GaN Based Power Conversion: Moving On!

Key Component Technologies for Power Electronics in Electric Drive Vehicles

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APEC 2013

International
IOR Rectifier

Acknowledgements

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(1) International Rectifier
(2) Delphi Automotive Systems, LLC
(3) Oak Ridge National Laboratory

Acknowledgment:

This material is partially based upon work supported by the Department of Energy, ARPA-E under Award Number DE-AR0000016, resulting from the collaborative development efforts of Delphi Automotive Systems, LLC; International Rectifier; and Oak Ridge National Laboratory.

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Abstract

The promise and potential of Gallium Nitride (GaN) based power conversion has recently been communicated and understood. As with other III-V semiconductors, Gallium Nitride, when compared to silicon, has a vastly improved trade-off between conducting losses (R_{DS}(on)), switching losses and voltage withstand capability. For example, at theoretical material limits, there exists 1-2 orders of magnitude lower conduction losses at a given blocking voltage and device size. More broadly, the application benefits of these revolutionary new devices have been demonstrated. This presentation will provide attendees with an update on the latest technology, product development and application information for International Rectifier's GaNpowIR® platform. Applications covered will range from PFC to DC:DC, to Class D Audio to power conversion for motor control. For motor control, compared to silicon devices, early GaN-on-Silicon power switch prototypes have already shown 3-5X improvement in a key device figure of merit. Finally, a projection of the benefits of GaN-based power conversion in automotive applications will be provided. Featured will be the results of a collaborative effort between International Rectifier, Delphi Automotive and Oak Ridge National Laboratories to develop, test and demonstrate high power 600V GaN based power conversion for automotive auxiliary power and electrified traction applications.

Outline

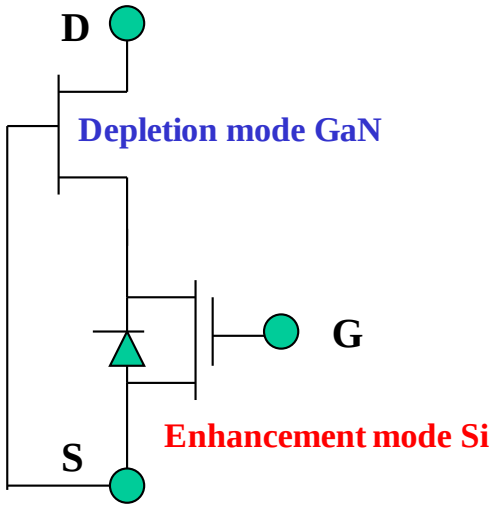
- III-V Semiconductor Requirements for Wide Adoption in Electrified Vehicles
- Status of GaNpowIR® GaN on Silicon Power Device Performance, Robustness, and Reliability
- How does GaN Performance Compare with Silicon in Electric Vehicle Drive?
- Is any III-V Semiconductor ready for use in automotive applications?

III-V Requirements for Automotive Applications

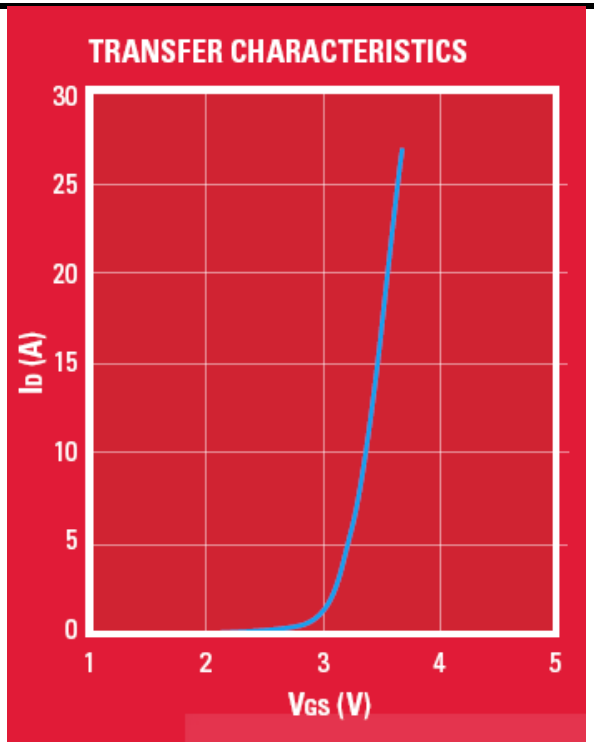
- Performance must be at least 3-5x better than Silicon equivalent
- For Wide adoption of fully electric vehicles, cost should be same or lower than than incumbent Silicon solution.
  - Goal is to provide vehicles for same or lower functional cost as gasoline vehicles
- Must have high Yield for Large Devices (>70 mm^2)
  - Highest switch power should require no more than 3-4 die in parallel
- Device technology and material must be proven in high volume applications before volume adoption for electrified vehicles

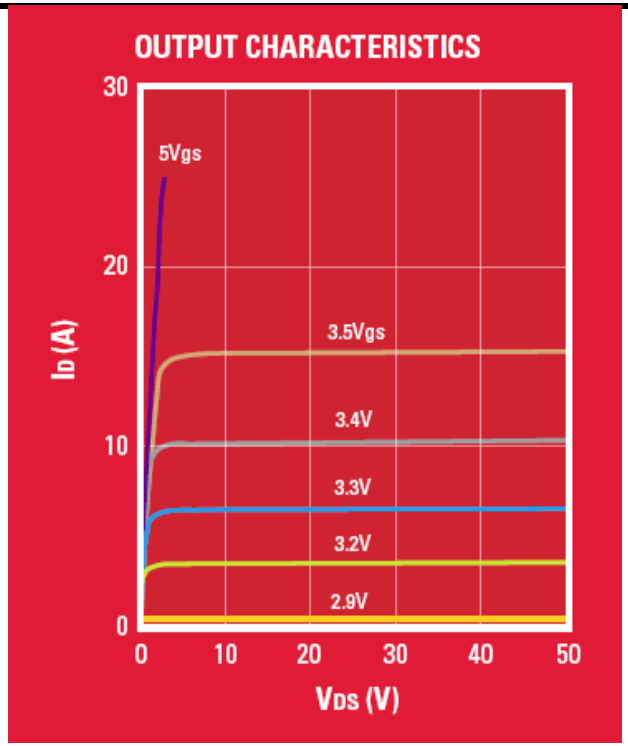
IR's GanpowIR® Device Performance and Robustness

