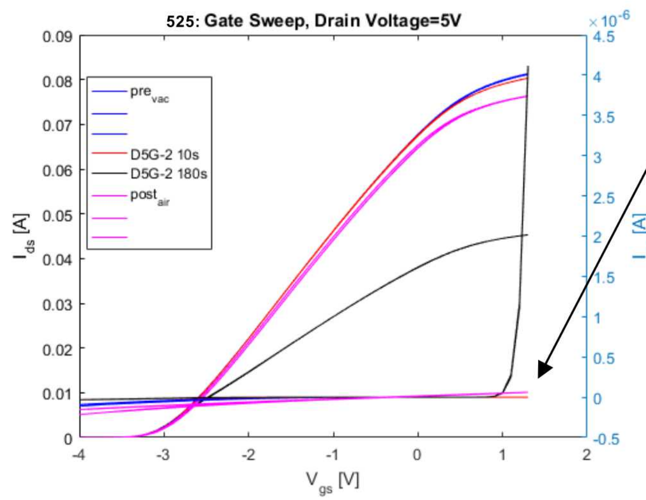
- Depending on where irradiation stopped, damage was either recoverable or permanent (Pink shows 30 day room temperature anneal)





Permanent change diode and transfer

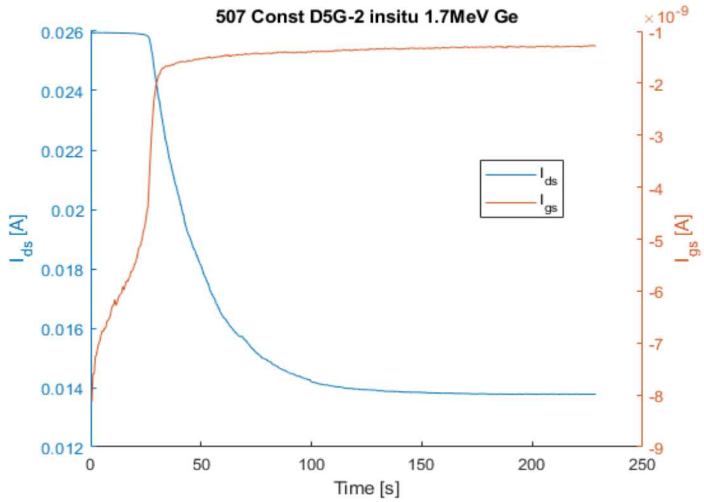


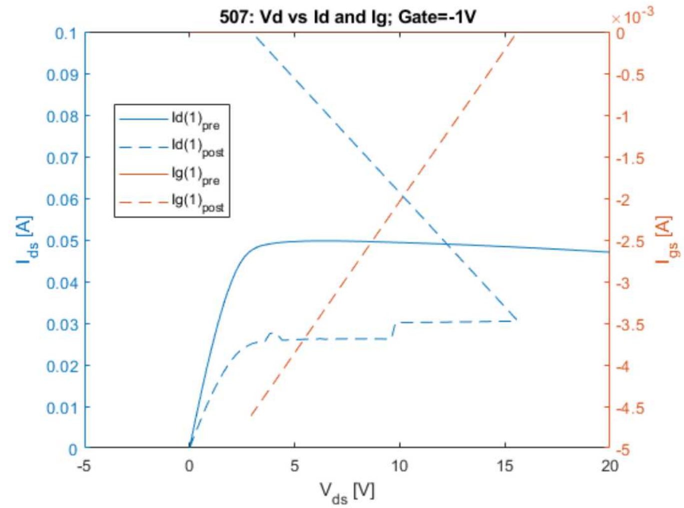


Recoverable diode and transfer

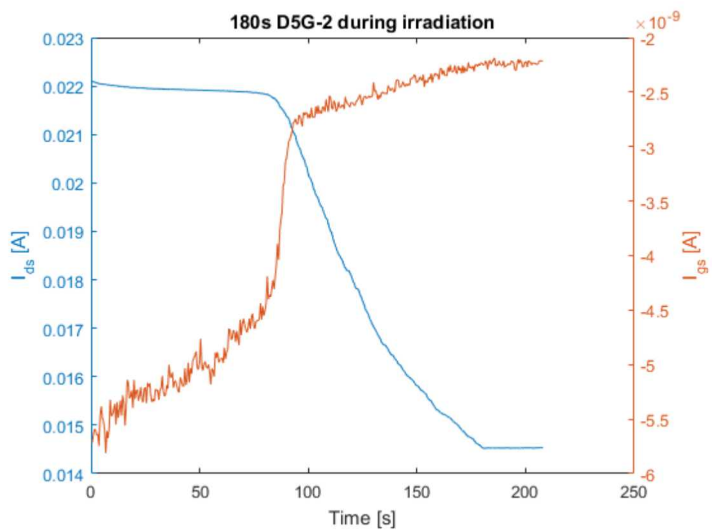
Post – Measurement Compliance Reached

- Semi-on state post measurements created too much stress for devices. 2 of 4 devices reached compliance during output measurement after completing a series of transfer characteristic measurements





