Progressive Breakdown in High-Voltage GaN MIS-HEMTs

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Purpose

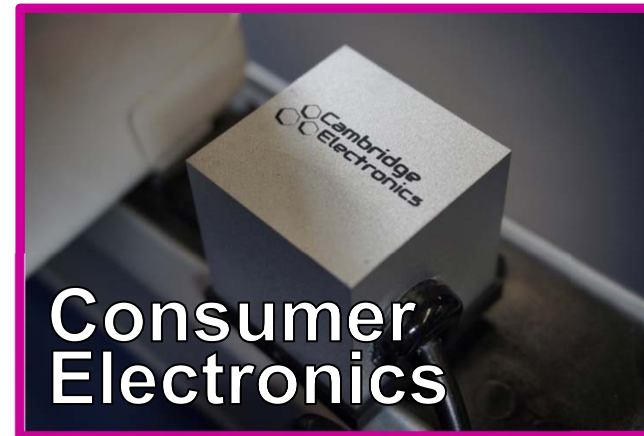
- Understand time-dependent dielectric breakdown (TDDB) in GaN MIS-HEMTs
- Explore progressive breakdown (PBD) as a means of better understanding physics of dielectric degradation

Outline

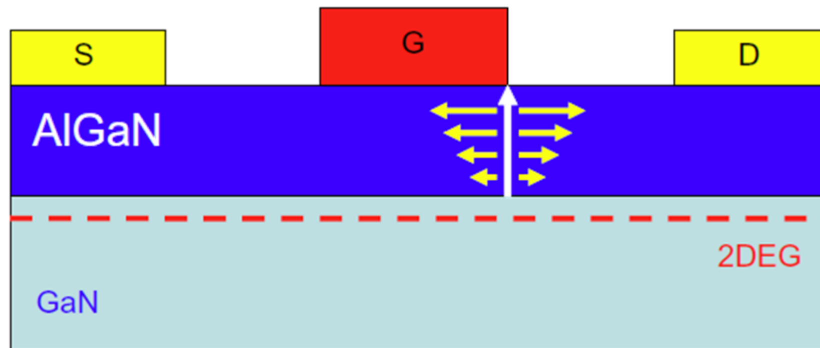
- Motivation & Challenges
- Experimental Methodology & Breakdown Statistics
- Characterizing PBD
  - Subthreshold I-V Measurements
  - C-V Measurements
- Conclusions

Motivation

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

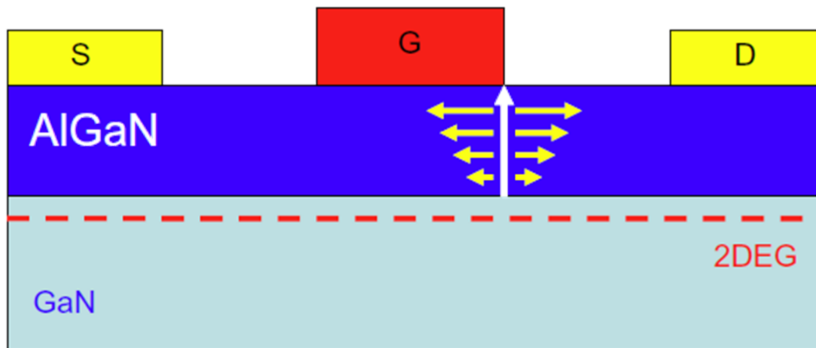


GaN Reliability Challenges



Inverse piezoelectric effect
J. A. del Alamo, MR 2009

GaN Reliability Challenges



Inverse piezoelectric effect

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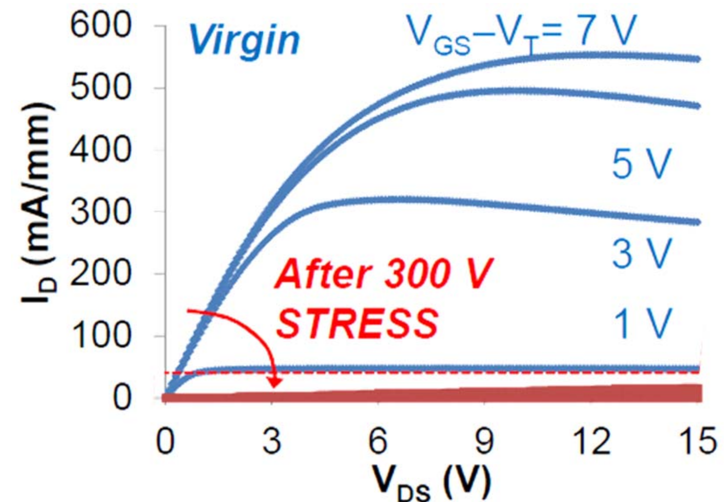
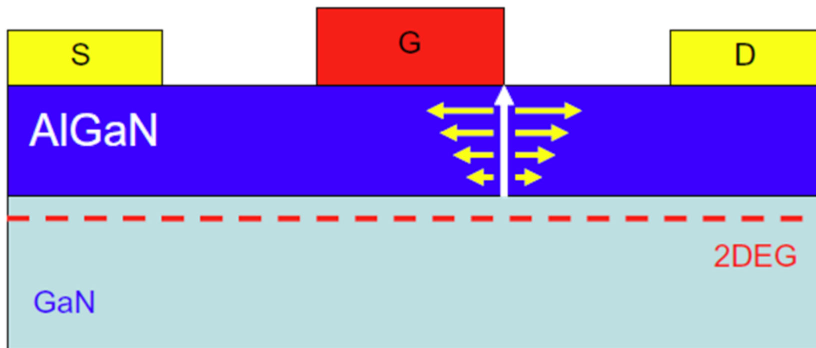


Current collapse

D. Jin, IEDM 2013

GaN Reliability Challenges



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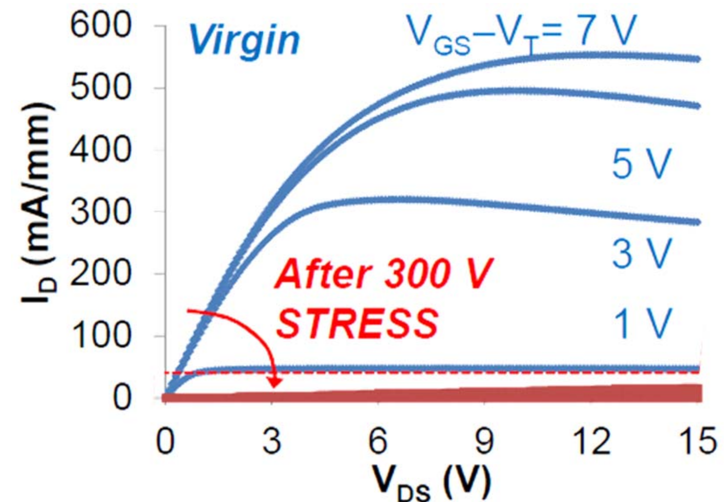

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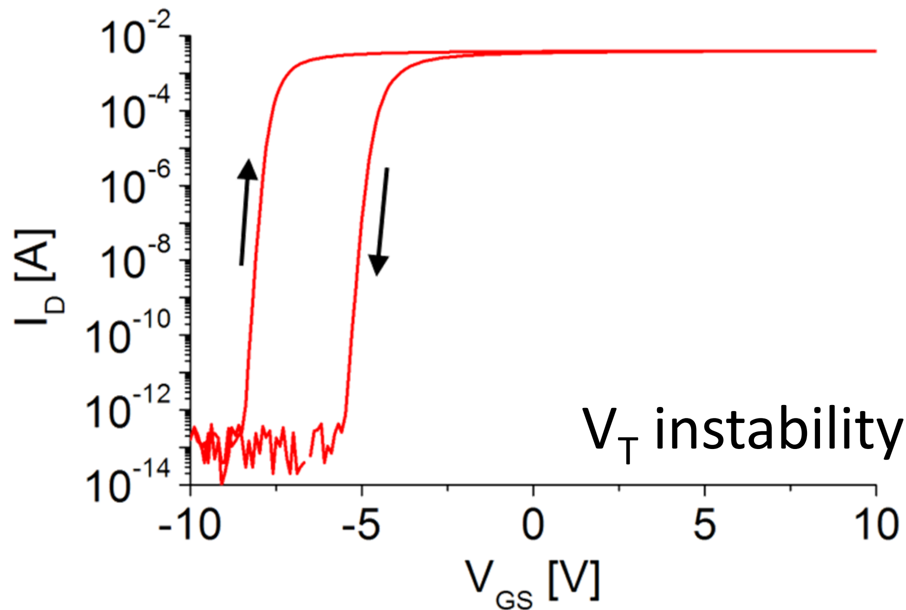
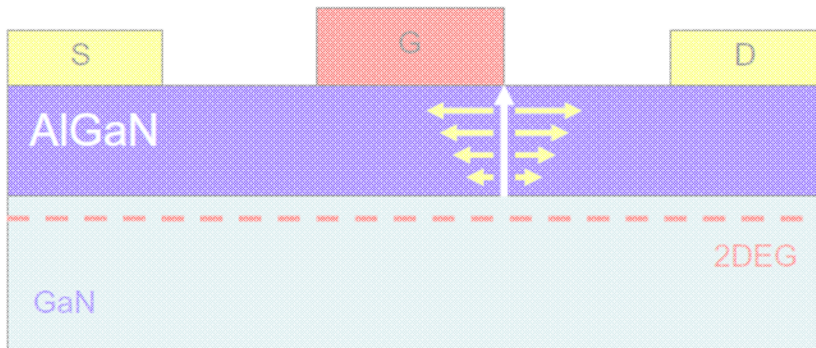
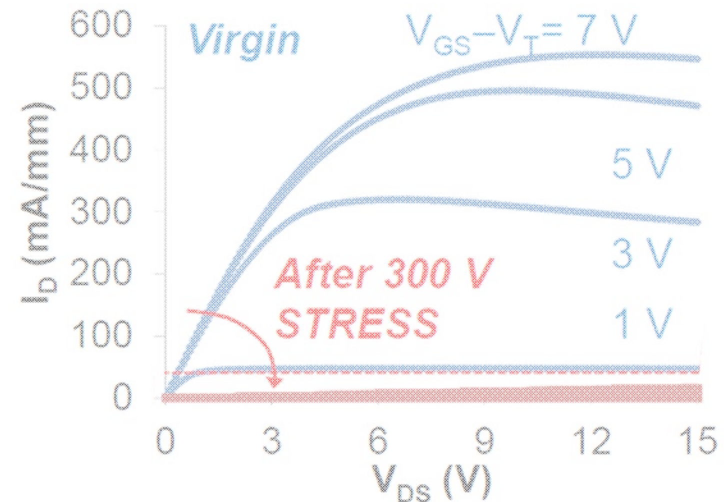


