Commercialization of GaN HEMT based power electronics

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July 31st, 2024

Infineon at a glance

Growth areas

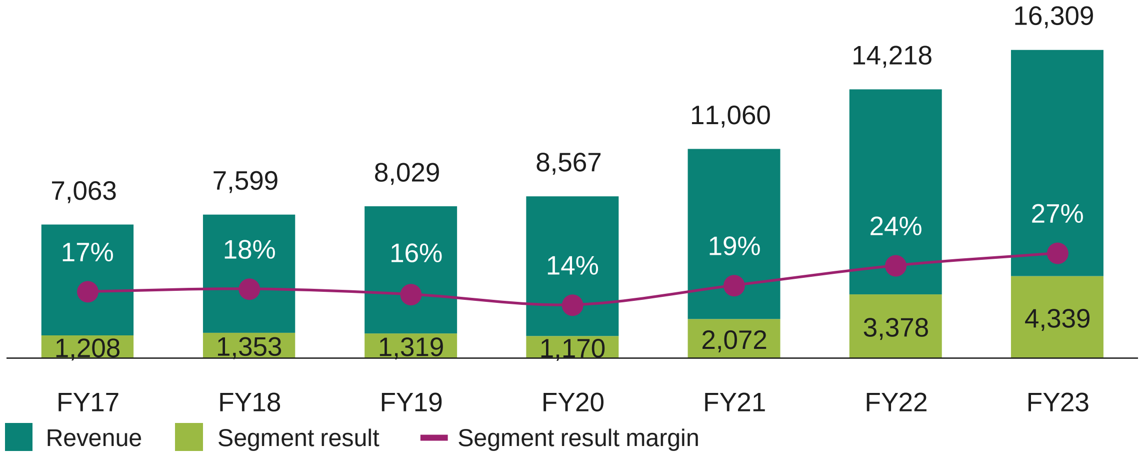
Energy
green and efficient

Mobility
clean and safe

IoT
smart and secure

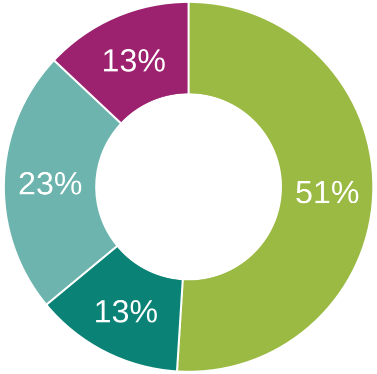
Financials

[EUR m]



FY23 revenue by segment[1]

- Automotive (ATV)
- Green Industrial Power (GIP)
- Power & Sensor Systems (PSS)
- Connected Secure Systems (CSS)

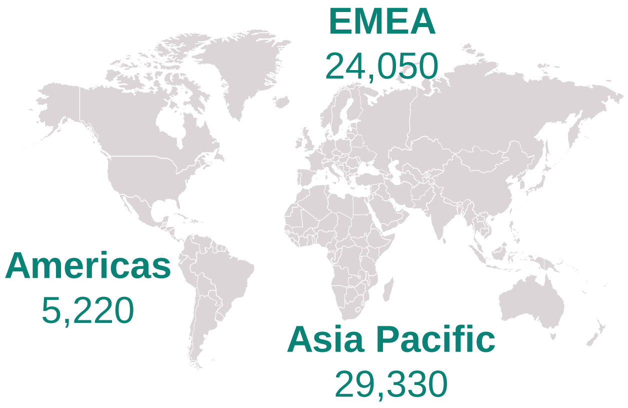


Employees[2]

58,600
employees worldwide

69
R&D and

17
manufacturing locations[2]



For further information: Infineon Annual Report.

[1] 2023 Fiscal year (as of 30 September 2023) | [2] As of 30 September 2023

Driving decarbonization and digitalization. Together.

Semiconductors are crucial to solving the energy challenges of our time and to shaping the digital transformation.

Infineon is committed to actively drive decarbonization and digitalization, and is one of the most sustainable companies in the world

As a global semiconductor **leader in power systems and IoT, we enable game-changing solutions for green and efficient energy**, **clean and safe mobility, as well as smart and secure IoT**.

Infineon is committed to binding CO_2 reduction targets

1 | Carbon neutrality[1] by 2030 – primarily by avoiding emissions

2 | Emissions reduction of 70 percent by 2025 compared to 2019

[1] Carbon neutrality is defined in terms of Scope 1 and Scope 2 emissions.

Infineon leading in power systems – mastering all three key materials

- Reliable multi sourcing of raw materials
- World-scale fabs

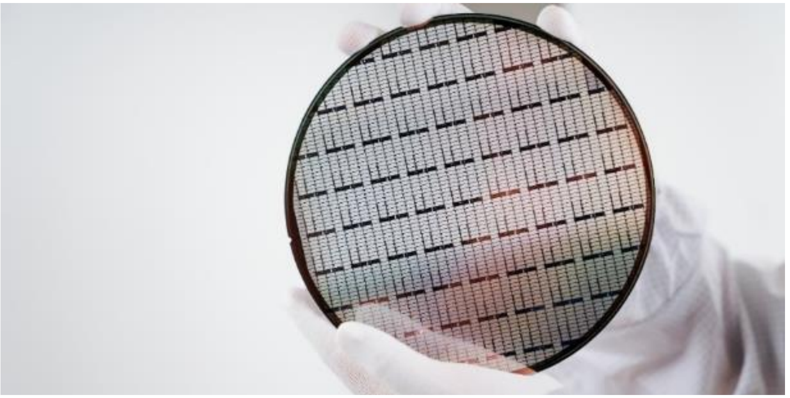
Controller → **Driver IC** → **Power switch** (GaN/SiC/Si)

