RF Driven Lifetesting of GaN Power MMICs

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19 June, 2019
NASA NEPP Conference
Beltsville, MD

Statement of the Problem

the qualification question…..

- GaN RF HEMT technology is an excellent option for high power SSPA applications in space
  - *VHF to mm-Wave*
  - *Single transistors up to 200W and beyond*
  - *MMICs to 50W and beyond*

However

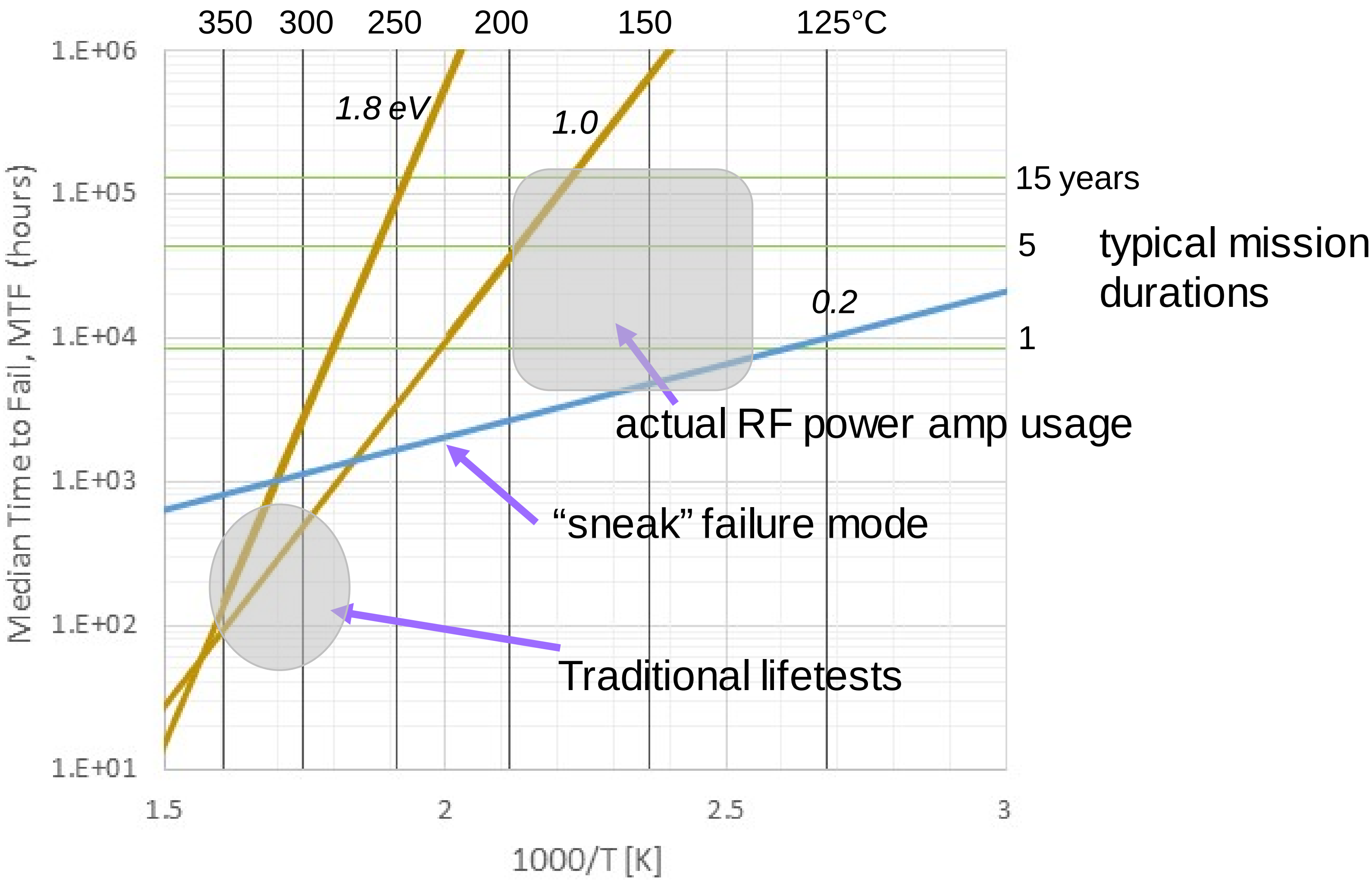
- GaN RF HEMT technology has not yet been flown in a Class A or B mission
  - *ultra-reliability must be proven*
  - *a handful of successful demonstration programs with relatively short durations*
- How to qualify?
  - *step stressing*
  - *DC lifetests, 3 temperatures*
  - *HTRB*
  - *SOA*
  - *ESD, etc.*
  - ***RF-driven lifetesting – "Test Like You Fly" (TLYF) - this presentation***

ref. Aerospace Technical Report, ATR-2017-0782 "DRAFT – Guidelines for Space Qualification of GaN HEMT Technology", J. Scarpulla & C. Gee, May 23, 2017

But "RF driven lifetests are hard!"

