Aerospace's Experience Using GaN Power HEMTs

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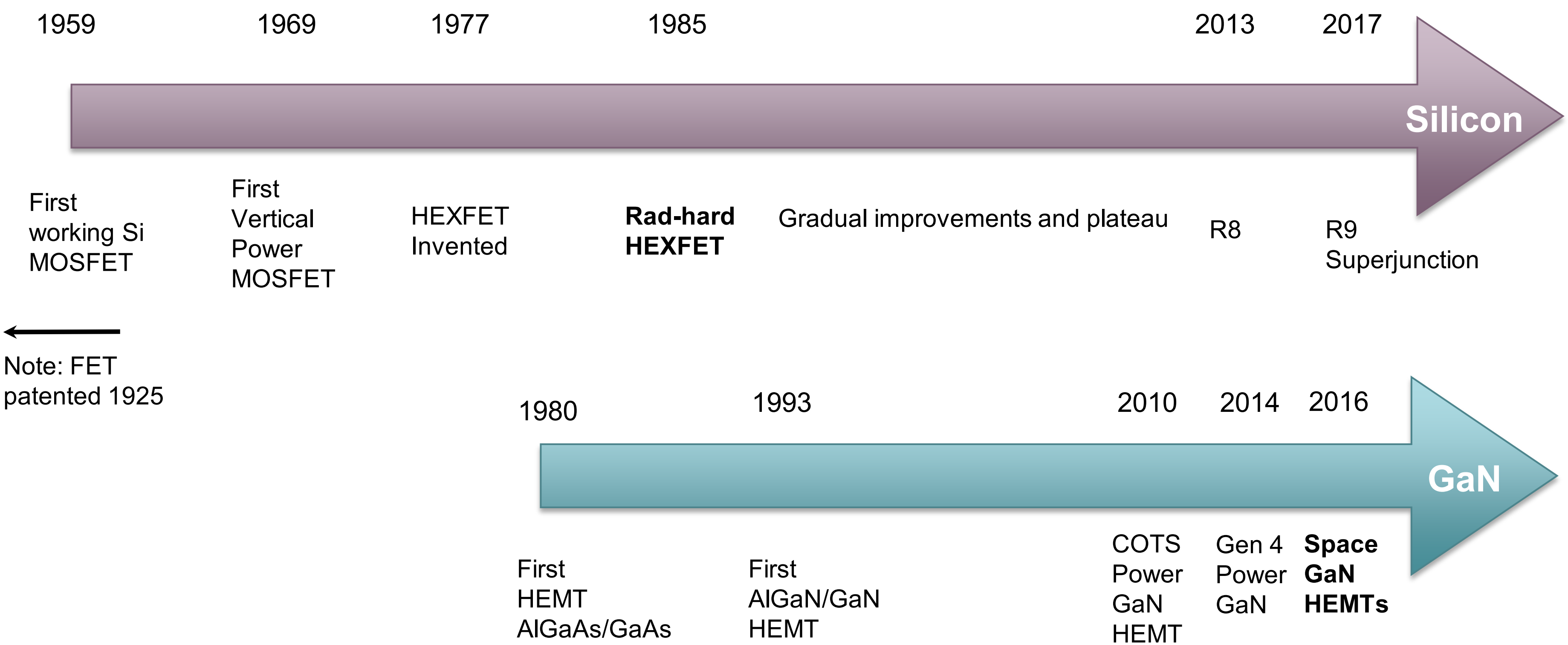
2022 Space Power Workshop

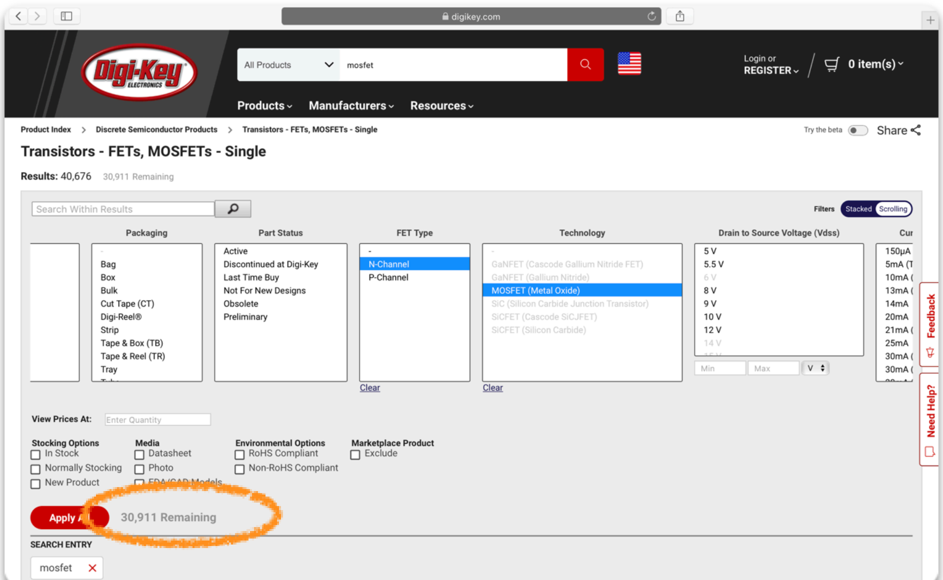
Outline

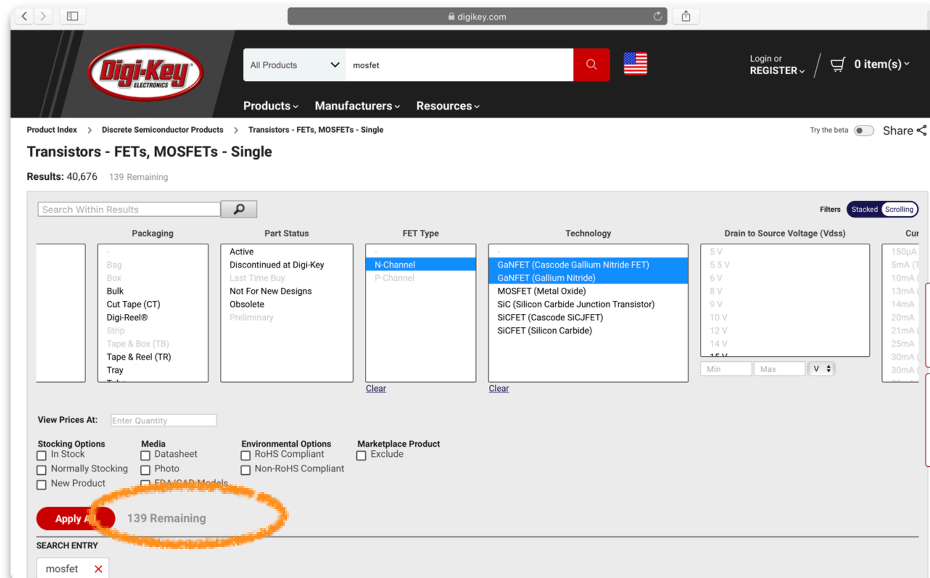
- The past and present of power converter switch technology
- Why consider GaN HEMTs?
  - *How can GaN help meet our needs?*
- Plan to invest for success
  - *Re-tool for power prototyping*
- Case studies: advantages and pitfalls that we have encountered
  - *Do the benefits outweigh the learning curve?*
- Plans to release guidance
  - *Feedback, industry issues and needs?*

The Past (Context)



The Present





- Near real-time power switch count: Si 30,911 and GaN 139
- But there is certainly a growing industry buzz
  - *Several recent SPW presentations have described GaN power designs*
  - *Have you recently purchased a phone or laptop charger?*
- Manufacturers have demonstrated interest in the space market
- GaN designs are flying right now (e.g. Aerocube)

GaN remains a limited player but use is growing

Why Use GaN?

