Characterization of Dielectric Breakdown in High-Voltage GaN MIS-HEMTs

Shireen Warnock and Jesús A. del Alamo

Microsystems Technology Laboratories (MTL)
Massachusetts Institute of Technology (MIT)

Massachusetts Institute of Technology

Outline

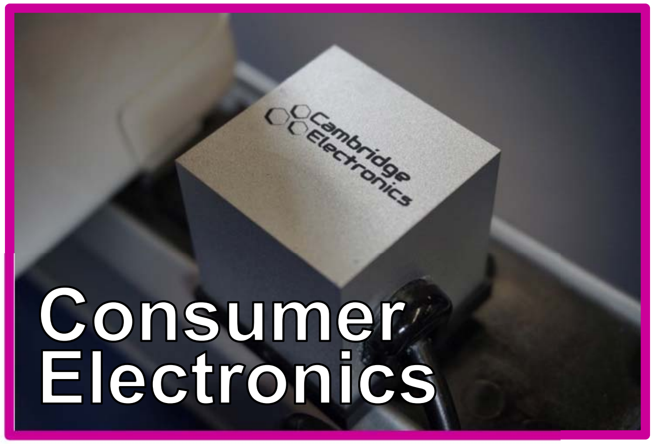
- Motivation & Challenges
- Time-Dependent Dielectric Breakdown (TDDB) Experiments:
  - Current-Voltage
  - Capacitance-Voltage
- Progressive Breakdown
- Conclusions

Motivation

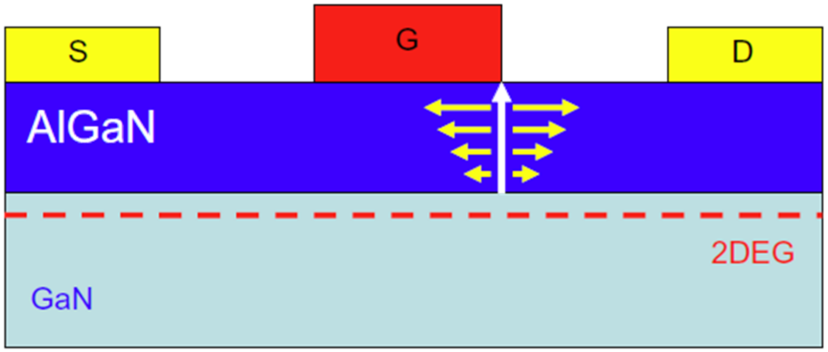
GaN Field-Effect Transistors (FETs) promising for high-voltage power applications → more efficient & smaller footprint