Traditional lifetests might miss "sneak" failure mode

low E_A mechanism(s) must be disproven



TLYF testing recommended to confirm high reliability

Flight-like Test Article

- Custom broadband MMIC power amp
  - *0.25µm gate length HEMTs process*
  - *Output Power 41dBm (12.5W) min.*
    - at 6dB compression
    - at pulsed duty cycle ≤ 50%
    - at T_{ch} = 200°C
  - *Power-added efficiency 40%*
  - *Drain voltage V_{DD} = 40V*
  - *Drain Current, Quiescent I_{DQ} =480 mA*
  - *bandwidth 150MHz – 2GHz*
  - *devices packaged in ceramic packages*
  - *removable lids*

- Success Criteria (in-situ)
  - *output power degradation, ΔP_{out} < 1 dB*
  - *small signal gain degradation, Δs_{21} < 1dB*
  - *current at I_D = 860 mA, I_G < 1mA/mm*

test goals: 4 DUTs tested for 5000 hours

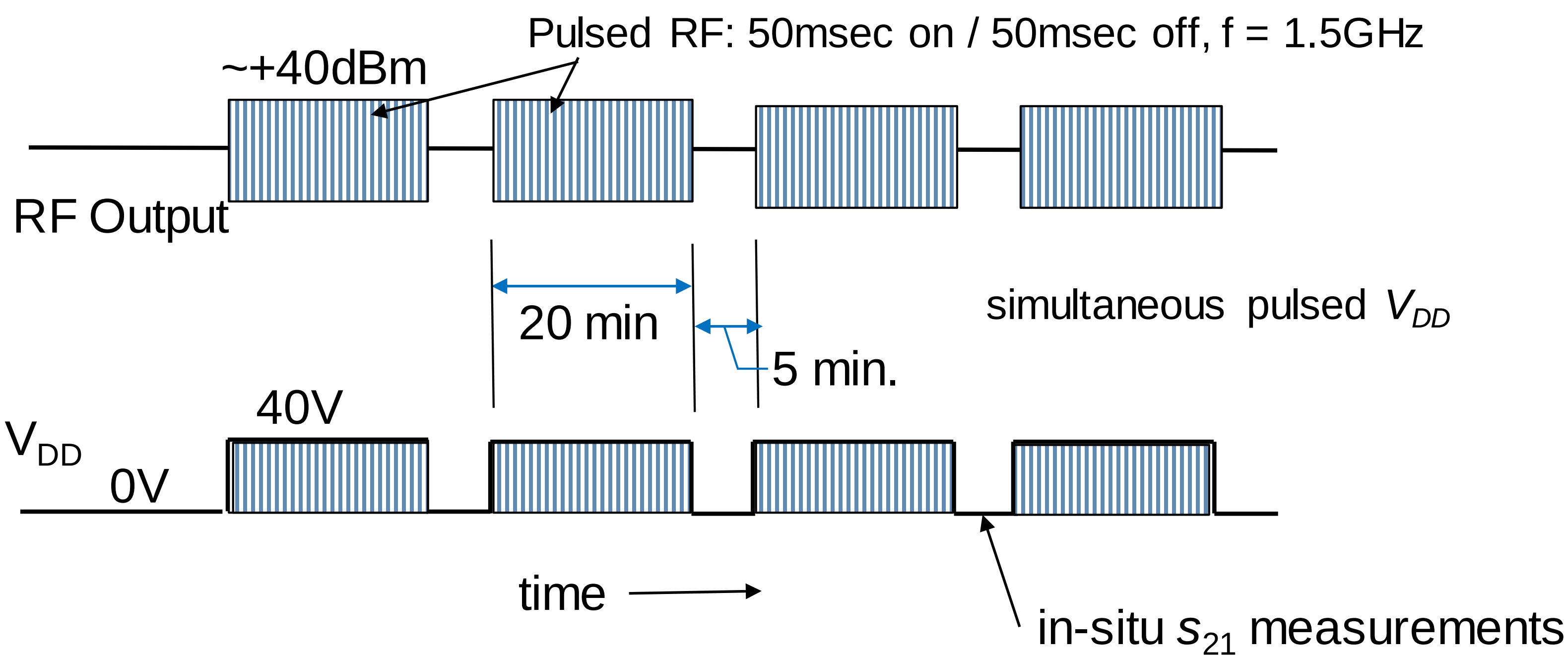
TLYF details

- Burn-in
  - *T = 200°C channel, 320 hours*
  - *DC only, V_{DD} = 40V, I_{DQ} =0.48 A*
  - *N_2 purged*
- pre/post measurements
  - *swept s-parameters*
  - *P_{out} vs. P_{in} at 1.5 GHz*
  - *pulsed IV*
- TLYF test
  - *defined pulsed waveform*
  - *P_{out} ~ 41 dBm*
  - *P_{in} ~ 10 dBm*
  - *T = 50°C baseplate, (est. 200°C channel)*
  - *lab air environment*
  - *I_D = 860 mA, pulsed*
  - *in-situ measurements of*
    - gain (s_{21}), P_{out}, I_G gate current

RF stress waveforms for TLYF

pulsed operation to simulate mission

- *RF input has a 50% duty cycle: 50msec on / 50 msec off f = 1.5 GHz*
- *Maintain pulsed RF input for 20 minutes on period*
- *Then RF input and VDD are switched off for 5 min. rest period*
  - s21 measurement at f=1.5GHz during each off period
- *Repeat the sequence for up to 5,000 hours*



- *Risetimes and falltimes of RF pulses = 1μsec*
- *VDD and VG on/off risetime and falltime = 50μsec*