525:



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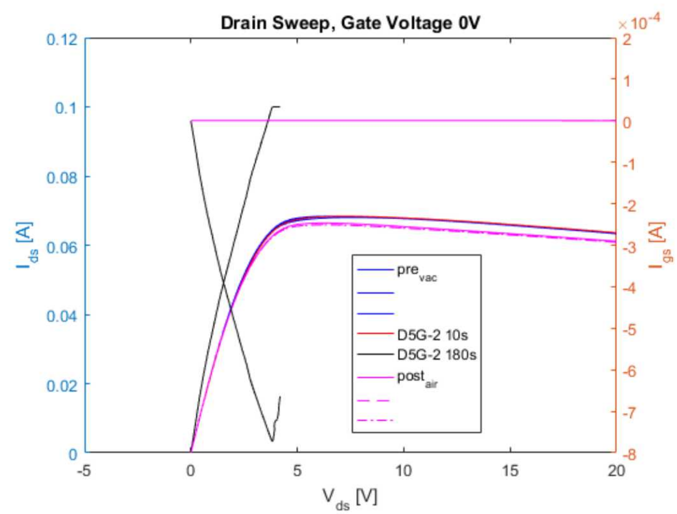
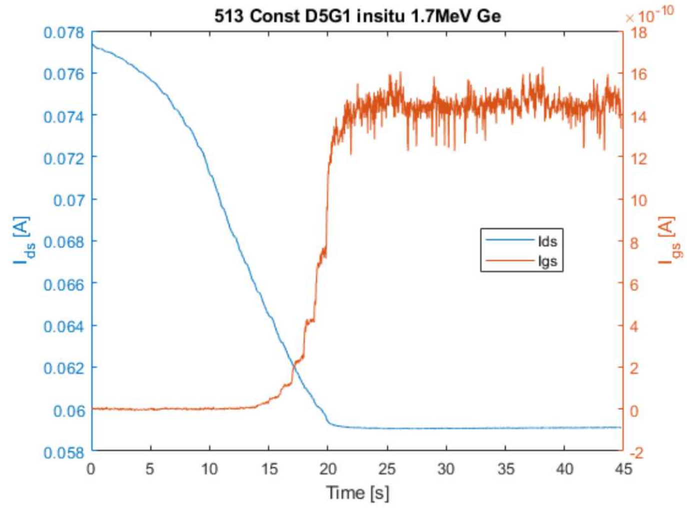
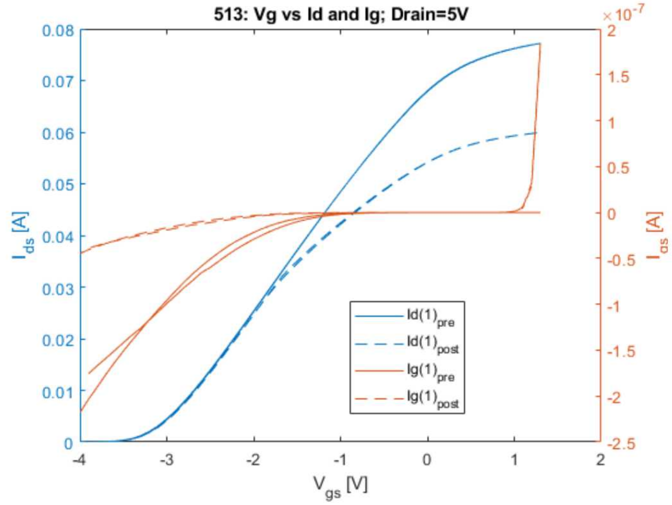
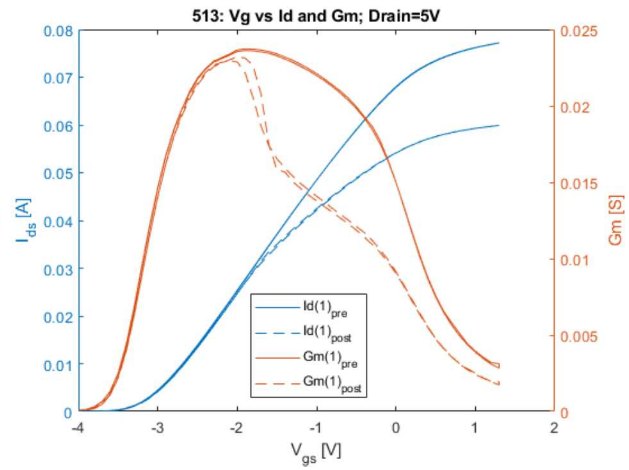