©esa

© Google



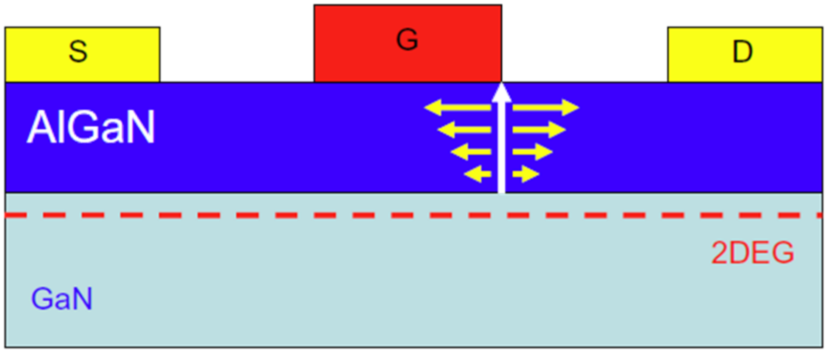
GaN Reliability Challenges



Inverse piezoelectric effect

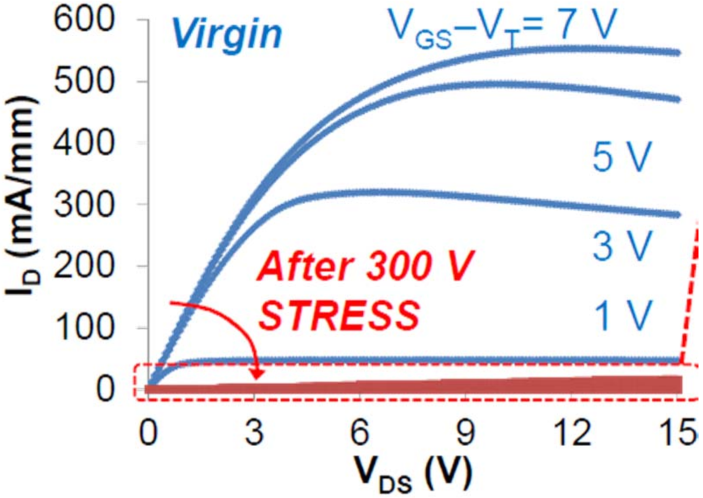
J. A. del Alamo, MR 2009

GaN Reliability Challenges



Inverse piezoelectric effect

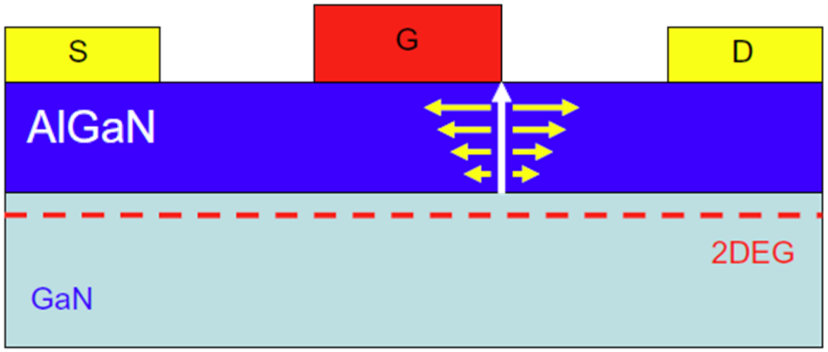
J. A. del Alamo, MR 2009



Current collapse

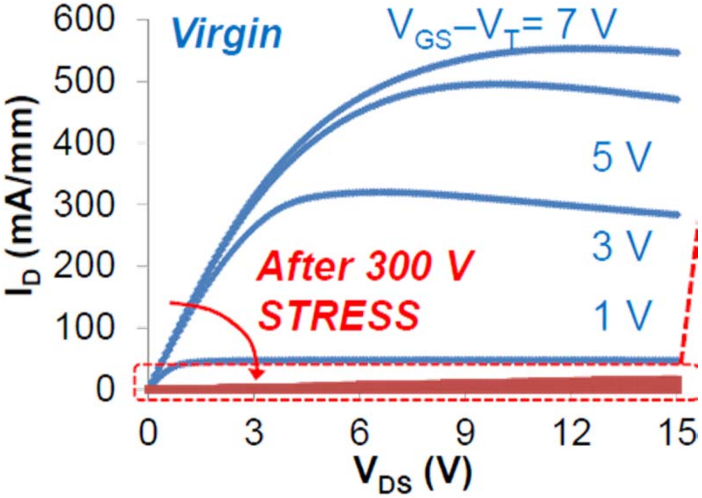
D. Jin, IEDM 2013

GaN Reliability Challenges



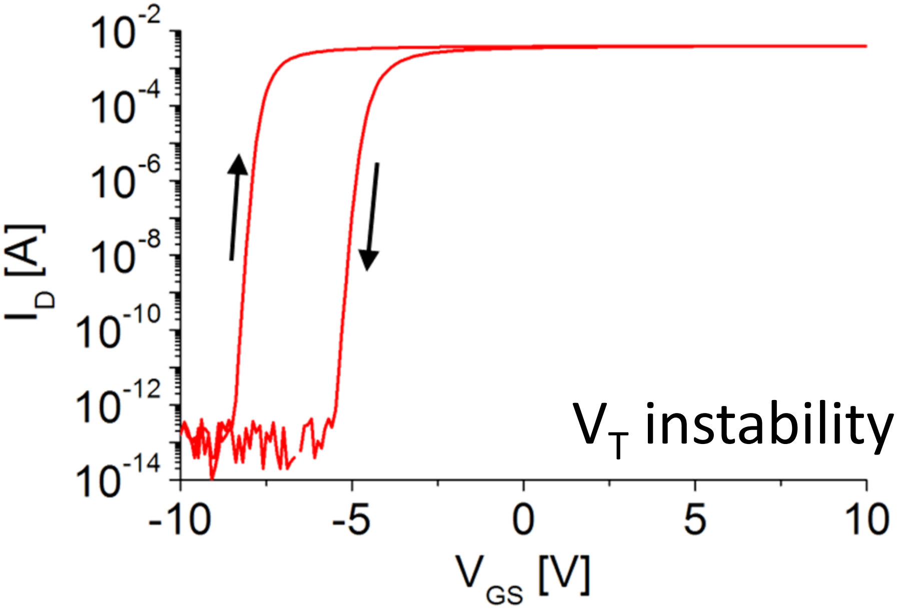
Inverse piezoelectric effect

J. A. del Alamo, MR 2009



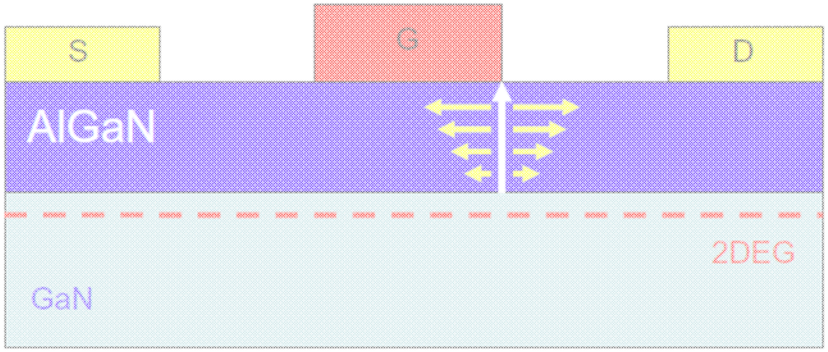
Current collapse

D. Jin, IEDM 2013



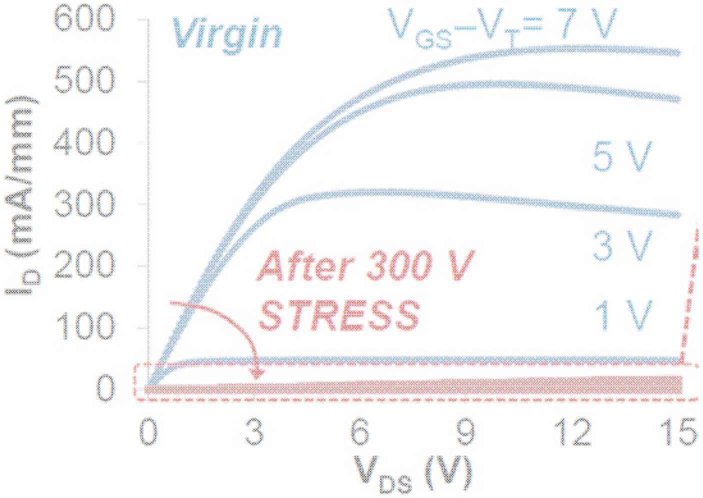
V_T instability

GaN Reliability Challenges



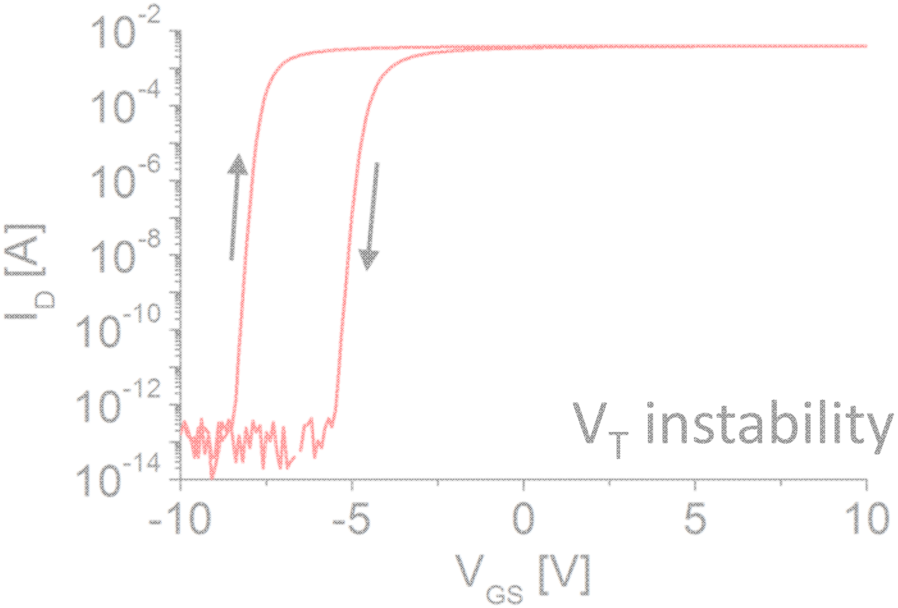
Inverse piezoelectric effect

J. A. del Alamo, MR 2009



Current collapse

D. Jin, IEDM 2013

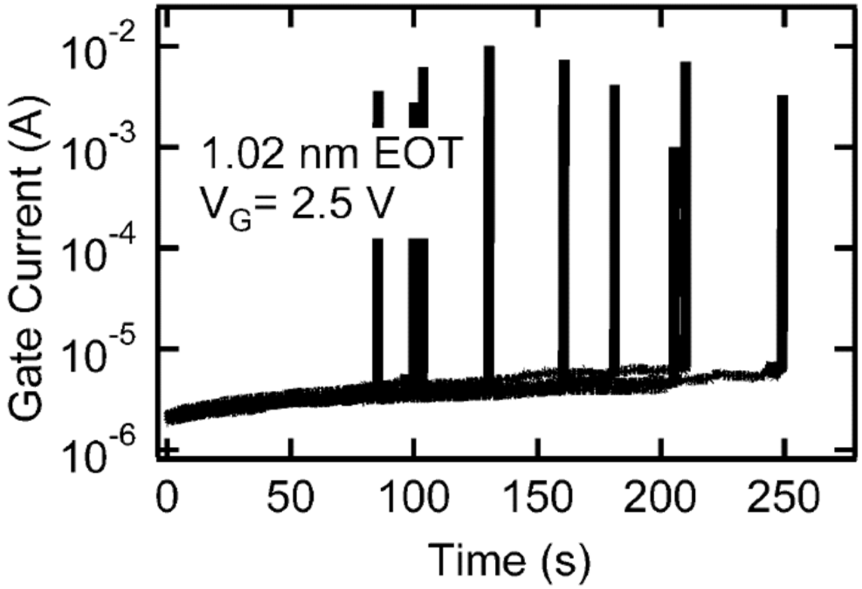


Gate oxide reliability

Time-Dependent Dielectric Breakdown

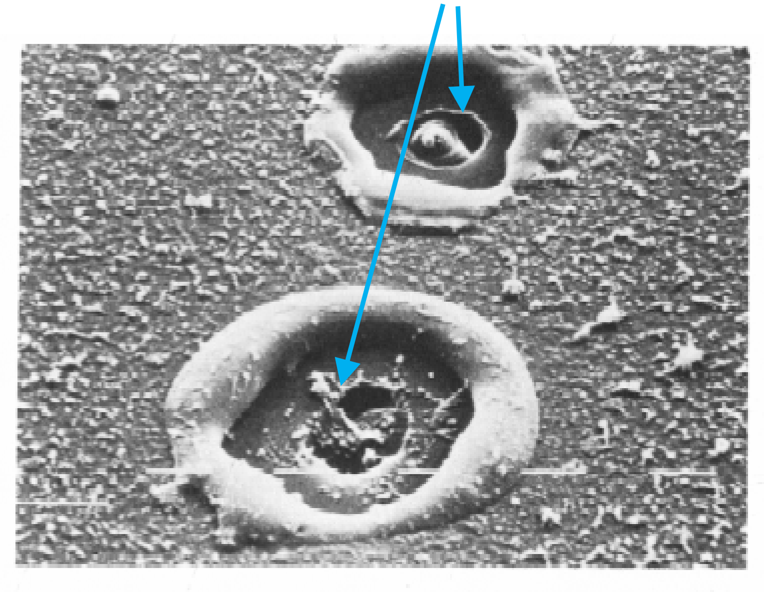
- High gate bias → defect generation → catastrophic oxide breakdown
- Often dictates lifetime of chip

Typical TDDB experiments:
Si high-k MOSFETs



T. Kauerauf, EDL 2005

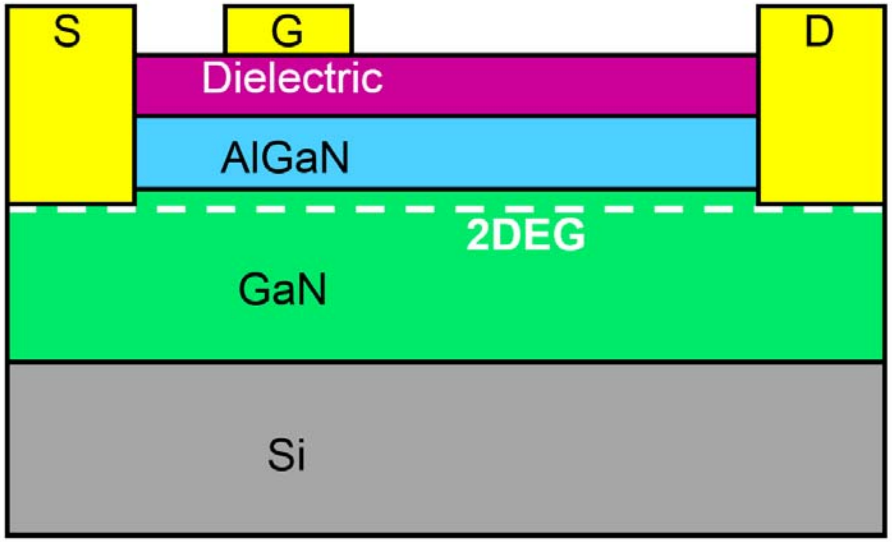
Gate material melted after breakdown

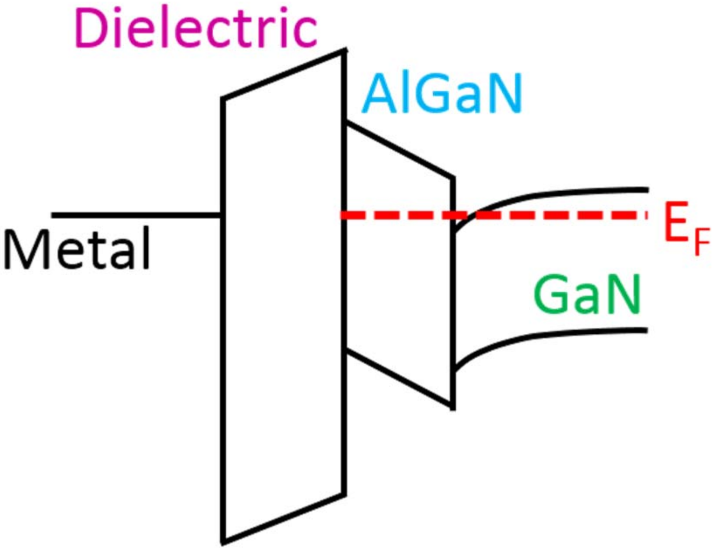


D. R. Wolters, Philips J. Res. 1985

Dielectric Reliability in GaN FETs

AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs)