Software + Algorithms

- Application understanding
- Packaging know-how and hybridization competence

Leadership in Power Systems across all materials and technologies

Gallium nitride
HEMT – Driver

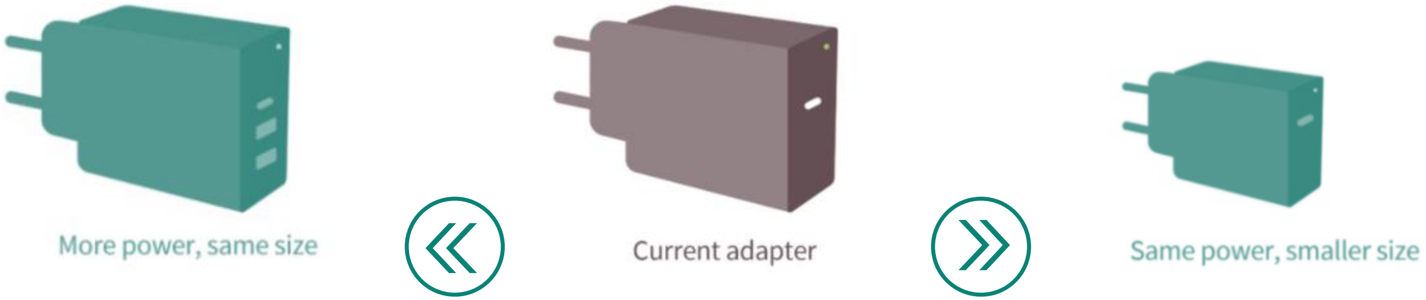


Silicon carbide
Diode – MOSFET

Silicon
Diode – MOSFET – IGBT – Driver – Controller

While doubling power density, Infineon's solutions are positioned to be the future of mobile charging

What higher power density means to customers



System savings

3x switching frequency

> 30% energy savings

20% lower System Cost

50% higher power density

2x less Size & weight

Energy saving potential with GaN and advanced technologies powered by Infineon

Did you know?

2% of total energy consumption in the EU is related to servers and data storage products

In **2030** this energy demand will reach **78 TWh** Which is higher than the yearly electricity consumption of Belgium, the Czech Republic, Portugal or Switzerland

Saving potential with CoolGaN™ per year if used in all worldwide data centers[1]

21 bn kWh

1.5 bn USD

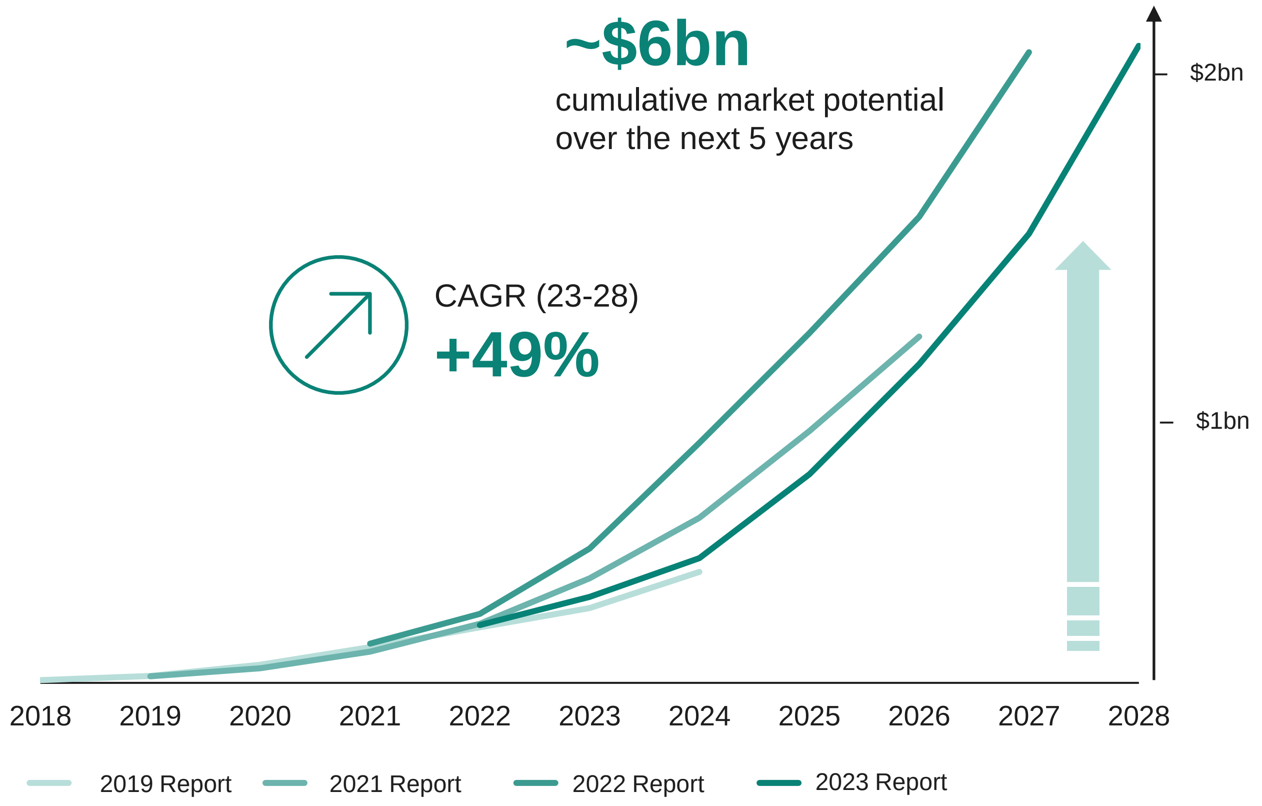
17 Mt CO_2

Infineon GaN Power transistors enable top notch efficiency and power density in SMPS