V_T instability

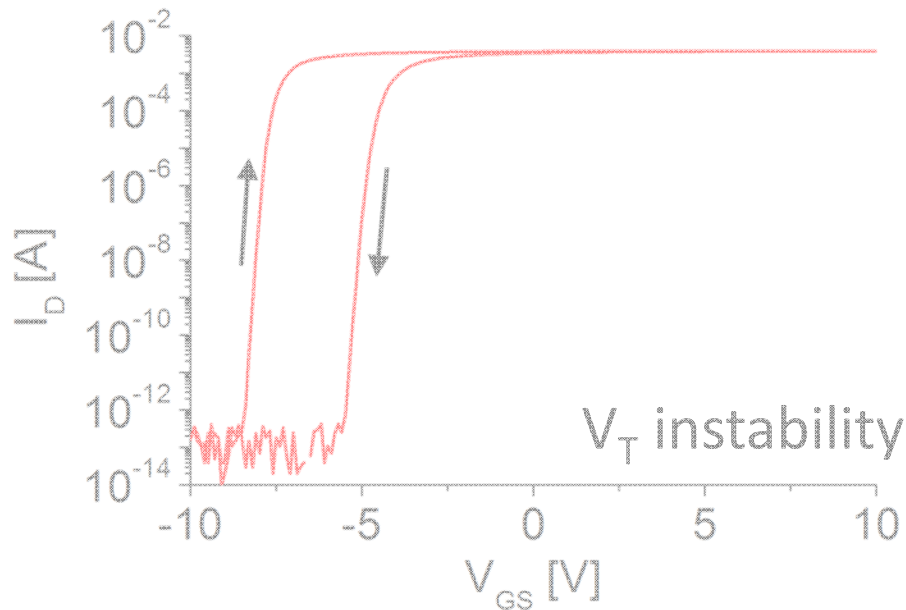
GaN Reliability Challenges



Inverse piezoelectric effect
J. A. del Alamo, MR 2009



Current collapse
D. Jin, IEDM 2013

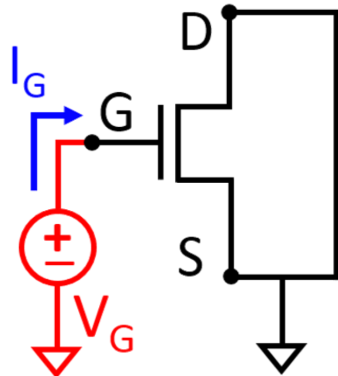


V_T instability

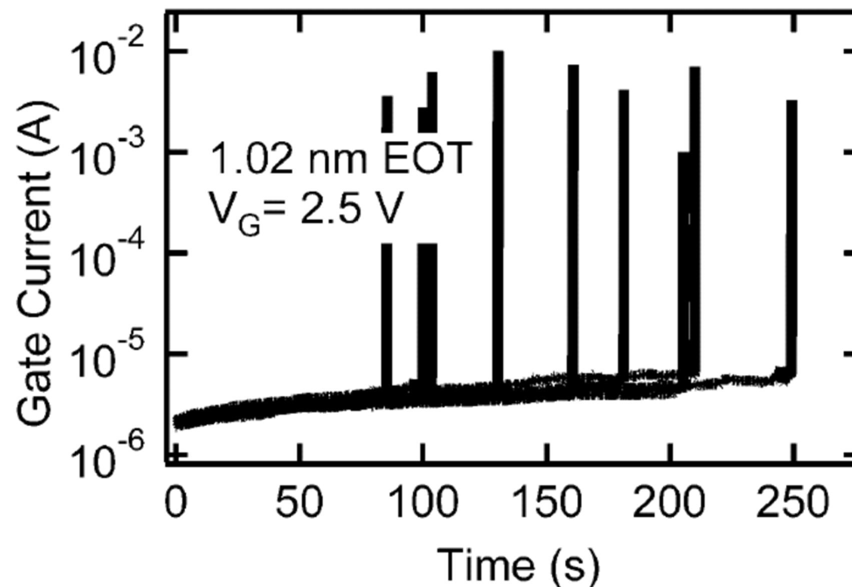
Gate dielectric reliability

Time-Dependent Dielectric Breakdown

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

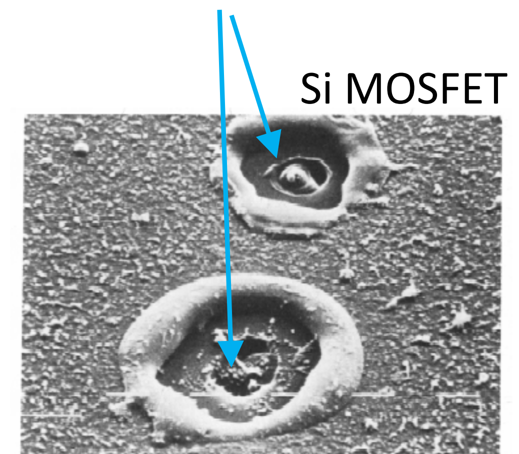


Typical TDDB experiments:
Si high-k MOSFETs



T. Kauerauf, EDL 2005

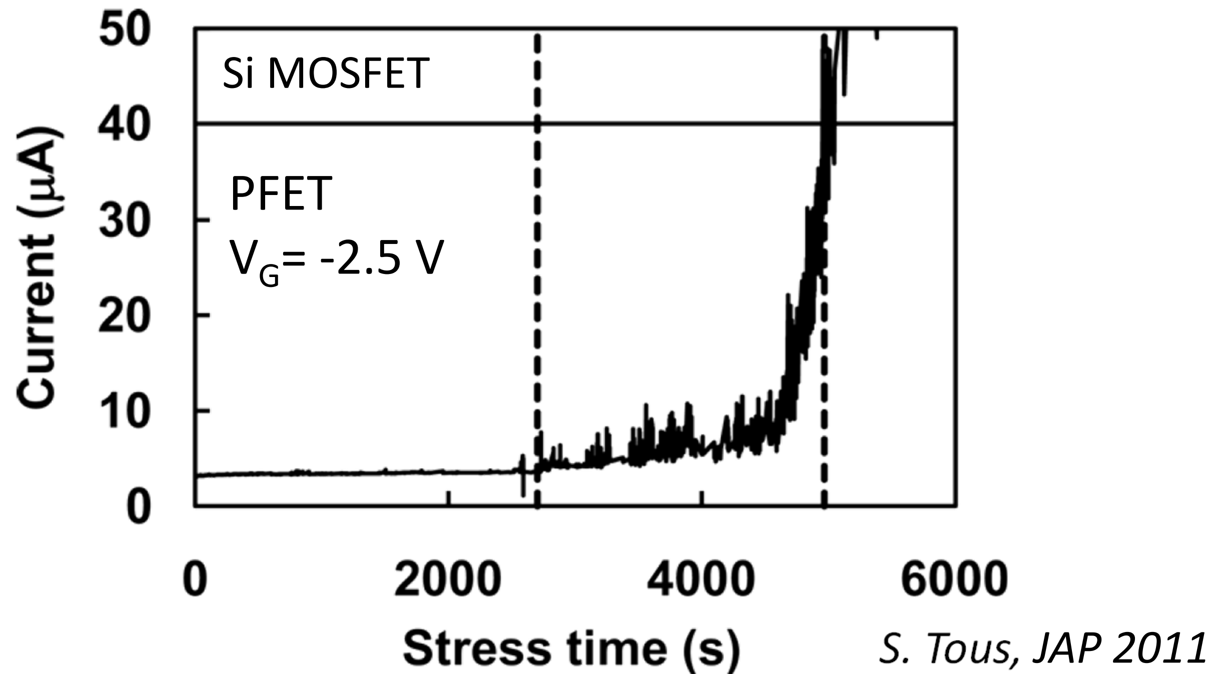
Gate material melted after breakdown



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

Progressive Breakdown (PBD)

Noise in gate current appears before final hard breakdown

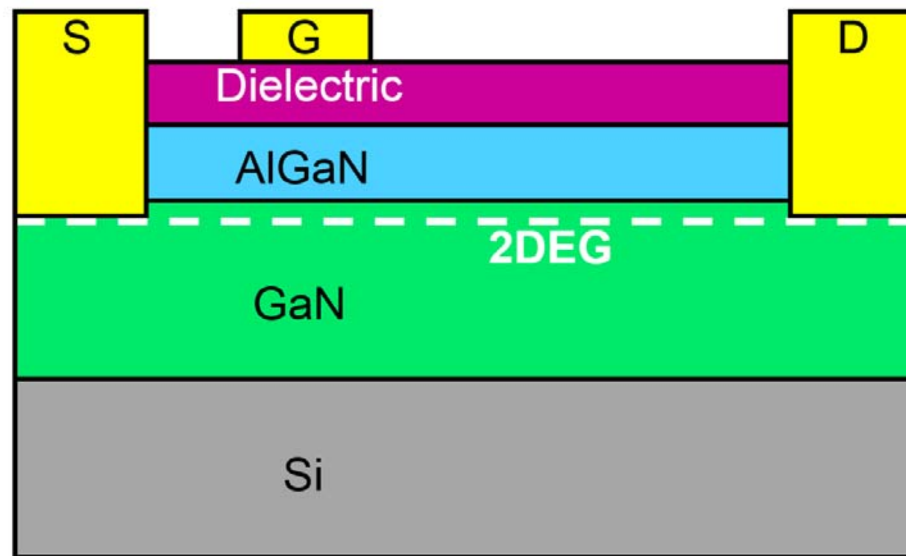


S. Tous, JAP 2011

- Understanding PBD necessary for accurate circuit lifetime prediction
- Study of PBD: insight into hard breakdown physics
- No reports of PBD in GaN FETs

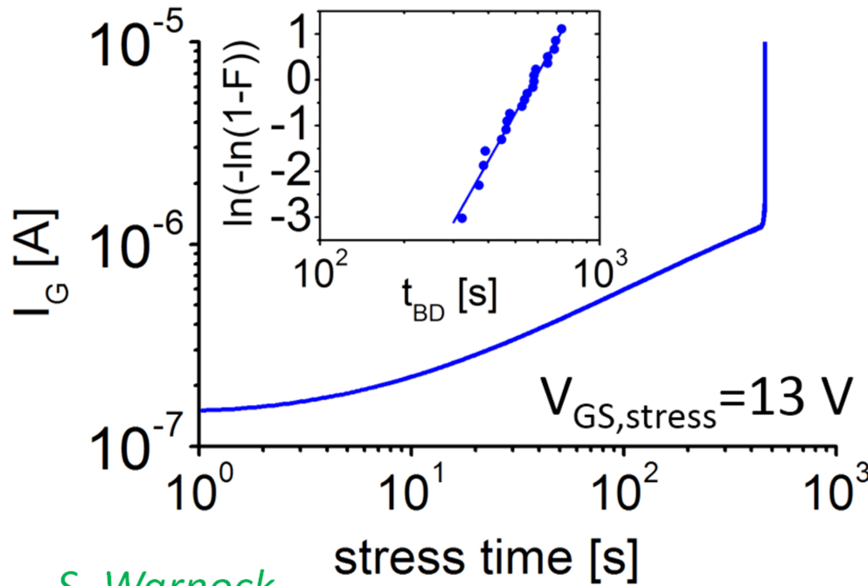
Dielectric Reliability in GaN FETs

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

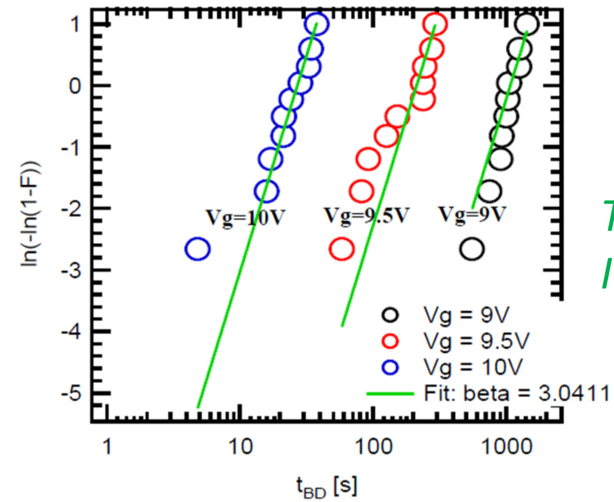


- Goals of this work:
  - What do TDDB and PBD look like in GaN MIS-HEMTs?
  - What can PBD tell us about breakdown physics?

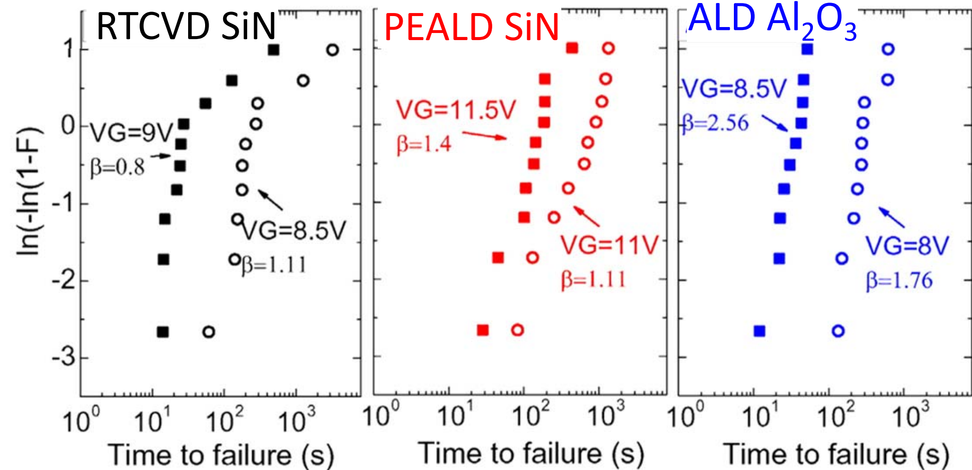
TDDB in GaN MIS-HEMTs



S. Warnock, CS MANTECH 2015



T.-L. Wu, IRPS 2013



G. Meneghesso, MR 2015

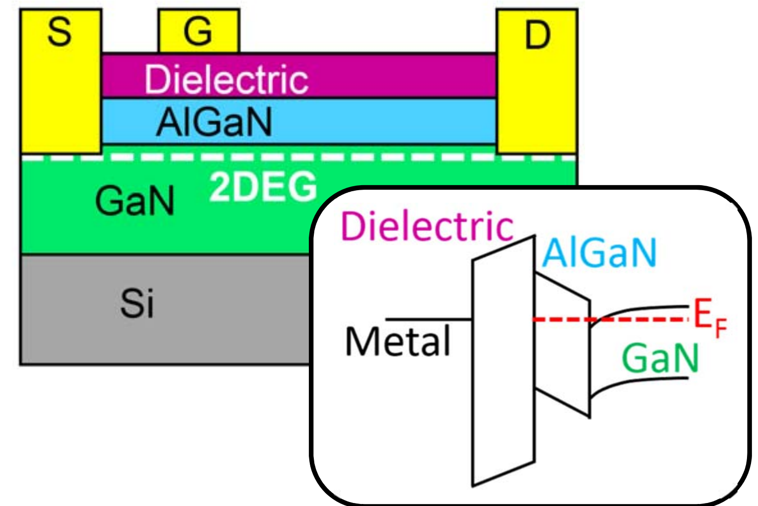
Focus largely on: breakdown statistics, lifetime extrapolation, evaluating different dielectrics