TLYF Essential Requirements

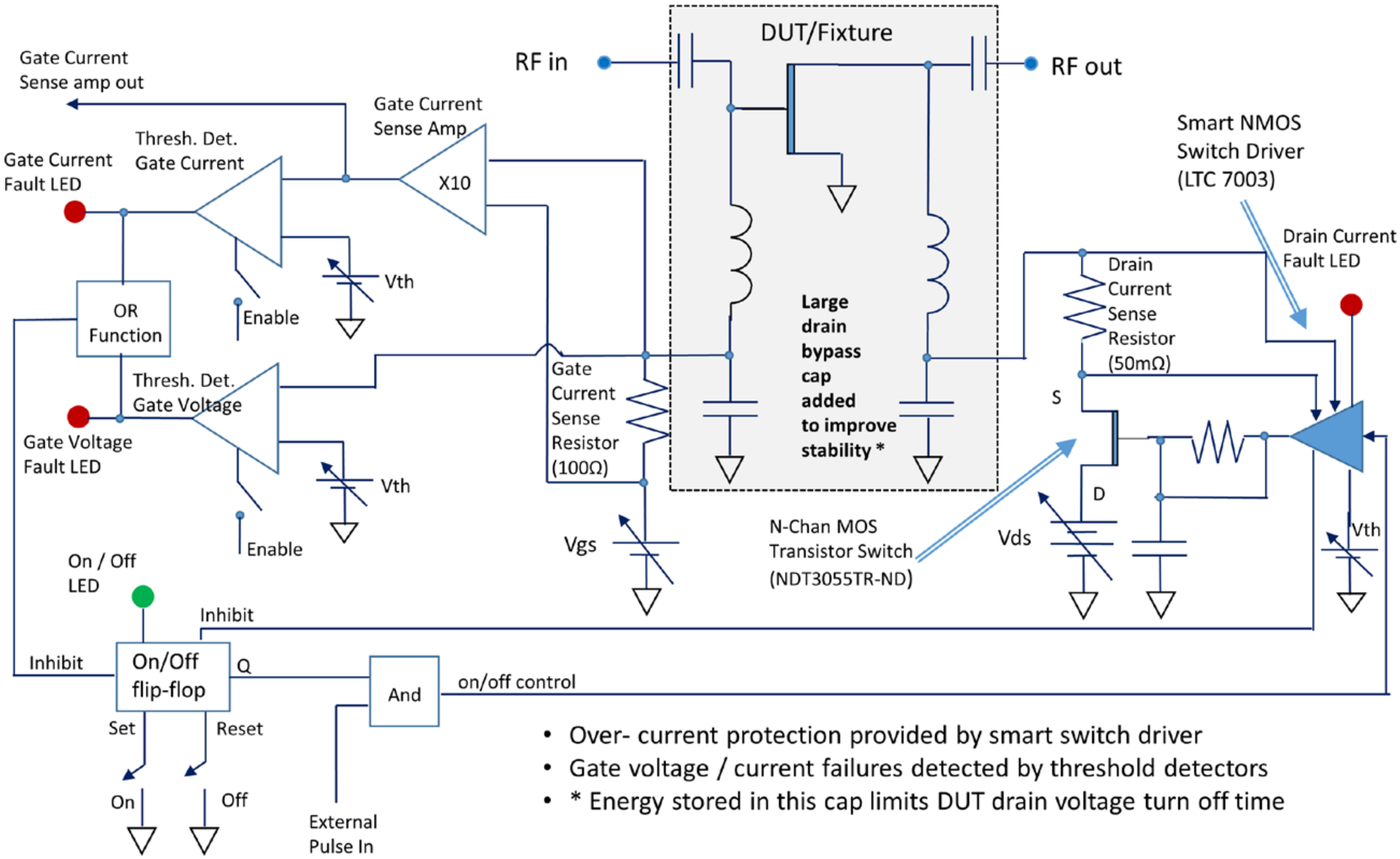
test set design features

- continuous measurement of P_{out}, I_D, I_G, V_D, V_G
  - *once per second, data stored*
- Protections (very important)
- Substantial V_{DD} power supply can potentially do serious damage
  - *GaN HEMT's are very susceptible to damage from improper DC biasing*
- Rapidly (within μ seconds) remove prime VDD power IF:
  - V_G *gate bias is lost,*
    - protects device from catastrophic destruction in case of a gate short failure
    - gate short could be a dendrite, a weak spot in field plate, MIMCAP failure etc.
  - I_G *gate currtent rises above acceptable limit (> 1mA/mm)*
    - possible indication of imminent failure
    - hot electron degradation or trap generation at drain-gate recess
  - *drain overcurrent,* I_D
    - protects device from catastrophic destruction in case a drain-source short develops
- In case bad things happen, the DUT does not suffer collateral damage
  - *DUT failure analysis can be performed*