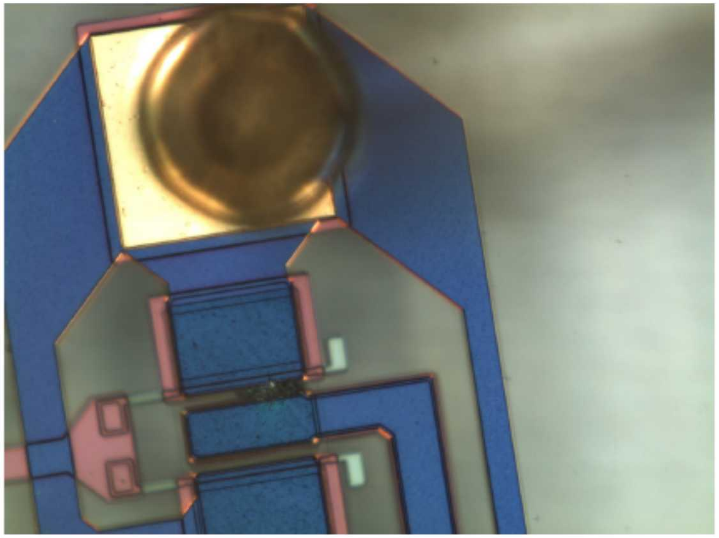
Part Burned Out

- On state device 2655-0013 burned out during post output measurements

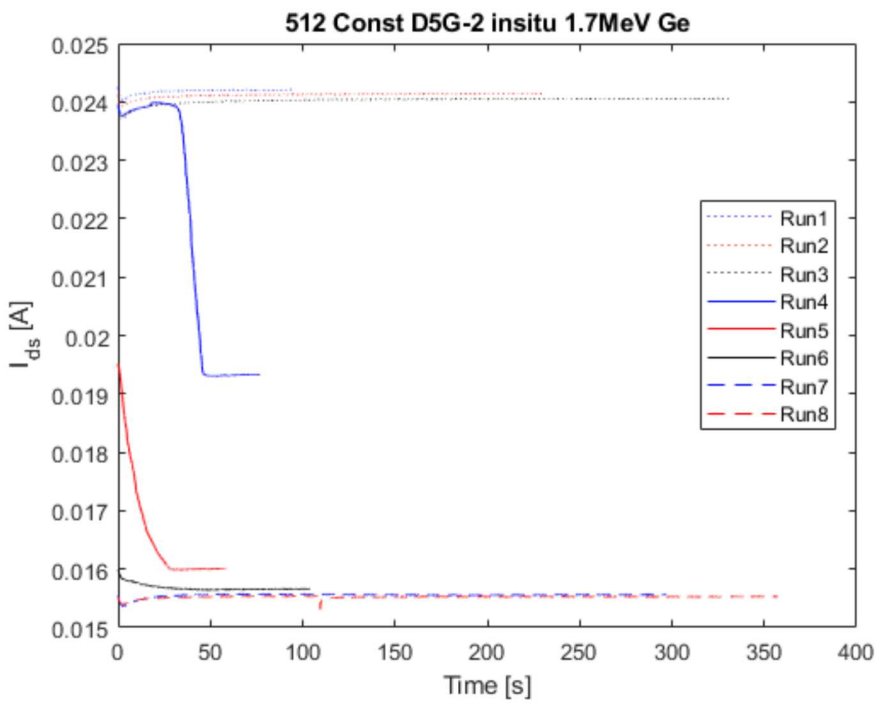


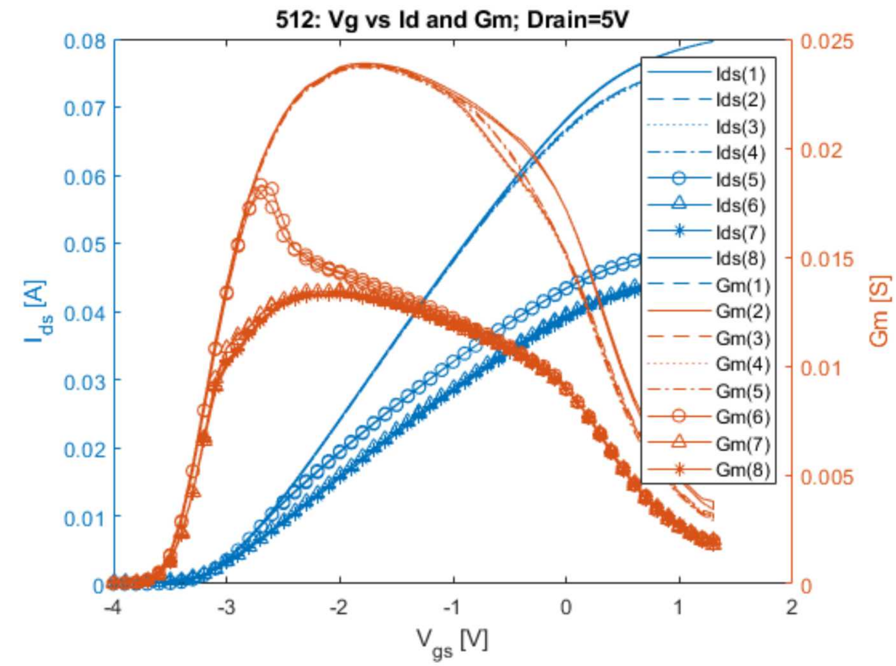


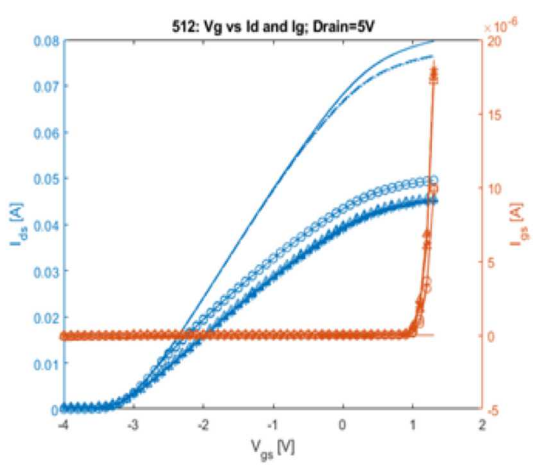


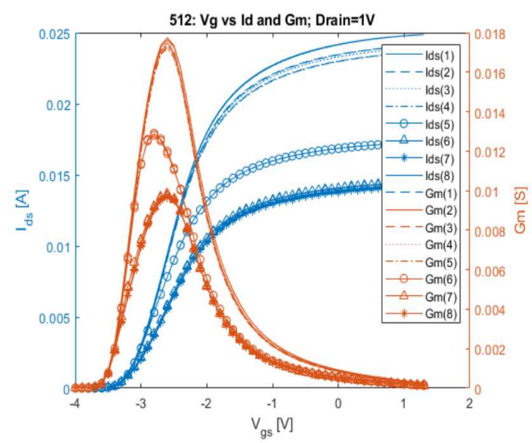


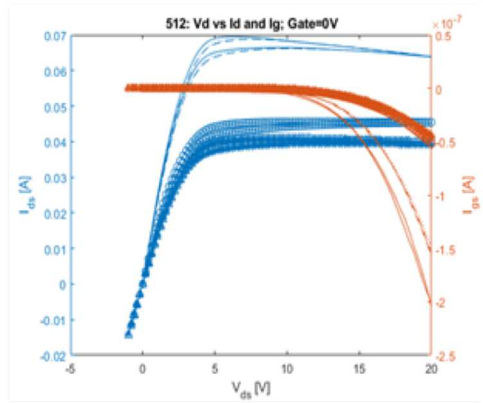
Cumulative Damage











Conclusion

- Damage of 5×10^4 Ge ions across 50 microns causes damage to on-state and semi-on state parts (fluence $1\text{x}10^{11}$ cm^{-2})
- All stress states (on, off, and semi-on) cause similar characteristic changes when the gate-drain gap is targeted with 1.7MeV Ge ions
  - Decreased transconductance
  - Gate diode characteristics affected at higher drain voltage (requires less voltage to exhibit diode behavior)
  - Decreased drain current
  - No threshold voltage shift, No change to Ron
- When high voltage post-measurement sweeps are accomplished after semi-on state irradiation; the parts can act abnormal (hit compliance).
  - This damage may be recoverable
- When high voltage post-measurement sweeps are accomplished after on state irradiation; the parts can blow up