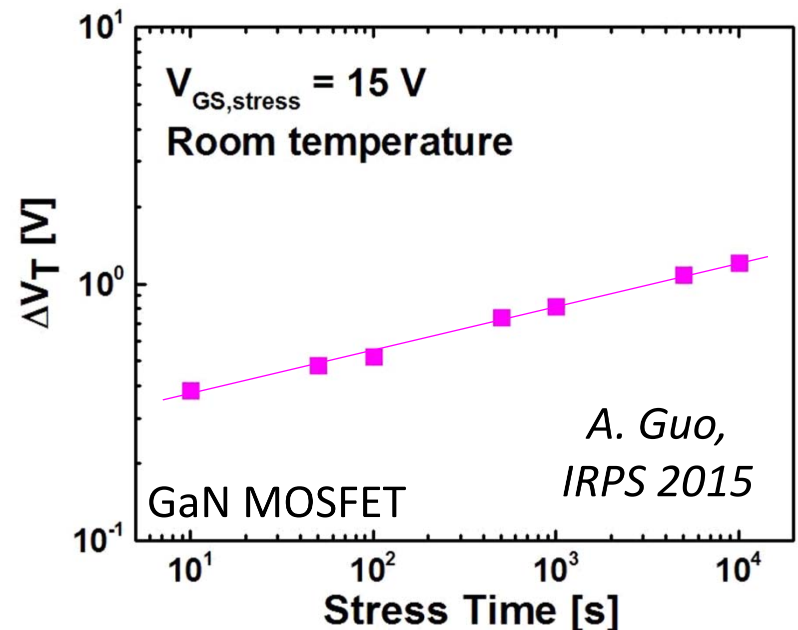
Progressive Breakdown in GaN MIS-HEMTs:

Experimental Methodology & Breakdown Statistics

GaN MIS-HEMTs for TDDB study

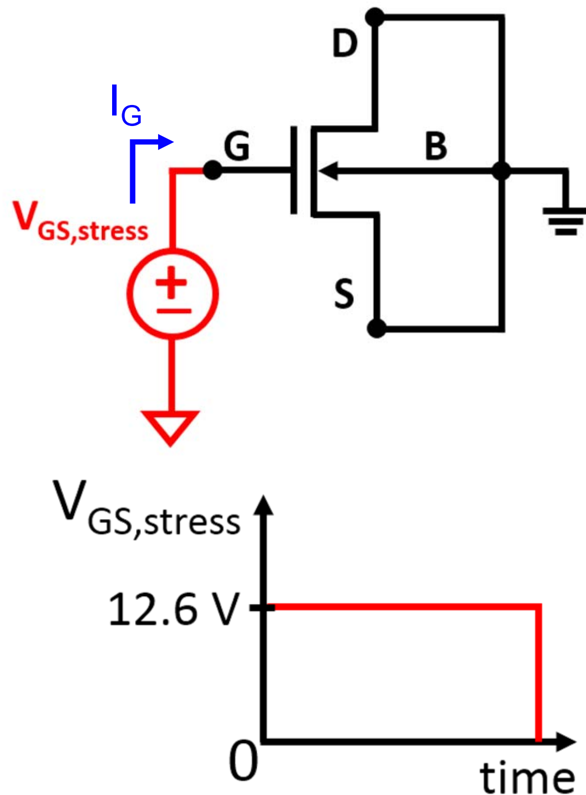
- GaN MIS-HEMTs from industry collaboration: depletion-mode
- Gate stack has multiple layers & interfaces
  - → Uncertain electric field distribution
  - → Many trapping sites
- Complex dynamics involved
  - → Unstable and fast changing V_T

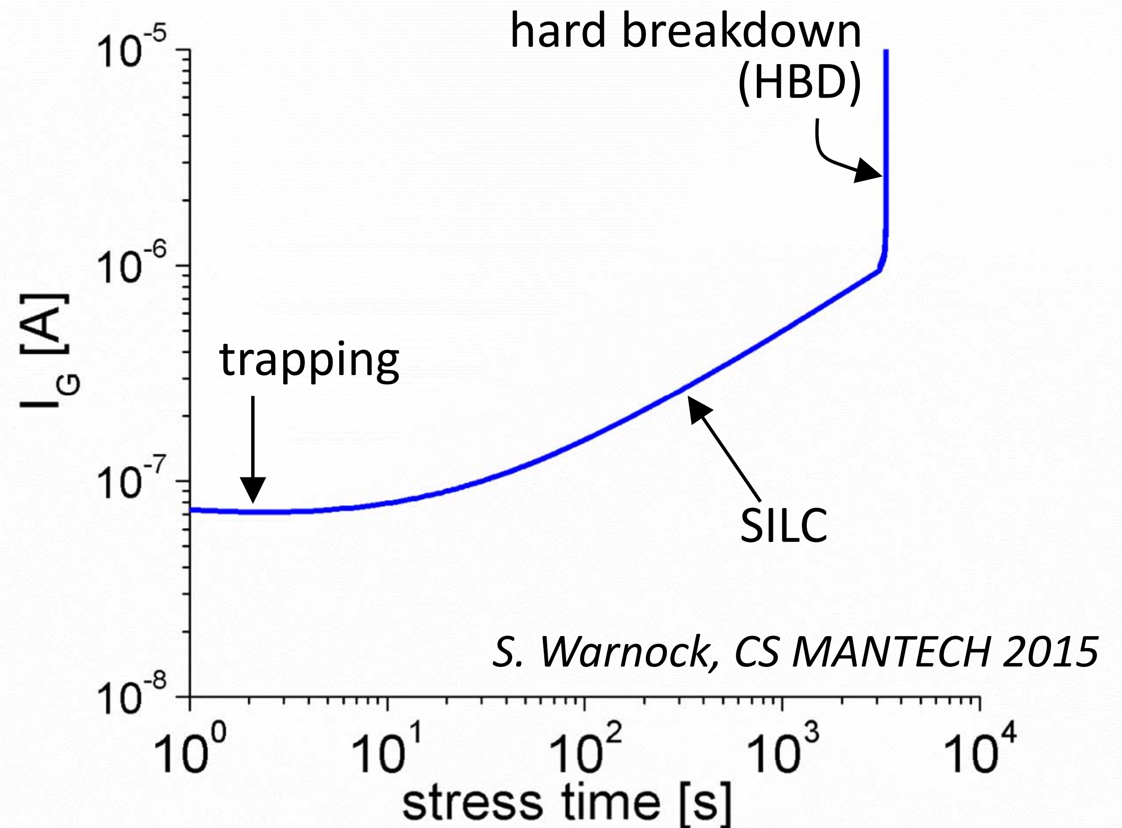




Classic TDDB Experiment

Constant gate voltage stress:

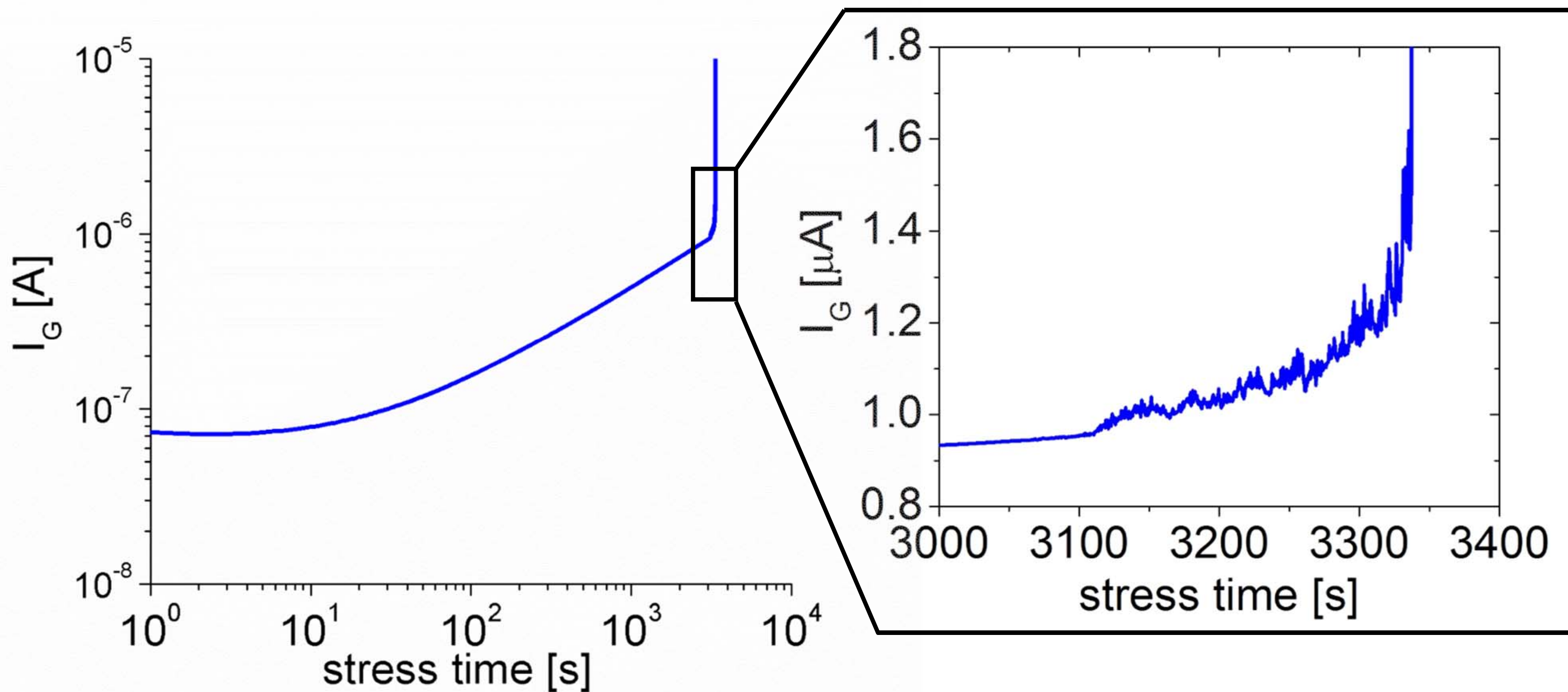




Experiment gives time to breakdown and shows generation of *stress-induced leakage current* (SILC)