- ~~GaN has wide bandgap, low Ron, low Qg, low mass, high Vcrit, and is efficient~~
  - *Jargon*

- What are our applications?
  - *Mostly DC/DC power conversion, some laser diode drive*
  - *Research and experiments*
  - *Usually short missions*
  - *Most space missions are LEO but there's interest in higher orbits*

- What are the desirable power switch features, given our applications*?
  - *Outperforms COTS silicon MOSFETs for DC/DC conversion*
  - *Has some inherent radiation tolerance*
  - *Cost effective*
  - *Available for delivery today*
  - *Easy to use*

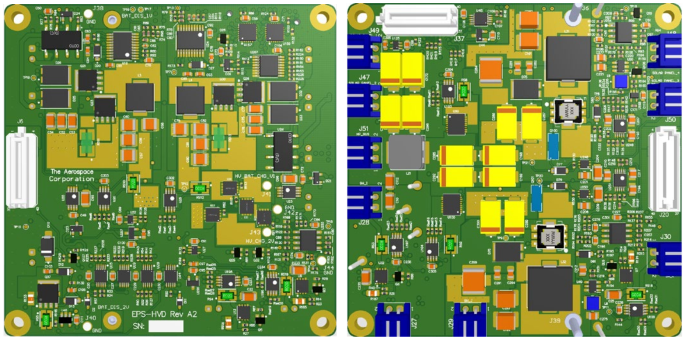
- How well does GaN meet these needs?
  - *Specifically, lateral GaN-on-Si HEMTs for the near-term*

* Your needs may differ…

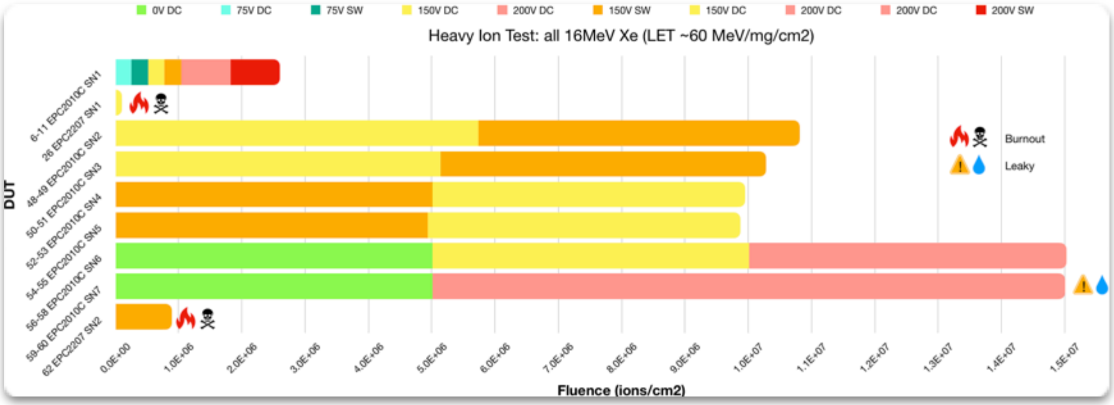
How GaN Can Help to Meet our Needs

- Our needs:
  - *Enables higher frequency switching, reducing size while preserving efficiency*

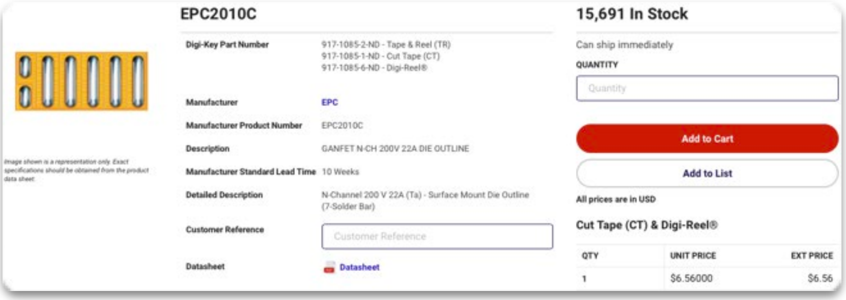
Application needs redundant solar array and battery converters in ~25in^2 (with height restrictions)



  - *Generally TID tolerant. For SEE, there are no COTS part "guarantees" and there's variability. But certain parts can perform well in test, and drain voltage de-rating helps.*



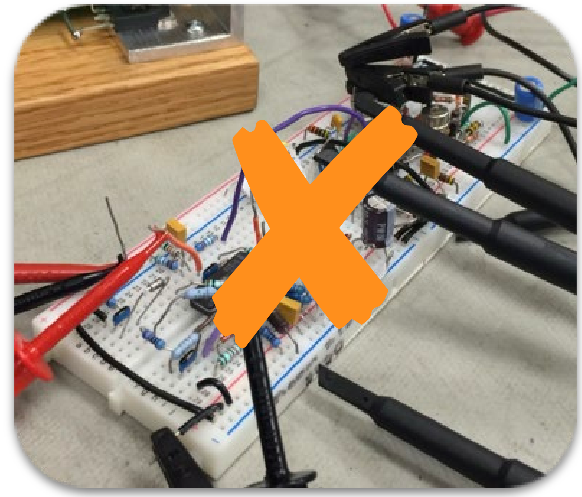
  - *They are readily available and cost effective*

