GaN HEMT Reliability

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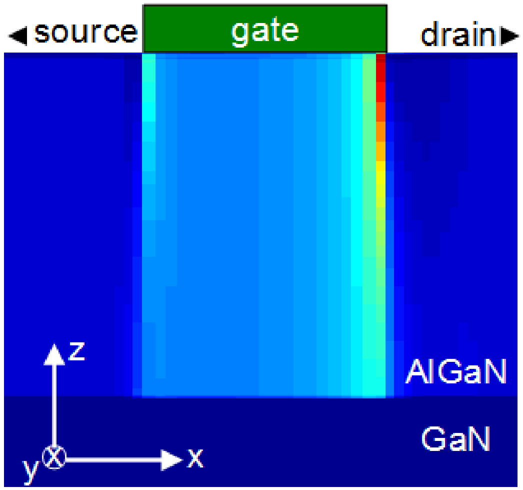
Jose Jimenez, Sefa Demirtas



1. Introduction: GaN Reliability

- GaN HEMT: commercial technology since 2005
- Great recent strides in reliability:
  - MTTF=10^7 h at 150 C and 40 V demonstrated [Jimenez, IRPS 2008]
- Unique issues about GaN HEMT reliability:
  - No native substrate (use SiC, Si, sapphire) → mismatch defects
  - High-voltage operation → very high electric fields (~10^7 V/cm)
  - Strong piezoelectric materials: high electric field → high mechanical stress
  - Electron channel charge set by polarization, not dopants
- Work to do before demonstrating consistent, reproducible reliability with solid understanding behind:
  - When will we be able to put GaN in space?

Outline

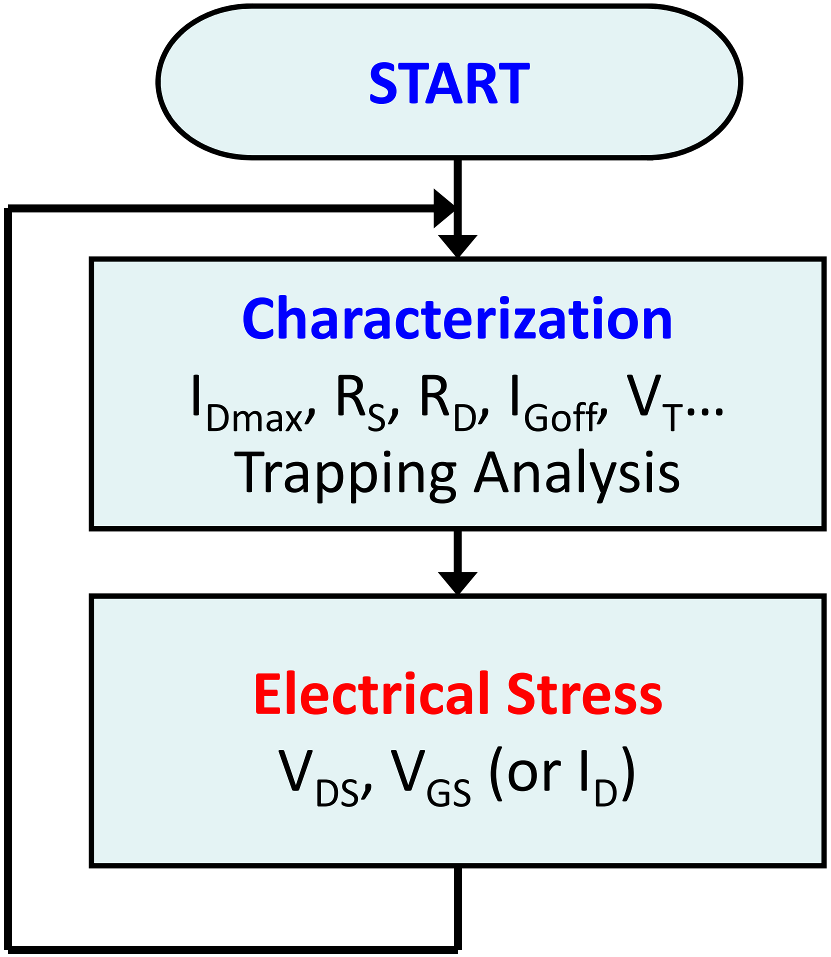
1. Introduction
2. Experimental
3. Results
4. Hypothesis for high-voltage degradation mechanism:
    - Defect formation through inverse piezoelectric effect
5. Discussion
6. Conclusions

2. Experimental

GaN HEMT Reliability Test Chip

- 3.25 x 3.175 mm^2
- DC and mmw HEMTs
- HEMTs with different dimensions (L_{rd}, L_{rs}, L_g, W_g, #fingers)
- HEMTs with different orientations (0, 30^o, 60^o, 90^o)
- TLM's, side-gate FET, FATFET
- Most devices completed before vias
- Implemented by BAE, TriQuint and Nitronex with own design rules