Observing Progressive Breakdown

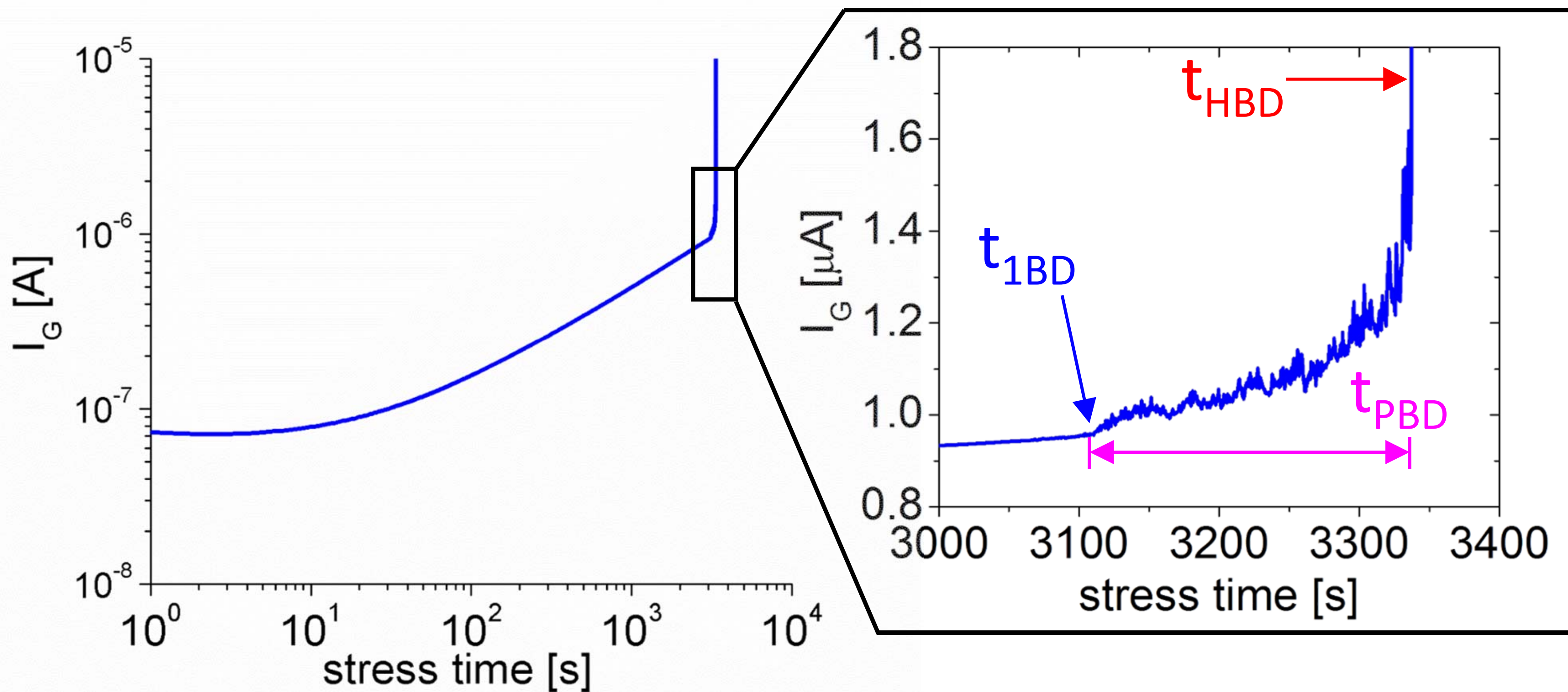
Classic TDDB experiment: $V_{Gstress}$=12.6 V, V_{DS}=0 V



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

Observing Progressive Breakdown

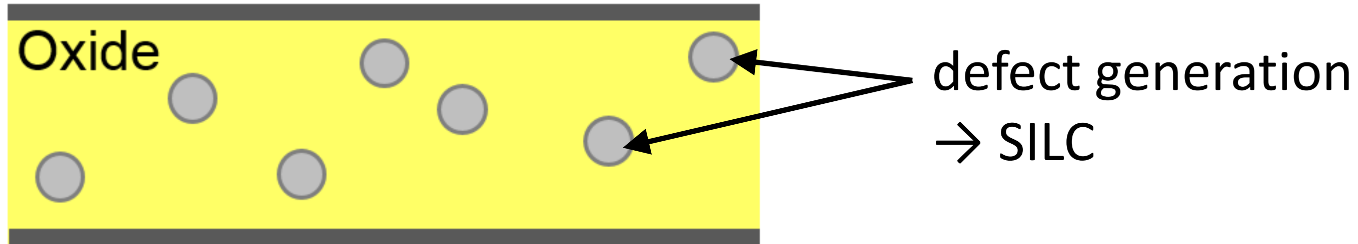
Classic TDDB experiment: $V_{Gstress}$=12.6 V, V_{DS}=0 V



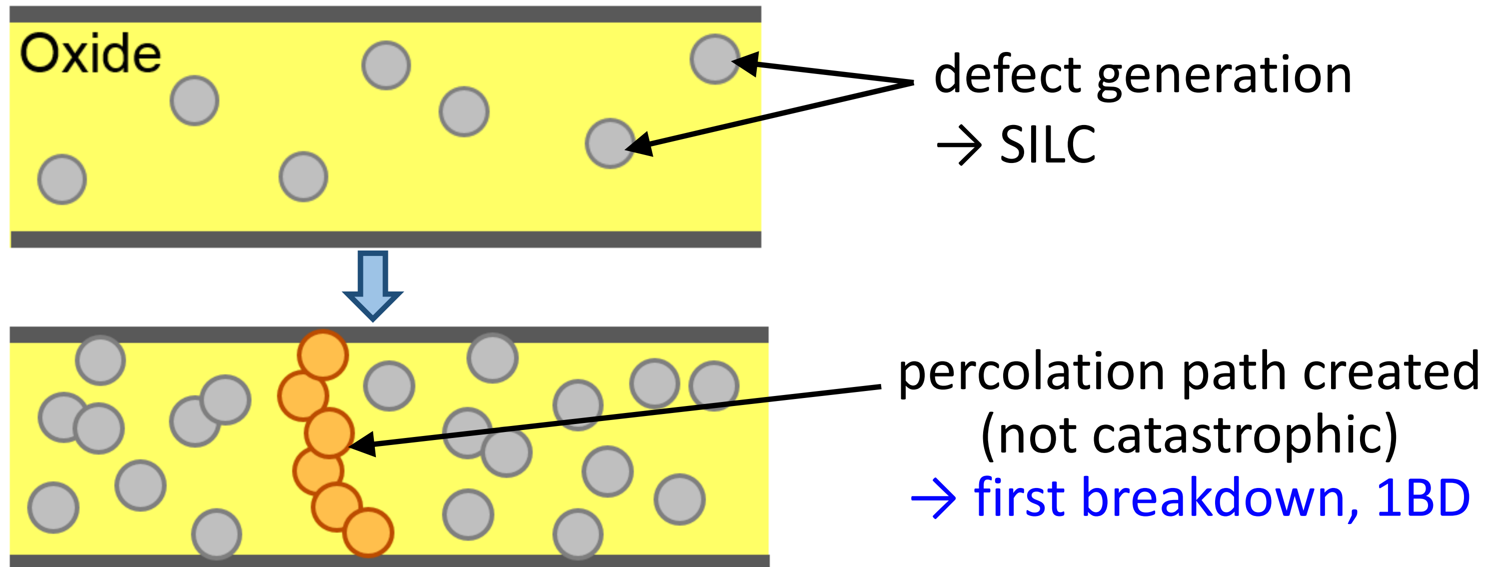
- Time-to-first-breakdown t_{1BD}: I_G noise appears
- Hard breakdown (HBD) time t_{HBD}: Jump in I_G, device no longer operational
- t_{PBD}: duration of progressive breakdown (PBD)