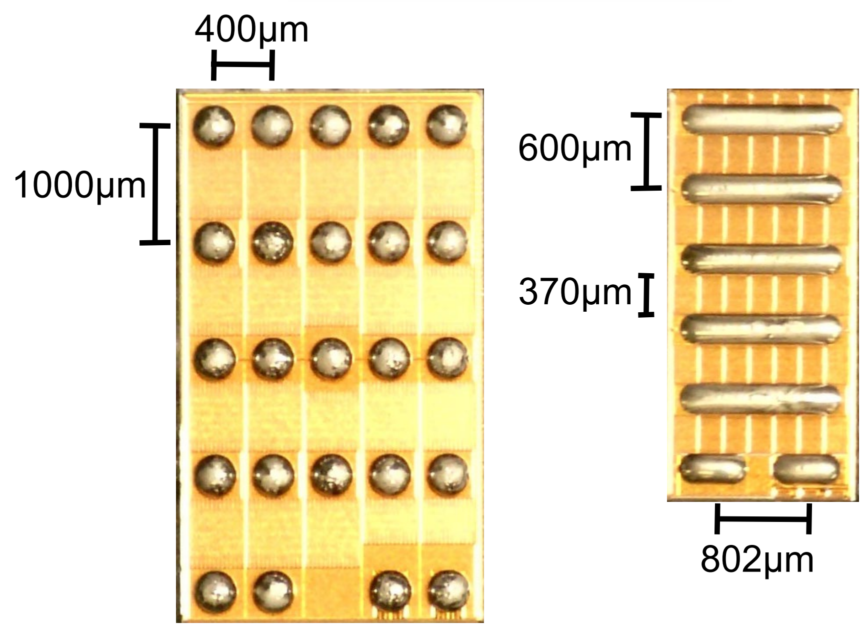


  - *Easy to use? (next page)*

Investment: Re-tool for Assembly and Prototyping

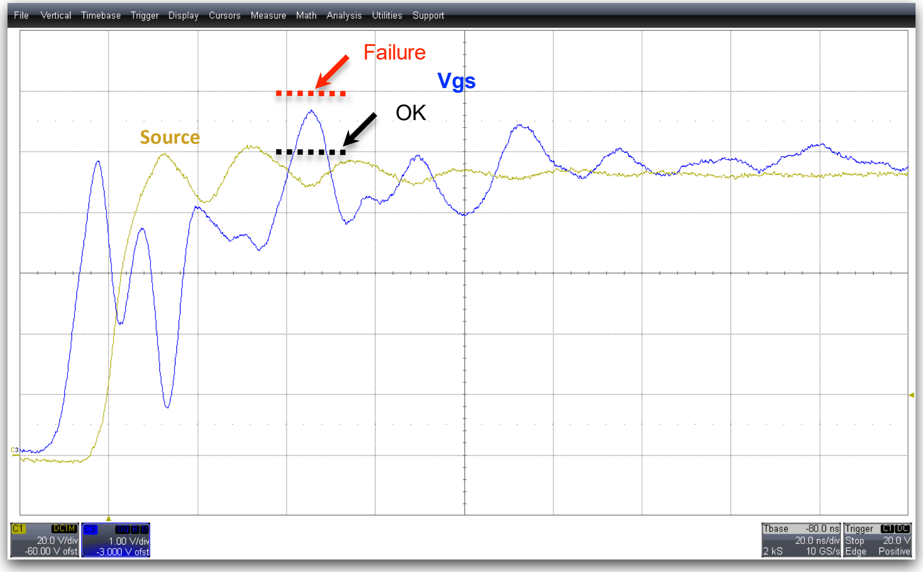
- Some GaN HEMTs only come as passivated die
- Even basic assembly is more like soldering an FPGA than a power part
  - *Ball-grid or land-grid array*
- Need in-house assembly for prototyping and rework. Minimum upgrades:
  - *Stencils and/or solder paste printer*
  - *Hot air soldering and reflow station*
  - *Vacuum pickup with 3-axis precision movement*
  - *10-70x optical inspection microscope*
- Additional considerations
  - *Check your IPC-2221A specs*
  - *Flux cleanup*
  - *Underfill*
  - *Die chips and cracks*
  - *And remember that the die substrate is electrically connected to the source*



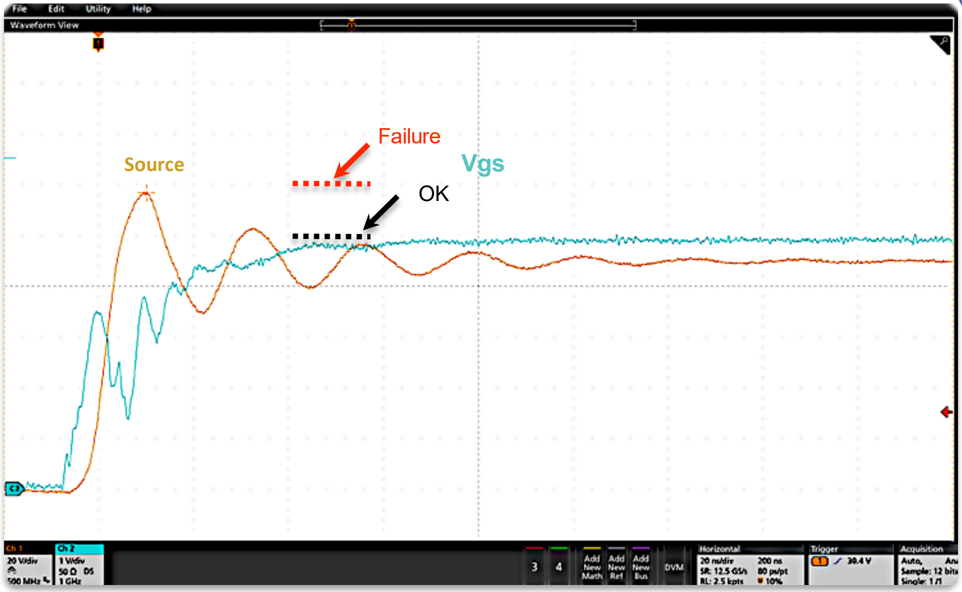


Investment: Test Equipment and Education

Typical Lab Diff Probe



Optically Isolated Probe



- Here's a measurement problem caused by using old probes to measure high-side gate drive
  - *Inadequate CMRR: large and fast common source signal with 1V of gate-source drive margin*
- Key equipment: isolated probes (voltage and CMRR), oscilloscope (bandwidth)
- Education: probing technique, making proper test points, when <u>not</u> to use the bandwidth limit and the ground lead

Even with good technique, old equipment can give untrustworthy results

Case 1: Drop-in Replacement for Si

- With GaN HEMTs boasting multiple advantages over their Si counterparts, why not just drop-in GaN for Si?