Special measures have been taken to protect the GaN DUTs

MMIC test set block diagram

detects three fault types that rapidly latch the DUT off

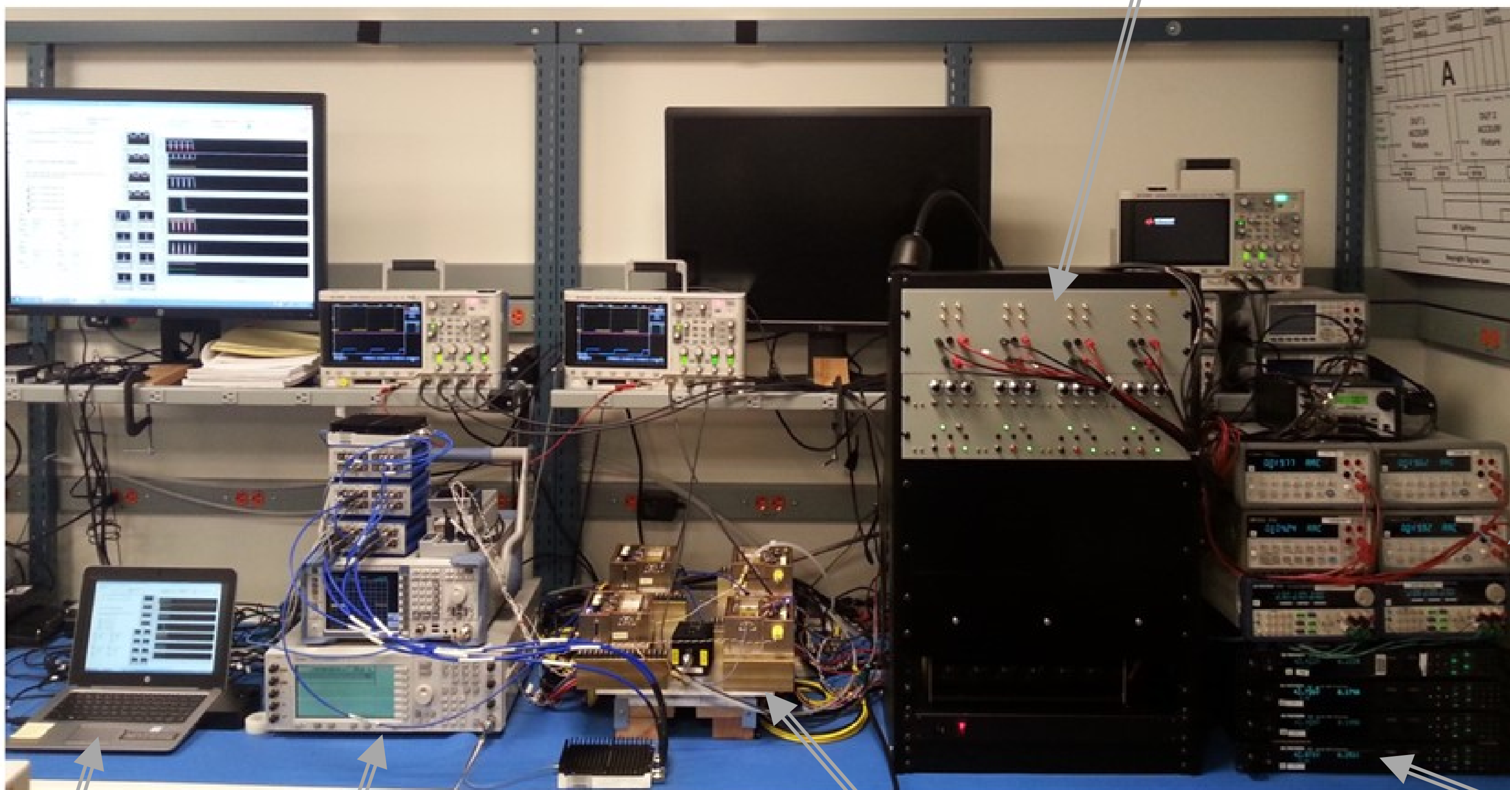


- Over- current protection provided by smart switch driver
- Gate voltage / current failures detected by threshold detectors
- * Energy stored in this cap limits DUT drain voltage turn off time

Luckily the protection circuits were only invoked in cases of operator error – no test failure conditions were detected

Test Set

protection circuits



voltage/
current
meters

LabView
software

Instruments:
spectrum analyzer,
RF switches,
oscilloscope,
pulser, RF source

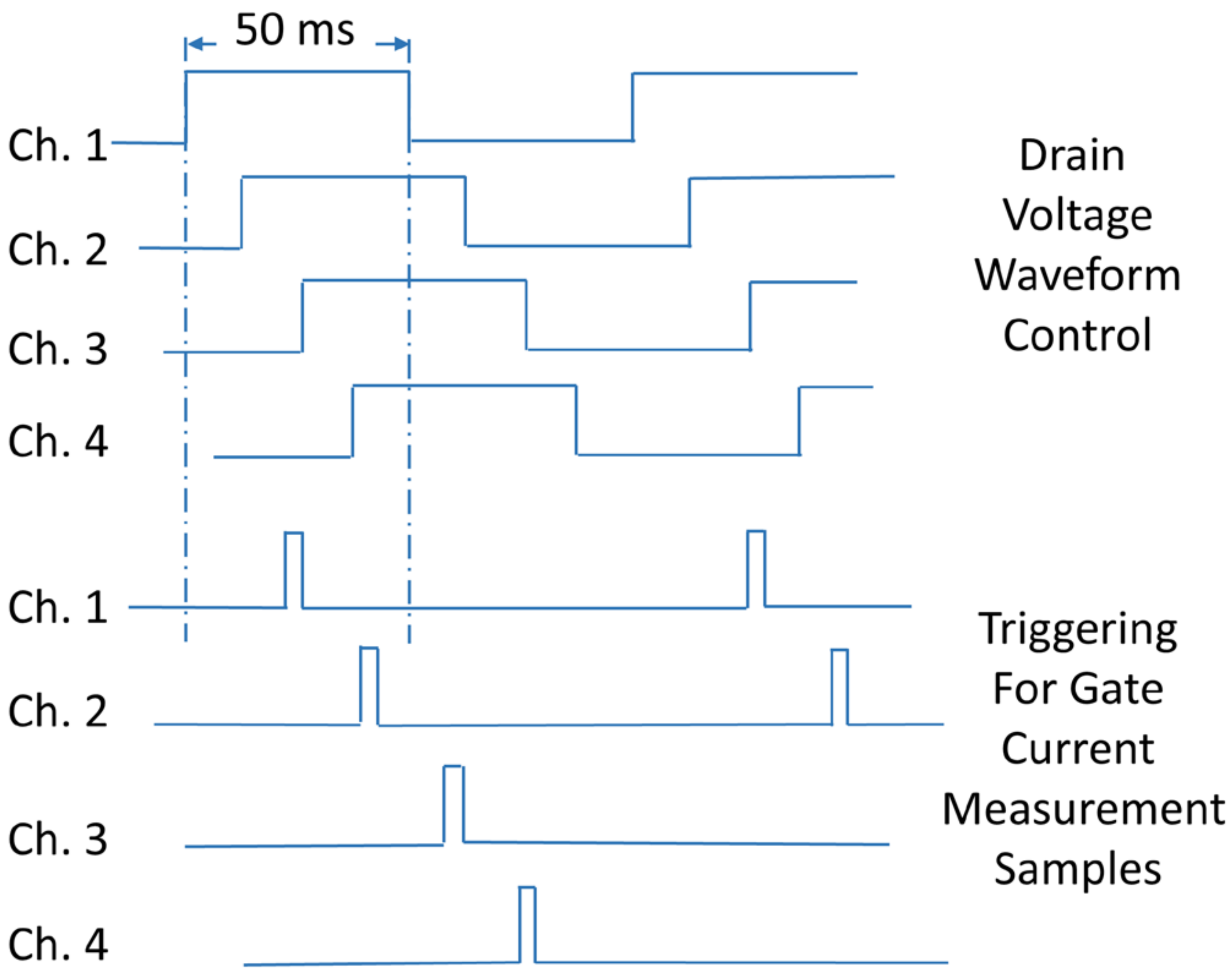
4 DUTs in modified Accel-RF™
fixtures mounted on cold plate