HV Cascoded GaN switch: A powerful Circuit



Cascoded Switch

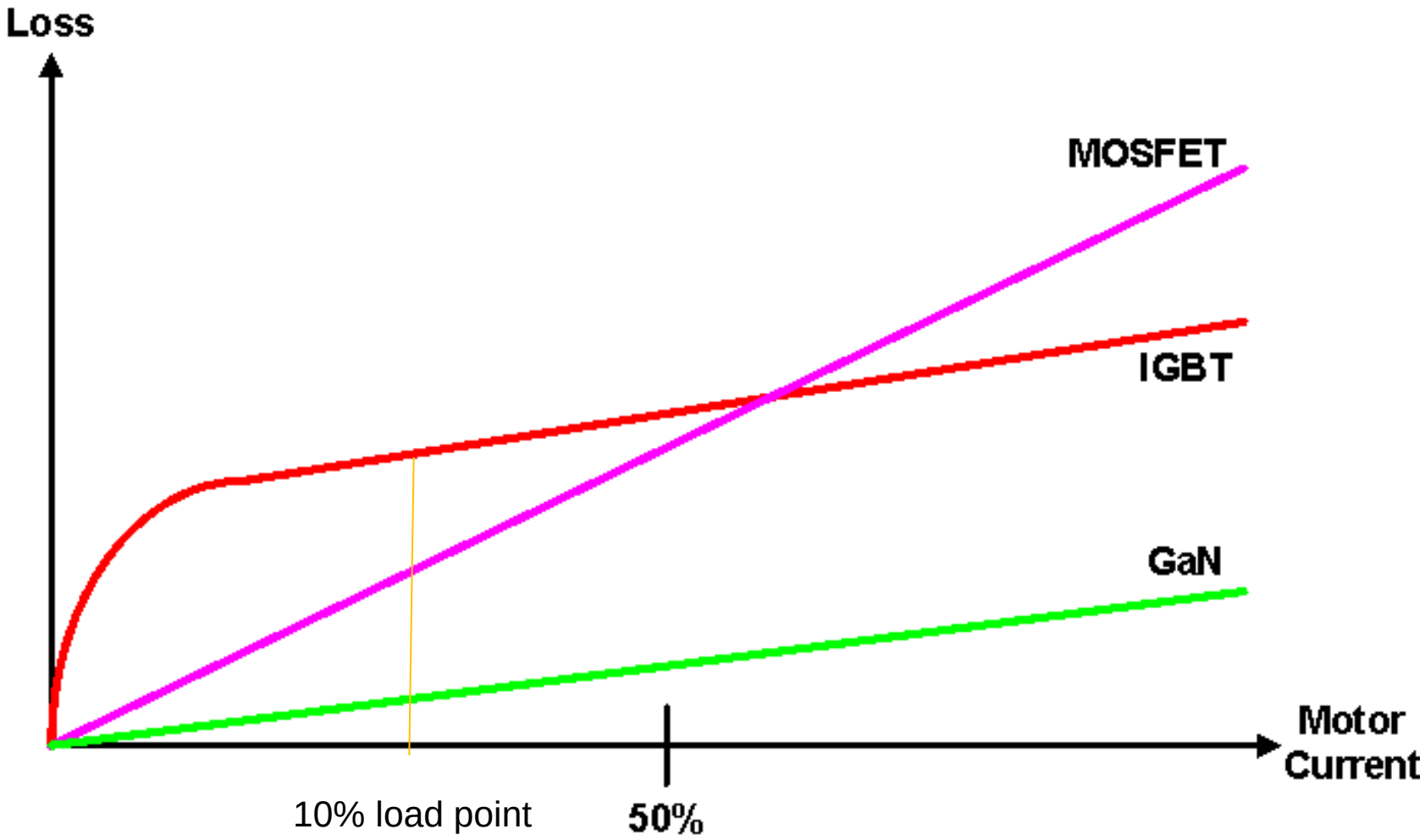




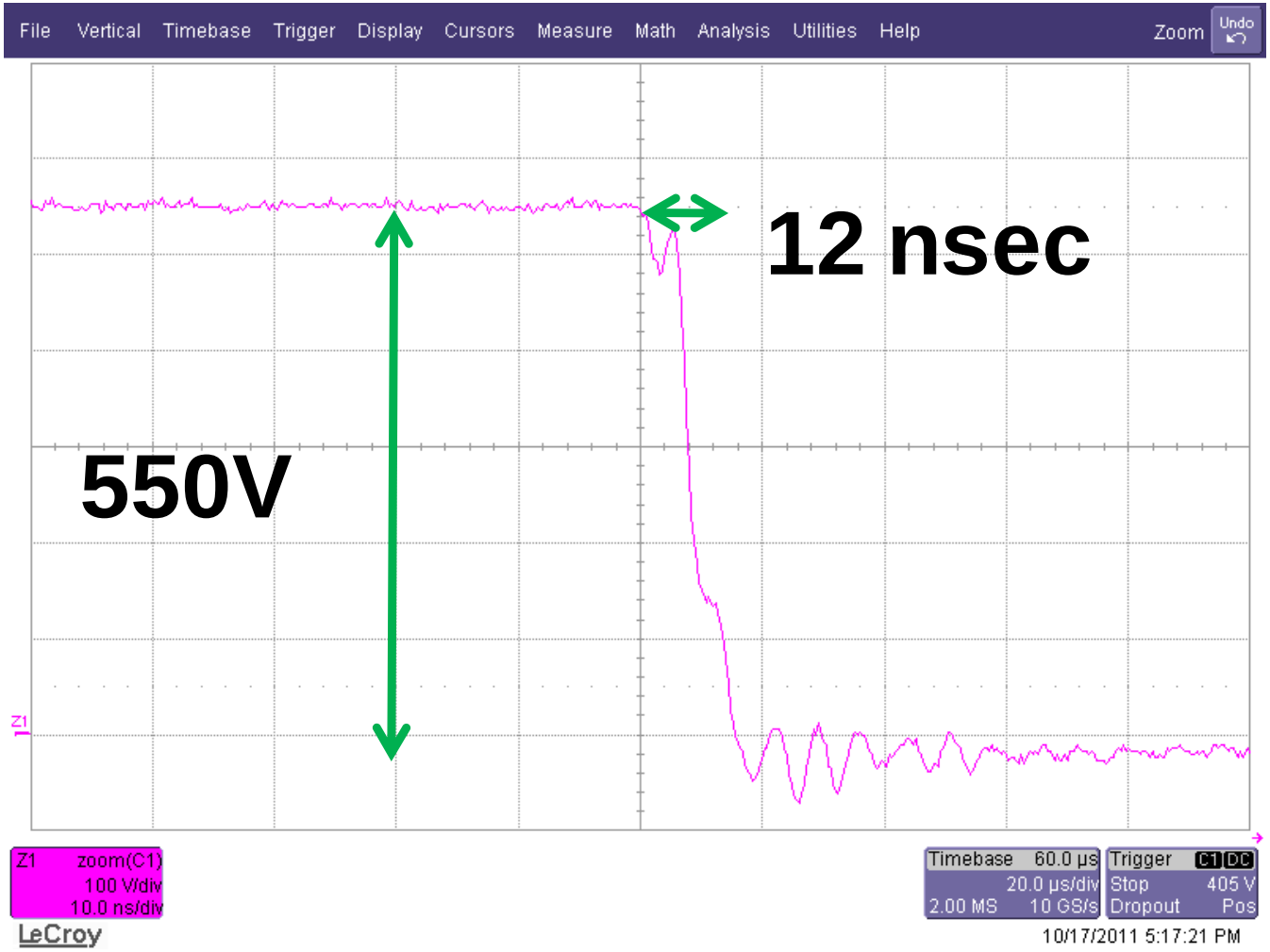
Leverages > 30 years of reliable drive experience

- **Normally Off operation**
- **Gate drive compatible with existing Silicon solutions: +/-10V, +/- 15V , etc.**
- **Vgs(th) set by low voltage Si FET:**
- **Select Vt (3 V vs SJ, 5 V vs. IGBT), high enough to avoid C*dV/dt induced turn on**
- **Anti-parallel diode included: much lower reverse recovery than Si switches**
- **Minimal compromise in GaN HEMT performance**