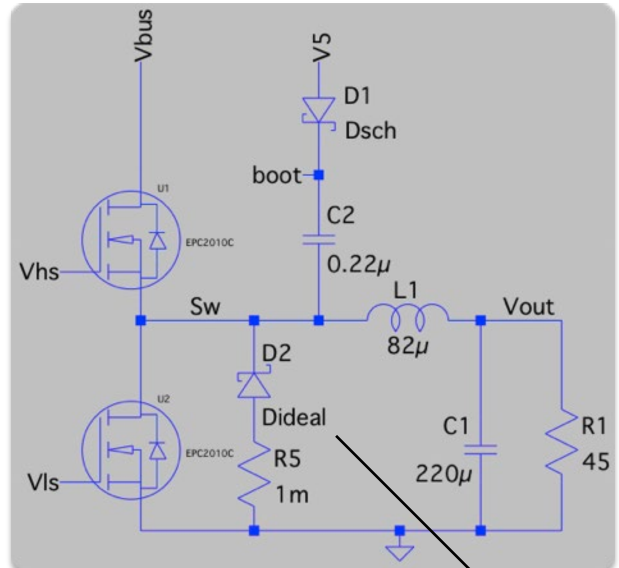
- A 100W buck converter was designed fabricated
  - *Straightforward specs: convert li-ion battery bus from 54-72V to 45V*
  - *Selected a synchronous half-bridge topology with GaN HEMTs*
  - *Eliminate reverse recovery loss and low Ron to maximize efficiency*

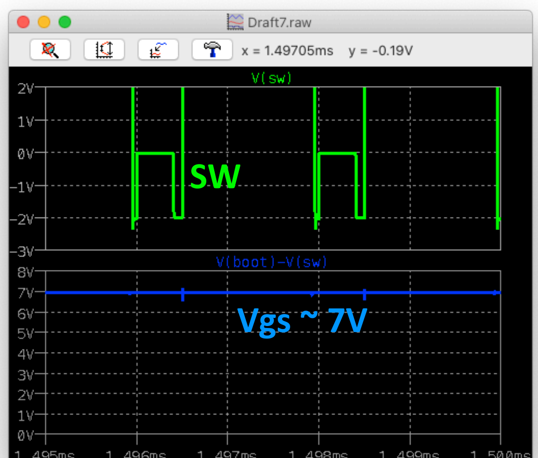
- Very few GaN PWM chips and drivers were available at the time
  - *Re-used a common PWM IC LM5116 proven in previous silicon designs*

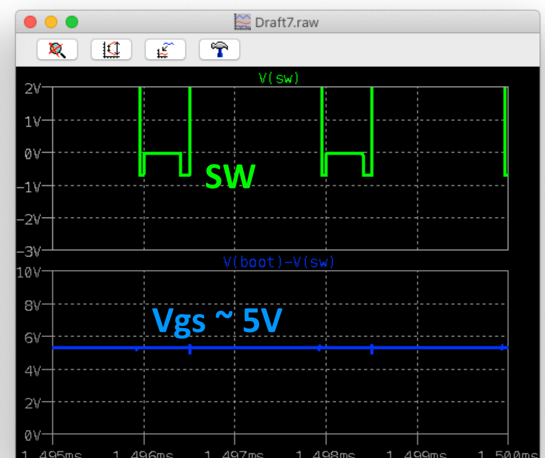
How hard can it be?

Drop-in Replacement Results

- The converter lasted 10 minutes before releasing the “blue smoke”
- Issue #1: LM5116 could not supply 5V
- Issue #2: bootstrapped high-side gate drive was poorly regulated
- Issue #3: 3rd quadrant GaN conduction during the dead time resulted in a ~2V drop, over charging the bootstrap to 7V
- Fixes: added new 5V supply, clamped the bootstrap voltage with multiple diodes, added a Schottky in parallel with the lower transistor
- Converter achieved 97% efficiency but it was not worth adding multiple extra parts
- We have seen this issue “in the wild”



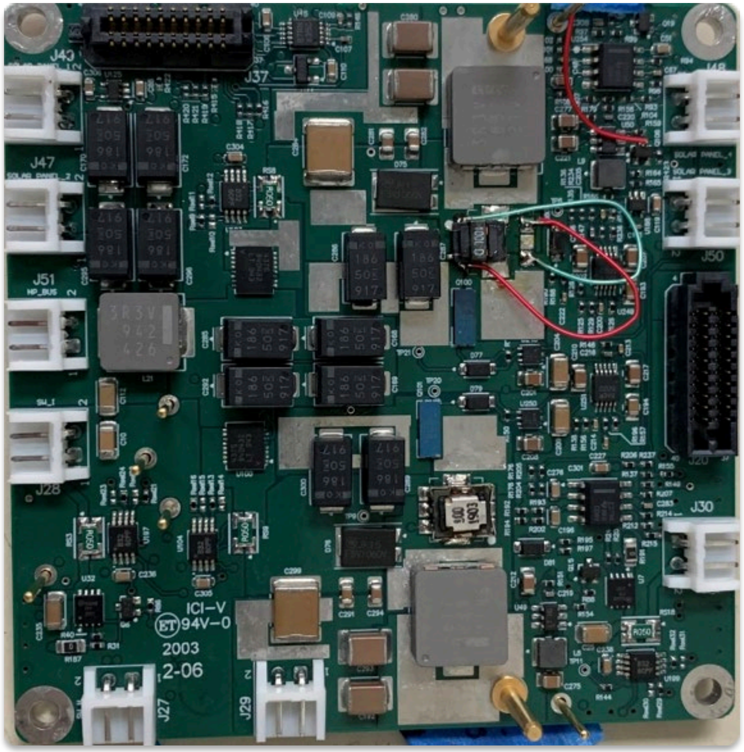


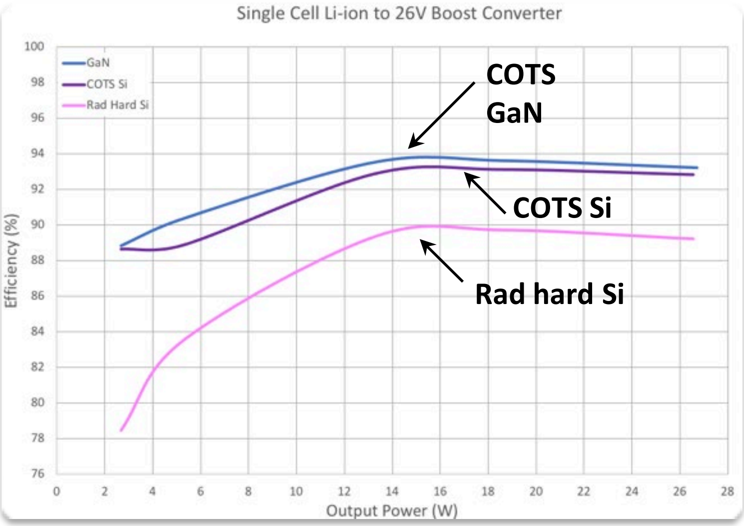


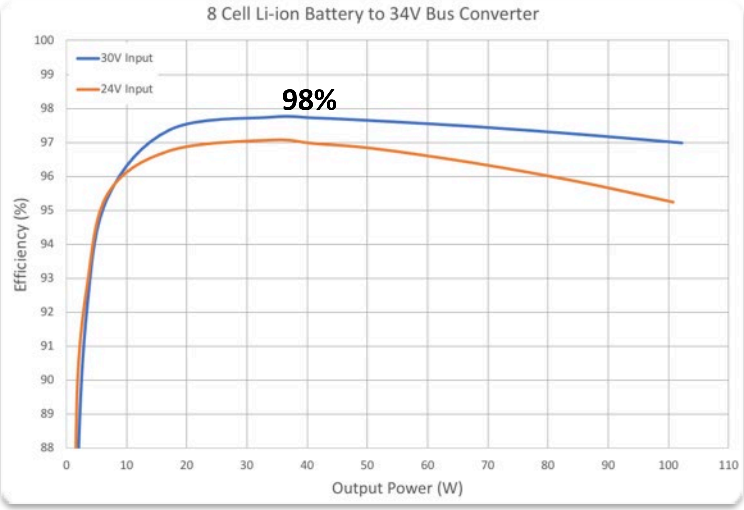
GaN can be a hassle to implement without a supporting cast of parts