Very little currently known about TDDB in GaN
→ goal of this work

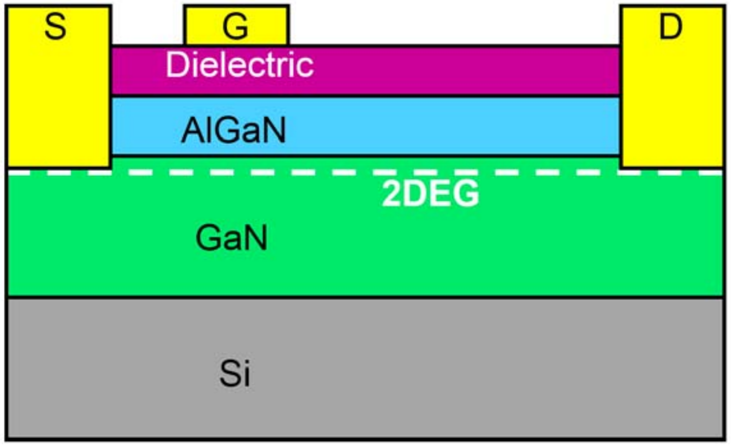
TDDB Experiments: Current-Voltage

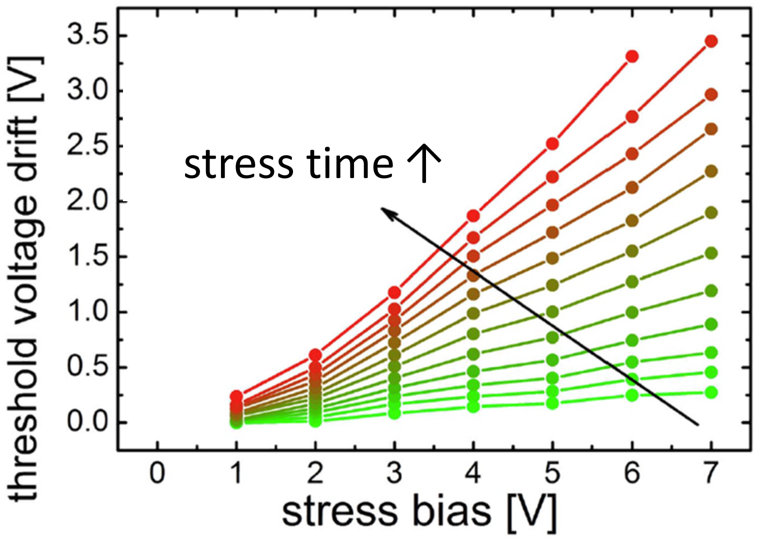
GaN MIS-HEMTs for TDDB study

- GaN MIS-HEMTs from industry collaboration: depletion-mode

- Gate stack has multiple layers & interfaces
  - → Uncertain electric field distribution
  - → Many trapping sites

- Complex dynamics involved
  - → Unstable and fast changing V_T

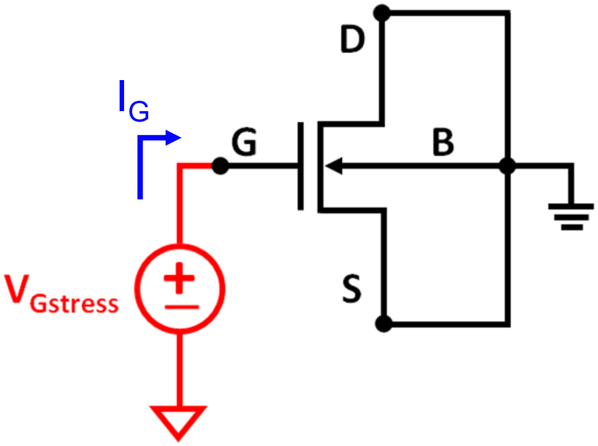


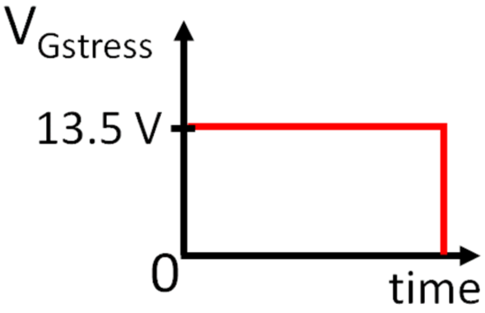


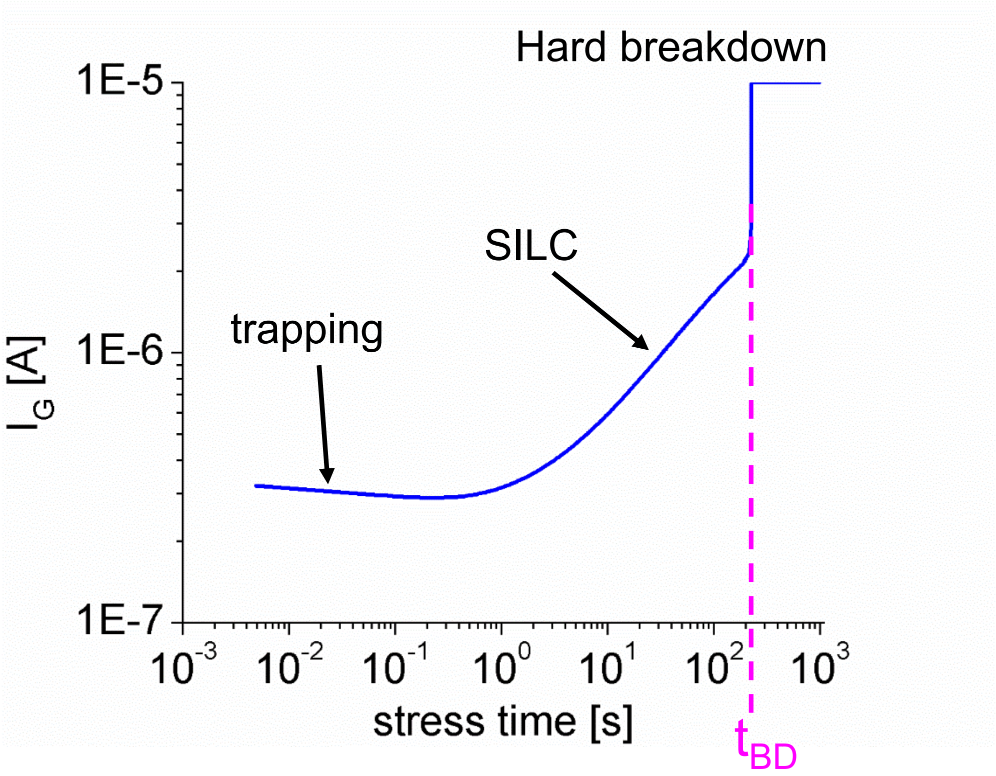
P. Lagger, TED 2014

Classic TDDB Experiment

Constant gate voltage stress experiment:





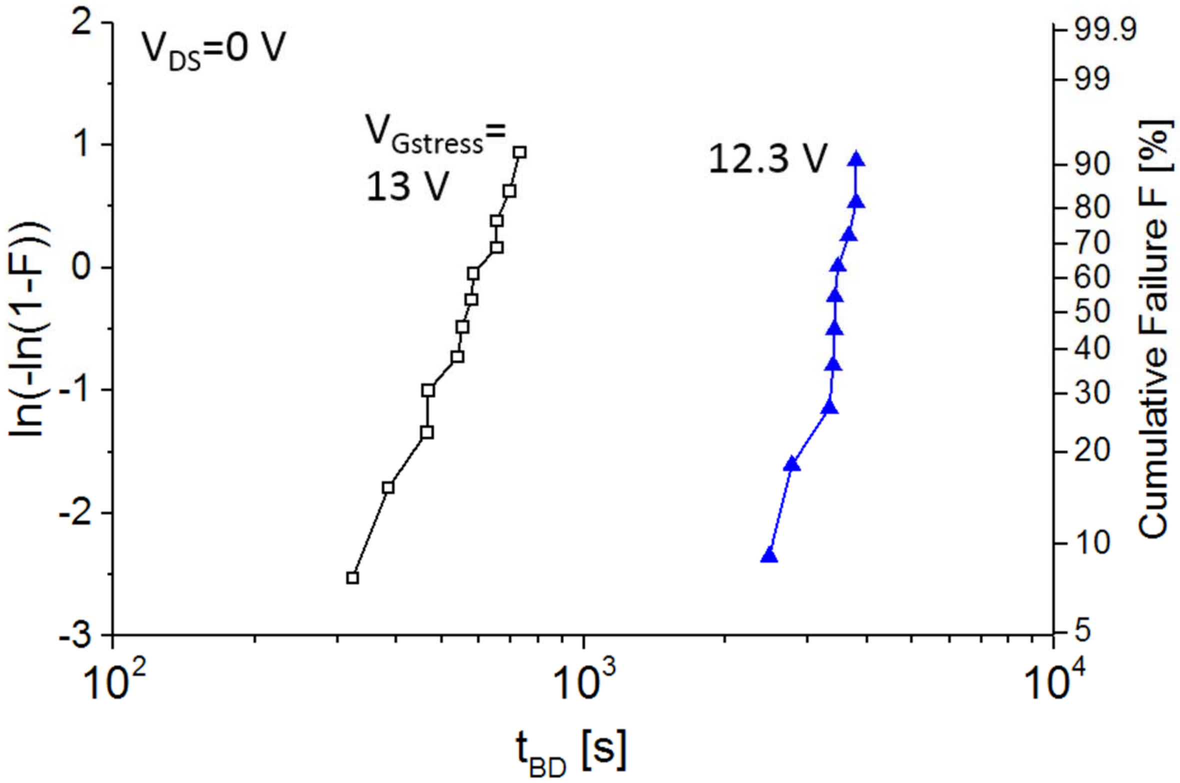


S. Warnock, CS MANTECH 2015

Experiment gives time to breakdown and shows generation of stress-induced leakage current (SILC)