DC Stress Experiments



START

Characterization

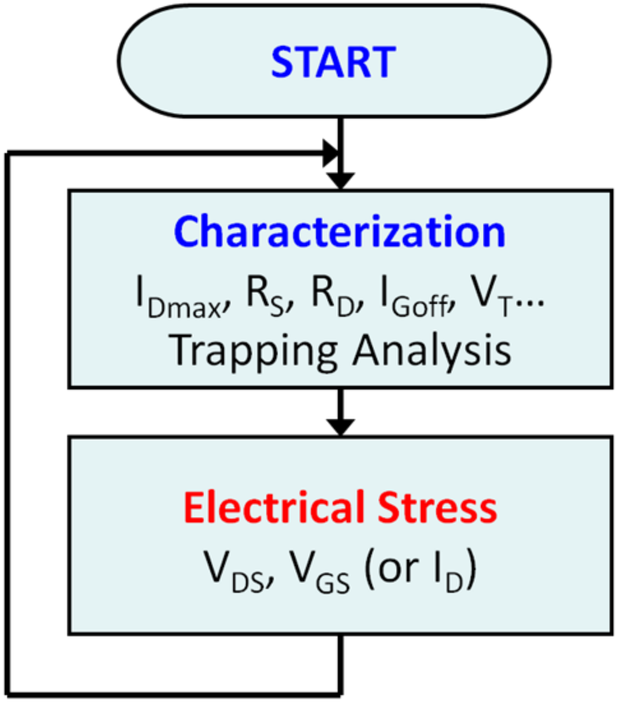
I_{Dmax}, R_S, R_D, I_{Goff}, V_T…

Trapping Analysis

Electrical Stress

V_{DS}, V_{GS} (or I_D)

Characterization Suite



START

Characterization

I_{Dmax}, R_S, R_D, I_{Goff}, V_T...

Trapping Analysis

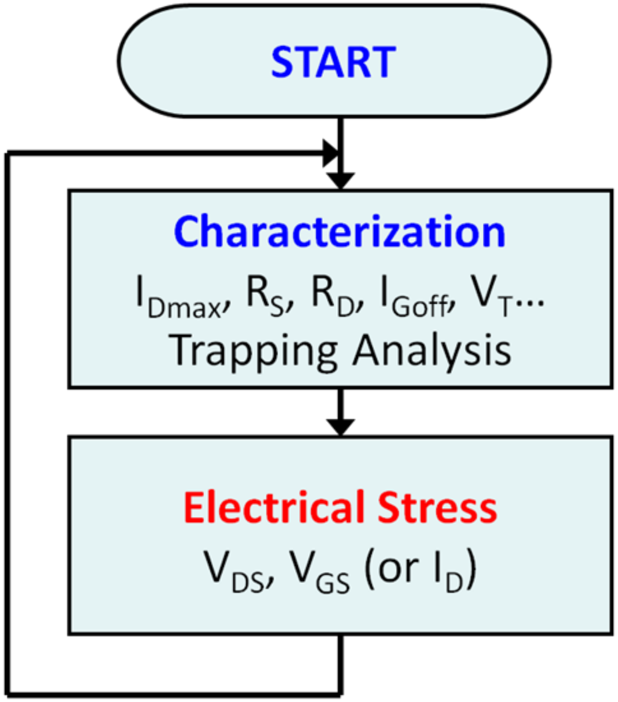
Electrical Stress

V_{DS}, V_{GS} (or I_D)

- *Comprehensive*, three sets of measurements:
  - –*Coarse characterization*: basic device parameters
  - –*Fine characterization*: + complete set of I-V characteristics (output, transfer, gate, subthreshold, kink)
  - –*Trap analysis*: transient analysis under various pulsing conditions
- *Fast*:
  - –Coarse characterization: <20 secs
  - –Fine characterization: <1 min
  - –Trap analysis: <10 min
- *Frequent*:
  - –Coarse characterization: every 1-2 mins
  - –Fine characterization, trap analysis: before, after, at key points
- *"Benign"*:
  - –100 executions to produce change <2% change in any extracted parameter

DC Stress Schemes

- *Stress-recovery* experiments:
  - to study trapping behavior
- *Step-stress* experiments:
  - to study a variety of conditions in a single device (for improved experimental efficiency)
- *Step-stress-recovery* experiments:
  - to study trap formation under different conditions in a single device