GaN has Much lower conduction loss vs IGBT, FET

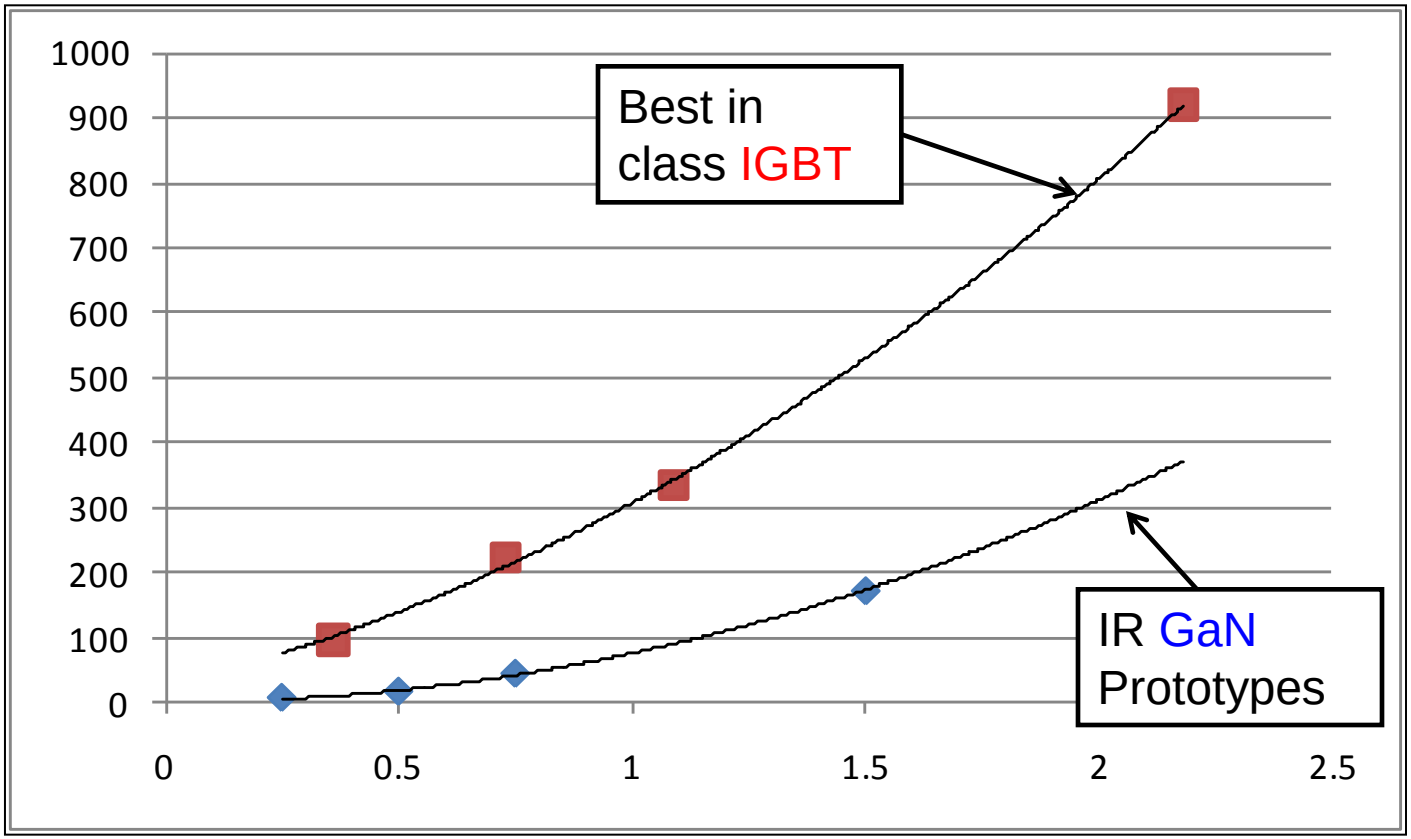


GaN Devices Switch at High Speed



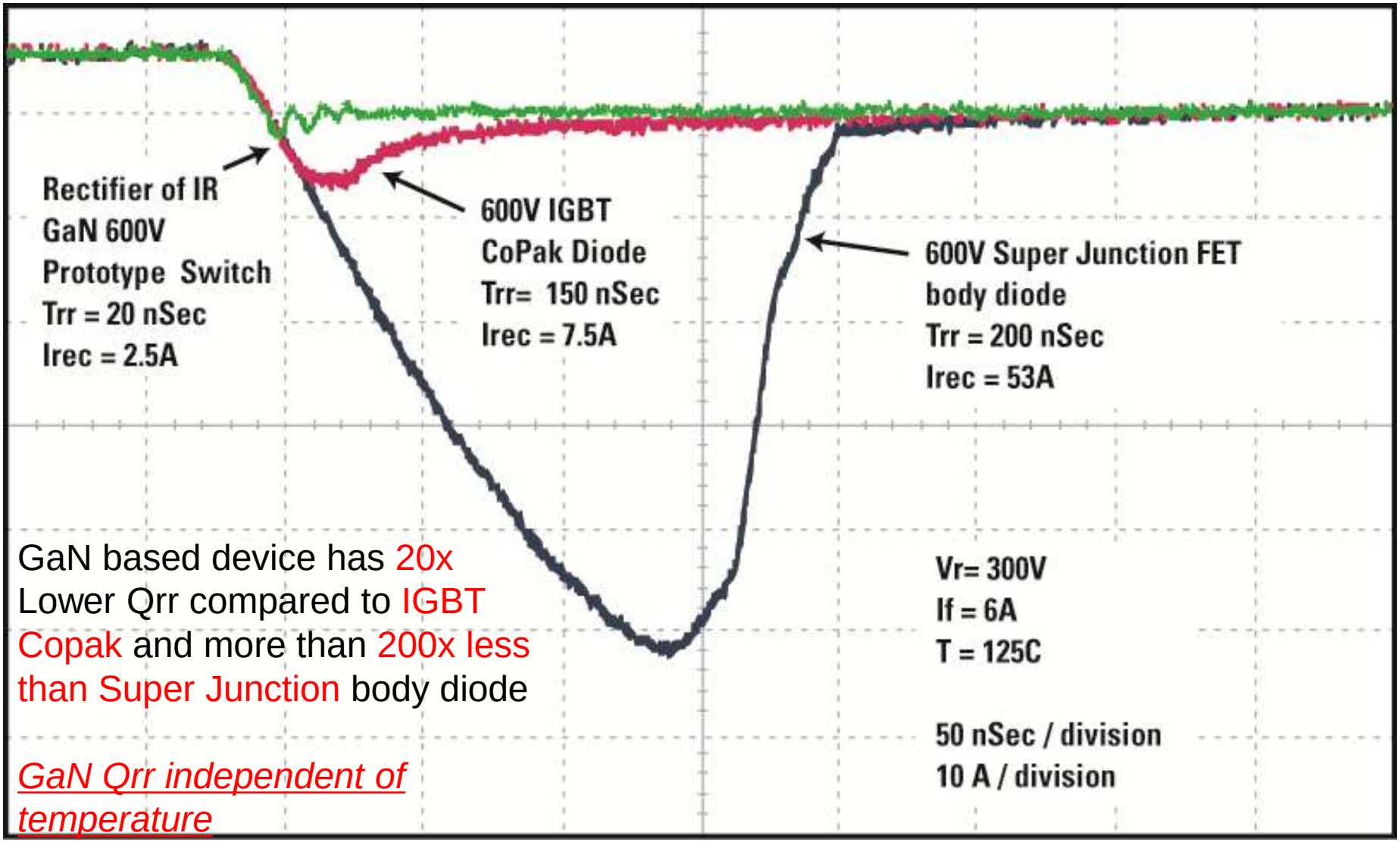
600 V Switch Performance vs. Current Density

GaN FOM is 3 to 5 x better than IGBT



Performance FOM: Vds(on) * (Eon + Eoff)

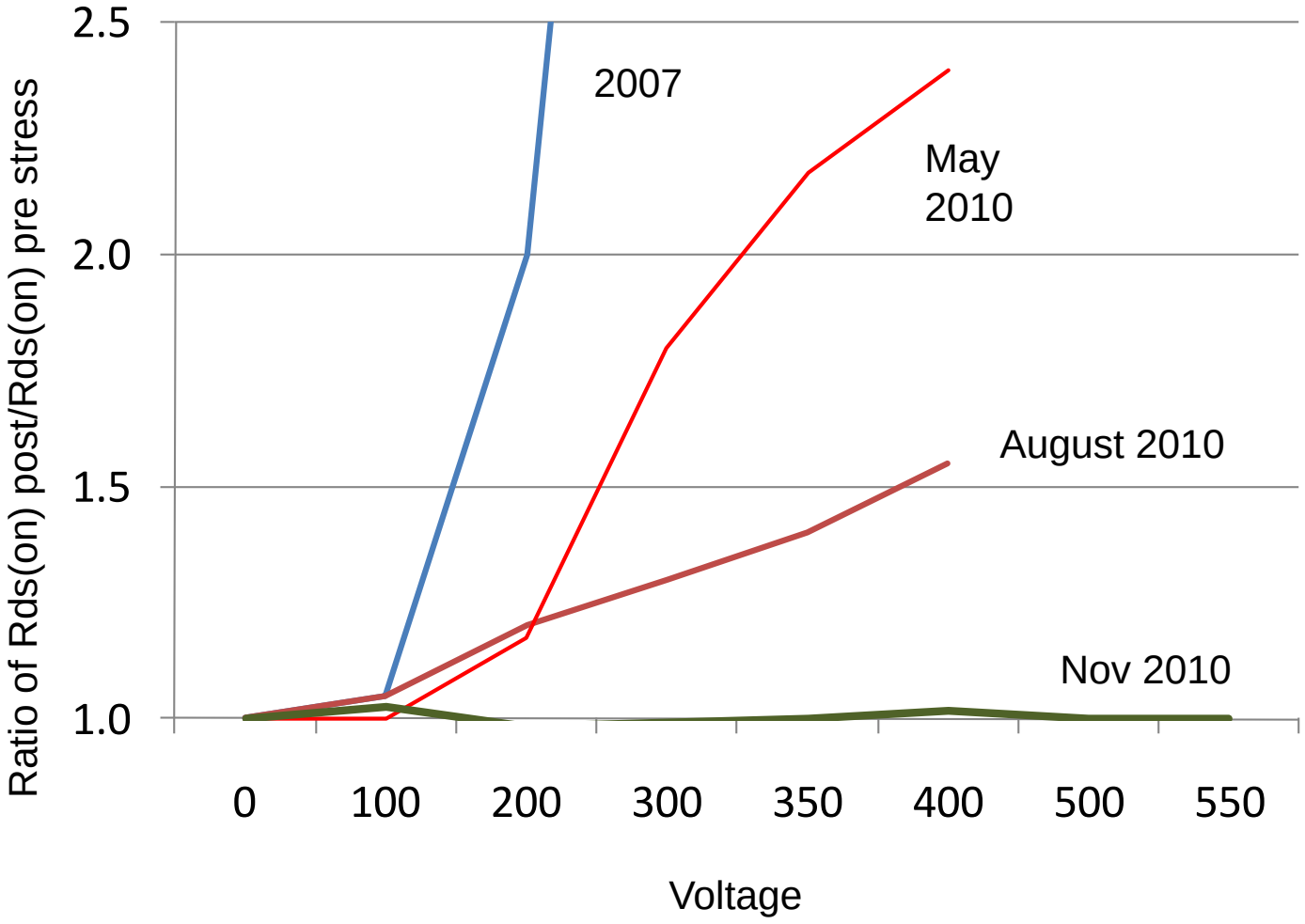
600 V Device Trr Performance Comparison



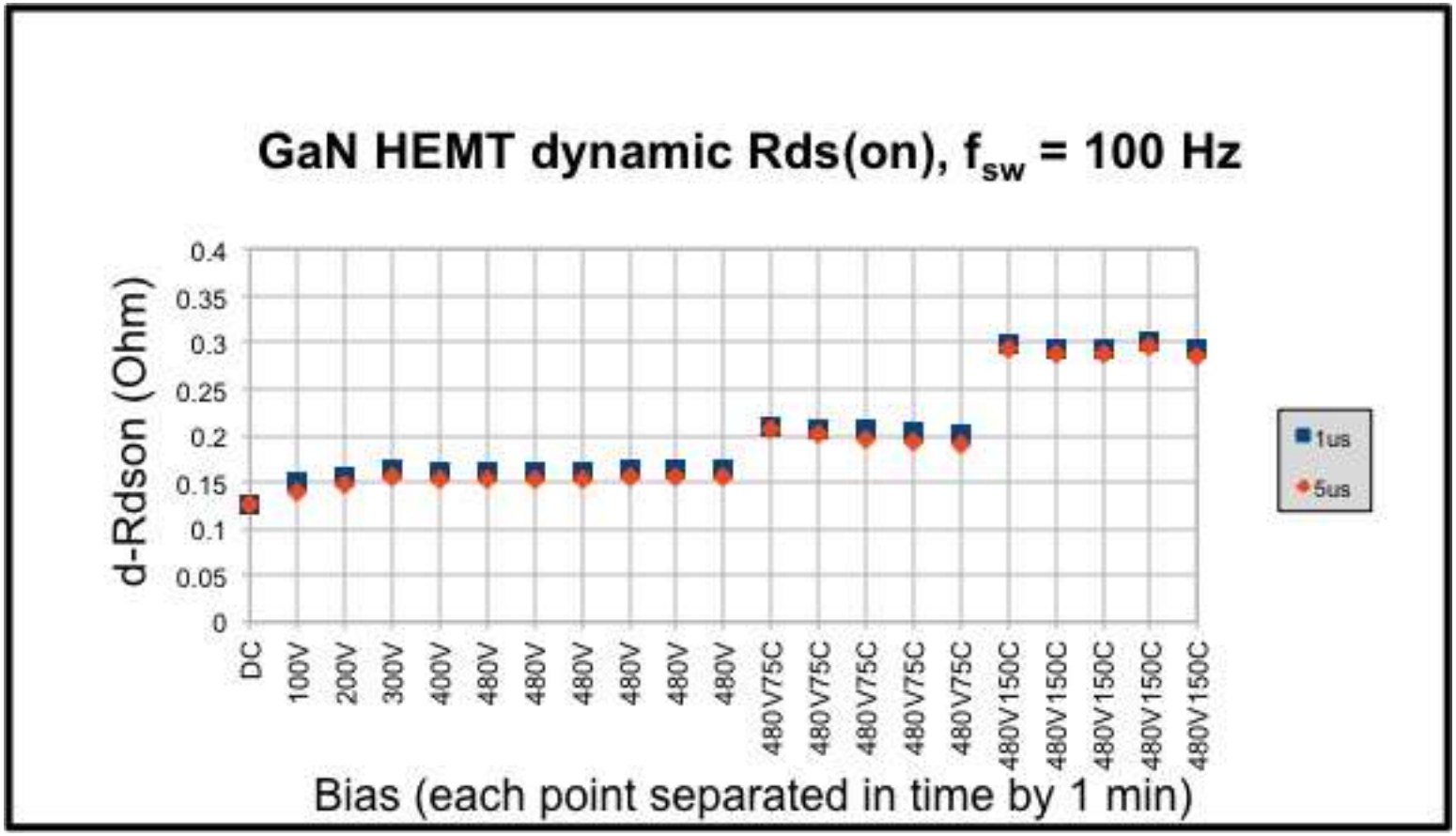
GaN based device has 20x Lower Qrr compared to IGBT Copak and more than 200x less than Super Junction body diode