GaN TDDB Statistics

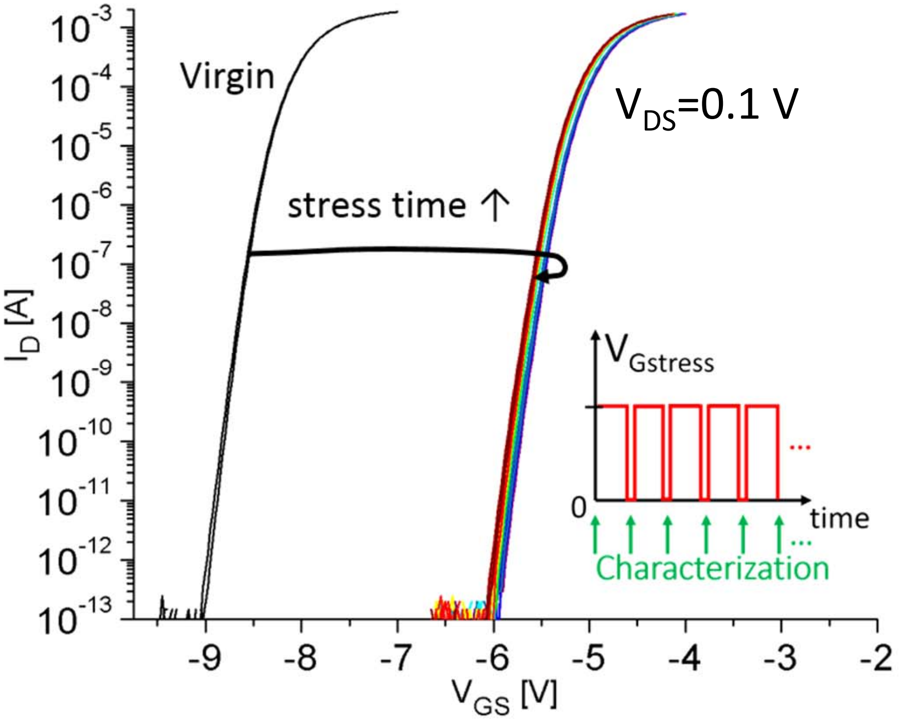
Examine statistics for different $V_{Gstress}$

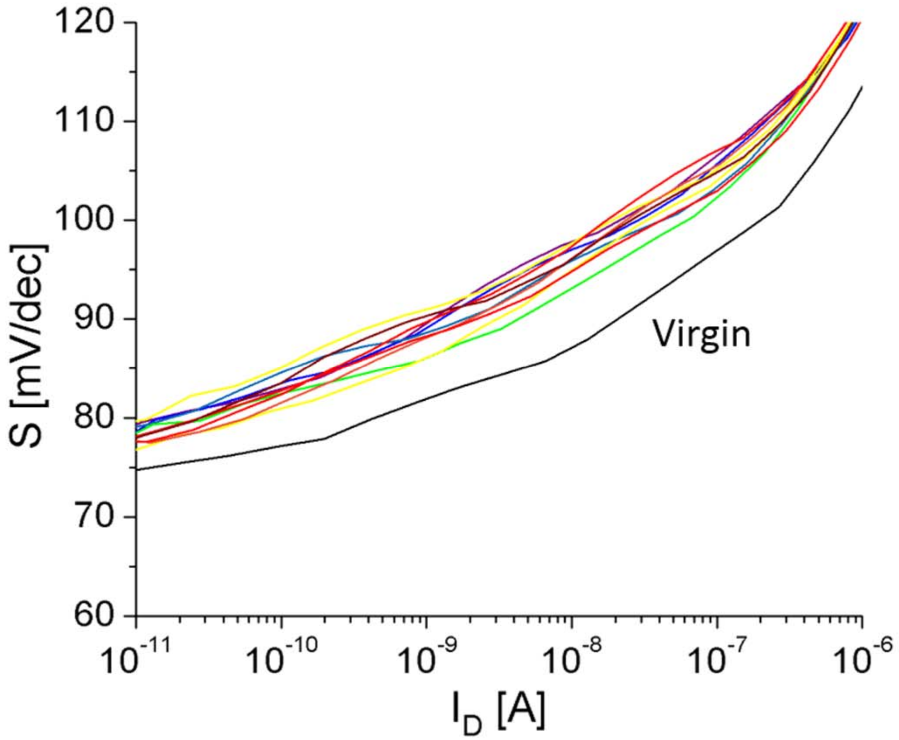


- Weibull distribution
- As $V_{Gstress}$ ↑, t_{BD} ↓
- Parallel statistics → consistent with results in silicon

TDDB with Periodic Characterization

Pause TDDB stress and sweep transfer characteristics at V_{DS}=0.1 V

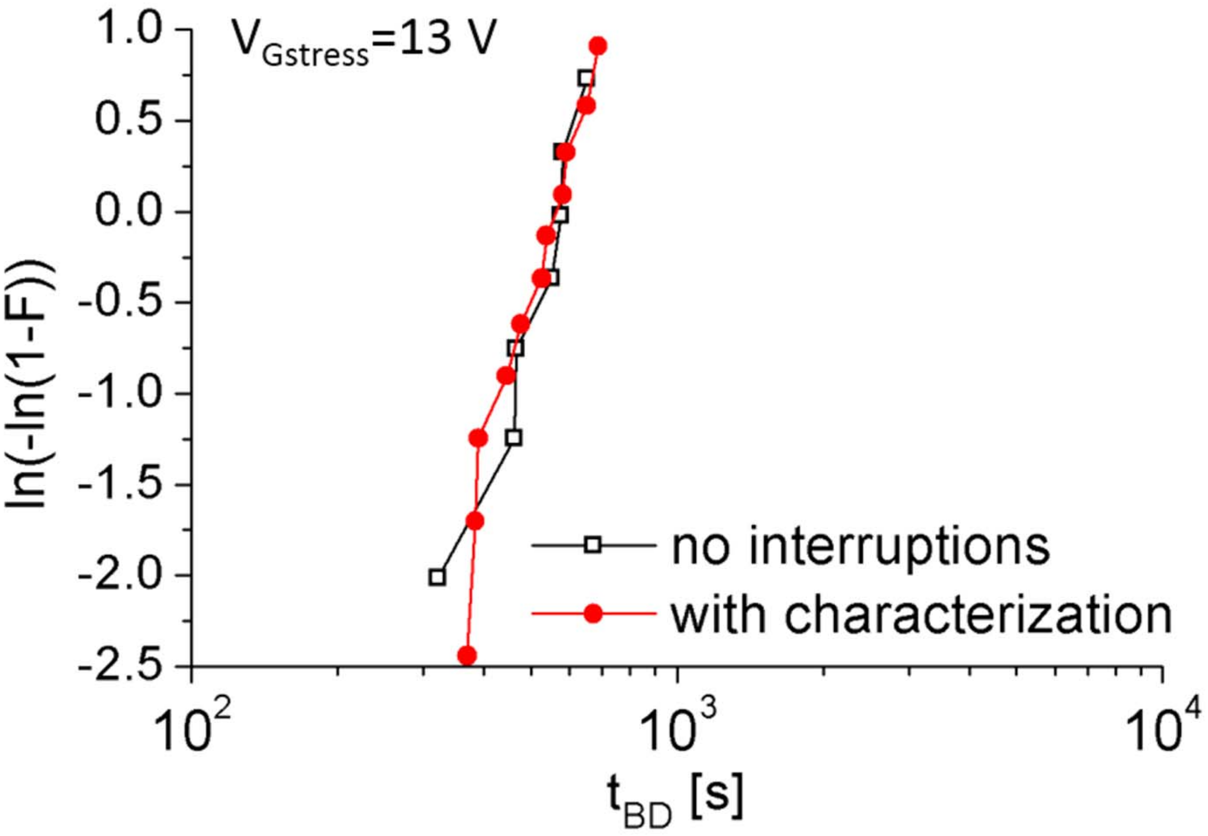




- Large V_T shift → trapping in dielectric or AlGaN
- Immediate S degradation → interface state generation early in experiment

Validity of Characterization Approach

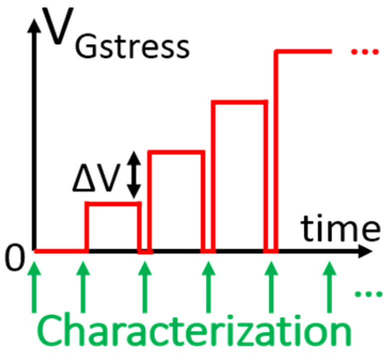
Compare statistics for standard and interrupted schemes