Case 2: Cubesat and Smallsat Boost Converters

- Needed a new common boost converter
- No great integrated switch options
- High input current (~11A) in a small area
- Compared several Si MOSFETs with GaN
- Selected GaN HEMT with very low Ron spec



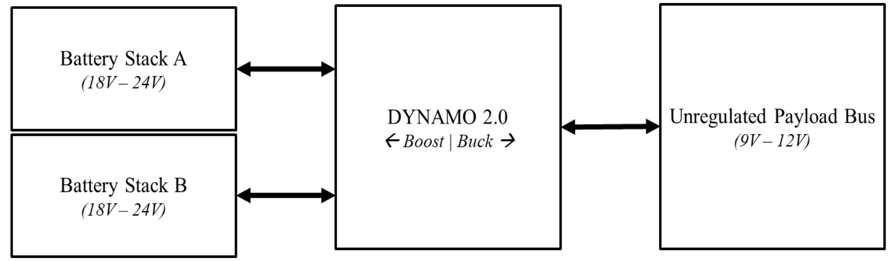




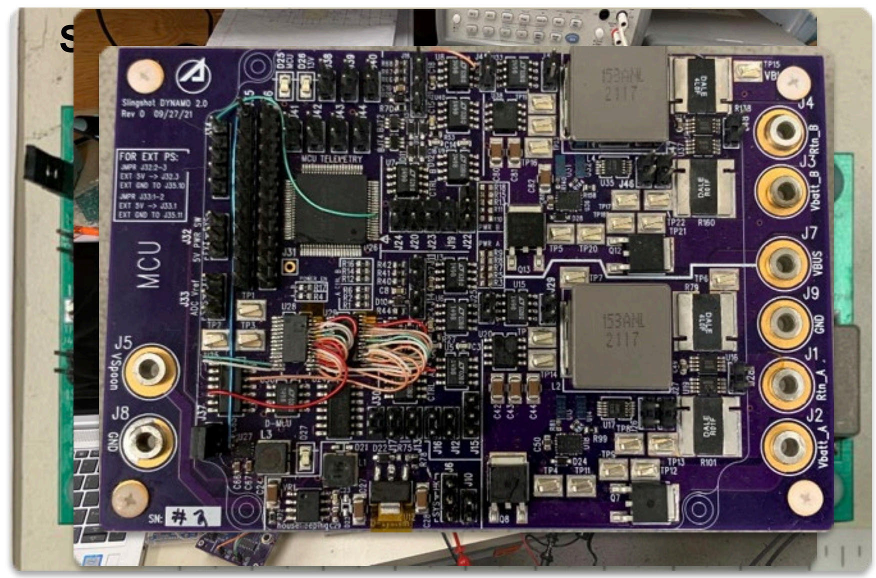
GaN outperformed all Si MOSFETs in our boost converters and was selected

Case 3: Auxiliary Power System "Payload"

- Project Dynamo is a "payload" that supplements main satellite power
- Batteries with different chemistries can augment bus power delivery
- Constrained to 1U packaging
- Bidirectional GaN HEMTs converters with average current mode control were selected
- GaN HEMTs were chosen to help with Size Weight and Power (SWaP)
- In this case, GaN's lack of packaging was a considerable size advantage



Project Dynamo Block Diagram

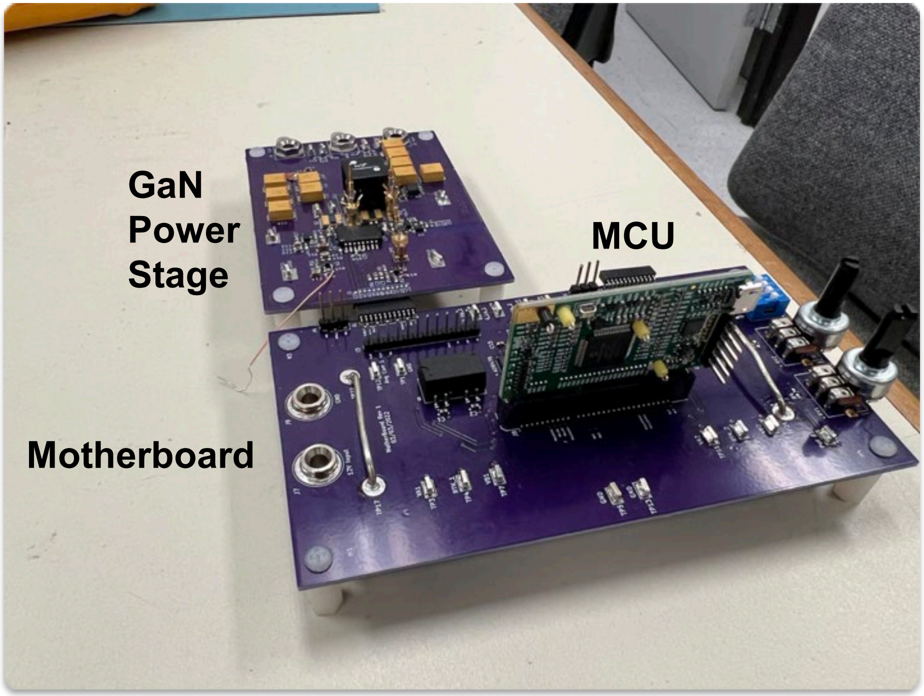


GaN: 5.1in^2
Si: 6.3in^2

GaN HEMTs allowed this project to meet its SWaP goals

Case 4: Digital GaN Power System Development

- Programs can undergo long and costly development cycles due to challenges with unique designs
- Off-the-shelf power converters can save time for simple designs but lack features for many other applications
- Combining digital control with GaN HEMTs potentially saves development and schedule costs
- Initially, an integrated GaN power stage was selected for SWaP
- Reverted to discrete GaN because integrated stage could not provided necessary duty cycle