Origins of Oxide Breakdown

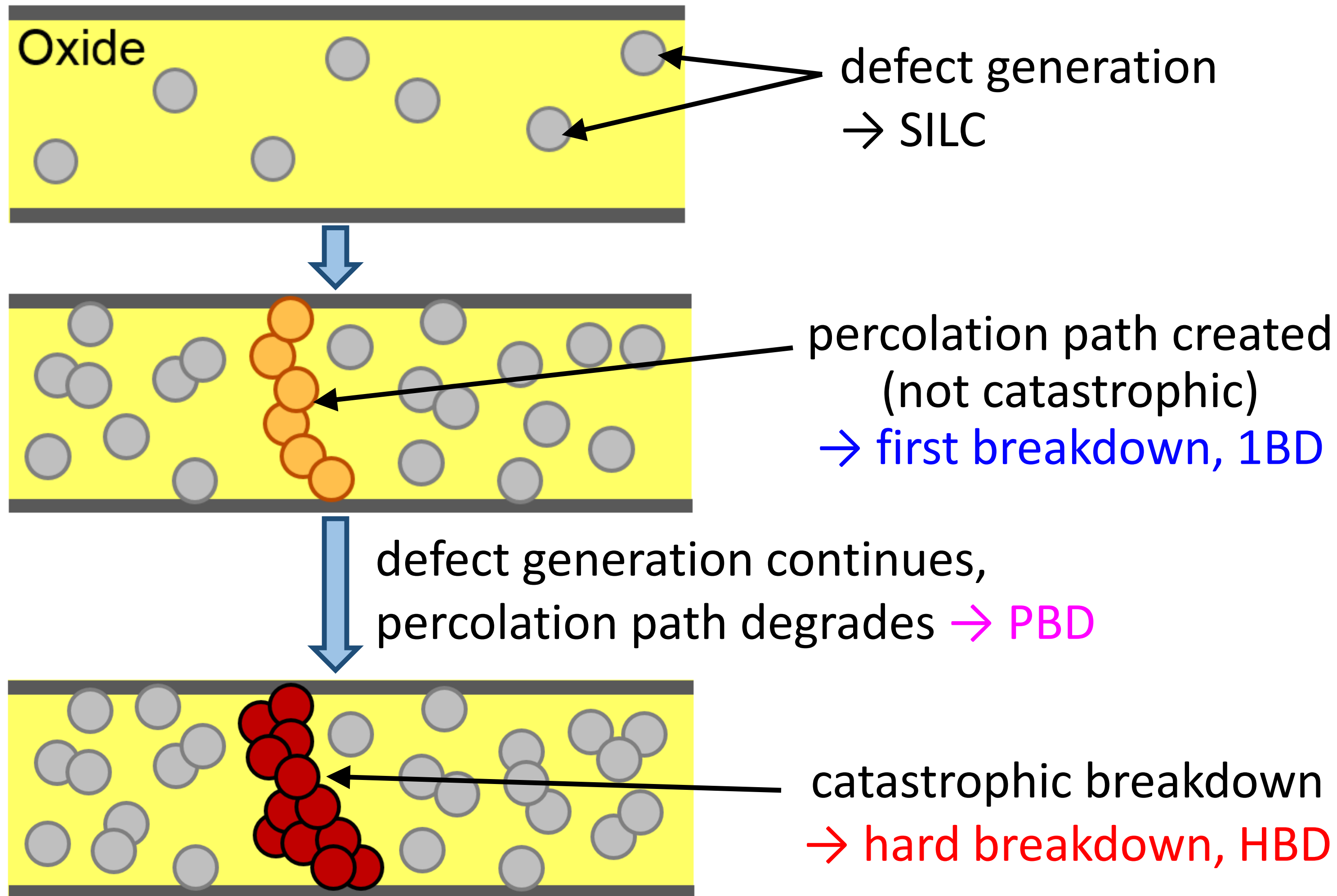
R. Degraeve, MR 2009



Origins of Oxide Breakdown

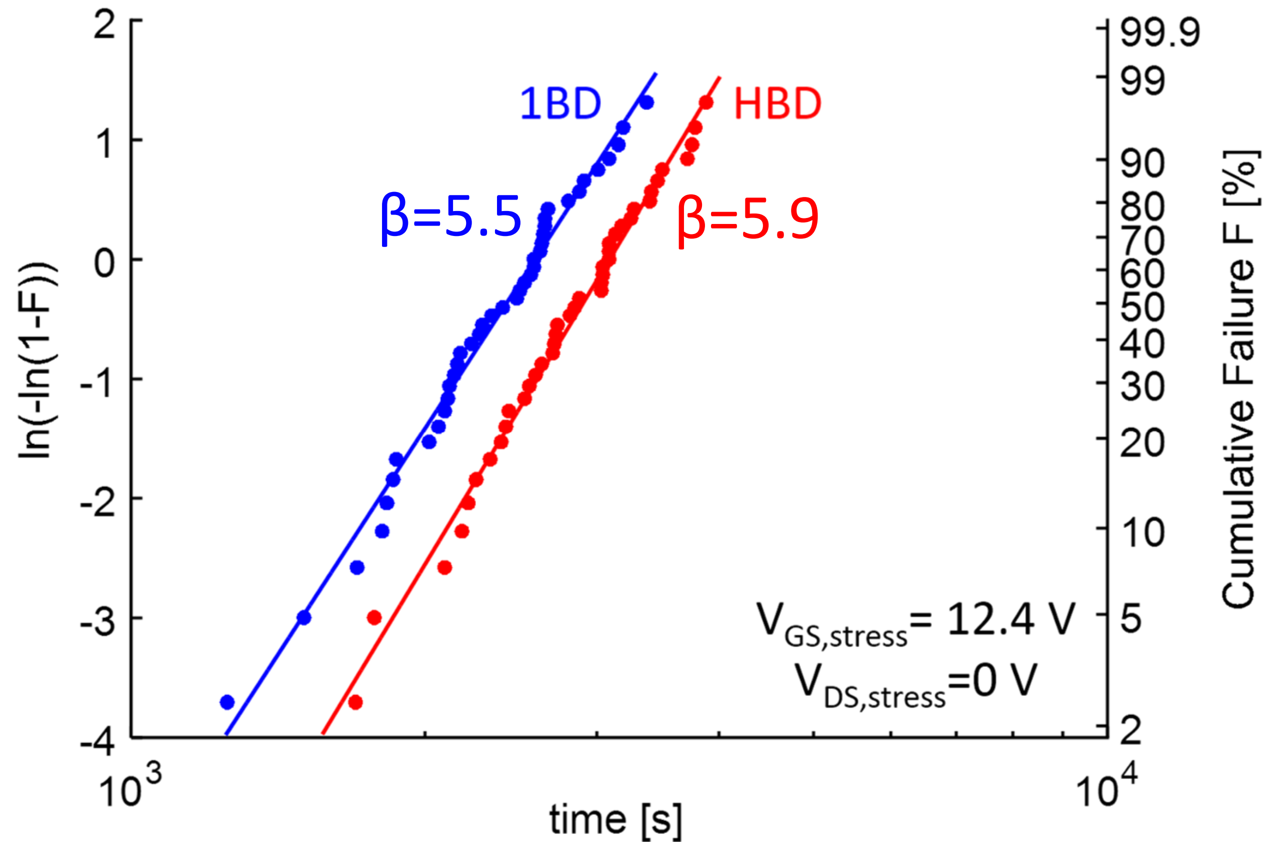


Origins of Oxide Breakdown



GaN Gate Breakdown Statistics

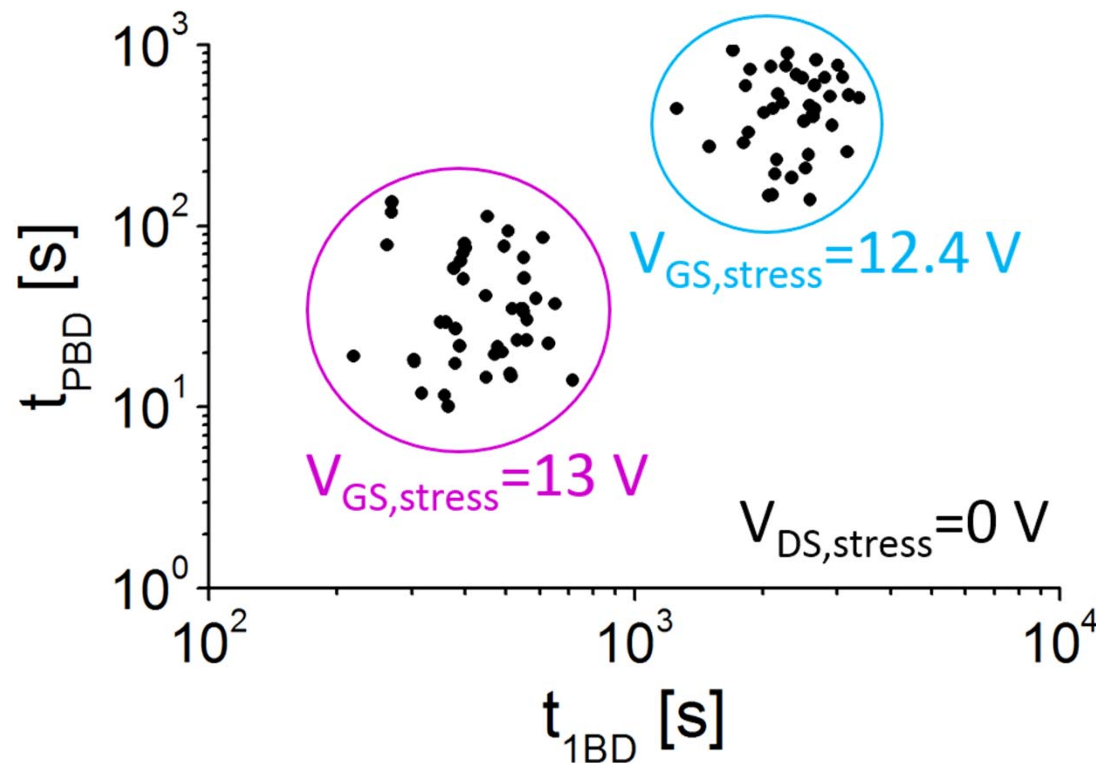
Statistics for time-to-first-breakdown t_{1BD} and hard breakdown t_{HBD}



- *Weibull distribution*: ln[-ln(1-F)] = βln(t) - βln(η)
- Nearly parallel statistics → common origin for t_{1BD} and t_{HBD}

GaN Gate Breakdown Statistics

Correlation between time-to-first-breakdown t_{1BD} and PBD duration t_{PBD}



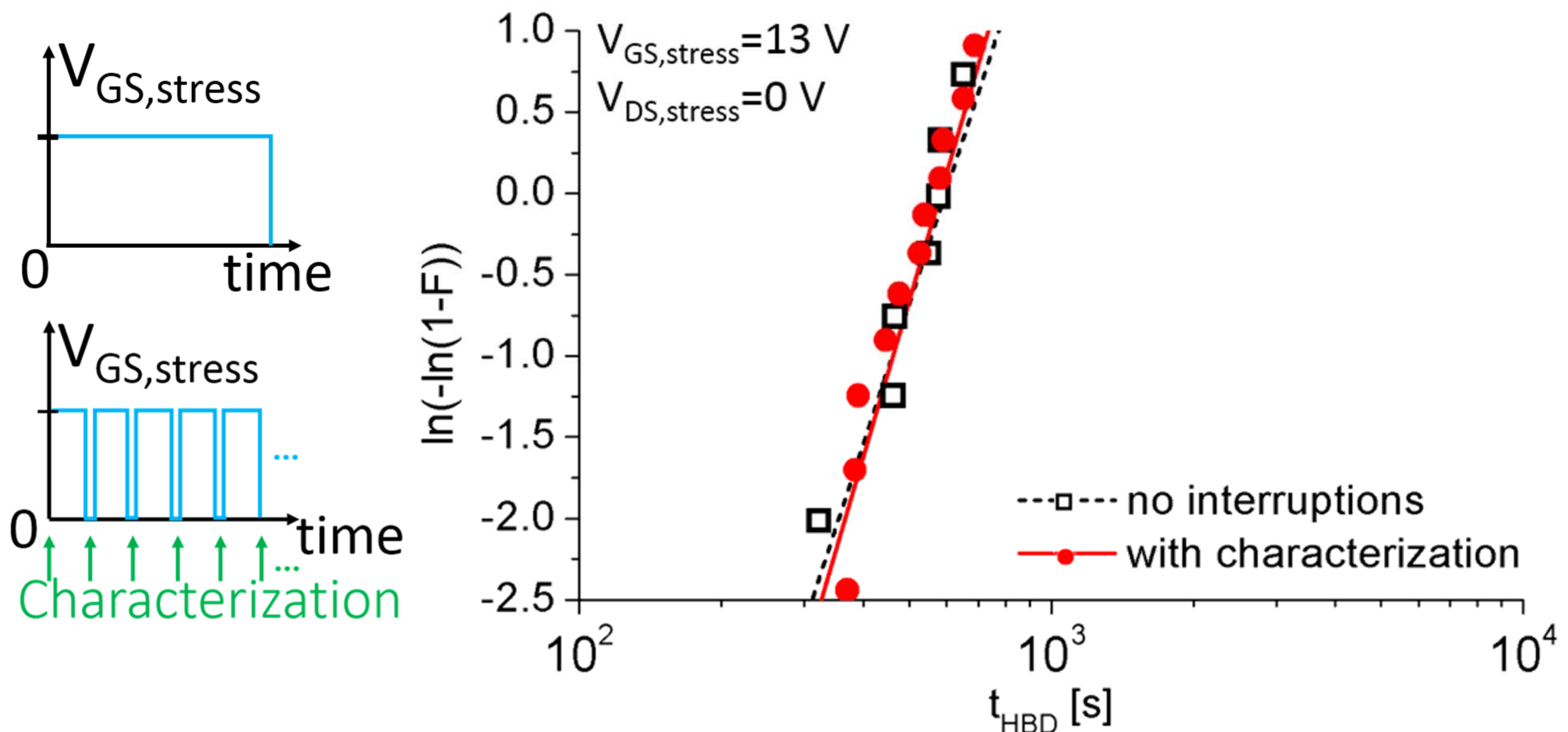
(following E. Wu, IEDM 2007)

t_{1BD} and t_{PBD} independent of one another → after first breakdown, defects generated at random until HBD occurs

Characterizing PBD:
Subthreshold I-V Measurements

Introduce Interruption and Characterization

- Would like to pause TDDB stress to periodically characterize device
- Compare Weibull statistics for standard and interrupted schemes

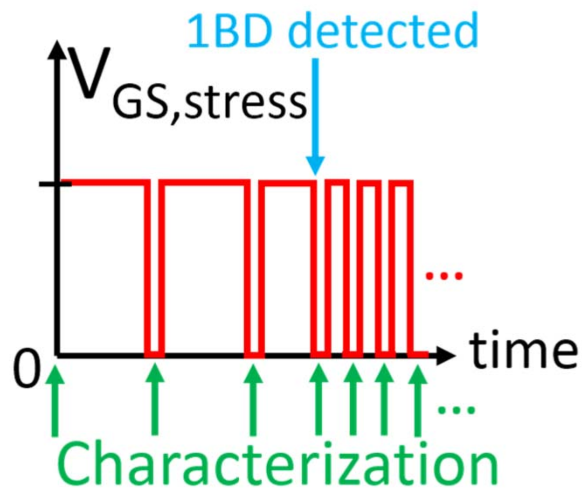


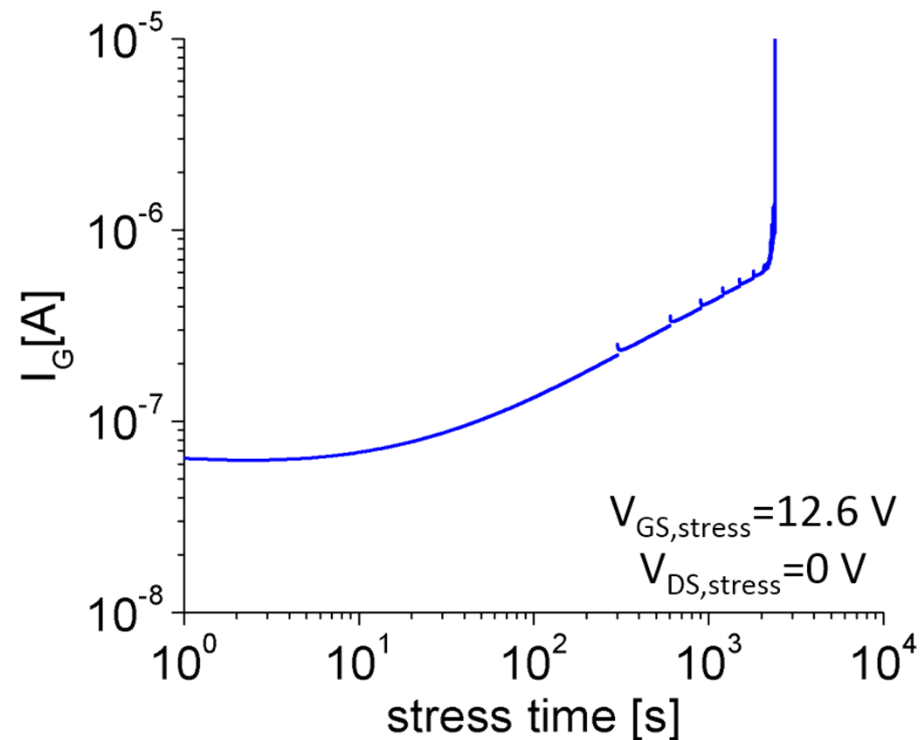
Same statistics for both schemes → characterization is benign

Capturing Pre-1BD and Post-1BD

Two-step stress-and-measure scheme:

- Once every 5 minutes before first breakdown
- Once every 20 seconds after first breakdown