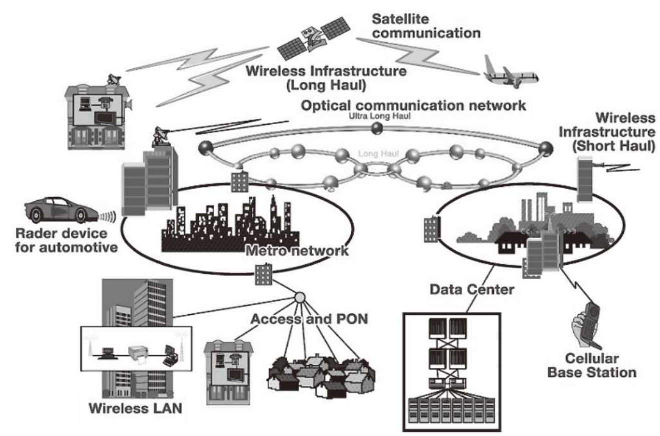
Questions

References

1. John Scarpulla and Caroline Gee. *Space Qualification of GaN HEMTs – Guidance Document Announcement*. The Aerospace Corp. NASA NEPP. 20 June 2018.
2. S.J. Pearton, F.Ren, E. Patrick, M.E. Law, A.Y. Polyakov. *Review-Ionizing Radiation Damage Effects on GaN Devices.* ECS Journal of Solid State and Technology, 5 (2) Q35-Q60 (2016).
3. J. Chen, et al. *Effects of Applied Bias and High Field Stress on Radiation Response of GaN/AlGaN HEMTs*. IEEE Transactions on Nuclear Science, Vol 62. No 6. December 2015.
4. B.S. Poling, G.D. Via, K.D. Bole, E.E. Johnson, J.M. McDermott. *Commercial-off-the-shelf algan/gan hemt device reliability study after exposure to heavy ion radiation*. Microelectronics Reliability. 68.(2017) 13-20.
5. Christiansen, Bradley D., et al. "A Very Robust AlGAN/GaN Technology to High Forward Gate Bias and Current." Active and Passive Electronic Components. 28 Jul 2012.
6. Cheney, D. J., et al. "Reliability studies of AlGaN/GaN high electron mobility transistors" Semicond. Sci Tecnol. 28 (2013) 074019 (12pp). doi: 10.1088/0268-1242/27/7/074019.
7. Paine, B.M. et al. "Lifetesting GaN HEMTs with Multiple Degradation Mechanisms. IEEE Transaction on Device and Material Reliability. 15(4):486-494, Dec 2015.
8. Chen et al. "Effects of Applied Bias and High field stress on the radiation response of GaN/ALGaN HEMTs." IEEE Transaction of Nuclear Science. Vol. 62, No 6, December 2015.
9. Meneghesso, G. et.al. Degradation of AlGaN/GaN HEMT devices: Role of reverse-bias and hot electron stress. Microelectronic Engineering. 109 (2013) 257-261. http://dx.doi.org/10.1016/j.mee.2013.03.017.
10. Chen, Chung-Hsu. Et al. "The causes of GaN HEMT bell-shaped transconductance degradation." Solid-State Electronics. 126(2016) 115-124.
11. J. Joh and J. A. del Alamo, "Critical voltage for electrical degradation of GaN high-electron mobility transistors," IEEE Electron Device Lett., vol. 29, no. 4, pp. 287–289, 2008.

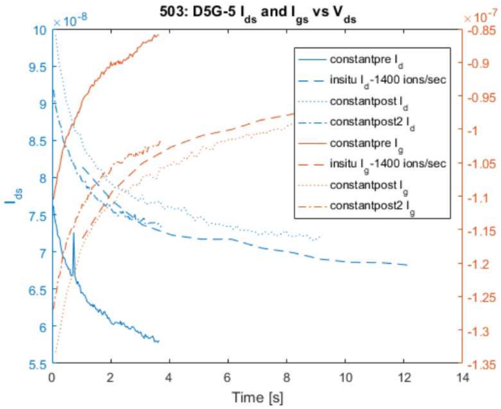
Motivation

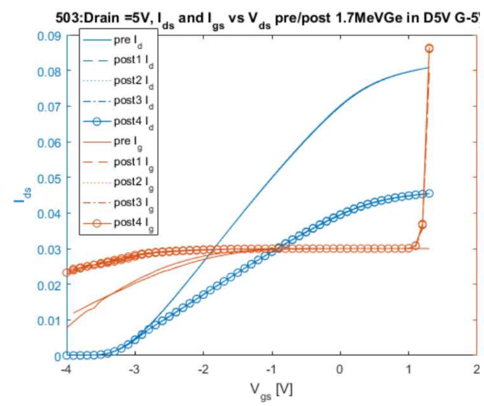
- Devices are smaller and faster aided by using wide-bandgap materials (GaN, Ga_2O_{3}, etc) reducing weight and volume
- Gallium Nitride High Electron Mobility Transistors (HEMTs) are designed to allow increased voltage and current to pass through the device
  - Greater efficiency than silicon in higher power output, speed, frequencies and temperature environments
  - Harder radiation tolerance due to wider bandgap
- GaN HEMT technology used in a variety of applications including
  - High speed switches, RF power in the GHz range
  - Communication
  - Satellite Radar – L, S, C, X and KU band
  - Power Amplifiers
  - Specific space-based versions of above