GaN Qrr independent of temperature

600V GaN Device Stability - Improvements

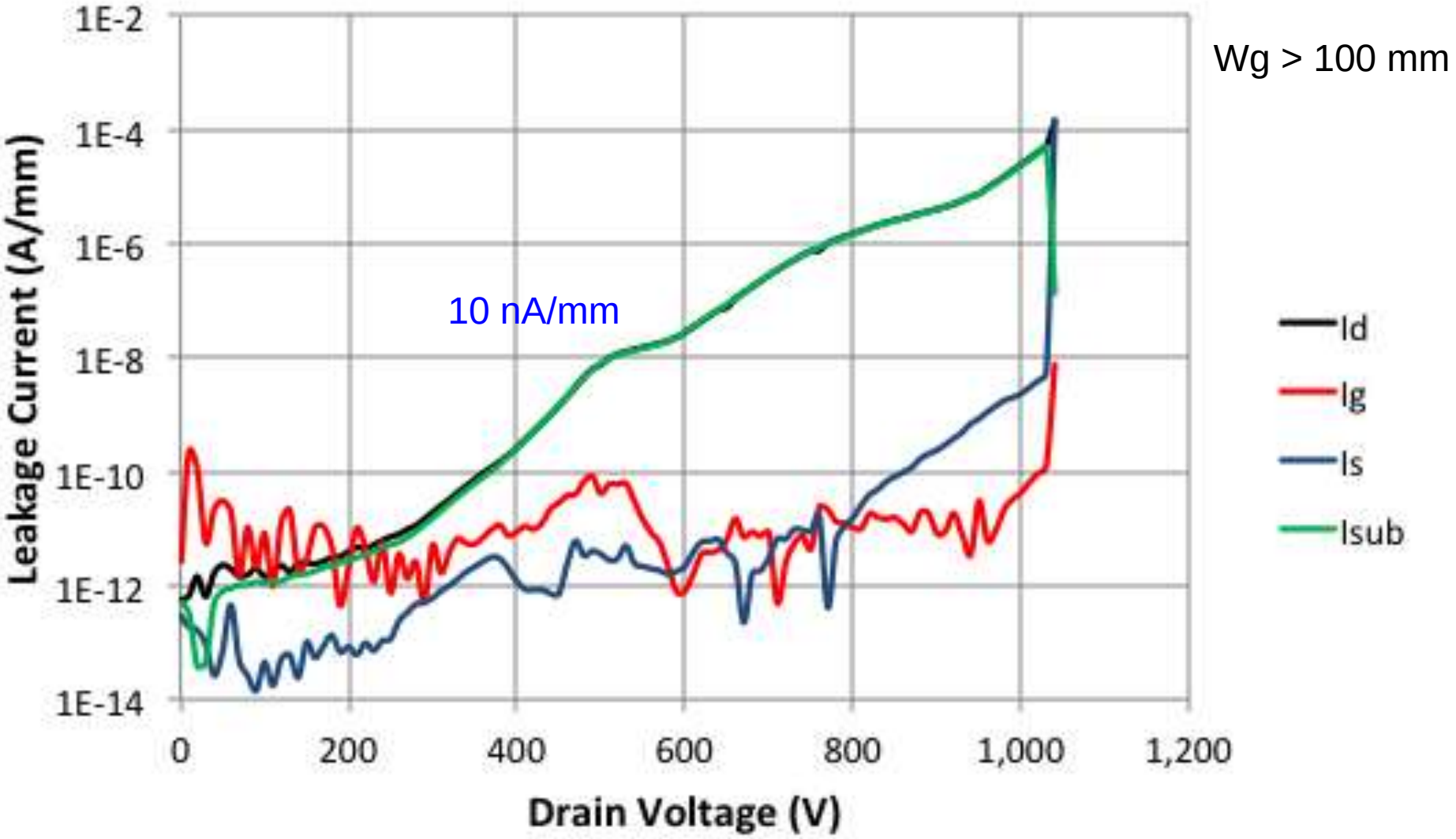


HV GaN HEMT dynamic Rds(on)



Negligible dynamic Rds(on) effect over drain voltages (up to 480V) and temperatures is observed.

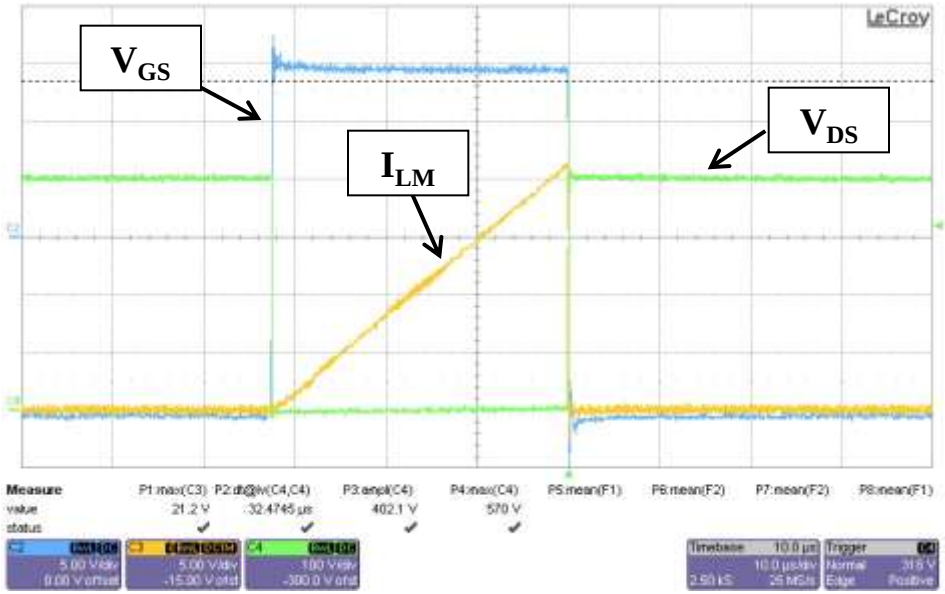
Dielectric Breakdown of 600 V rated device > 1000 V.



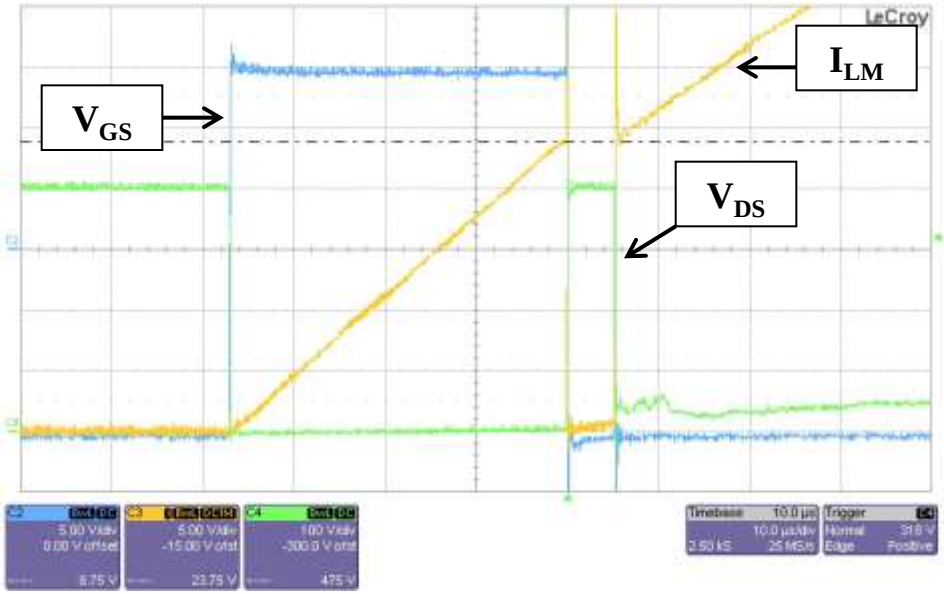
Clamped Inductive Switching (ILM)