Capturing Pre-1BD and Post-1BD

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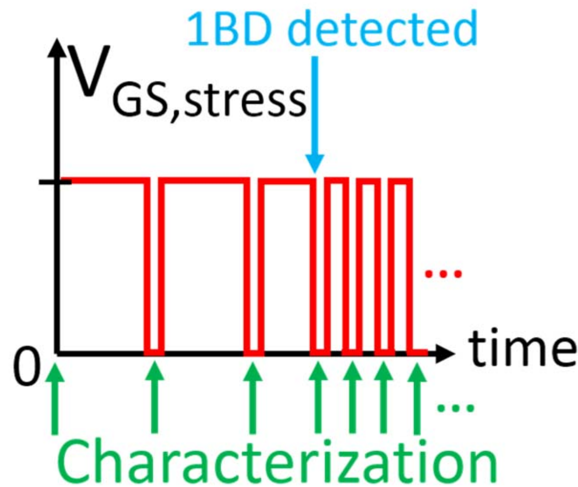
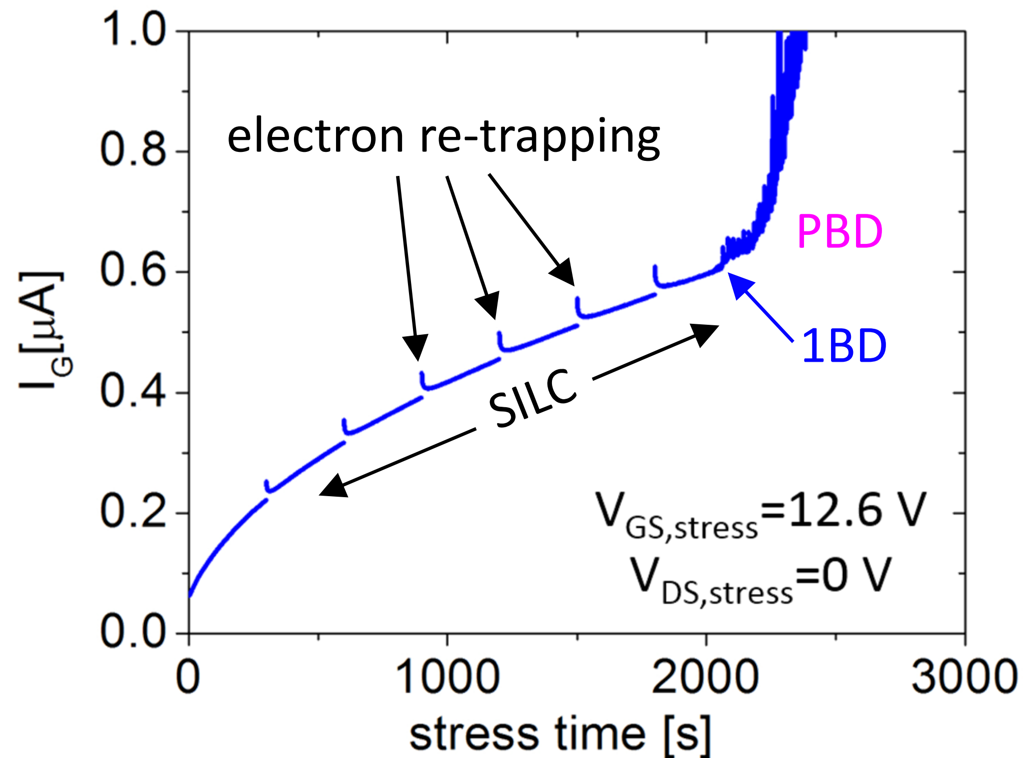
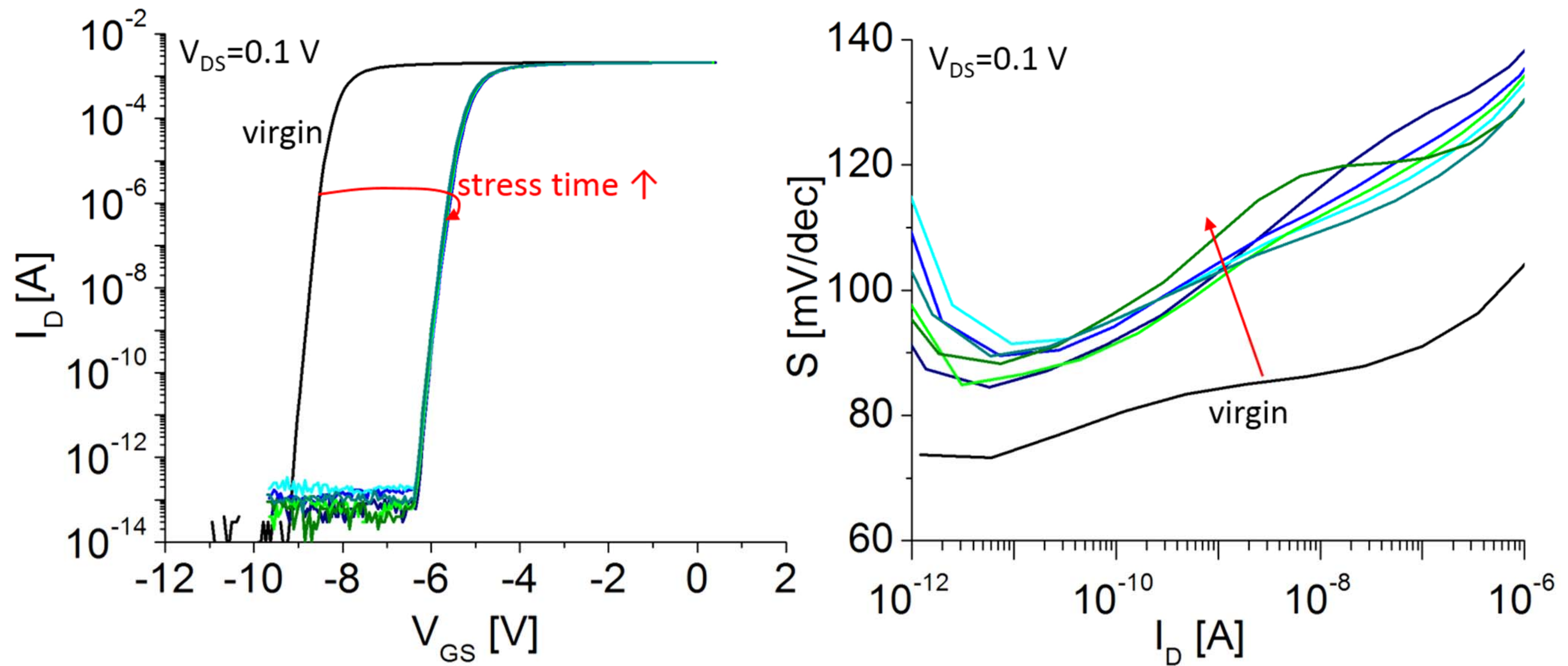




Partial de-trapping (in dielectric or AlGaN barrier) during characterization phase → re-trapping during stress

Before First Breakdown

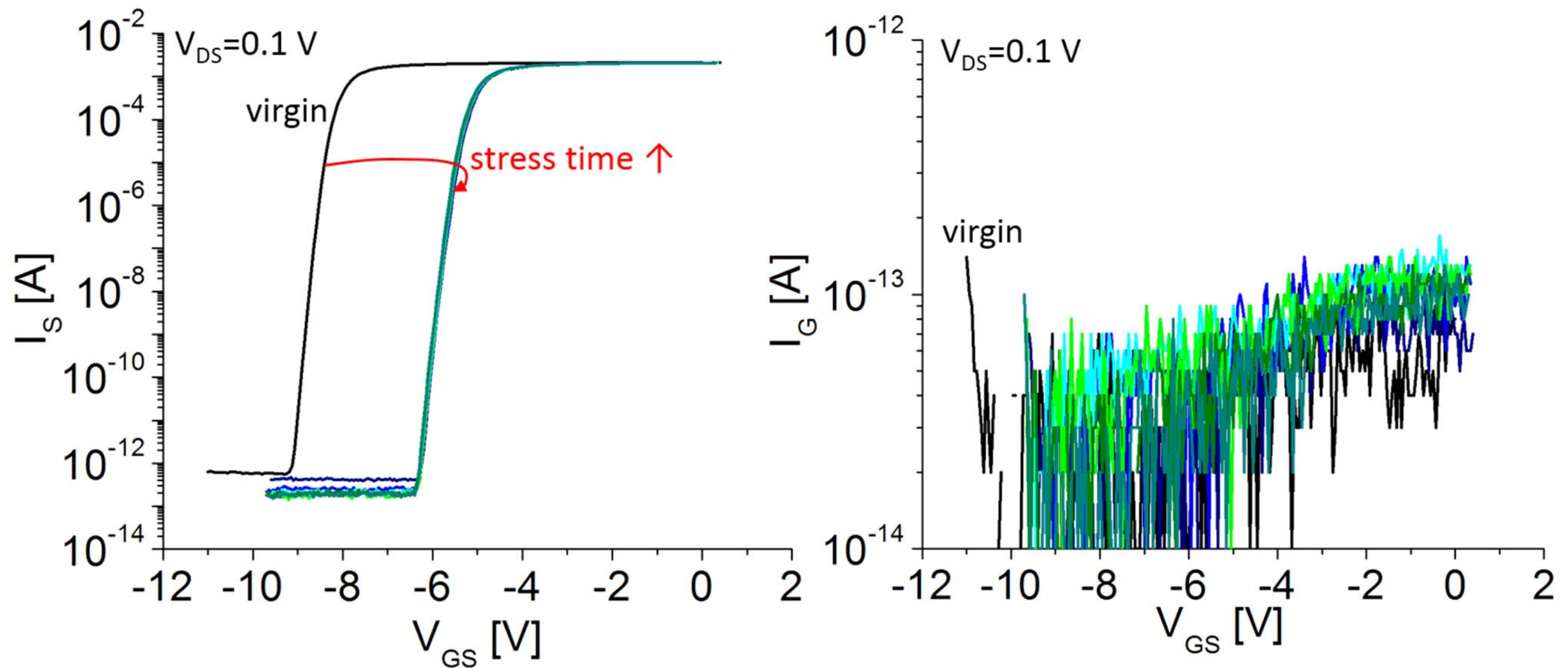
Transfer characteristics every *5 minutes* between stress



- Large positive V_T shift → trapping in dielectric or AlGaN
- Immediate S degradation but no further change

Before First Breakdown

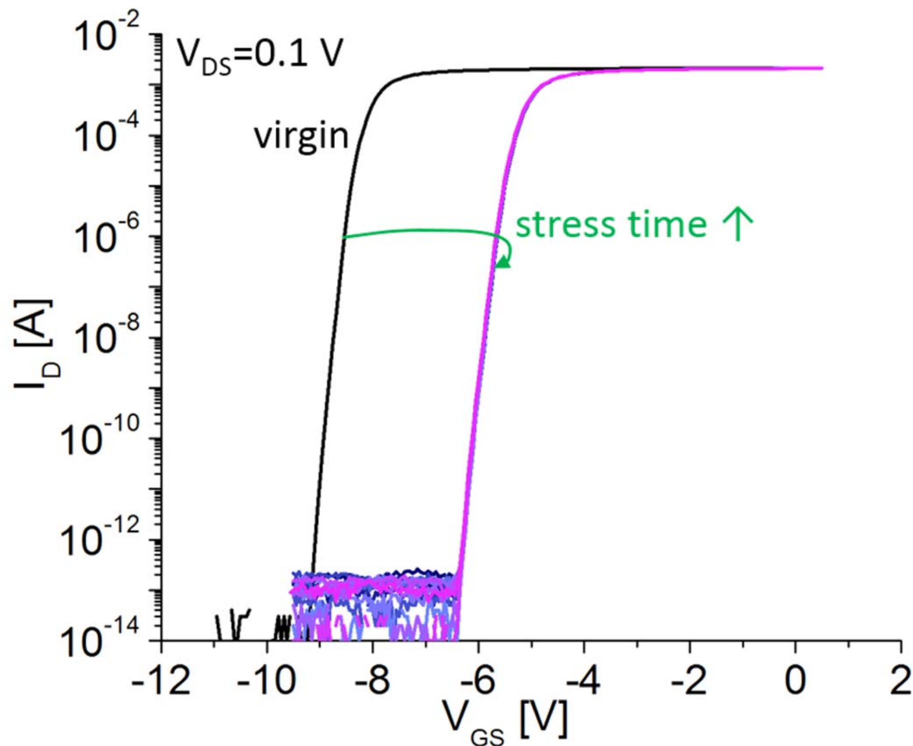
Transfer characteristics every *5 minutes* between stress