START

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Trapping Analysis

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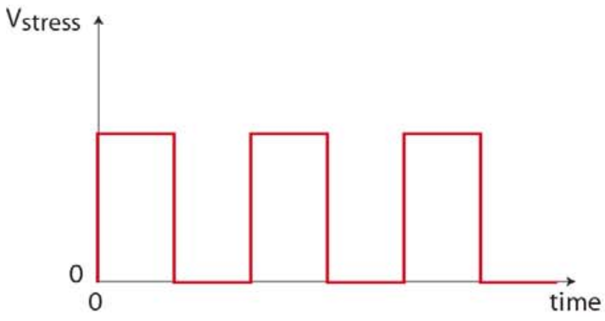
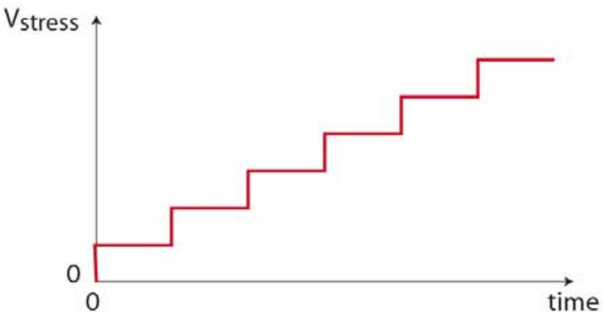
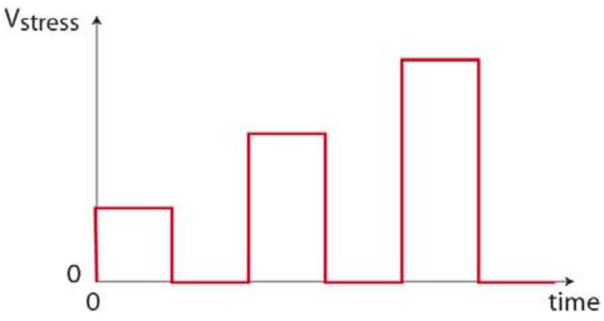
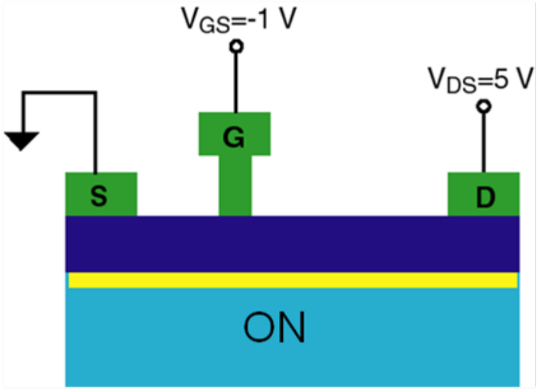