V_{DD} = 400V
L = 585 µH
V_{GS} = -15V/15V

400V/21A ILM switching



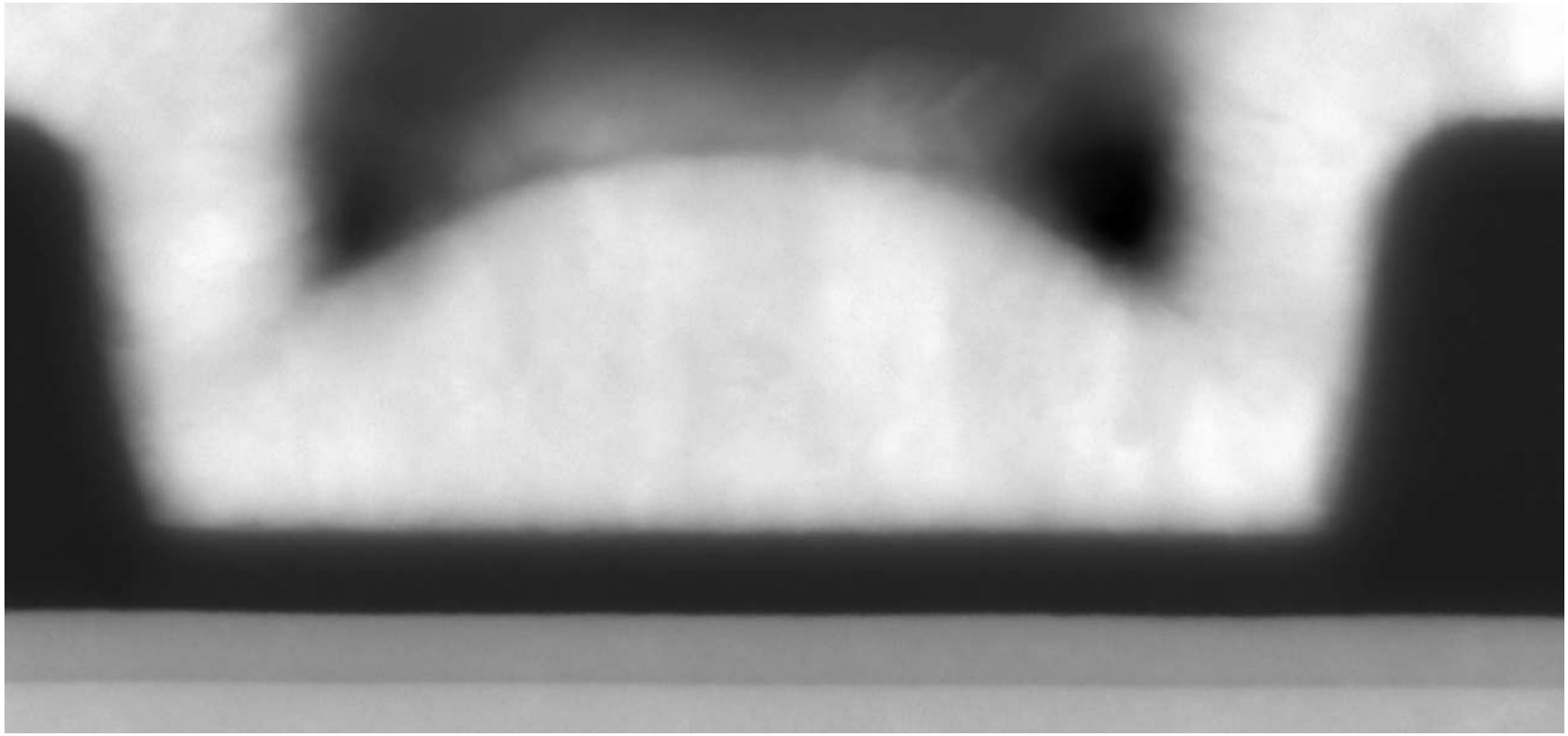
Failed at 400V/24A ILM switching



GaN cascode switch shows good ILM switching capability even well above the rated current (failed at 24A vs rated current of 10A)

GanpowIR® Reliability

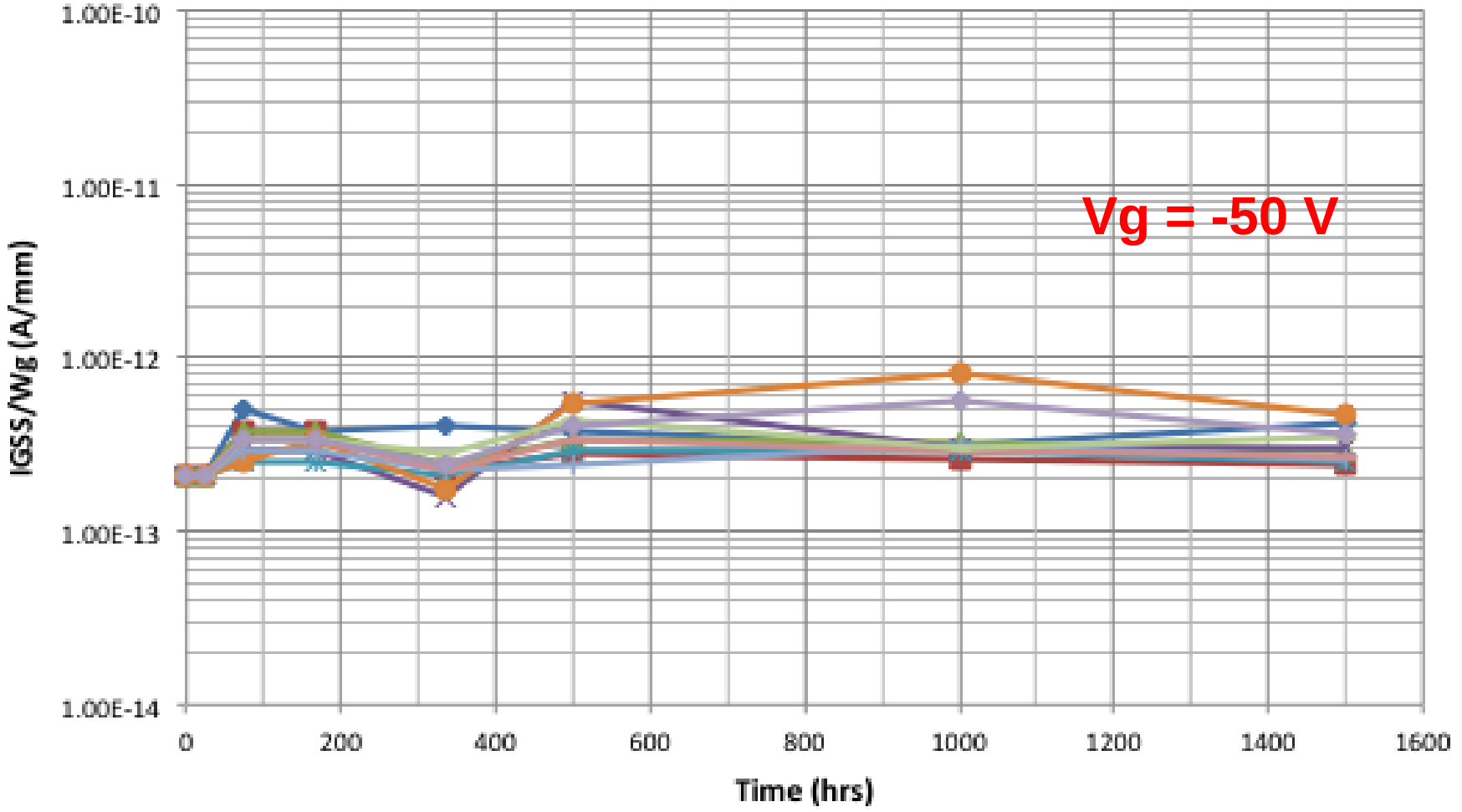
No Evidence of Inverse Piezo-Electric Effect in GaNpowIR® devices