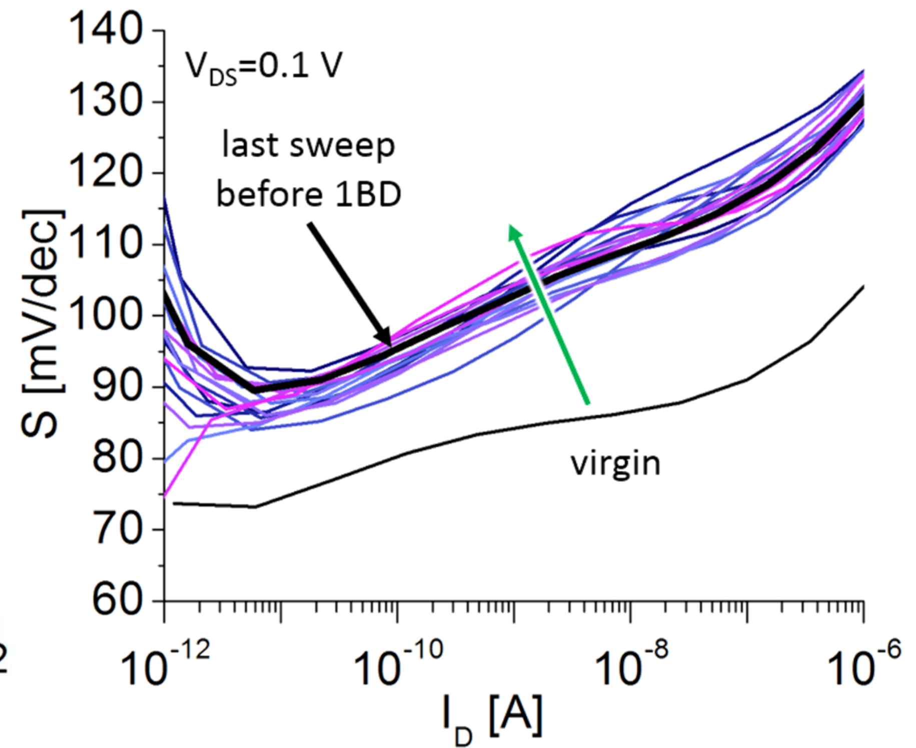


- Large positive V_T shift → trapping in dielectric or AlGaN
- Subthreshold I_G remains below noise floor

After First Breakdown

Transfer characteristics every *20 seconds* between stress

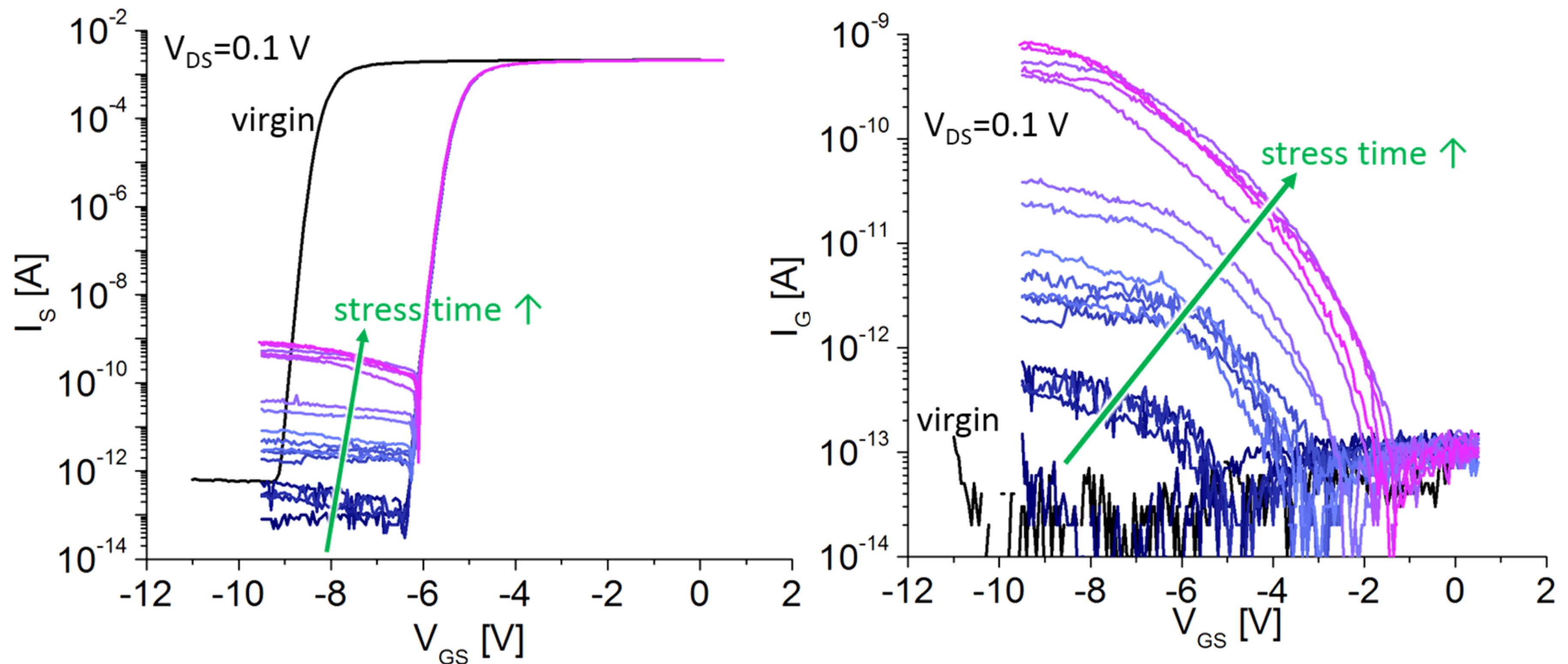




- I_D unaffected by first breakdown
- No change in S after first breakdown → ΔS unrelated to dielectric defect generation

After First Breakdown

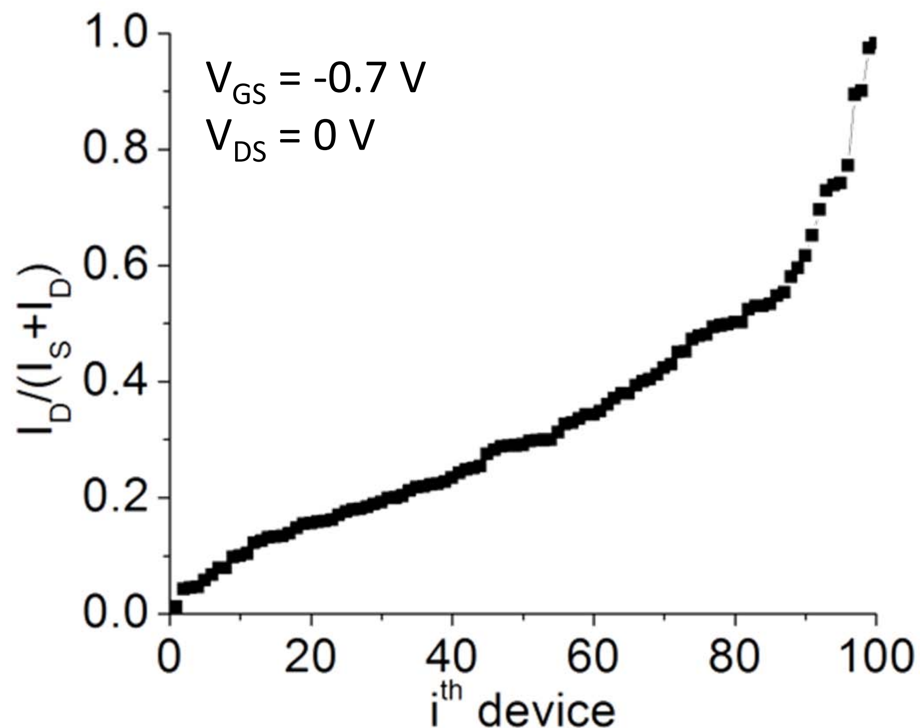
Transfer characteristics every *20 seconds* between stress

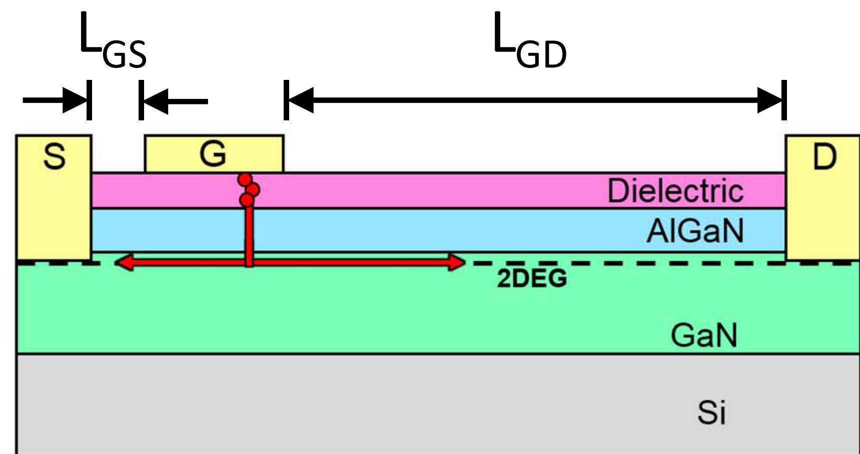


- Leakage from I_G runs preferentially through source (in this particular device) → BD path likely closer to source
- I_G increases in sudden jumps → discrete formation of defects along breakdown path

After Hard Breakdown

Lateral location of BD path: measure $I_D/(I_S+I_D)$ at V_{DS}=0 V





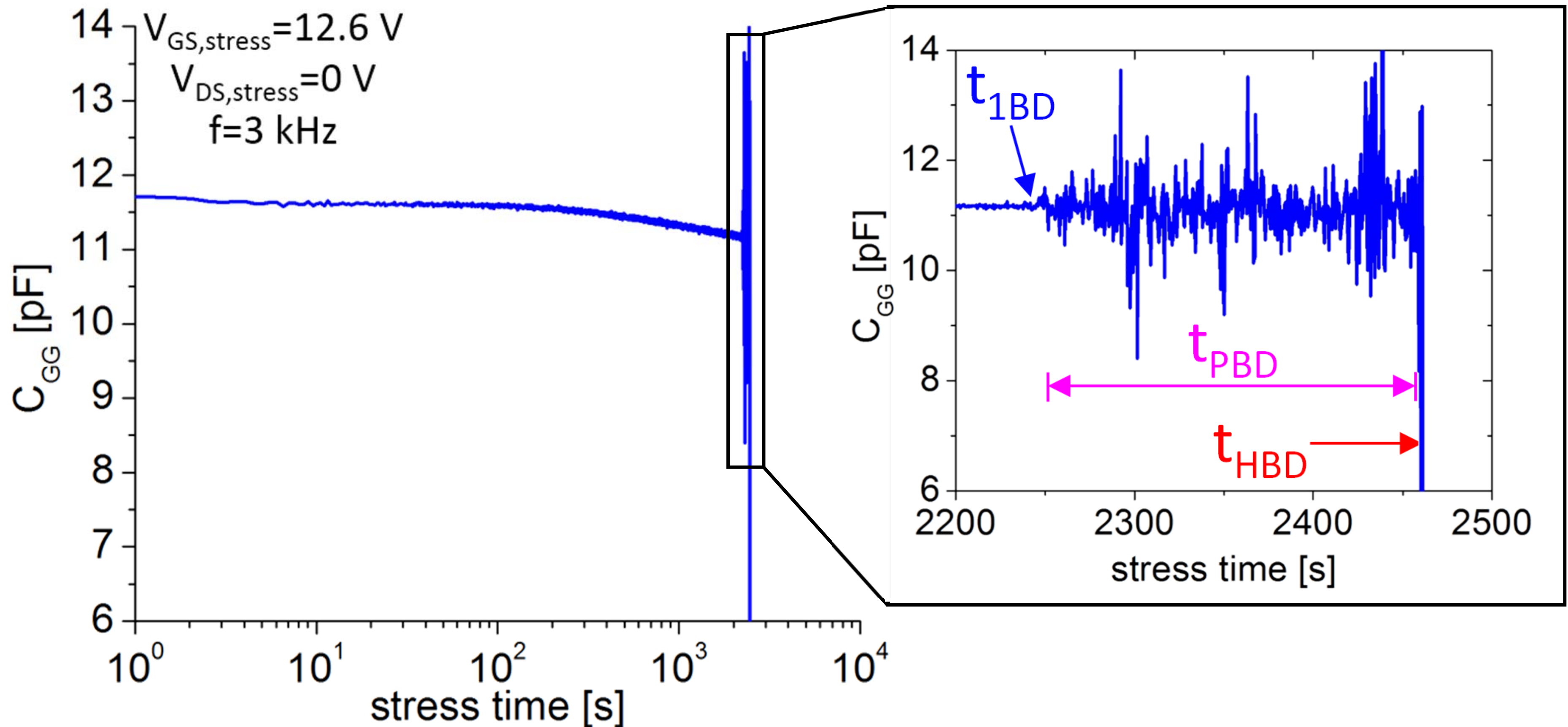
(following R. Degraeve, IRPS 2001)

- Spread of BD locations across channel
- L_{GD} > L_{GS} → current preferentially flows through source terminal