1 Transition from Si-based power supplies in enterprise architecture to GaN-based power supplies in hyperscale architecture

GaN market is taking off, driven by key power applications

GaN market forecasts over time



Superior switching performance results in **higher efficiency** and **lower system cost.**

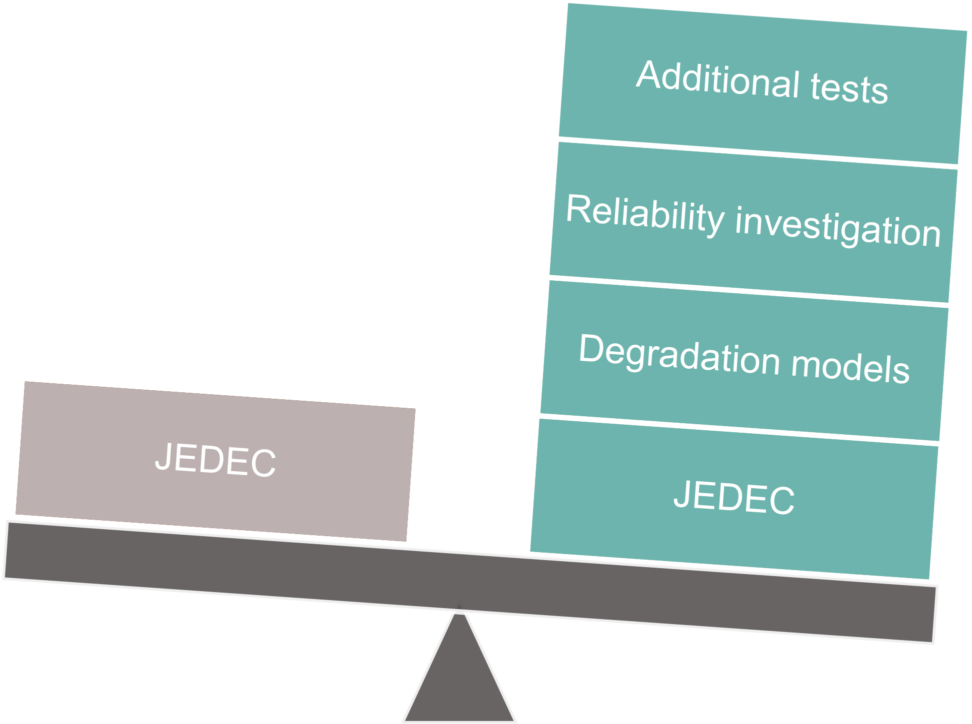
Applications with **tipping point** reached or in sight:

Charger, adapter	Server (high voltage)
Residential solar	On-board charger

Source: Yole: Power GaN Report 2023 & Compound Semiconductor Market Monitor-Module I Q4 2023

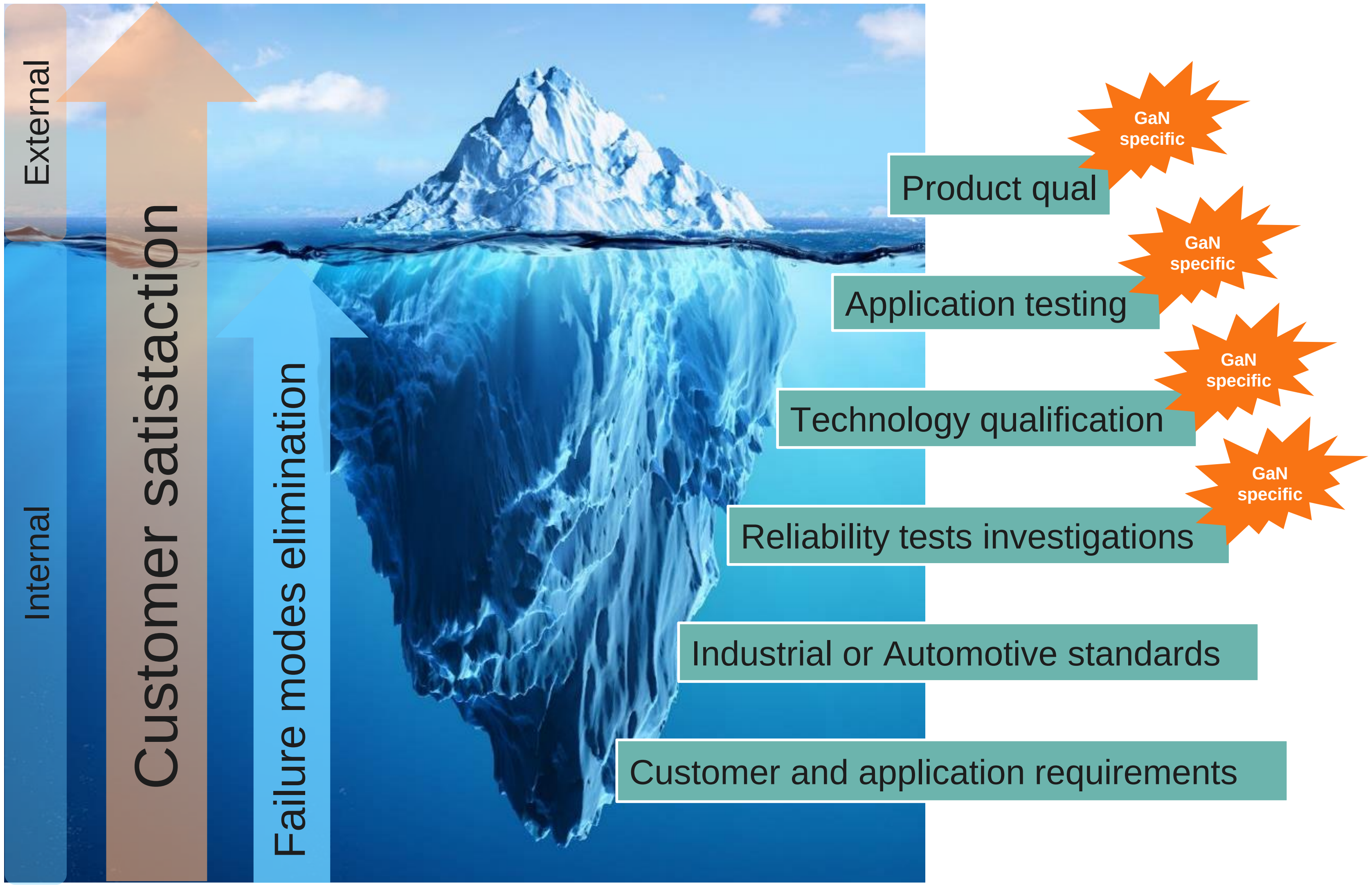
Infineon's GaN qualification approach is leading in the industry