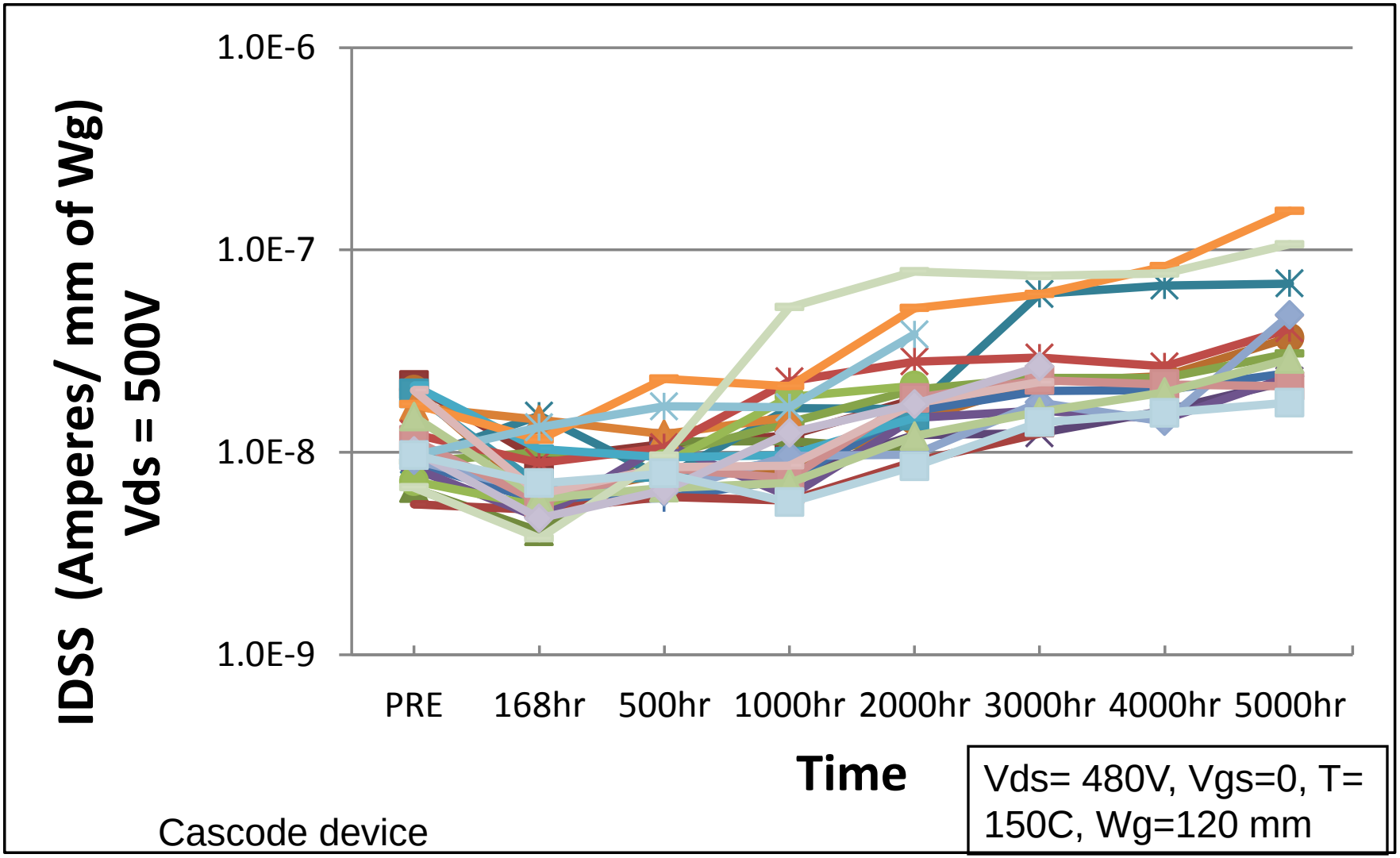
- TEM Image (No physical damage) from stress :
- HTRB (Vd=26 V, Vg=-14 V at 150 C) > 3000 Hours.
- HTRB (Vd=26 V, Vg=-7V at 175 C) > 3000 hrs
- HTRB (Vd = 34 V, Vg=-22V at 150 C) > 600 hrs
- HTGB of -50 V for > 3000 hrs
- Foward conduction (I=200 mA/mm, Vd= 25 V)

IR GaNpowIR Gate Dielectric Reliability

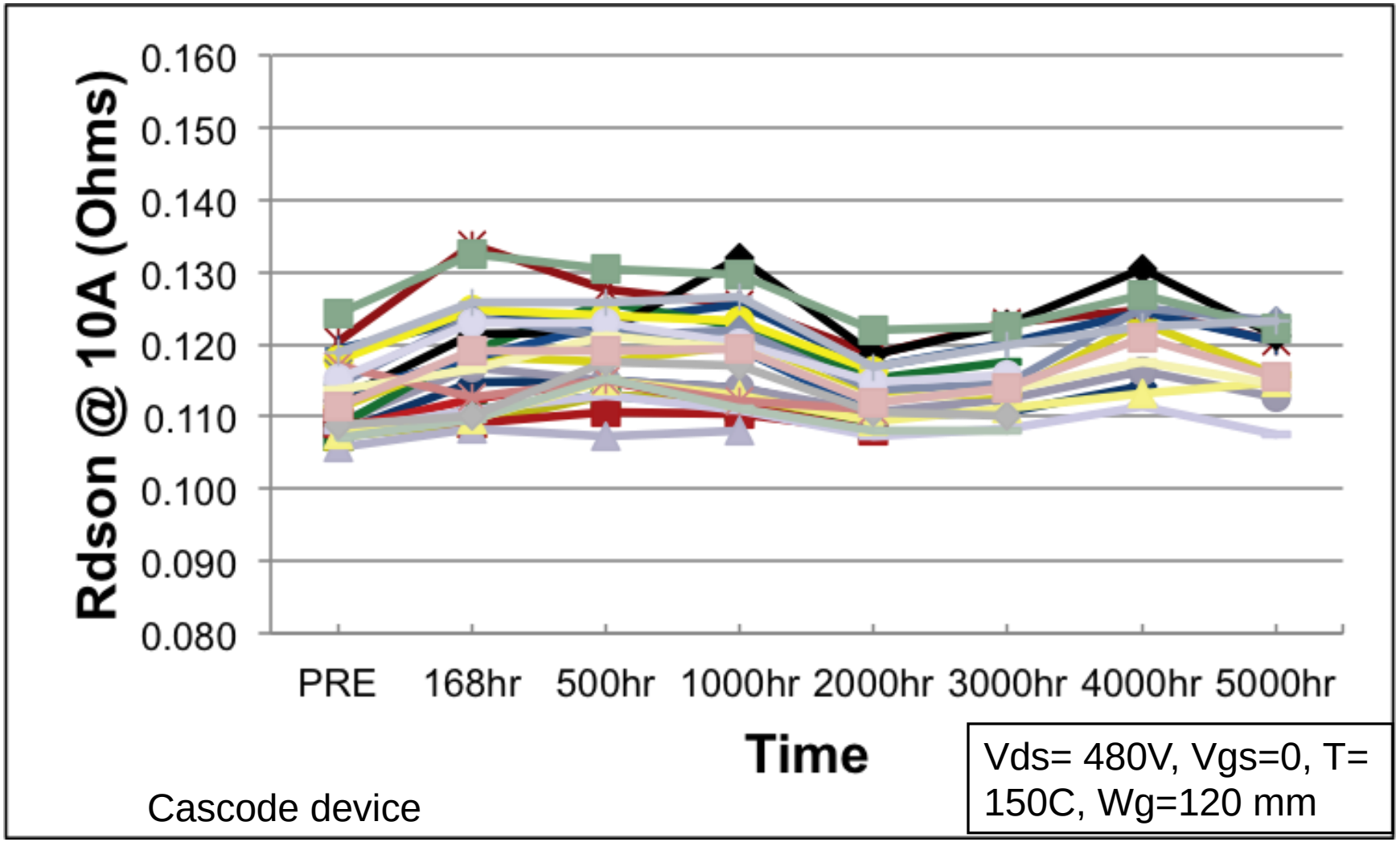
MTTF at 150 C and Vg = - 20 V : > 10^8 hours



600V GaN Idss Stability in HTRB up to 5,000 hours

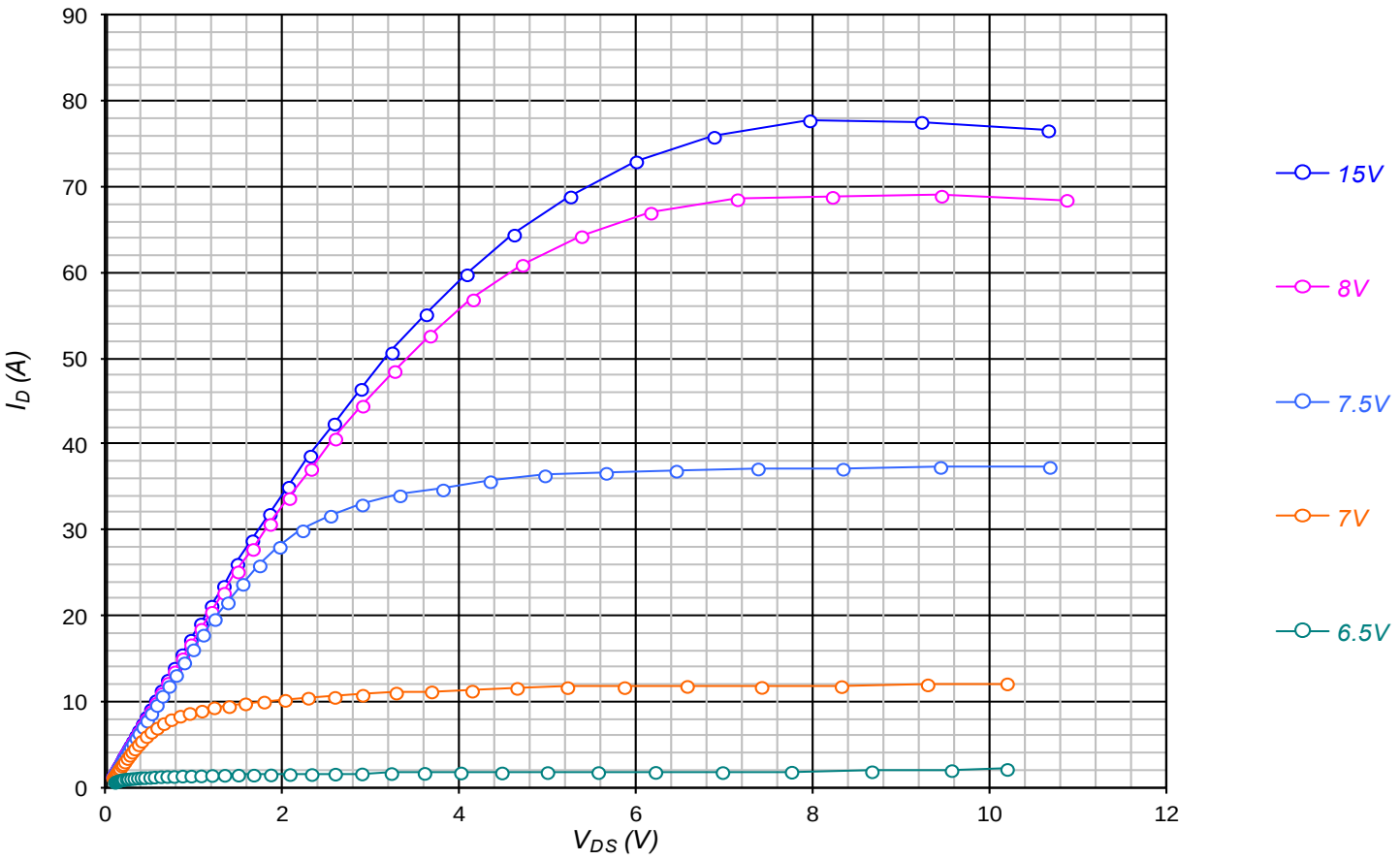


600V GaN R_{DS}(on) Stability in HTRB up to 5,000 hours



How does GaN Performance Compare with Silicon in Electric Vehicle Drive Application?