drain power
supplies

Custom test set developed for unattended continuous operation

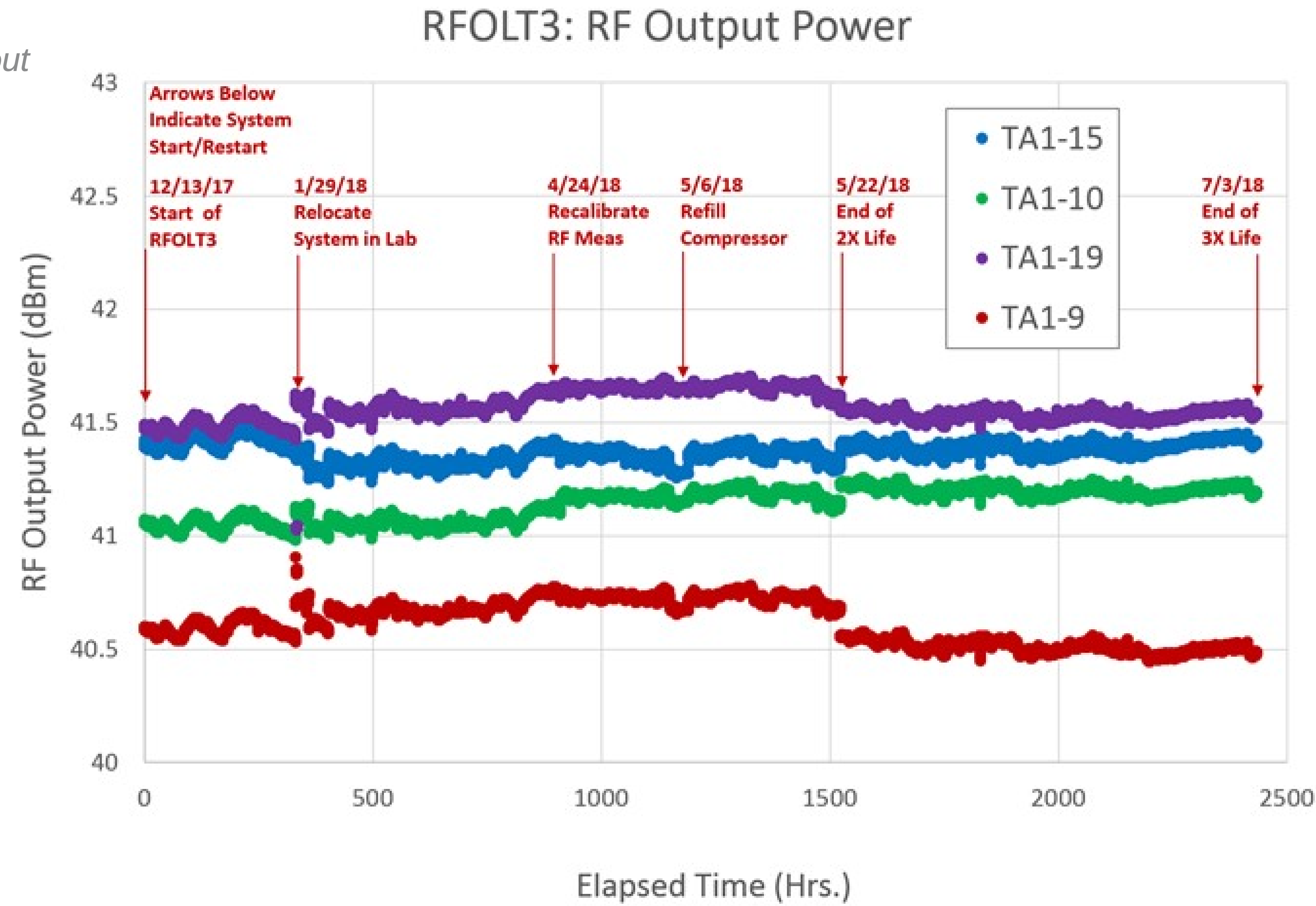
Pulse Scheme

staggering of pulses to reduce noise



in-situ Results

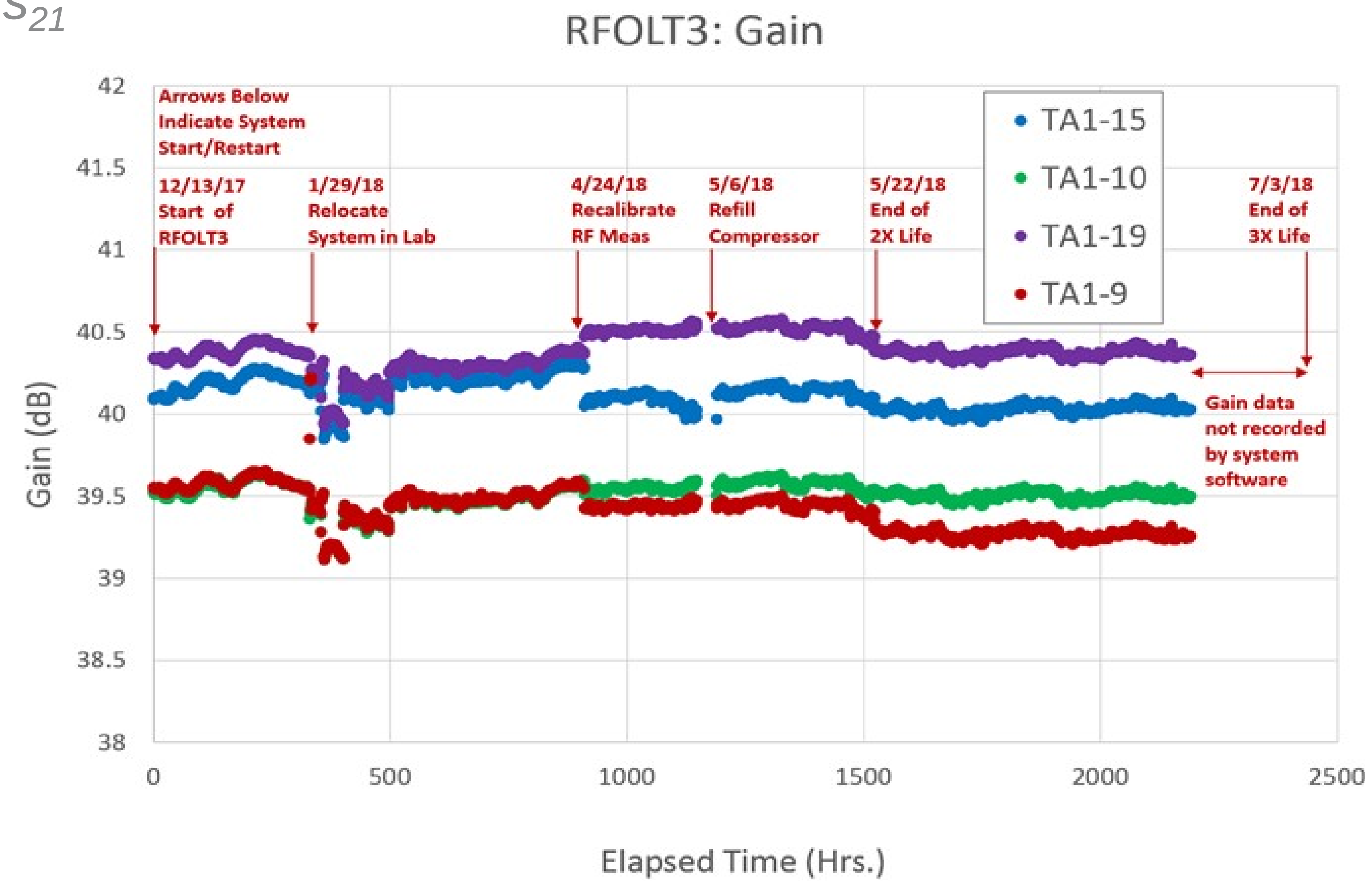