Aerospace Power System Prototype

Tradeoff between highest levels of integration and operational control

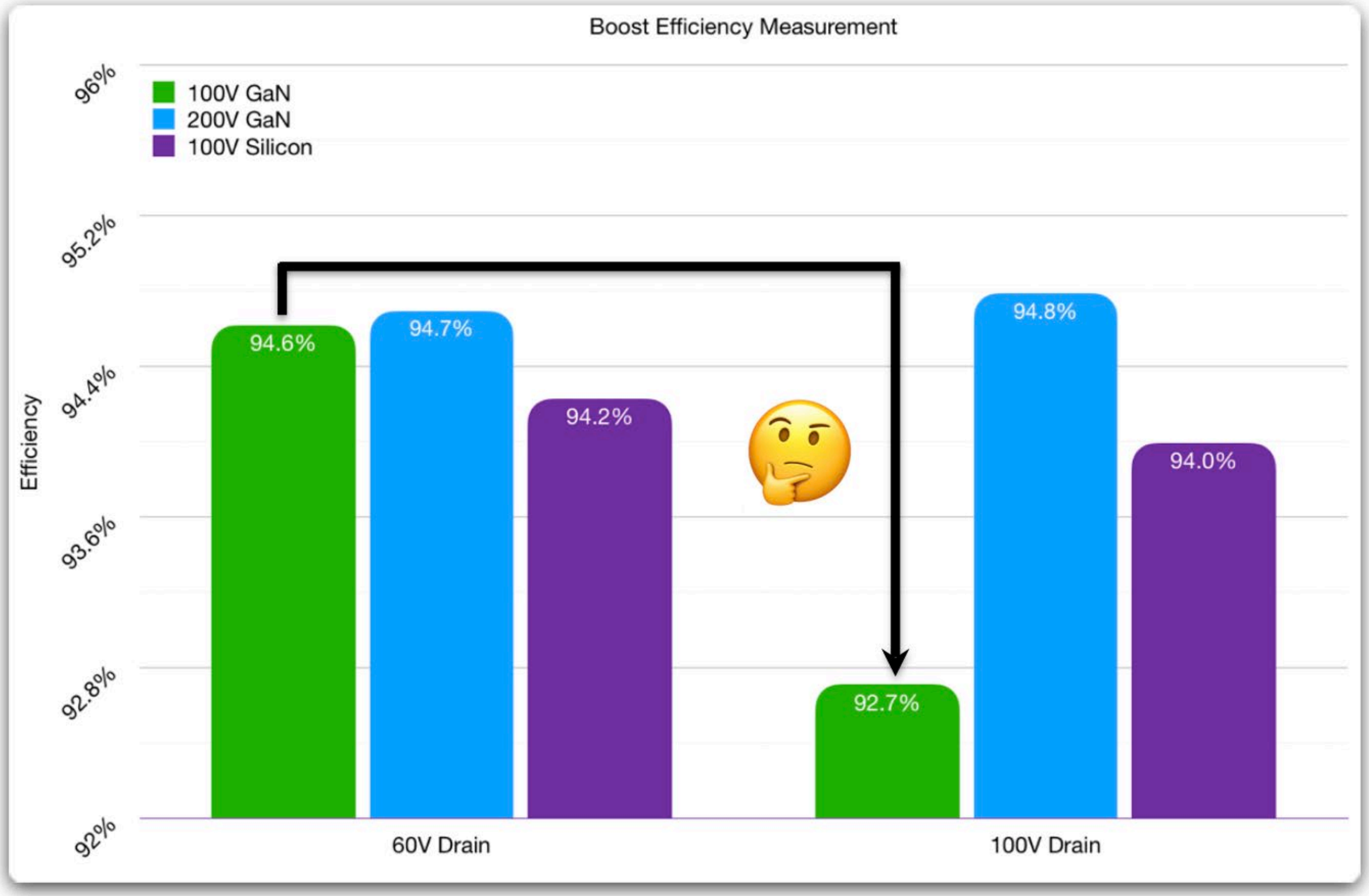
New Technology "Features" and Considerations

- Like any new technology, GaN HEMTs introduce new features. Some of the better known ones were presented earlier.

- *GaN's* "dynamic" features are unfamiliar to some engineers used to MOSFETs
  - *Dynamic operation (i.e. switching) can result in departures from datasheet specs*
  - *Circuit dependent: characterize GaN HEMTs in your circuit*
  - *Datasheet specs usually describe static behavior*

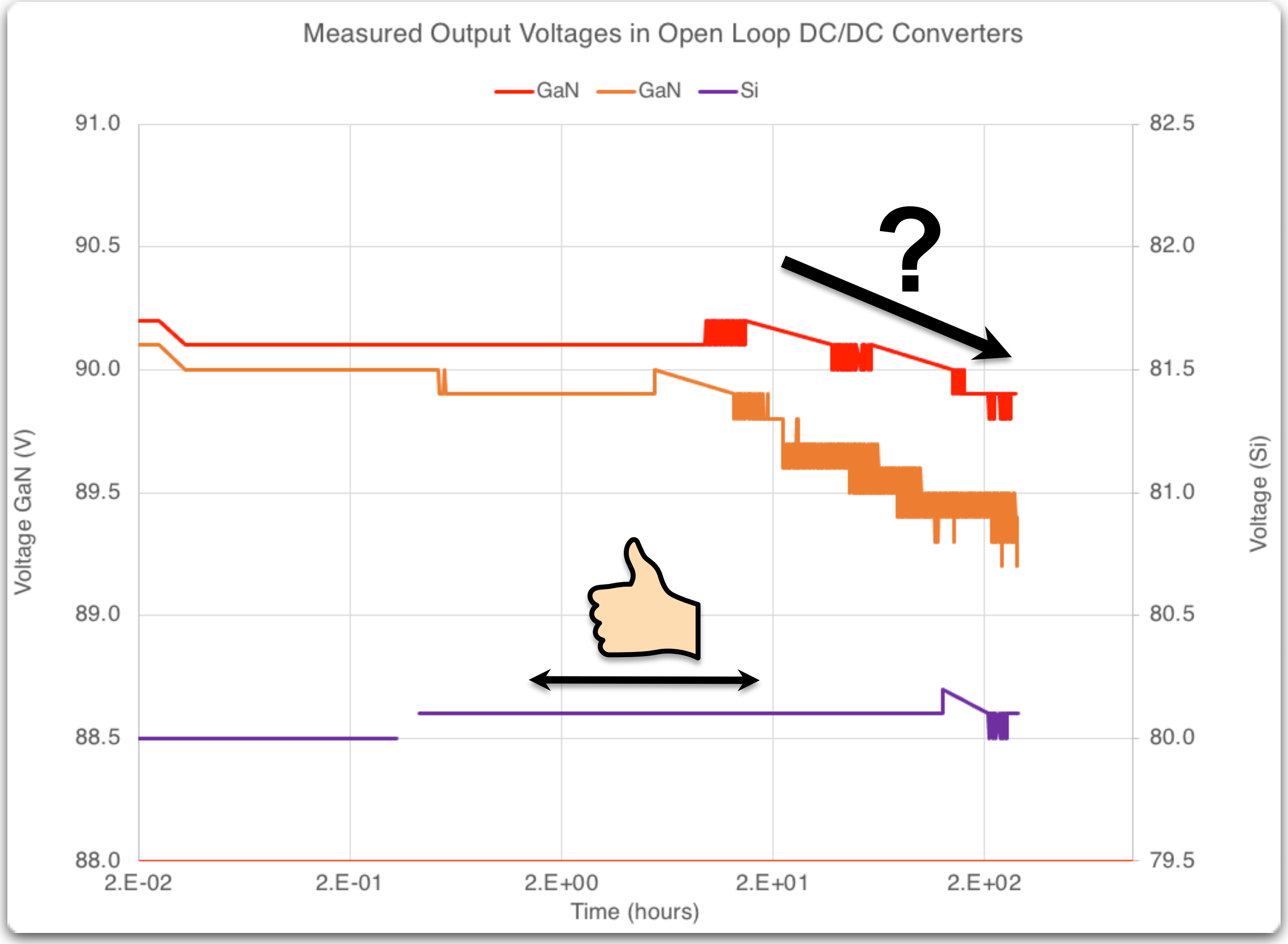
- Several difficult to explain observations led us to develop a new resistance measurement method
  - *Provides a real-time view of GaN HEMT resistance while switching (dynamic Ron)*
  - *The next charts illustrate features related to dynamic Ron*