Most reliable GaN HEMTs in the industry



Infineon applies **stringent qualification plans,** including failure models to predict lifetime and in-field failure rates

CoolGaN^{TM} final product quality and robustness is achieved by stringent multiple gates and based on the customer needs

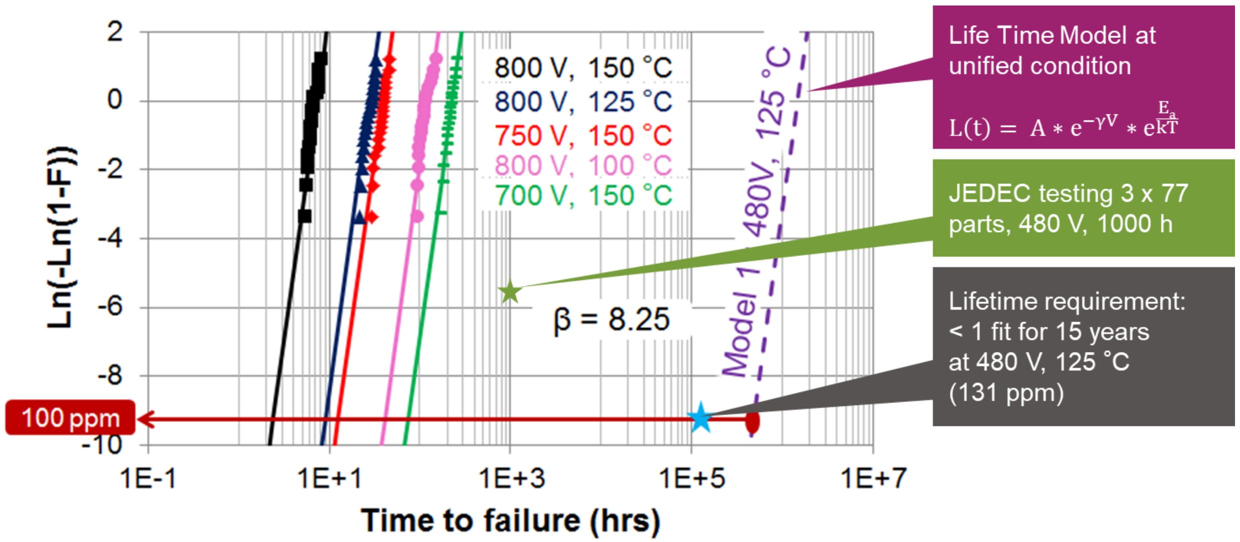


Reliability

Intrinsic Branch (TDB (HTRB))