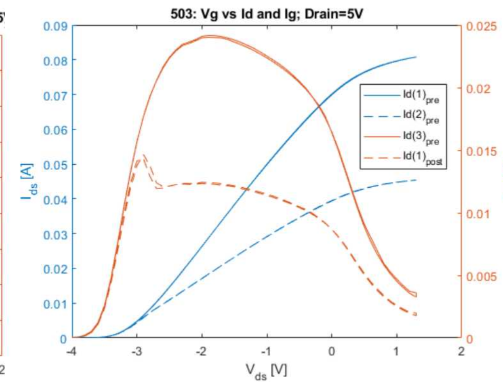


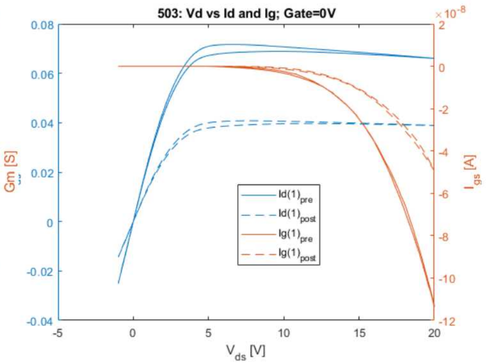
https://global-sei.com/technology/tr/bn86/pdf/86-13.pdf