Characterizing PBD:
C-V Measurements

Detecting First BD with Capacitance

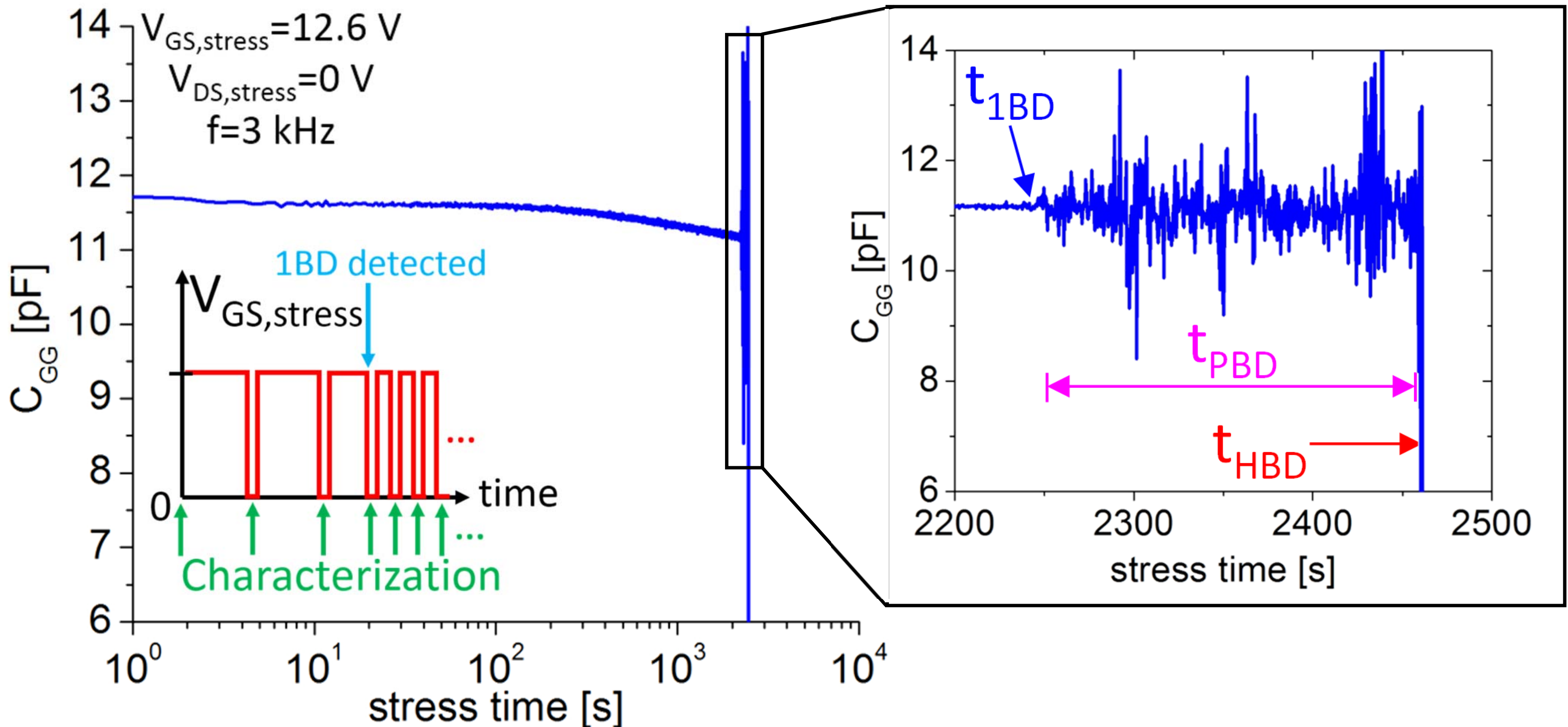
Classic TDDB experiment, measure C_{GG} vs. time



Low frequency C_{GG} susceptible to I_G noise → can detect 1BD

Detecting First BD with Capacitance

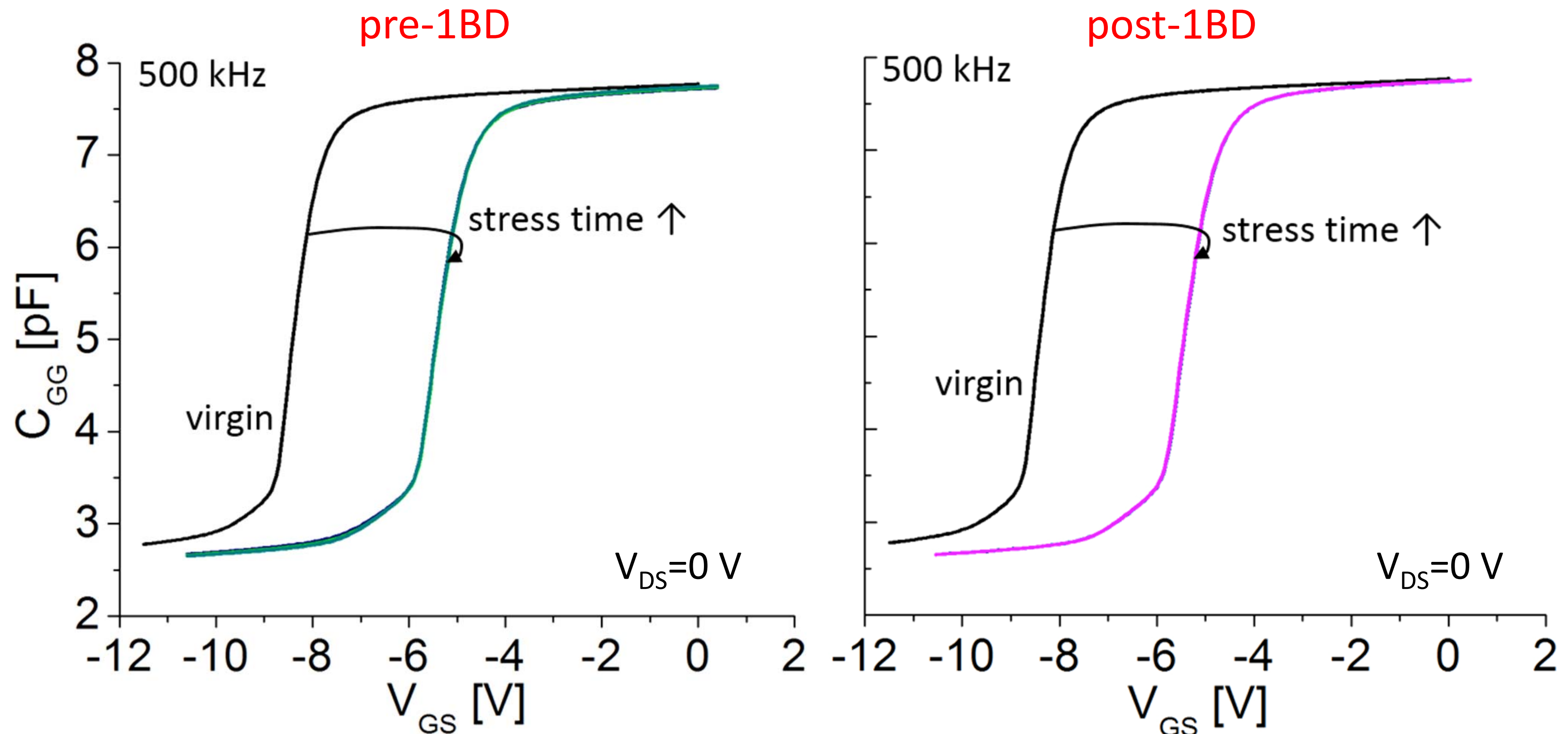
Classic TDDB experiment, measure C_{GG} vs. time



- During stress, measure C_{GG} at low frequency (3 kHz) to detect 1BD
- Characterize device C-V at higher frequency (500 kHz)

Before and After First BD

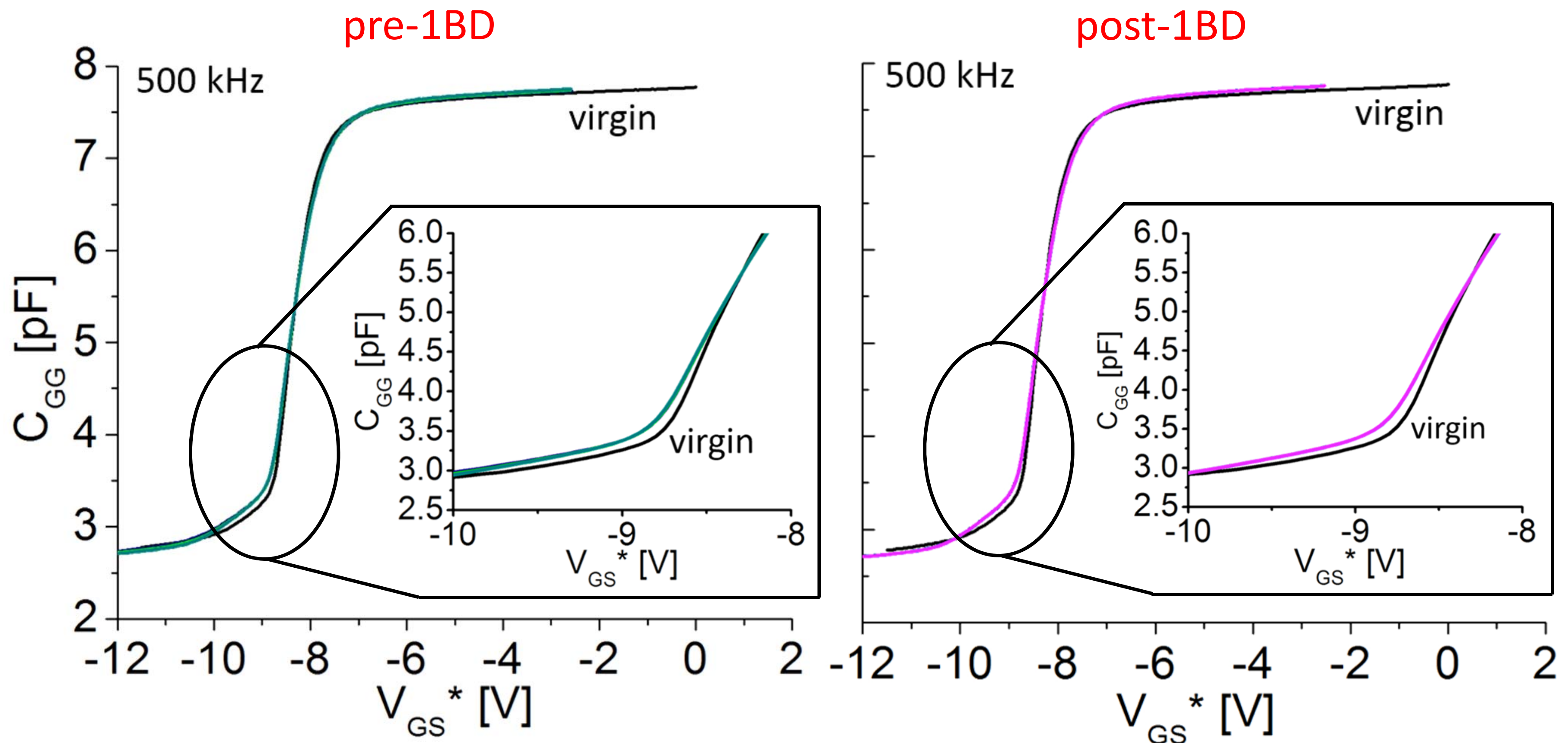
Measure C_{GG} at 500 kHz every 5 minutes before 1BD, every 20 seconds after 1BD



- Large V_T shift → trapping in dielectric or AlGaN
- No major changes after 1BD → damage limited to dielectric

Before and After First BD

Shift stressed C-V curves to lie on top of virgin sweep



- Small C-V stretch-out after first stress step → common origin with early S degradation?
- Confidence in electrostatics → lifetime prediction model

Conclusions

- Developed methodology to study TDDB in GaN MIS-HEMTs, explored PBD in GaN for the first time
- Classic t_{1BD} and t_{HBD} statistics
  - Common physical origin for first breakdown and hard breakdown
  - However, t_{1BD} not predictive of t_{HBD}
- Before first BD:
  - $\Delta V_T > 0$
  - S degradation
  - C-V stretch-out
- After first BD:
  - AlGaN/GaN interface largely unaffected
  - I_G rises in noisy manner until HBD
  - Excess I_G leakage flows through source/drain
  - HBD spot randomly located across channel

Acknowledgements

Dr. Ernest Wu, IRPS 2016 mentor

Questions?