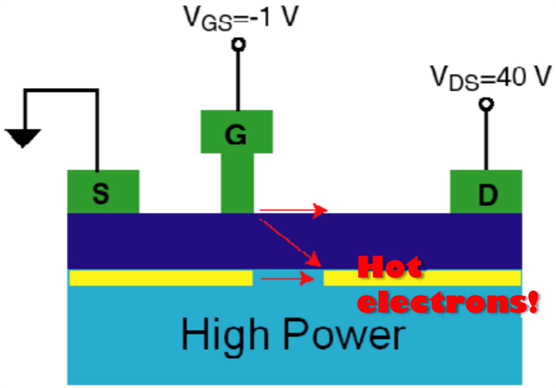




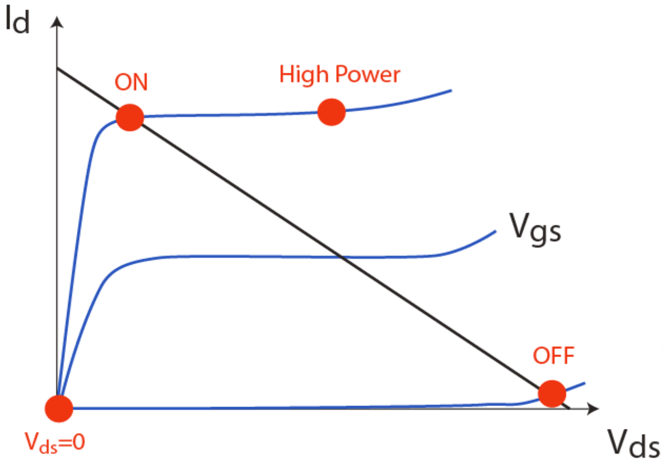
Electrical Stress Bias Points

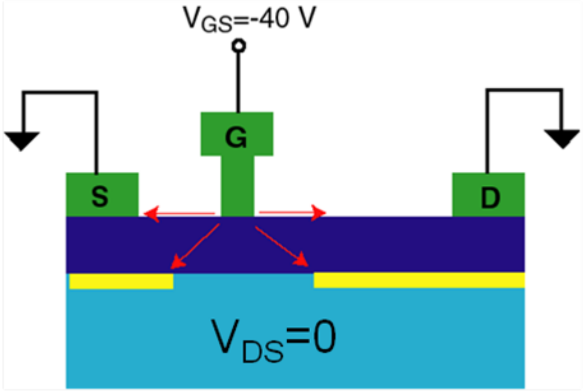


High current, low field

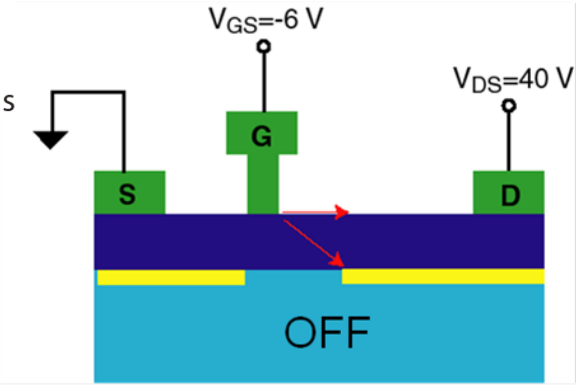


High current, high field