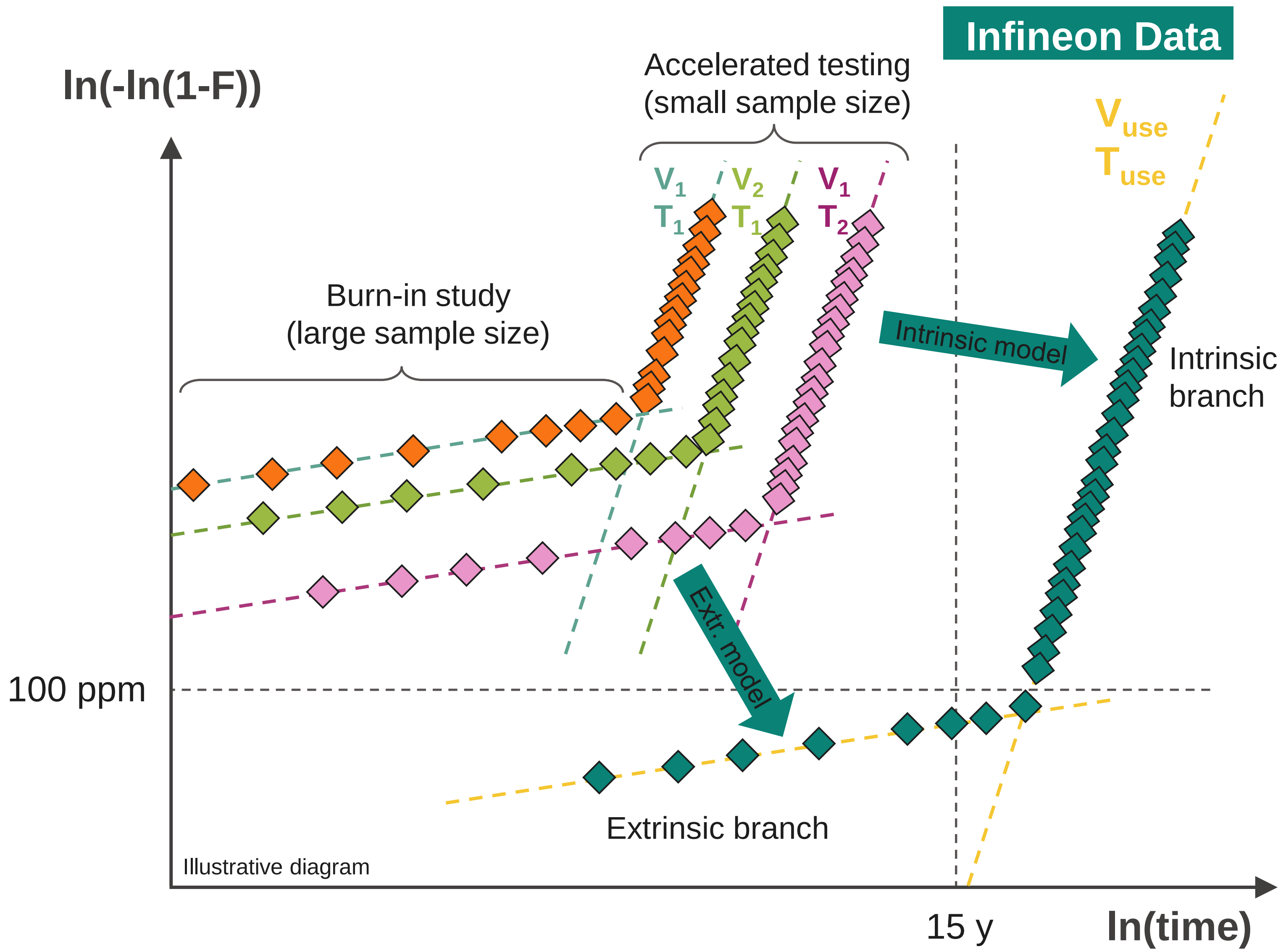
Intrinsic Branch

- Currently the most conservative model is used
- In JEP-122 (Silicon), various models are listed
  - JC701.1 is attempting to answer degradation physics questions and compile a document similar to JEP122
- Since the Physics and Electrostatics of DC-TDB can be different from AC-TDB, the methodology should rely on the application mission profile and use case



H. Kannan et. al. “Reverse Bias Lifetime Analysis of 600V Enhancement Mode GaN Devices,” WiPDA 2017

Only large scale extrinsic study proves industrial fitness

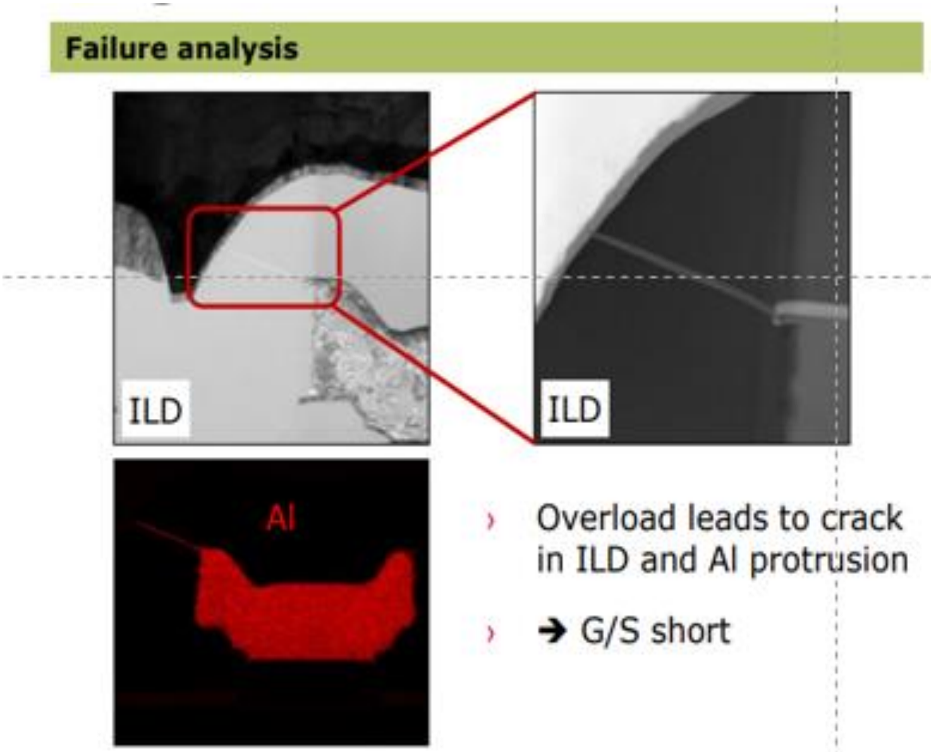


– Need to perform a **large scale** burn-in study on > **100k+** parts to assess the extrinsic failure rate

– A lifetime model for extrinsic fails Can be extracted

Maturing the GaN technology by addressing extrinsics through defects density improvement and proper screening

– Defect Characterization are key to understanding Extrinsics
– Publications on defects related failures are scarce