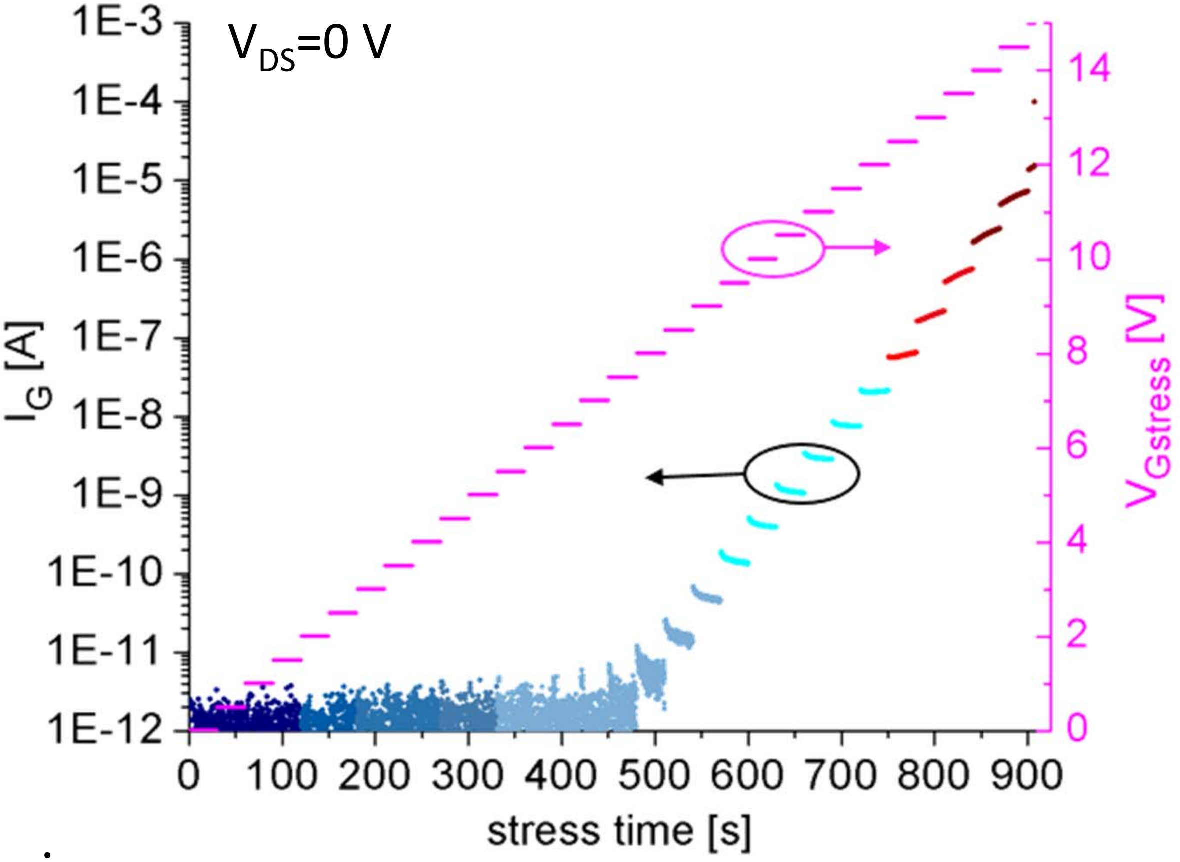


Same statistics for both schemes → characterization is benign

Step-Stress TDDB

- Step-stress to examine early stages of degradation
- Step $V_{Gstress}$ in 0.5 V increments until breakdown

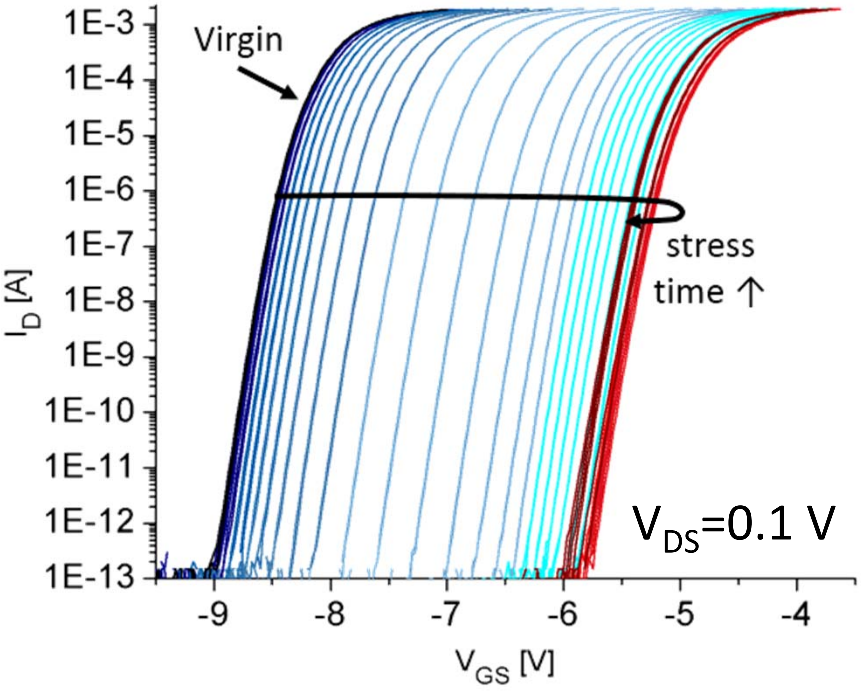


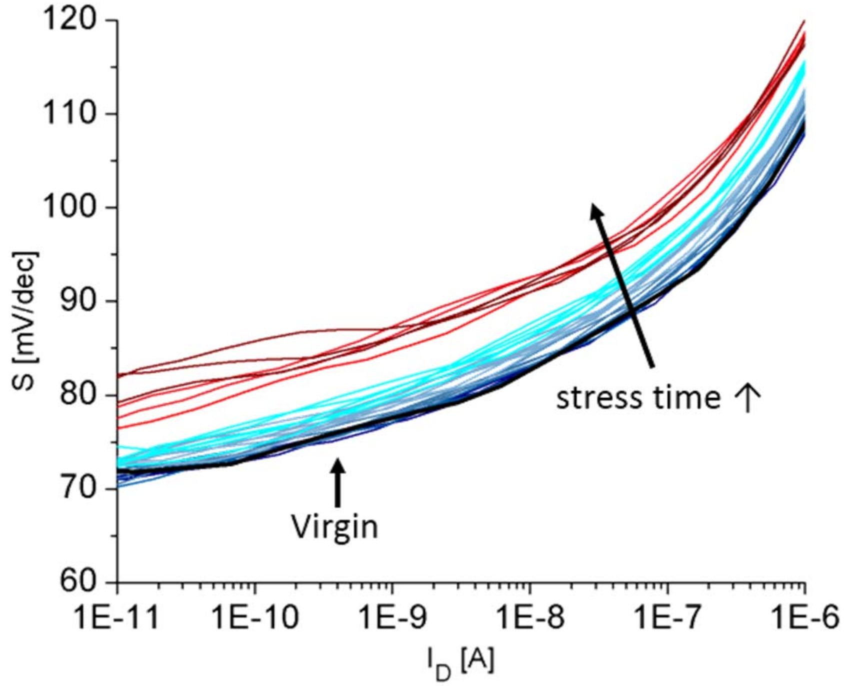


- Low $V_{Gstress}$: $I_G \downarrow$ ⇒ trapping
- High $V_{Gstress}$: $I_G \uparrow$ ⇒ SILC

Step-Stress TDDB

Transfer characteristics in between stress steps

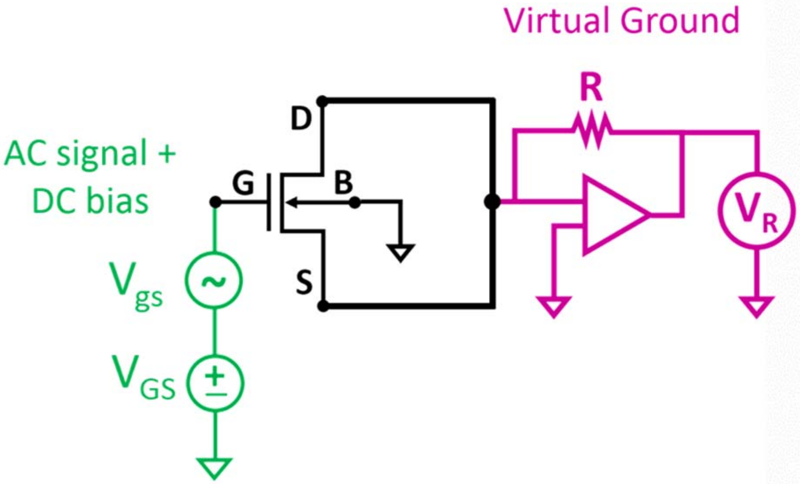


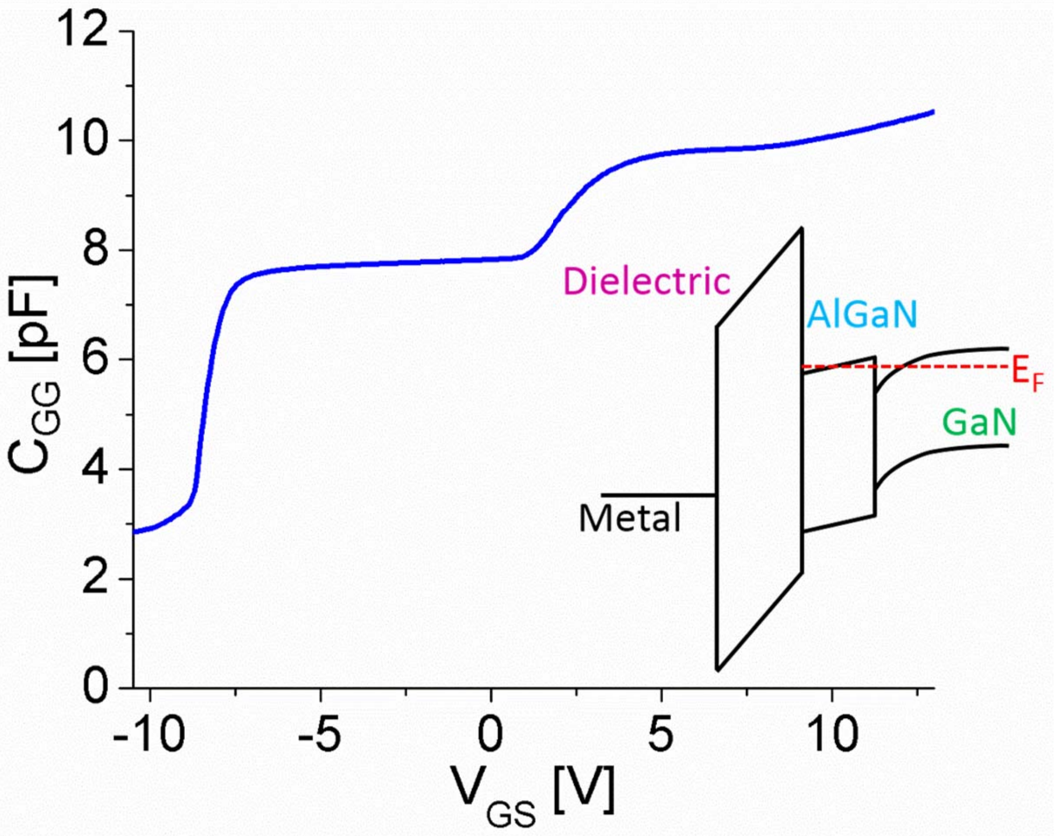


- S and V_T degradation is progressive
- At $V_{Gstress}$ ~12.5 V, $\Delta V_T < 0$ (red lines)
  - Sudden increase in S, appearance of SILC→ interface state generation