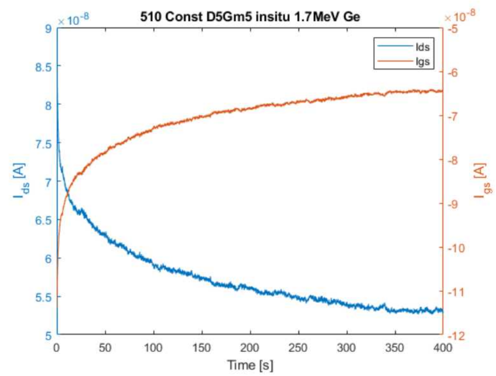
Results – Off State

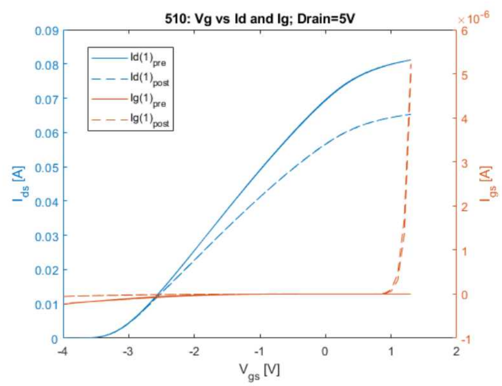


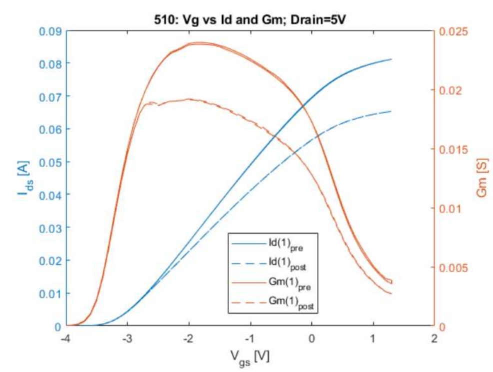


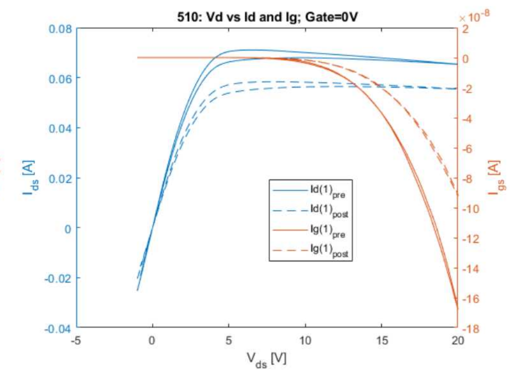


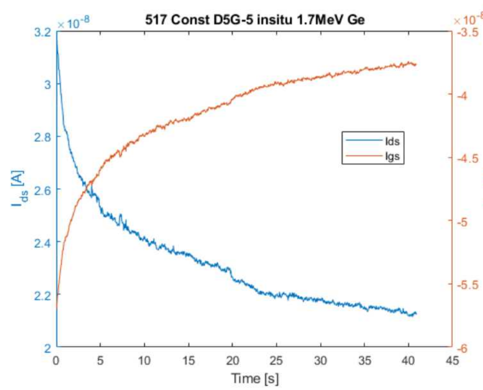


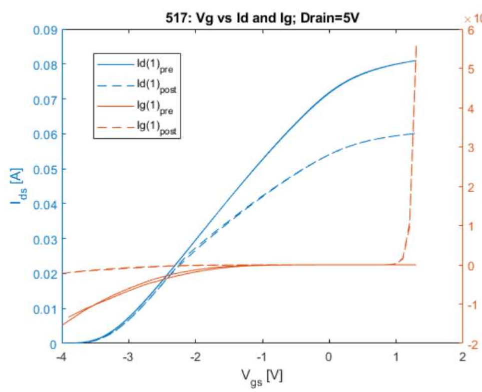


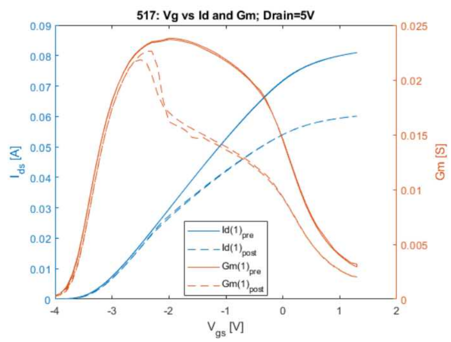


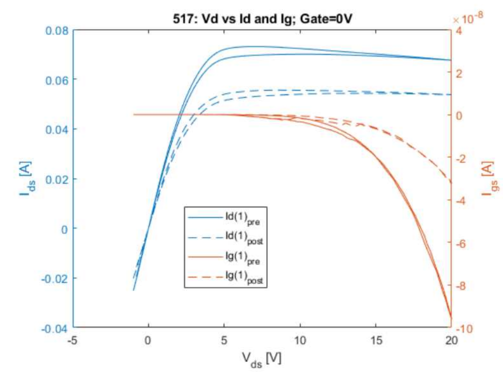




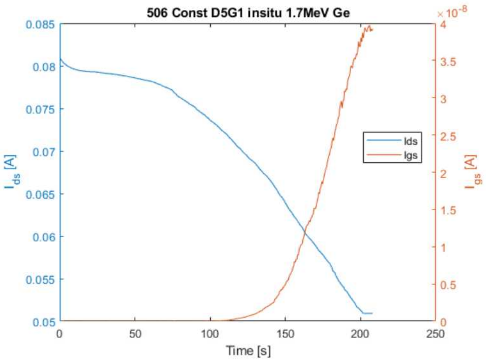


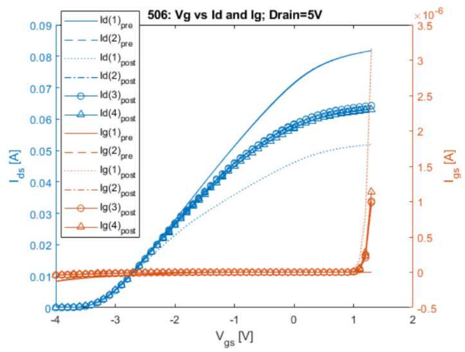