- A trap is a defect originating from a structural defect or the presence of an impurity or a sudden loss of continuity in the crystal lattice (as in interfaces)
- A defect disrupts the periodicity of the crystal lattice

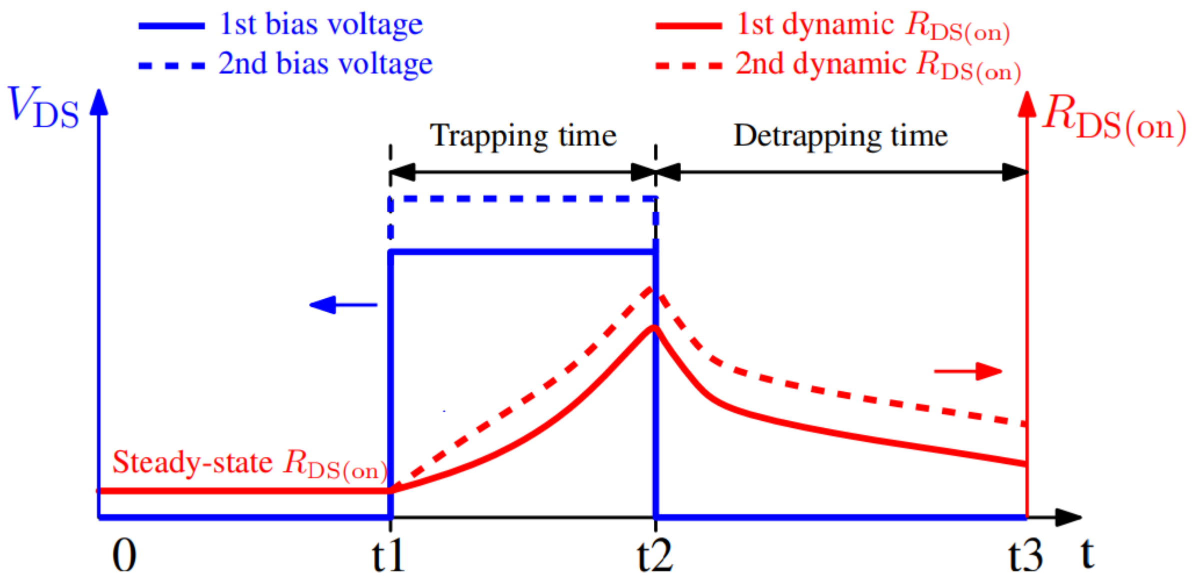
Stacking fault in the saguaro cactus

Self-interstitial in the corncob

Application testing

Dynamic $R_{DS(on)}$

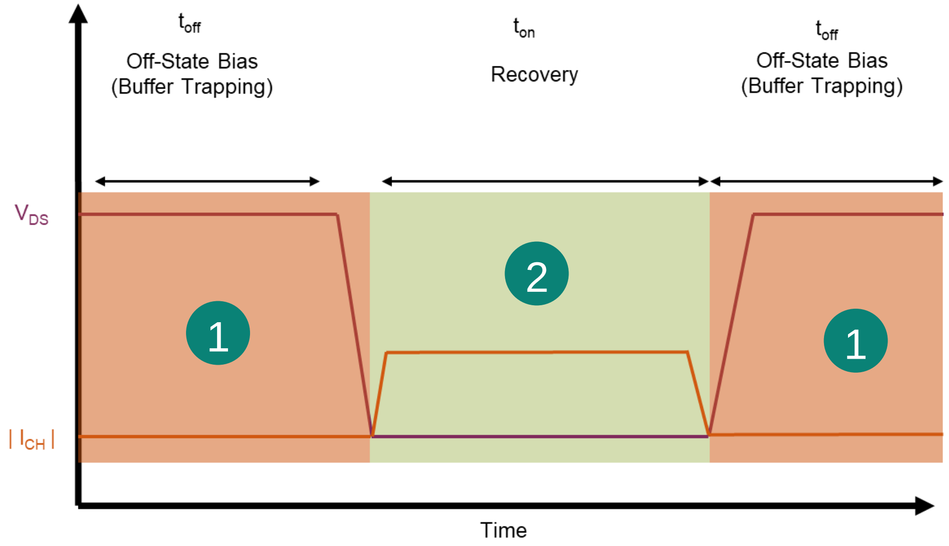
- A phenomena that occurs with all power GaN HEMT, but not with Si FET
- When GaN HEMT first transitions from off to on state, the effective $R_{DS(on)}$ is higher than the DC / steady-state value and “slowly” decreases to the DC value while on
- Bias that causes this behavior typical operation for switched mode power supplies, resulting in the effective $R_{DS(on)}$ during operation to be a higher dynamic $R_{DS(on)}$ ($dR_{DS(on)}$) value



K. Li, P. Evans and M. Johnson, "GaN-HEMT dynamic ON-state resistance characterisation and modelling," 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), Trondheim, Norway, 2016, pp. 1-7, doi: 10.1109/COMPEL.2016.7556732.