Motivation - Power Designer's Perspective

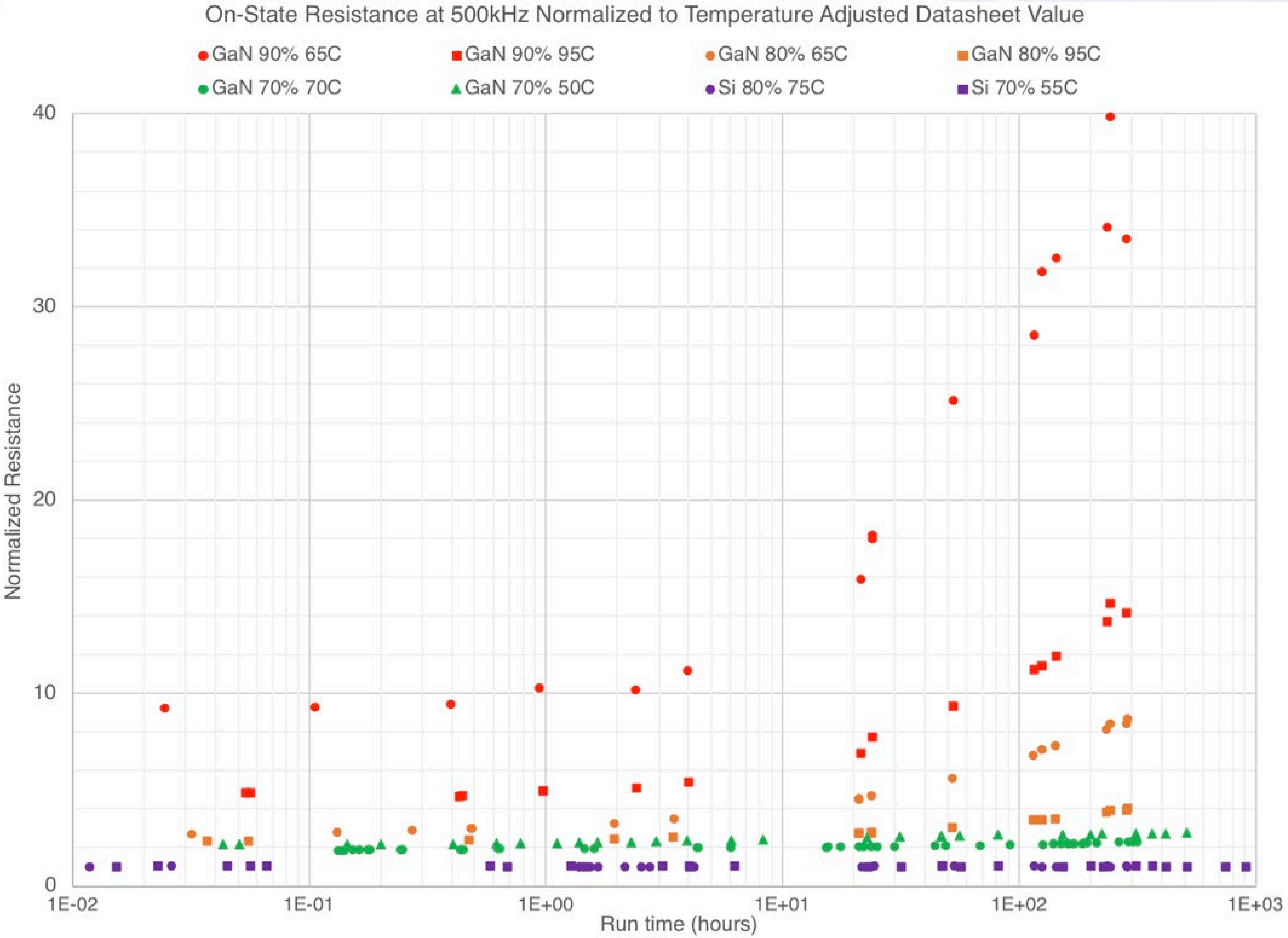


All devices used the same circuit and test conditions…

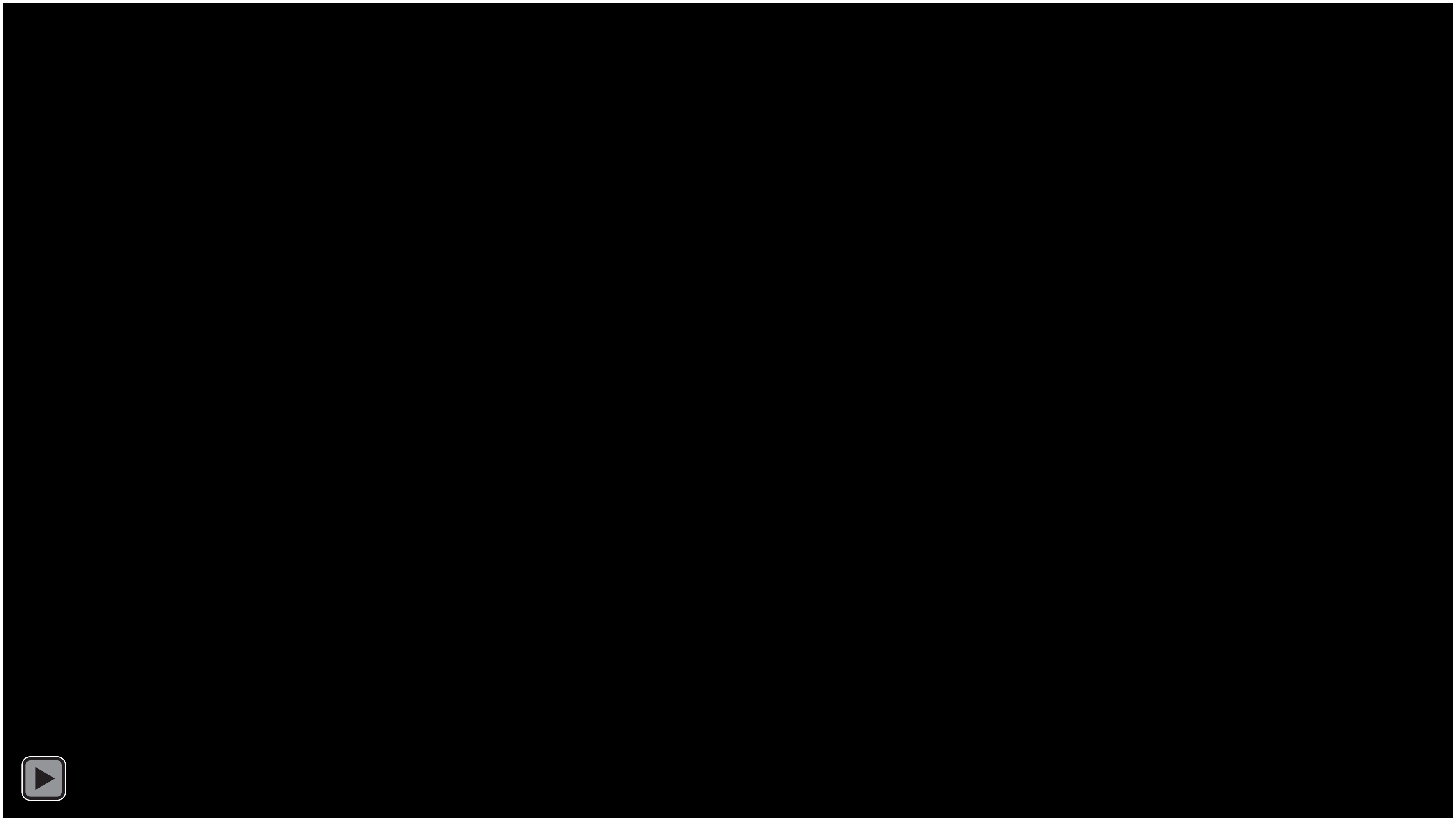
Motivation - Reliability Perspective



Why does the output voltage droop over time?

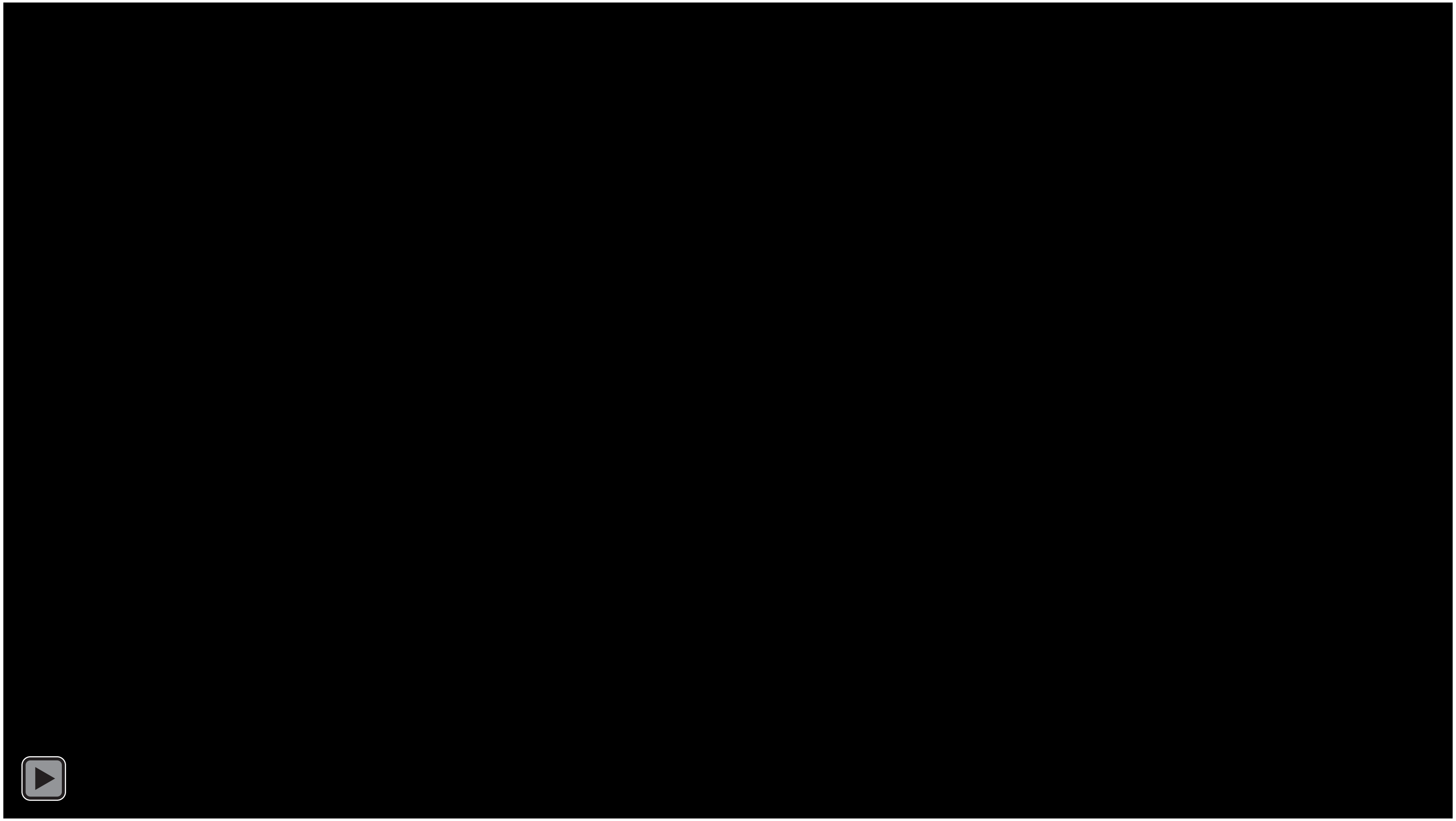

On-State Resistance at 500kHz Normalized to Temperature Adjusted Datasheet Value
GaN 90% 65C
GaN 90% 95C
GaN 80% 65C
GaN 80% 95C
GaN 70% 70C
GaN 70% 50C
Si 80% 75C
Si 70% 55C
Normalized Resistance
40
30
20
10
0
1E-02
1E-01
1E+00
1E+01
1E+02
1E+03
Run time (hours)

Hot to Cold Sweep (Si MOSFET)



Warm = 36mΩ, cold = 22mΩ

Hot to Cold Sweep (GaN 90% of Rated Vds)



Warm = 61mΩ, cold = 1.1Ω

Summary

- GaN HEMTs are exciting devices that will continue to impact space power development for some time to come

- Through several case studies, we shared the types of investment needed to successfully prototype with GaN and applications where it has made a positive impact

- New technologies have unfamiliar features, like dynamic resistance
  - *Users should factor into device de-rating decisions and qual plans*

- Aerospace is developing a power GaN HEMT TOR with guidance
  - *Focus on physics of failure, de-rating, and qualification compared to MOSFETs*
  - *Effort led by Dr. John Scarpulla*