TDDB Experiments: Capacitance-Voltage

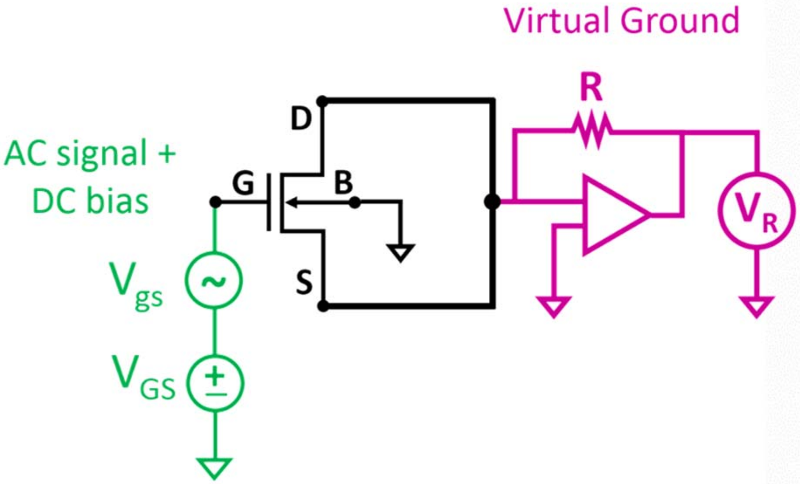
C-V Characterization

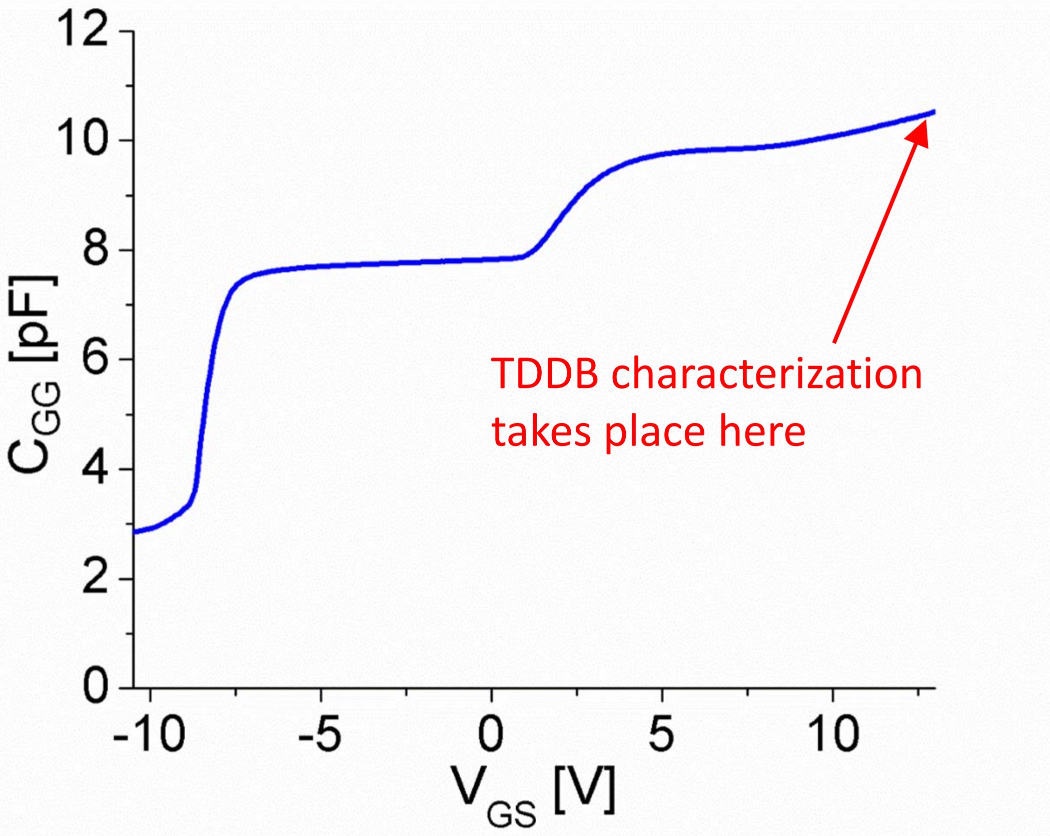




- At V_{GS}>1 V, conduction band of AlGaN starts being populated

C-V Characterization



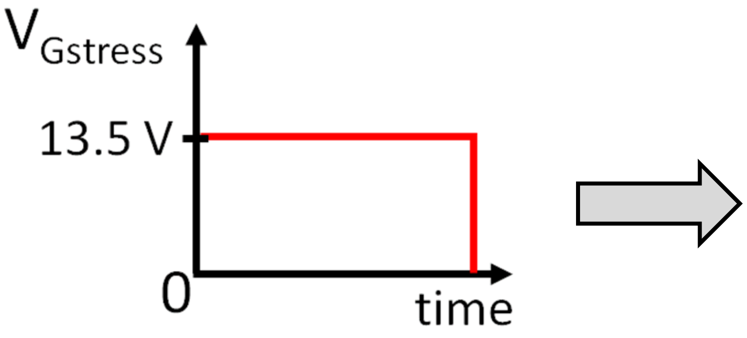


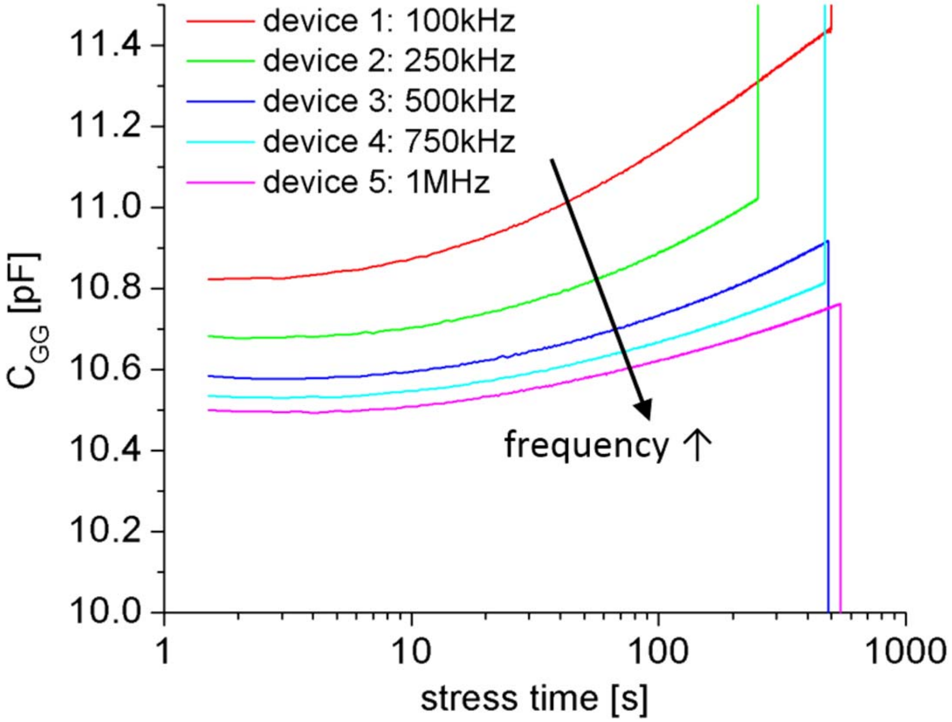
TDDB characterization takes place here

- TDDB characterized in regime where AlGaN is populated with electrons

Constant $V_{Gstress}$ TDDB

C_{GG} vs. stress time in 5 devices at 5 different frequencies:



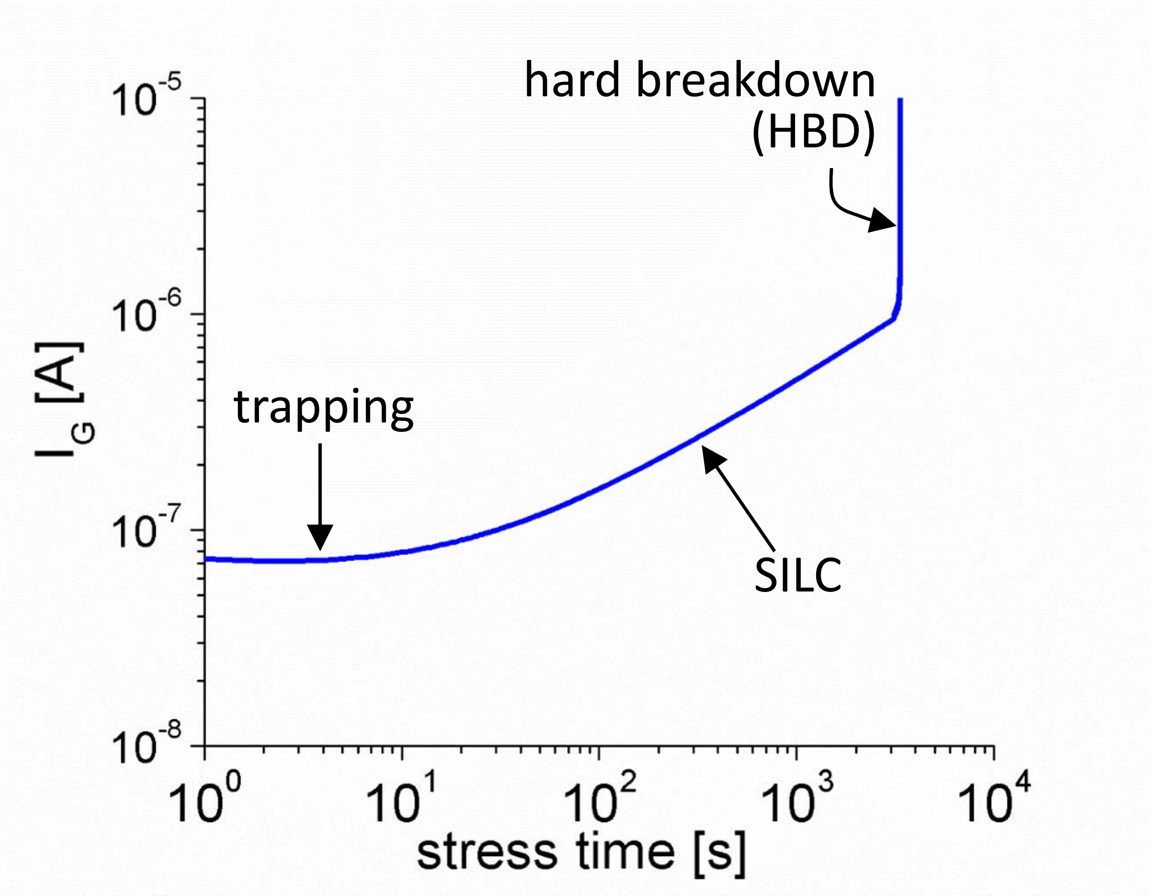


- As stress time ↑
  - → C_{GG} ↑
  - → Frequency dispersion ↑
- Consistent with trap creation and trapping
  - In dielectric and/or at MIS interface

Progressive Breakdown

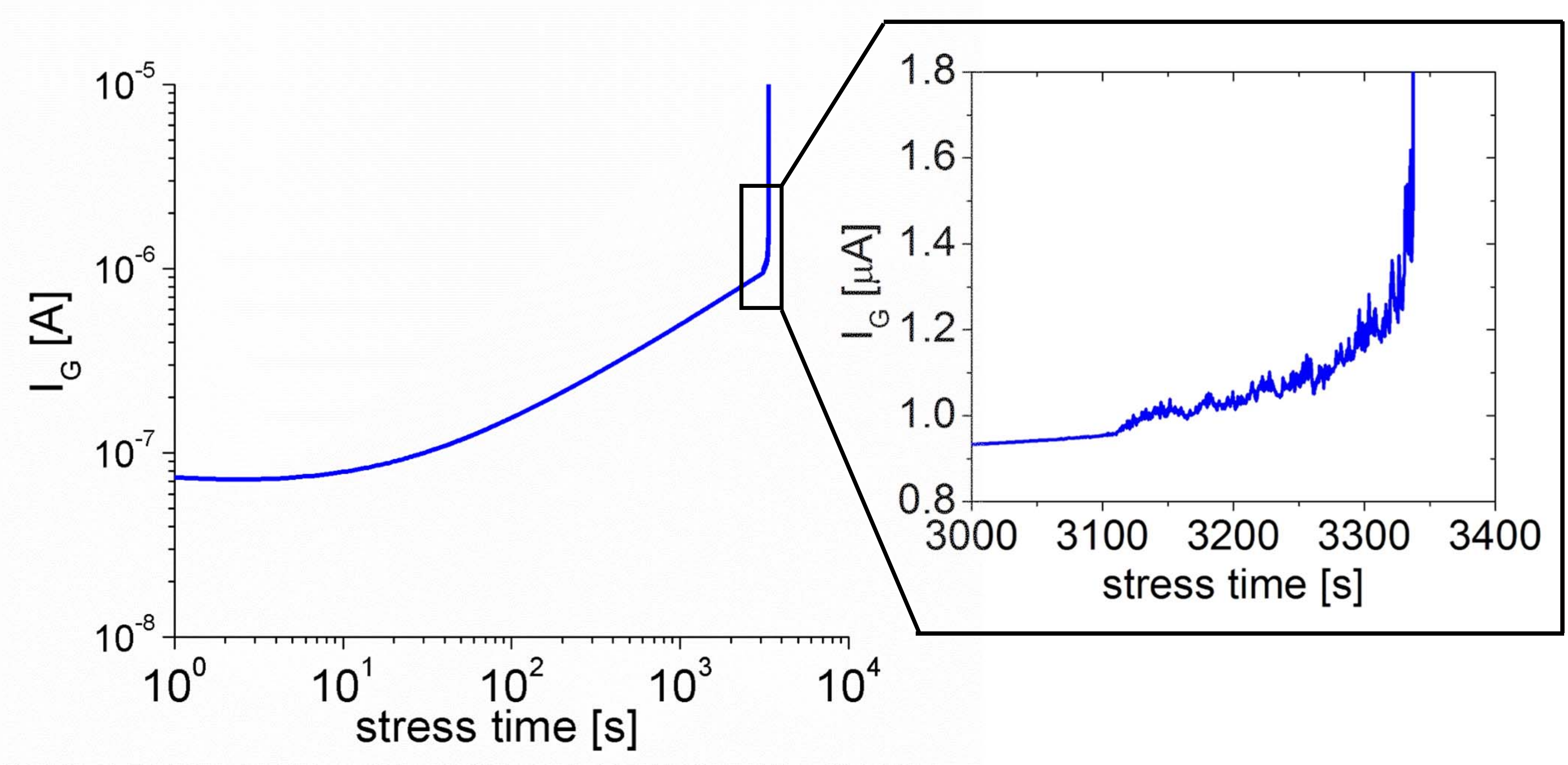
Observation of Progressive Breakdown

Revisit classic TDDB experiment: $V_{Gstress}$=12.6 V, V_{DS}=0 V



Observation of Progressive Breakdown

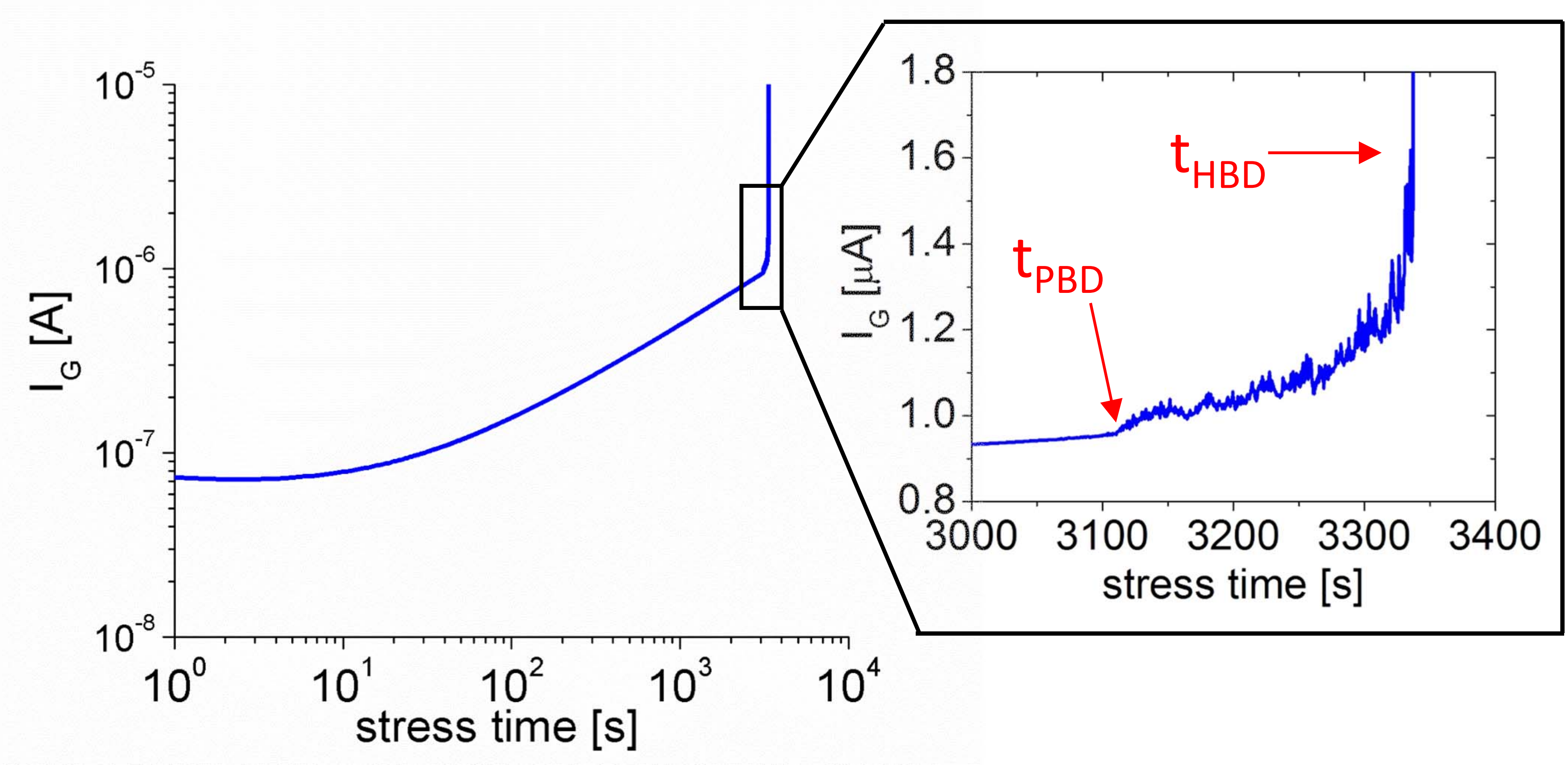
Revisit classic TDDB experiment: $V_{Gstress}$=12.6 V, V_{DS}=0 V