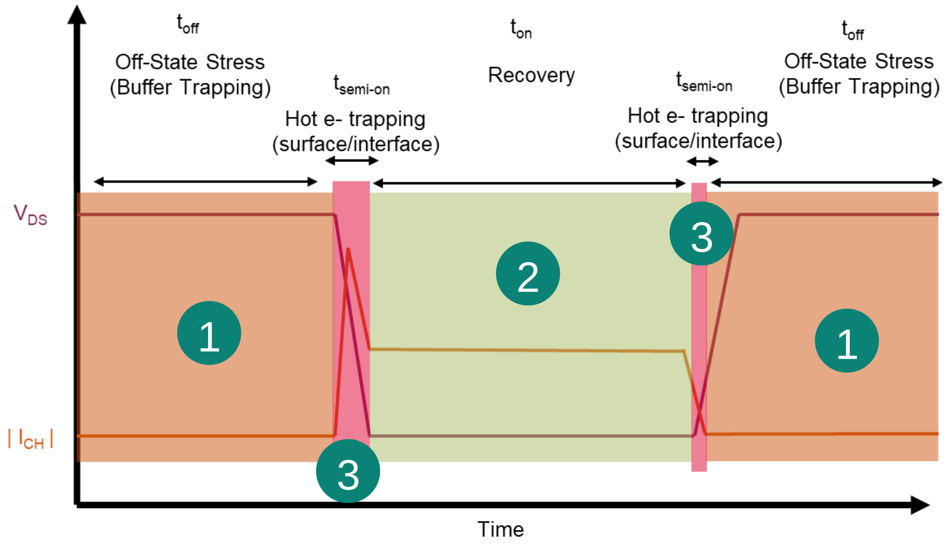
What causes dynamic $R_{DS(on)}$?

Soft switching operation



1. Pure off-state (with drain bias) → OSB
2. Pure on-state → none

Hard switching operation



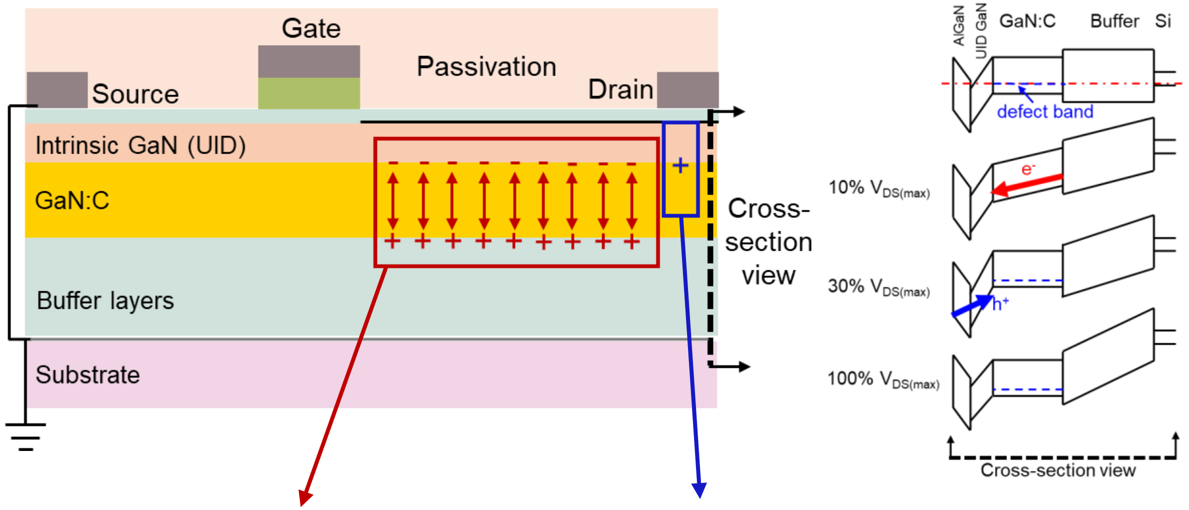
1. Pure off-state (with drain bias) → OSB
2. Pure on-state → none
3. Semi-on state (with I-V overlap) → HCI

Only off-sate bias (OSB) generated with soft switching, while both off-sate bias (OSB) and hot carrier injection (HCI) are generated with hard switching

N. Dellas and E. Jones. "Dynamic $R_{DS(on)}$ in GaN HEMTs: Physical origins and system design considerations," PCIM 2023

What causes dynamic $R_{DS(on)}$?

Off-State Bias (OSB)



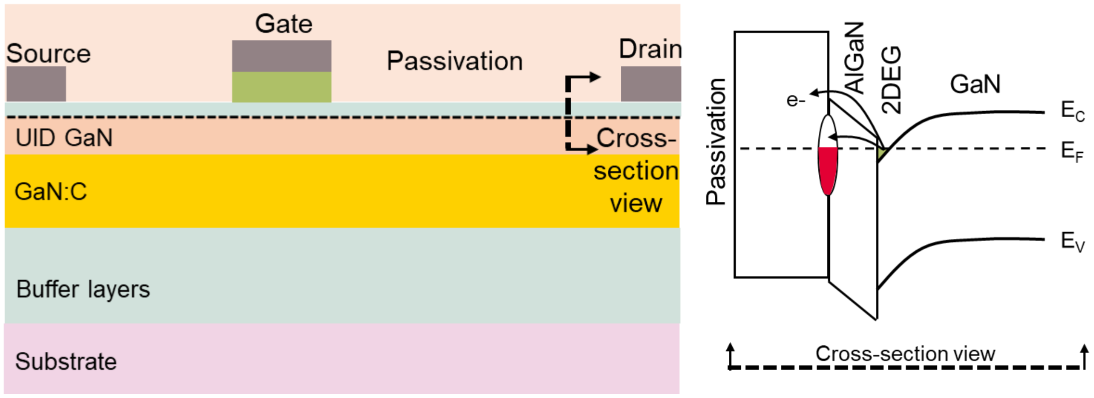
Charge redistribution in carbon-doped GaN (GaN:C):

Under electric field, charges redistribute in GaN:C, resulting in negative charge separation towards 2DEG, causing depletion and increasing $R_{DS(on)}$