P_{out}



ΔP_{out} is within $\pm$0.2 dB for 2450 hours, success criterion is $\pm$1 dB

in-situ Results

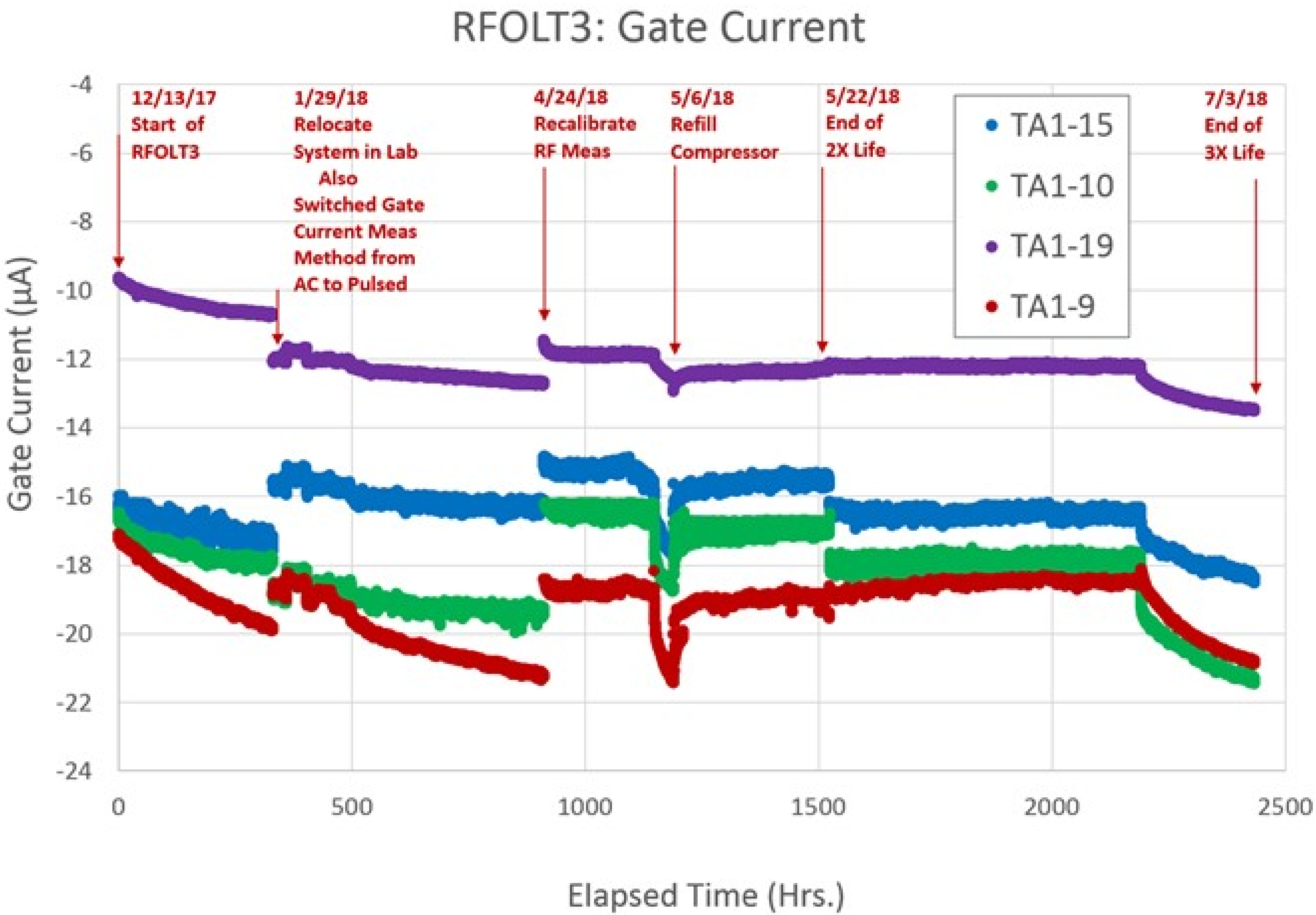
s_{21}



Δs_{21} is within $\pm$0.5 dB for 2450 hours, success criterion is $\pm$1 dB

in-situ Results