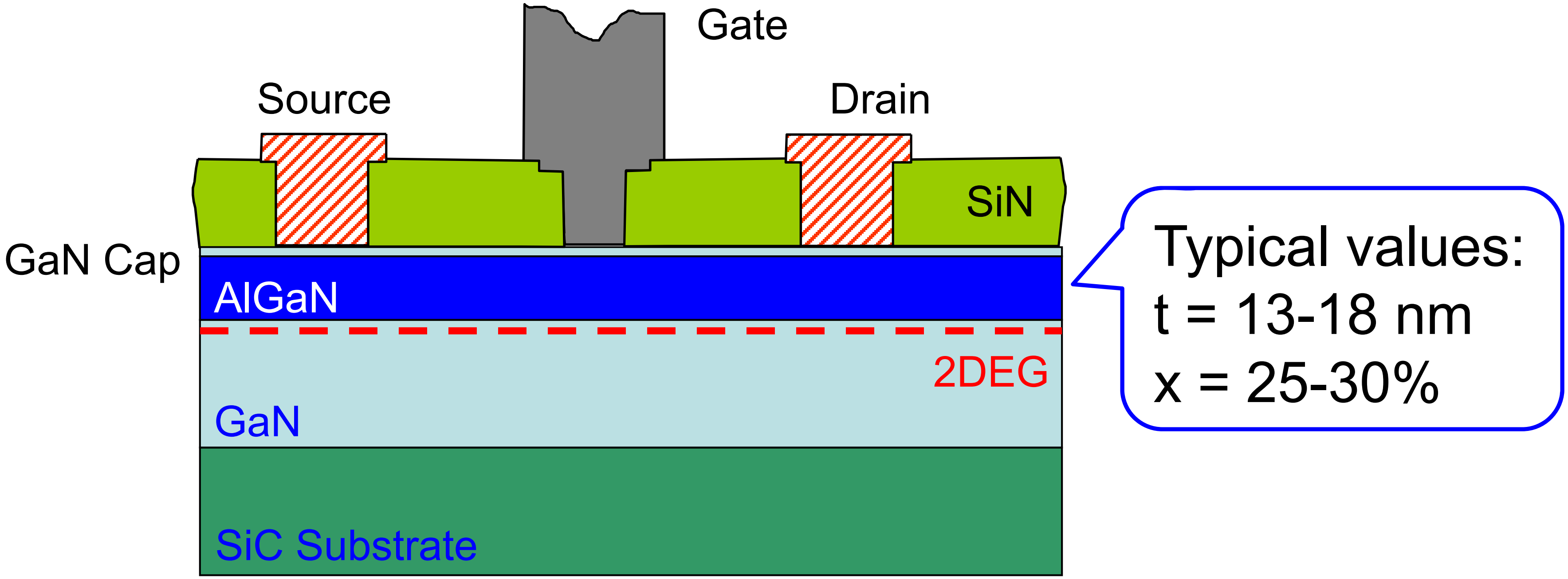


Low current, high field in barrier, low field in buffer



Low current, high field

Typical GaN HEMT



Typical values:
t = 13-18 nm
x = 25-30%

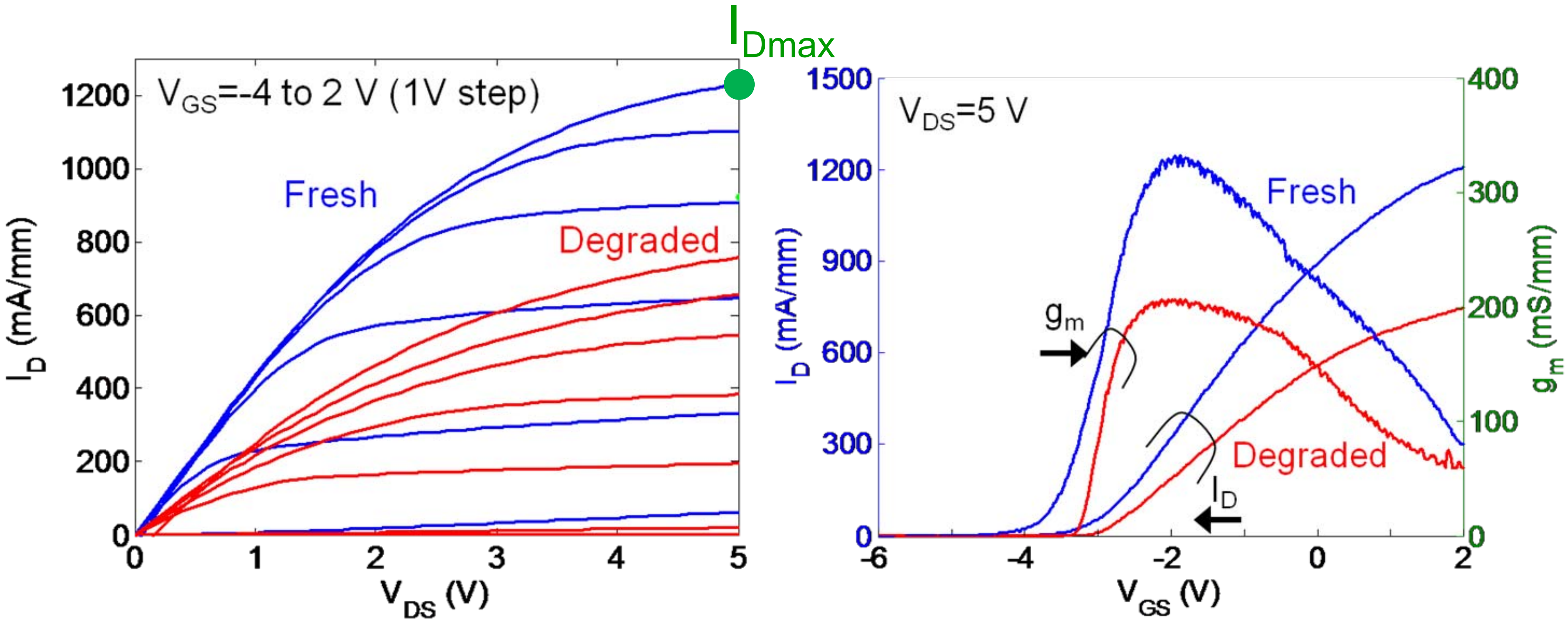
Standard device with integrated field plate :