Hole (h+) injection from drain:

Positive charge compensation from V_{DS} results in net recovery of 2DEG and $R_{DS(on)}$ over time, increasing with higher bias

Hot carrier injection (HCI)

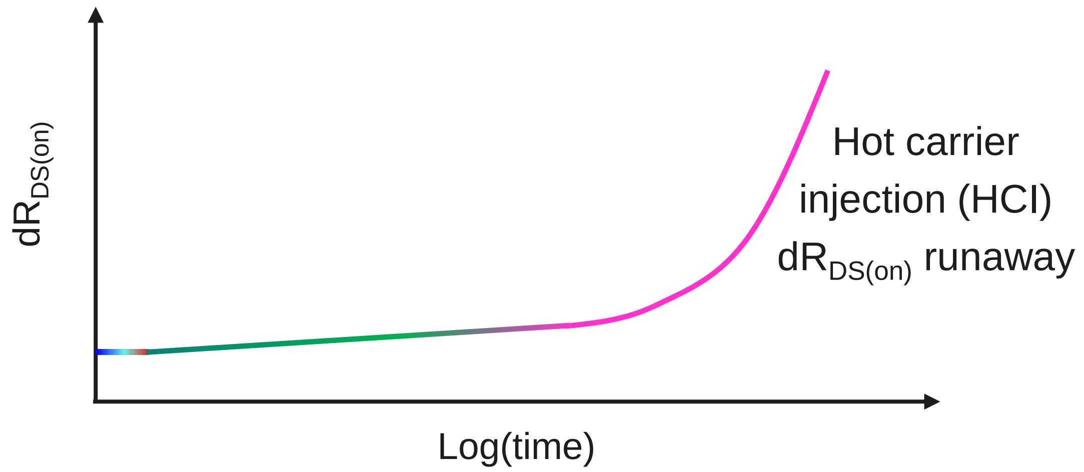


Hot carrier injection:

- As high potential is applied to the drain, with current flowing in the channel – electrons are rapidly accelerated, gaining kinetic energy under the strong E-field (hot carrier generation)
- These electrons can then tunnel from the 2DEG into surface and interface states, causing $dR_{DS(on)}$

N. Dellas and E. Jones. "Dynamic $R_{DS(on)}$ in GaN HEMTs: Physical origins and system design considerations," PCIM 2023

Dynamic $R_{DS(on)}$ impact over lifetime



- Hot carrier injection (HCI) effects can worsen over operating lifetime
- Electric field distribution during hard-switching (semi-on state) changes over the lifetime of the device
- In the case that significant depletion of the channel occurs in the access region, the electric field drastically increases toward the drain side of the device, resulting in significant generation and trapping of hot carriers
- This positive feedback eventually leads to “runaway” of $dR_{DS(on)}$, over time, full channel depletion can occur

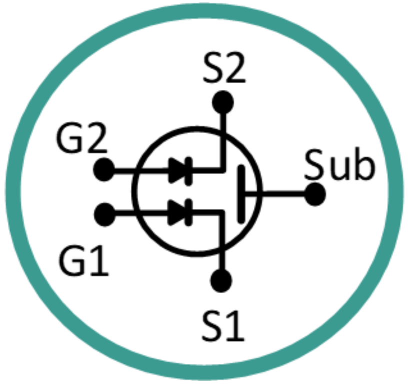
- Behavior can be modelled using either methodology
  - Switching Accelerated Lifetime Test (**SALT**)
  - Dynamic High Temperature Operating Life (**DHTOL**)
- Results from accelerated tests can be extrapolated back to use conditions to estimate useful lifetime criteria
- JEP180 developed to drive standardization for testing

Factor	Impact on OSB $dR_{DS(on)}$	Impact on HCI $dR_{DS(on)}$
Voltage ↑	Nonlinear	Higher rate
Current ↑	--	Higher rate
Operating time ↑	Increasing (saturates)	Increasing
Temperature ↑	Higher rate	Lower rate
Frequency ↑	--	Higher rate
Duty cycle ↑	Lower final value	--

Dynamic $R_{DS(on)}$ performance highly dependent on application bias, environment, and operating life

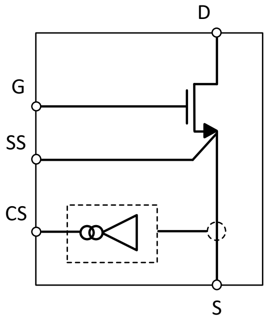
N. Dellas and E. Jones. “Dynamic $R_{DS(on)}$ in GaN HEMTs: Physical origins and system design considerations,” PCIM 2023

What’s next for GaN?



Bi-Directional Switch (BDS)

- True normally-Off monolithic bi-directional switch
- Replace **two discrete uni-directional switches** in bidirectional configuration with a single device
- Enables size reduction and performance improvement for load switch and SMPS topologies that require bidirectional switch (e.g. current source inverter, Vienna rectifier)



Integrated functionality

- Increase functionality with new features, reducing size and improving performance
- Examples include integrated current sense with intrinsic ‘passive GaN FET’

Space applications

- Lack of gate oxide in GaN HEMT eliminates primary degradation mechanism of Si FETs, where trapped charges cause $V_{GS(th)}$ shift
- Still experience degradation and failure due to heavy ion / cosmic rays
- Greater need for robust understanding of quality and robustness

Conclusion

- GaN is enabling next generation of power conversion, helping to drive decarbonization and digitalization

- The quality and robustness of GaN must improve as it expands to new applications

- New structures, functionality and markets will further push need for continual improvement in quality and robustness

Infineon