Large area (AA =8 mm^2) 600 V rated device Current Handling Capability



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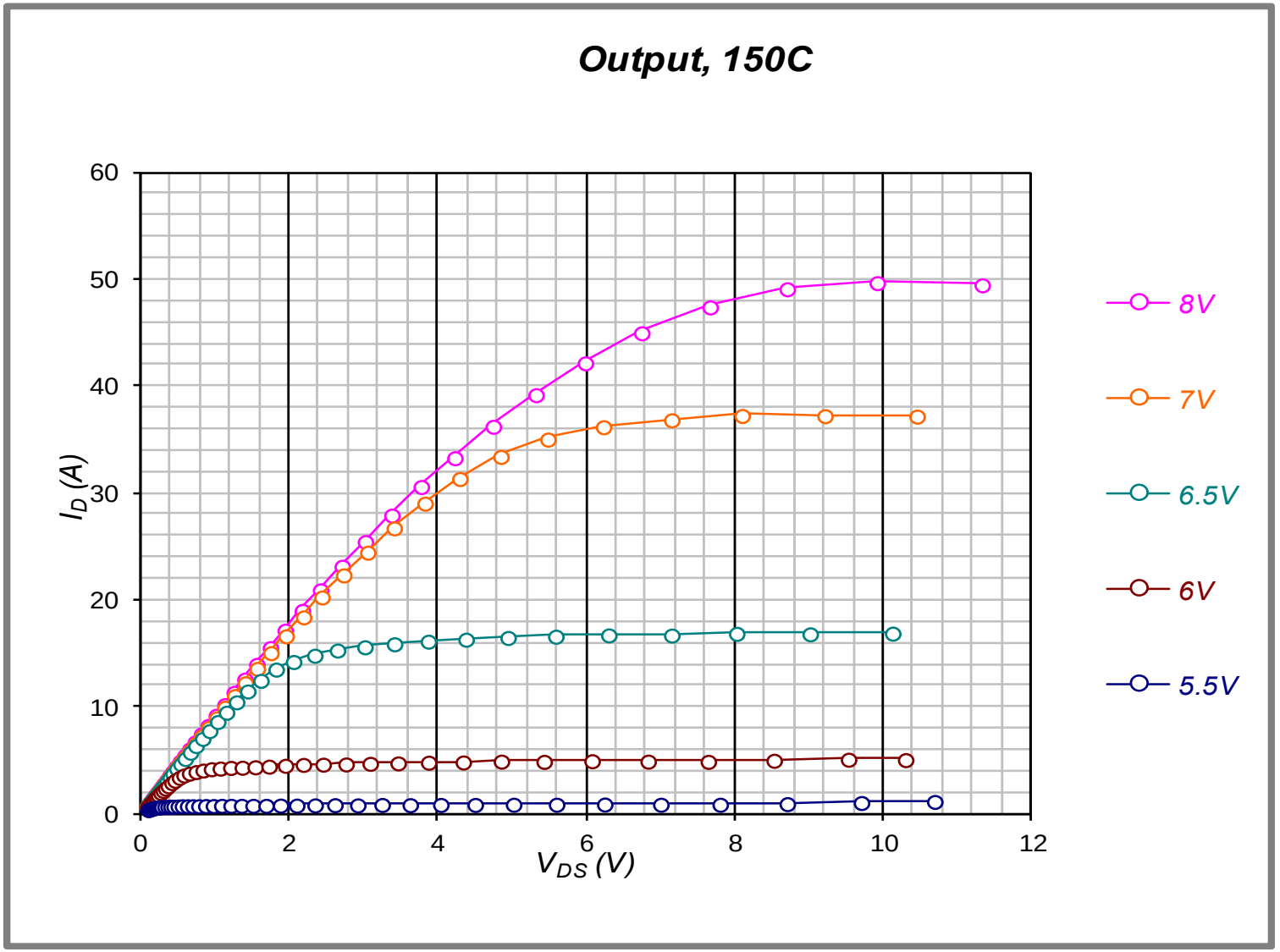
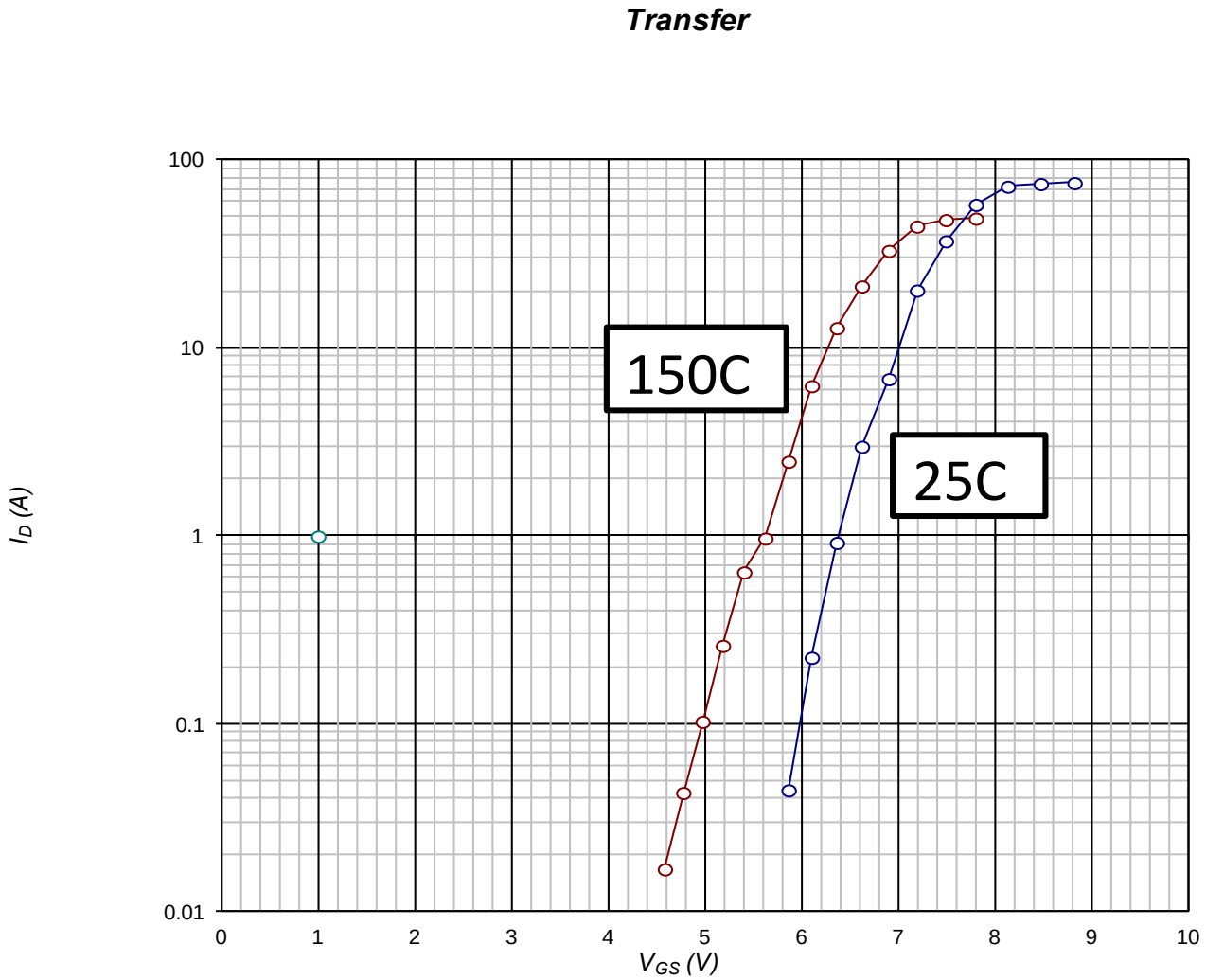
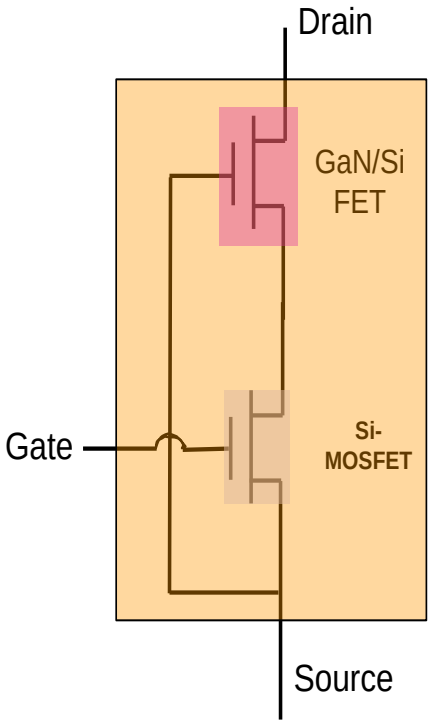
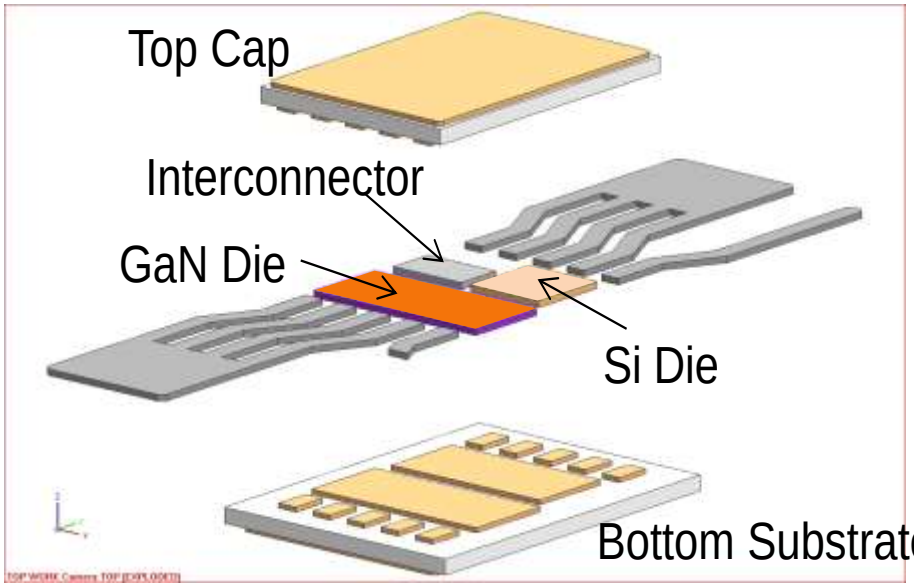