- L_G=0.25 um, W=4x100 um
- f_T=40 GHz, I_{Dmax}=1.2 A/mm
- P_{out}=8 W/mm, PAE=60% @ 10 GHz, V_D=40 V

Test device: W=2x25 um

3. Results: V_{DS}=0 Degradation

V_{DS}=0 step-stress; V_{DG}: 10 to 50 V, 1 V/step, 1 min/step

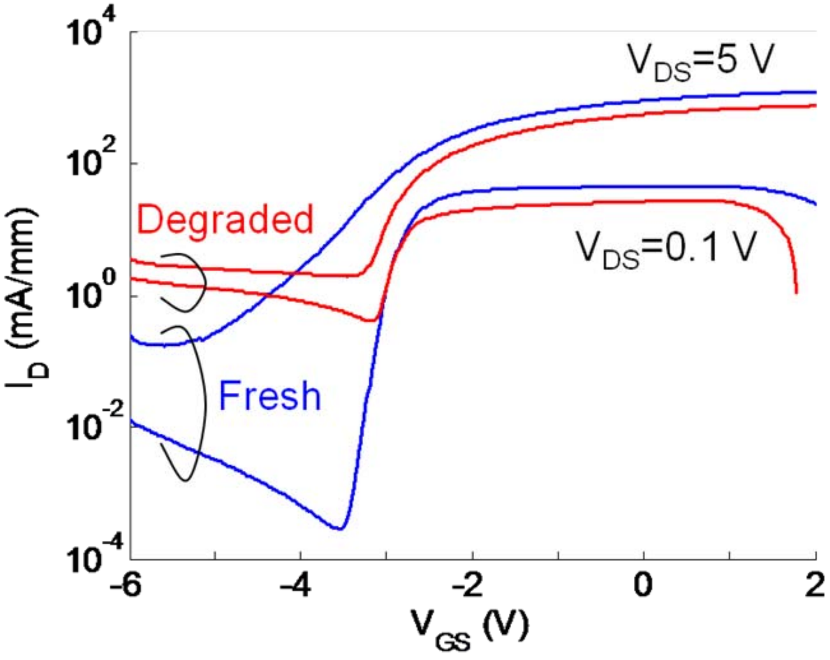


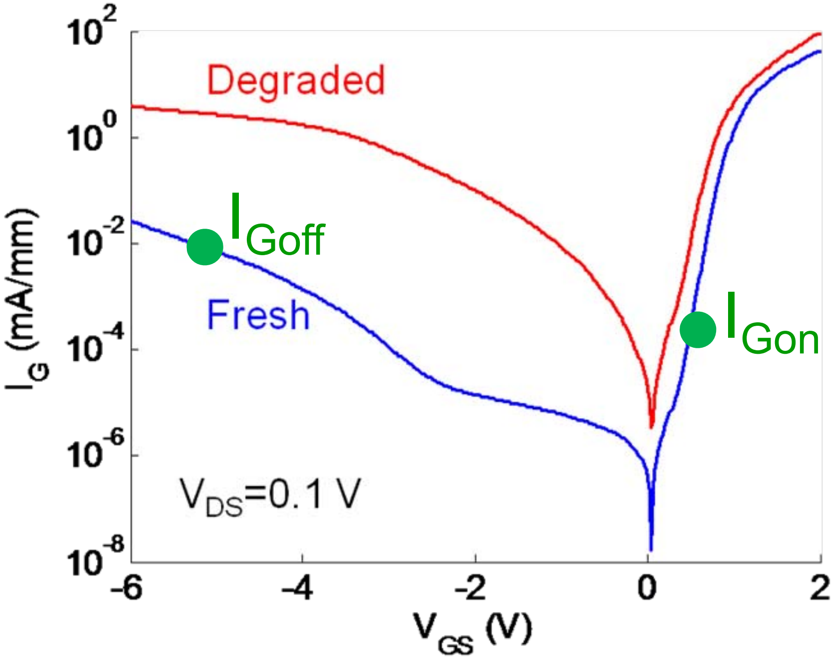
I_{Dmax} ↓
R_{ON} ↑