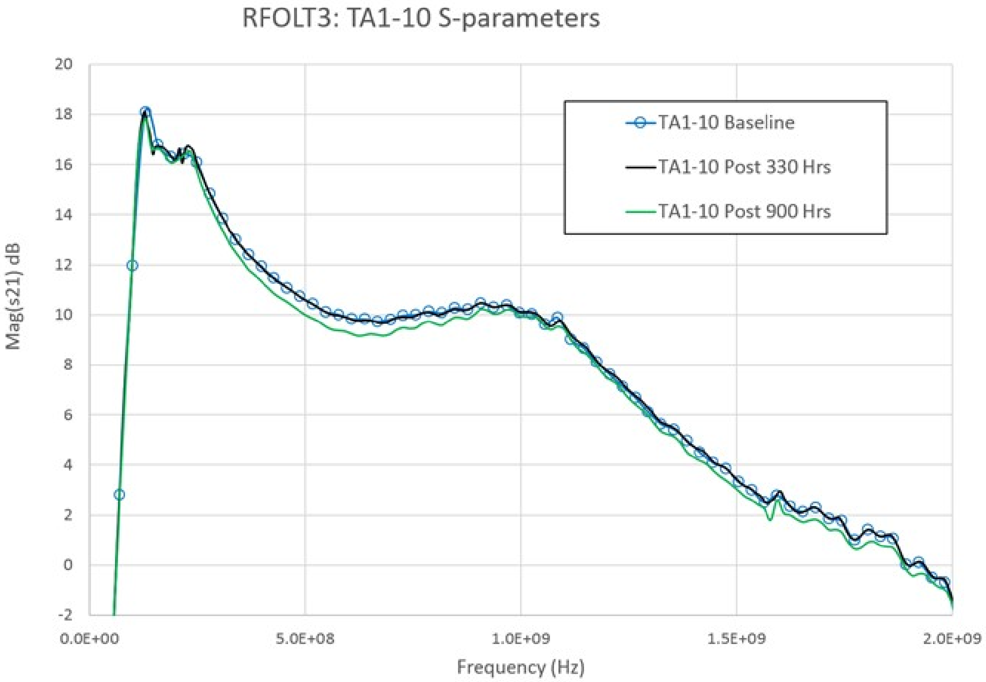
I_G

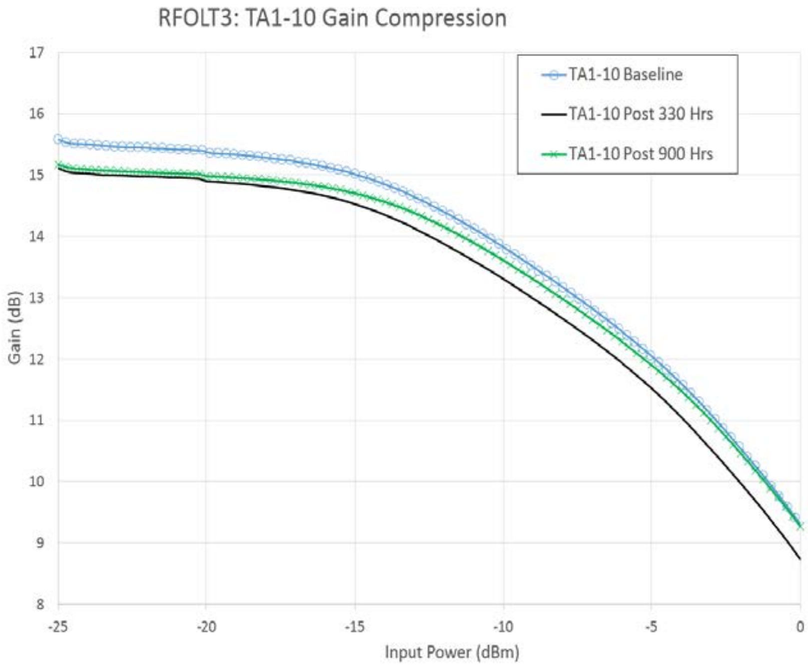


|IG| < 22 μA (< 18.3 μA/mm)   success criterion is < 1 mA/mm

Ex-situ results

gain and gain compression, at 0, 330 and 900 hrs (test still running)