Near breakdown, I_G becomes noisy → progressive breakdown (PBD)

Observation of Progressive Breakdown

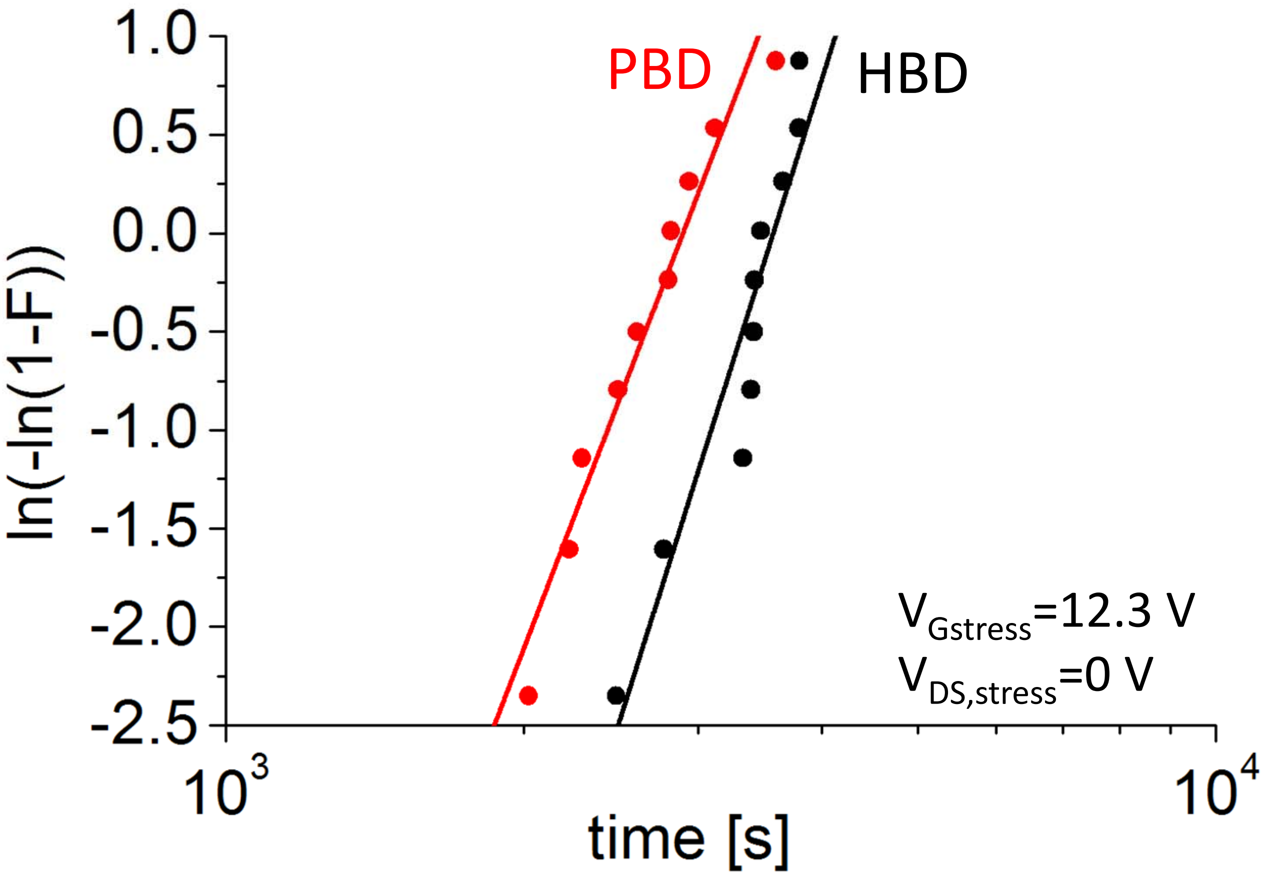
Revisit classic TDDB experiment: $V_{Gstress}$=12.6 V, V_{DS}=0 V



Near breakdown, I_G becomes noisy → progressive breakdown (PBD)

PBD Statistics

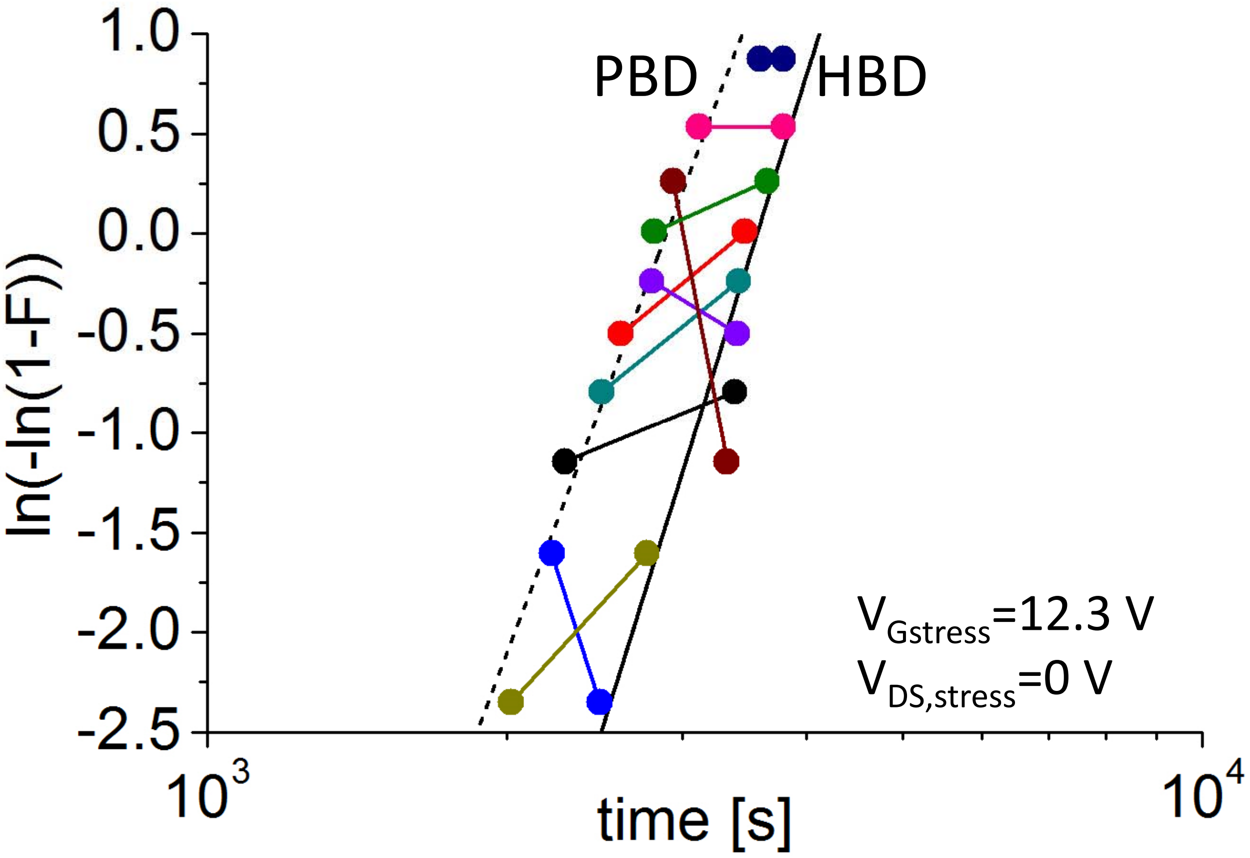
Compare statistics for t_{PBD} and t_{HBD}



Statistics nearly parallel → breakdown mechanism is same

PBD Statistics

- Examine PBD and HBD times for each individual device
- PBD and HBD in same device linked by a line



S. Warnock, IRPS 2016

HBD, PBD uncorrelated from device to device → dielectric defect generation is truly random

Conclusions

- Developed methodology to study TDDB in GaN MIS-HEMTs
- TDDB behavior consistent with Si MOSFETs:
  - Weibull distribution
  - SILC before breakdown
  - Clear observation of Progressive Breakdown
- For moderate gate voltage stress:
  - $\Delta V_T > 0$
  - I_G ↓
- Beyond critical value of $V_{Gstress}$:
  - $\Delta V_T < 0$
  - Sudden ΔS ↑
  - Capacitance frequency dispersion ↑

Conclusions

- Developed methodology to study TDDB in GaN MIS-HEMTs
- TDDB behavior consistent with Si MOSFETs:
  - Weibull distribution
  - SILC before breakdown
  - Clear observation of Progressive Breakdown
- For moderate gate voltage stress:
  - $\Delta V_T > 0$
  - I_G ↓

  Consistent with electron trapping
- Beyond critical value of $V_{Gstress}$:
  - $\Delta V_T < 0$
  - Sudden ΔS ↑
  - Capacitance frequency dispersion ↑

Conclusions

- Developed methodology to study TDDB in GaN MIS-HEMTs
- TDDB behavior consistent with Si MOSFETs:
  - Weibull distribution
  - SILC before breakdown
  - Clear observation of Progressive Breakdown
- For moderate gate voltage stress:
  - $\Delta V_T > 0$
  - I_G ↓

  Consistent with electron trapping
- Beyond critical value of $V_{Gstress}$:
  - $\Delta V_T < 0$
  - Sudden ΔS ↑
  - Capacitance frequency dispersion ↑

  Onset of trap generation in dielectric/at MIS interface

Acknowledgements

TEXAS INSTRUMENTS

MTL
microsystems technology laboratories
massachusetts institute of technology

Questions?