Large area (AA =8 mm^2) 600 V rated device Current Handling Capability

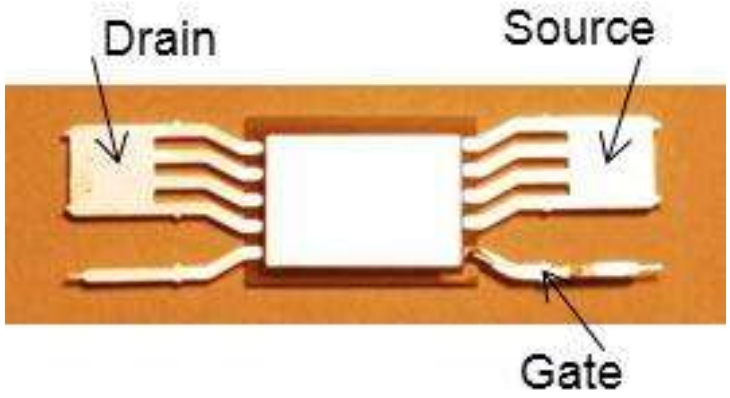


Test Device Packaging

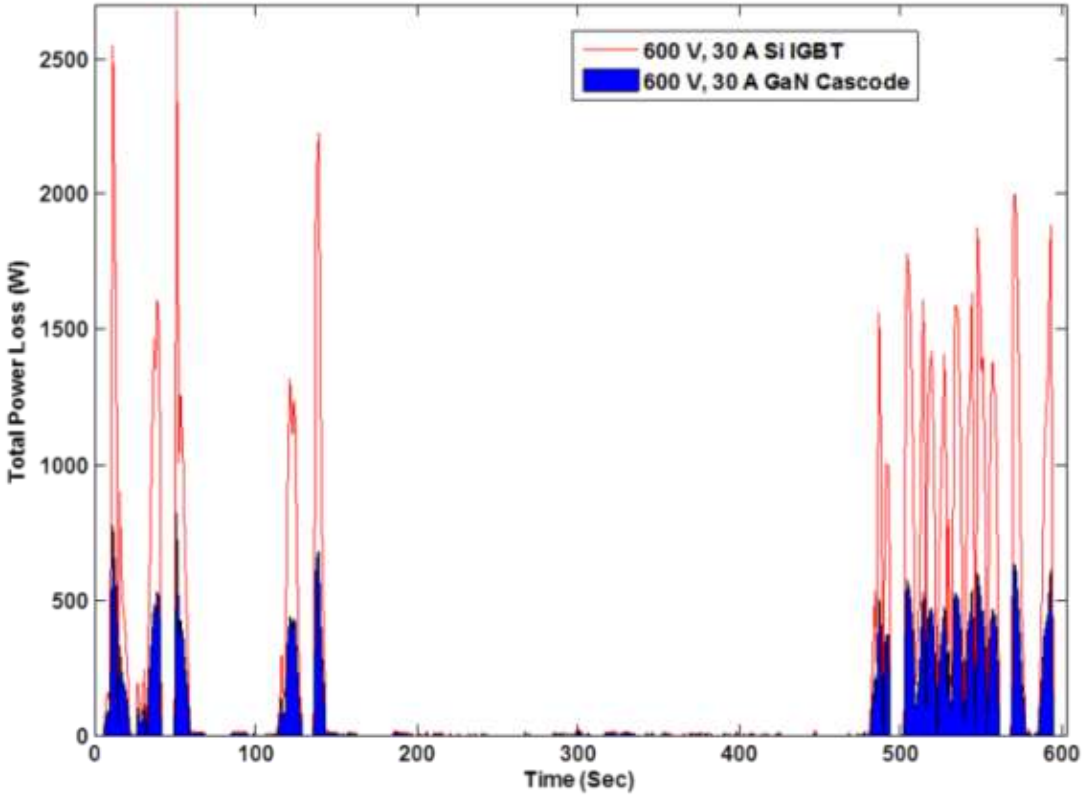




Device Active area = 8mm2 (much larger devices have also been fabricated : 35 mm^2)



Power Dissipation: GaN vs IGBT in EV Inverter



- Modeled Power Dissipation of Silicon IGBT vs GaN devices in US06 Drive Cycle (standardized, 20 minute, 8 mile long drive)
- 55 kW electric motor in hybrid drive system: average power = 25 kW, Peak Power = 100kW
- **GaN based solution has close to 50% lower average power loss than IGBT**
- F=20 kHz, T = 105C, buss voltage = 325V.

Is any III-V Semiconductor ready for use in automotive applications?

Silicon Reliability Considerations

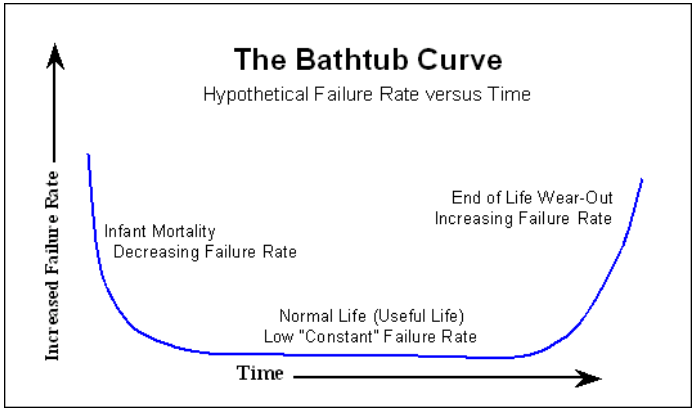
- Standard reliability qualification testing requires qty 77 parts from each of 3 different lots
- 1 failure in 241 pcs. Allowed (~2500 ppm)
- Elevated temperature biased test duration is 1000 hours
- For Silicon, 50 years learning and testing shows useful (biased) lifetime (MTTF) decreases 2x for every 10C rise in temperature (ie: E_A = 0.65V)
- Thus testing for 1000 hours at 150C equates to 32x acceleration in failure rate at 100C (~4 years).

GaN Reliability Considerations

- For GaN devices, IR sets same standard for qualification: Qty 77 parts from each of 3 different lots
- 1 failure in 241 pcs. Allowed (~2500 ppm)
- Elevated temperature biased test duration is 1000 hours typically at 150C
- How much does GaN based power device biased lifetime decrease for each 10C increase over operating temperature?
- How much useful life is guaranteed by 1000 hours testing?

Early vs. useful life failure rate

- Due to “infant mortality/freak failures, initial failure rate is higher than inherent useful life failure rate
- “Infant mortality /freak failures are reduced through testing to identify failure modes which then must be eliminated
  - Can be contained by 100% burn in
  - Source of non uniformity must be eliminated
  - Volume dependent occurrence (can not predict all sources of failure based on initial production)
- Automotive Applications require sustainably very low Infant Mortality and certainty of useful life duration
- **Thus adoption is paced by both volume/quality improvement and enhanced understanding of the relevant activation energies for the appropriate failure mechanism**



Summary

- III-V Semiconductors face significant hurdles for adoption in Automotive applications
- The required performance has been demonstrated with GaN on Silicon based devices on IR's GaNpowIR® platform.
- GaN on Silicon technology when developed with CMOS compatible processing can achieve functional cost parity or better with silicon solutions
- GaNpowIR® devices have been fabricated with the die size necessary for automotive applications
- For adoption off III-V's in automotive applications volume production must first be realized (other markets)
  - Required to reduce infant mortality, determine Ea's and reduce costs