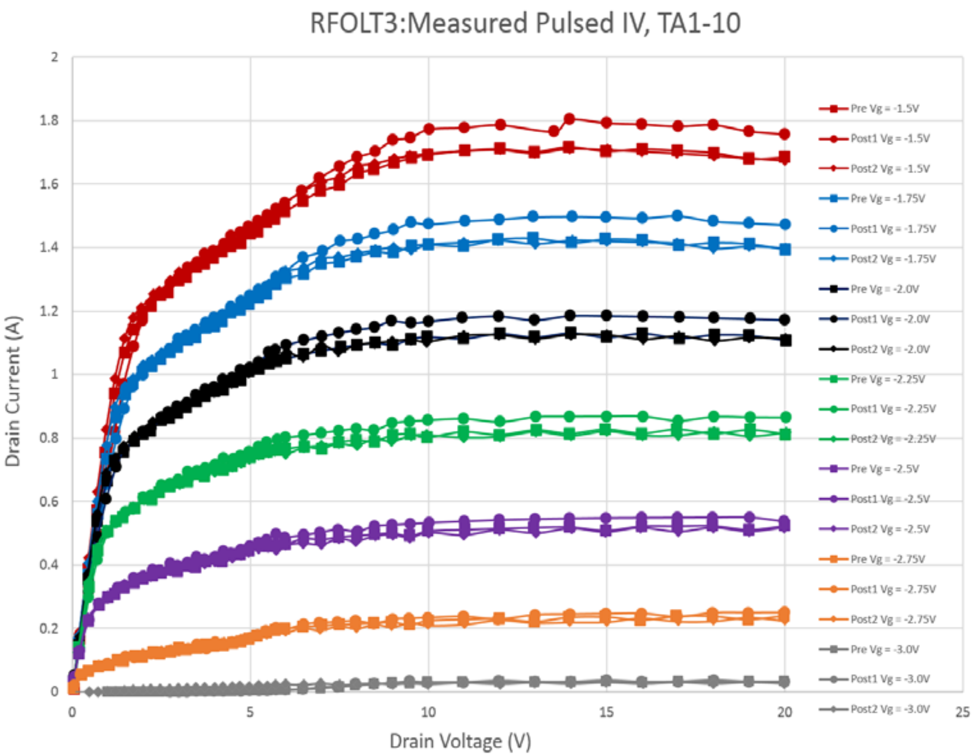


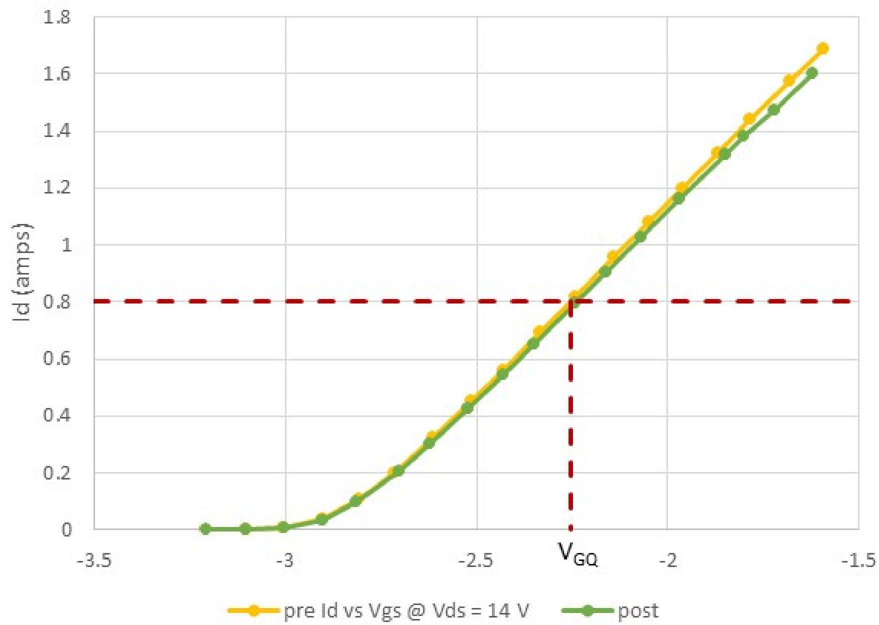


small changes are insignificant and within instrument and configurational errors

Ex-situ results

Pulsed IV and transfer characteristic at 0, 330 and 900 hrs.





small changes are insignificant and within instrument and configurational errors

Conclusions

GaN RF-driven lifetest

- A RF-driven lifetest system has been configured
  - *pulsed operation at 1.5GHz*
  - *special attention paid to protection of the devices in case of faults or failures*
  - *custom software*
  - *in situ measurements of key parameters of interest:*
    - output power, gain and gate current
- a custom wideband GaN MMIC device has been tested under TLYF conditions
  - *tests have successfully run to ~2,500 hours*
  - *with goal to run to > 5,000 hours*
  - *output power, gain and gate current changed negligibly to ~2500 hours*
  - *goal is to run to 5,000 hours or longer*
- qualification of the GaN device and fabrication process was enhanced
  - *eliminates concerns about low E_A mechanisms*
  - *low E_A "sneak" mechanisms could be missed in traditional qual*
- Lessons learned
  - *implement an elapsed time counter*
  - *dry runs to simulate power shutdown, air conditioning failure ,etc.*
  - *rehearse the startup and shutdown*
  - *careful fixture design*

Acronyms

- HEMT high electron mobility transistor
- DUT device under test
- IV current (I) vs. voltage (V)
- TLYF test like you fly
- RF radio frequency
- DC direct current
- VHF very high frequency
- HTRB high temperature reverse bias (stress test)
- SOA safe operating area
- ESD electrostatic discharge
- mmW millimeter wave
- MMIC monolithic microwave integrated circuit
- E_A activation energy
- HPA high power amplifier
- SSPA solid state power amplifier
- GaN Gallium Nitride
- I_{DQ} drain current, quiescent point
- V_{DD} drain power supply voltage
- T_{ch} channel temperature
- N_2 nitrogen (gas)
- RFOLT RF operational life test
- P_{out} vs. P_{in} measurement and plot of output power vs. input power