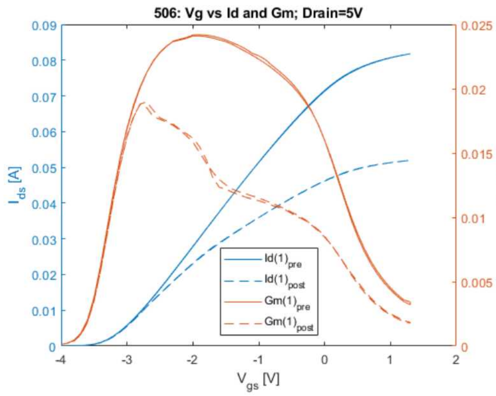


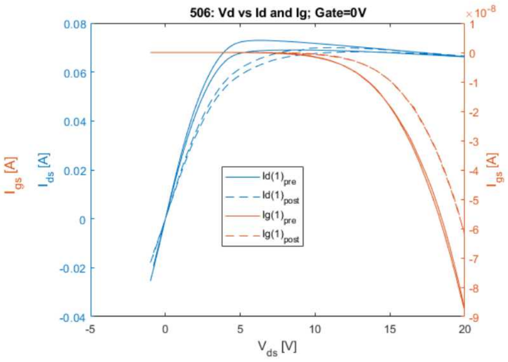


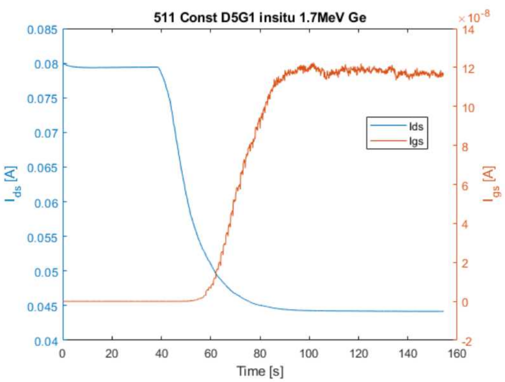
Results – On State

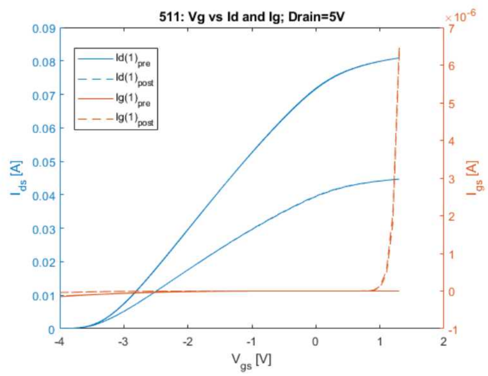


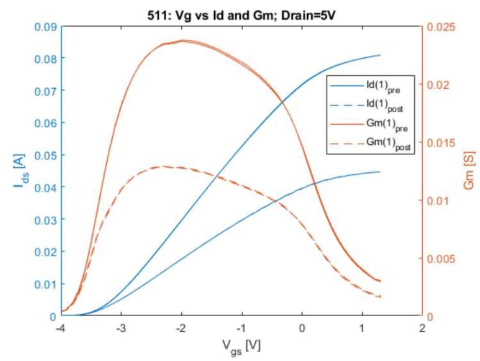


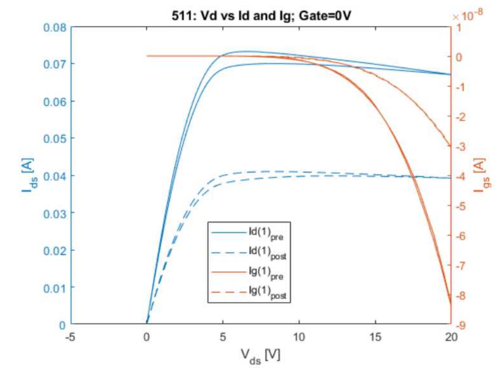


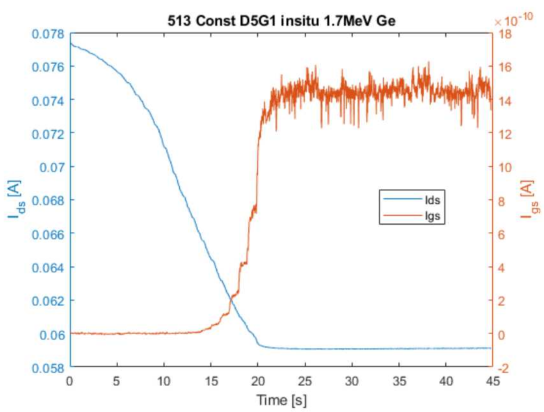


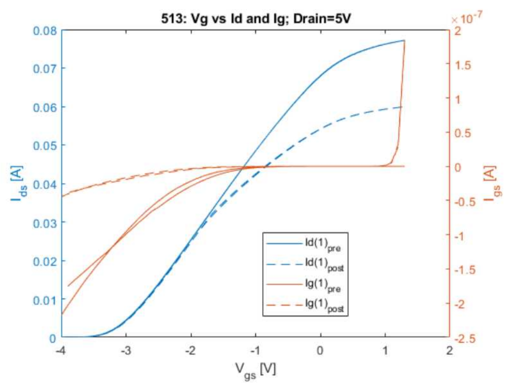


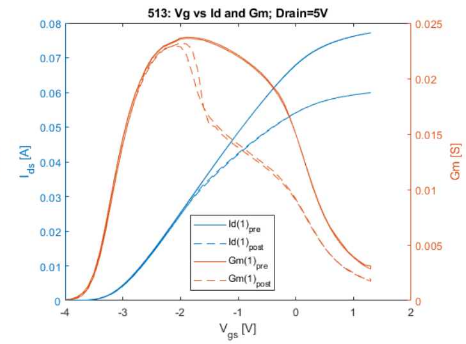


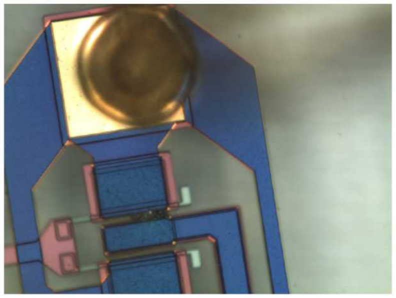












Results – Semi On State