g_m ↓

V_{DS}=0 Degradation

V_{DS}=0 step-stress; V_{DG}: 10 to 50 V, 1 V/step, 1 min/step

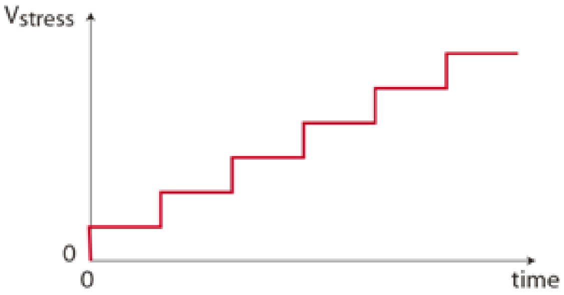




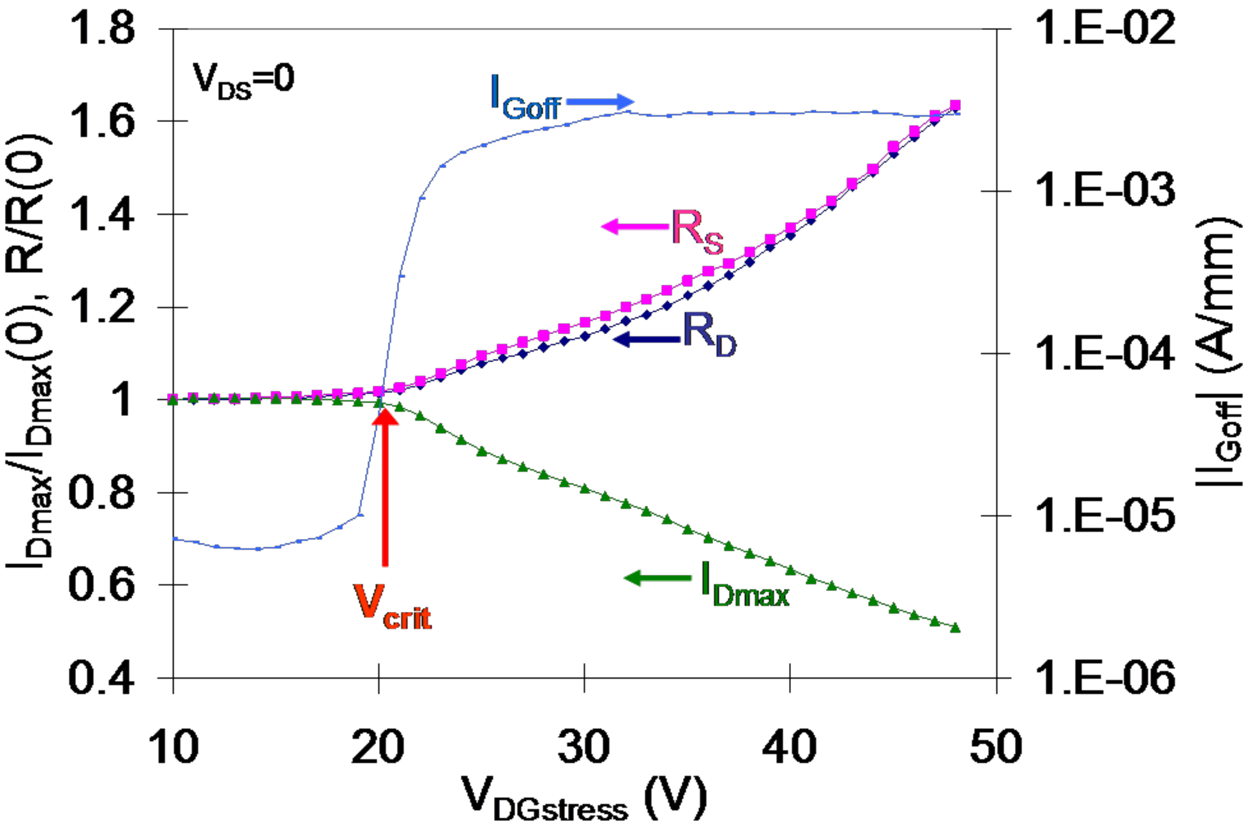
I_{Doff} ↑

I_{Goff} ↑↑
I_{Gon}↑

V_{DS}=0 Degradation



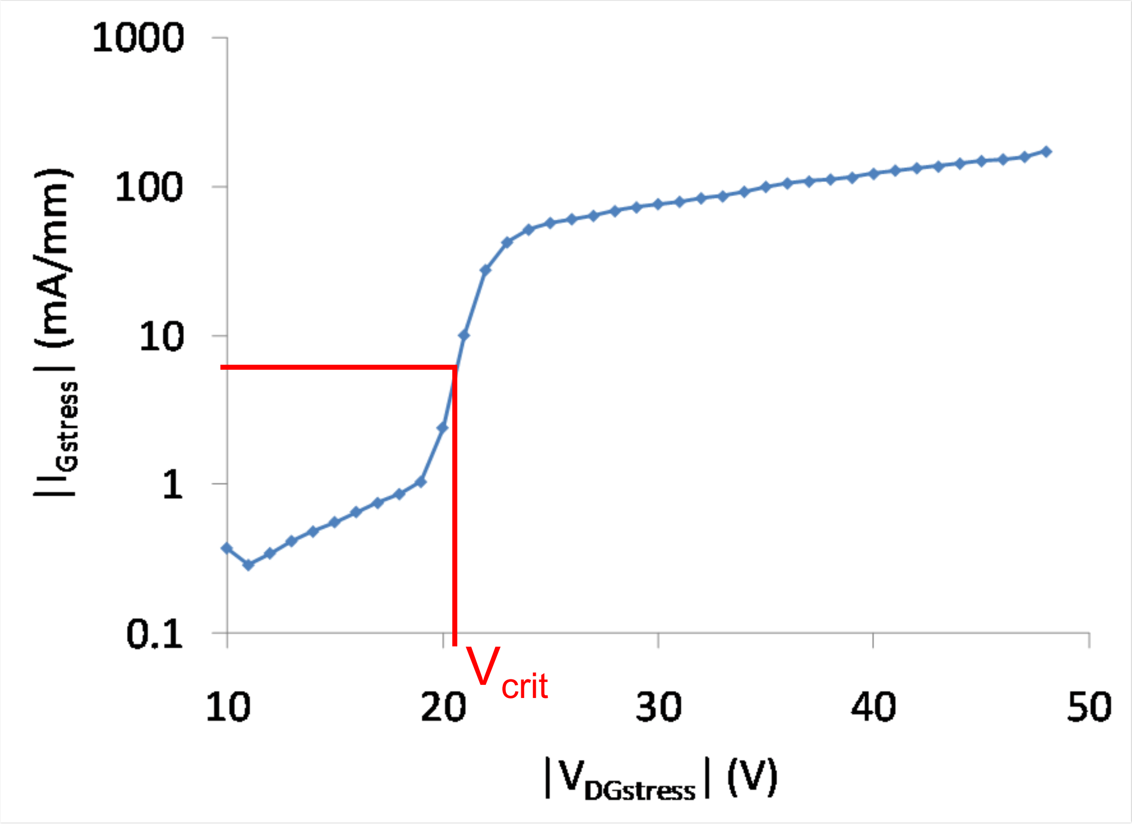
Joh, EDL 2008



Critical voltage for degradation:

At V_{crit}≈21 V, I_{Goff} increases ~100X, I_{Dmax}, R_S, R_D start degrading

V_{DS}=0 Degradation

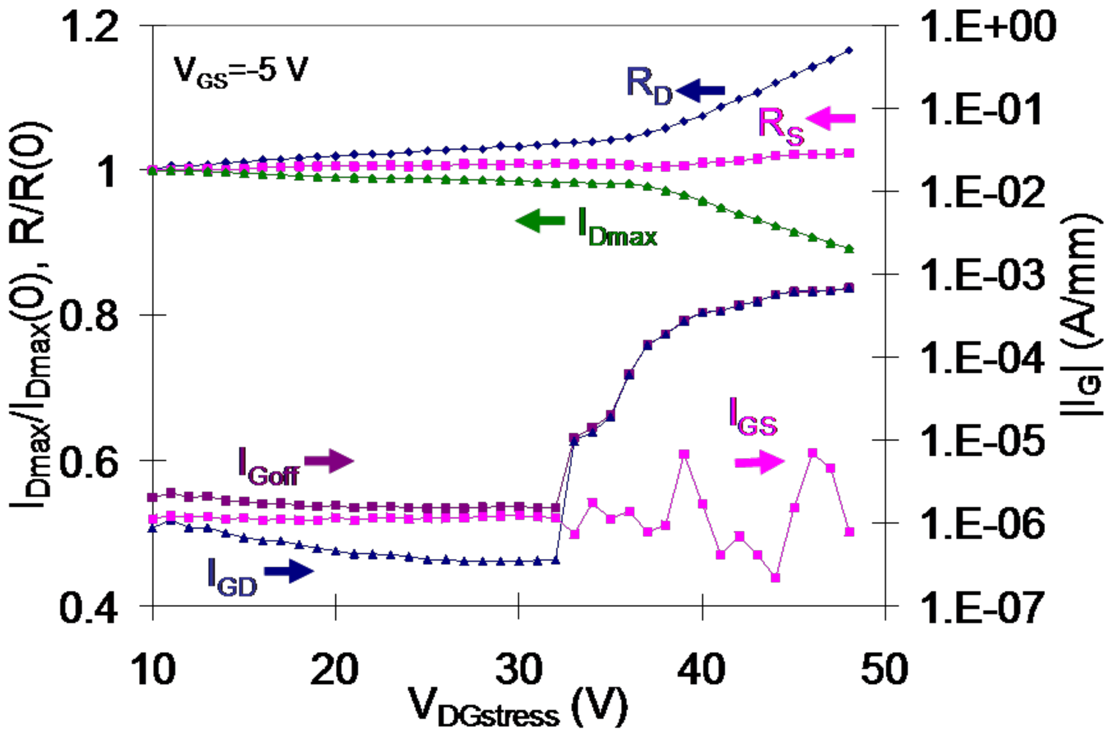


At $V_{crit} \approx 21$ V, $|I_{gstress}| < 10$ mA/mm

→ self-heating, hot electrons not responsible for V_{crit} degradation

OFF-state Degradation

OFF-state step-stress: V_{GS}=- 5 V; V_{DS}: 5 to 45 V, 1 V/step, 1 min/step;

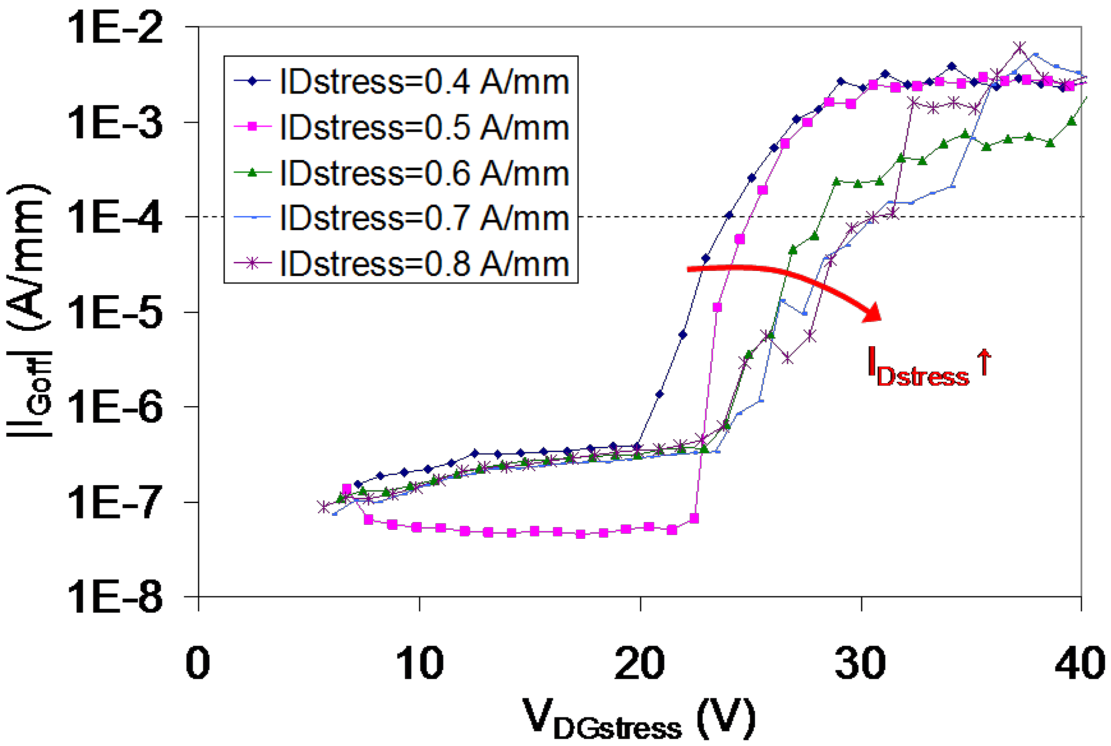


- Critical behavior, but V_{crit}≈34 V → V_{crit} depends on detailed bias
- R_S does not degrade
- I_{GDoff} ↑, I_{GSoff} unchanged

] Drain side degrades, source side intact

High-Power Degradation

High-power step-stress (fixed $I_{Dstress}$); V_{DS}: 5 to 40 V, 1 V/step, 1 min/step



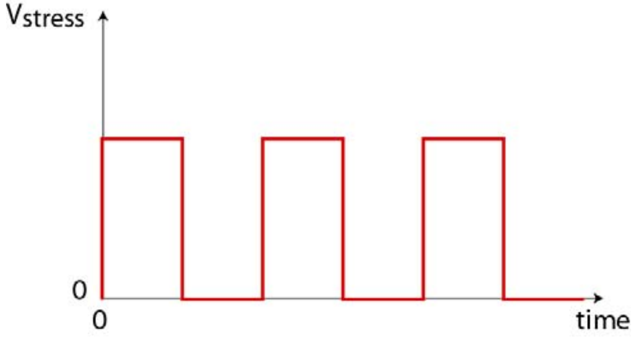
Joh, IEDM 2007

Critical behavior, but $I_{Dstress}$↑ → V_{crit}↑

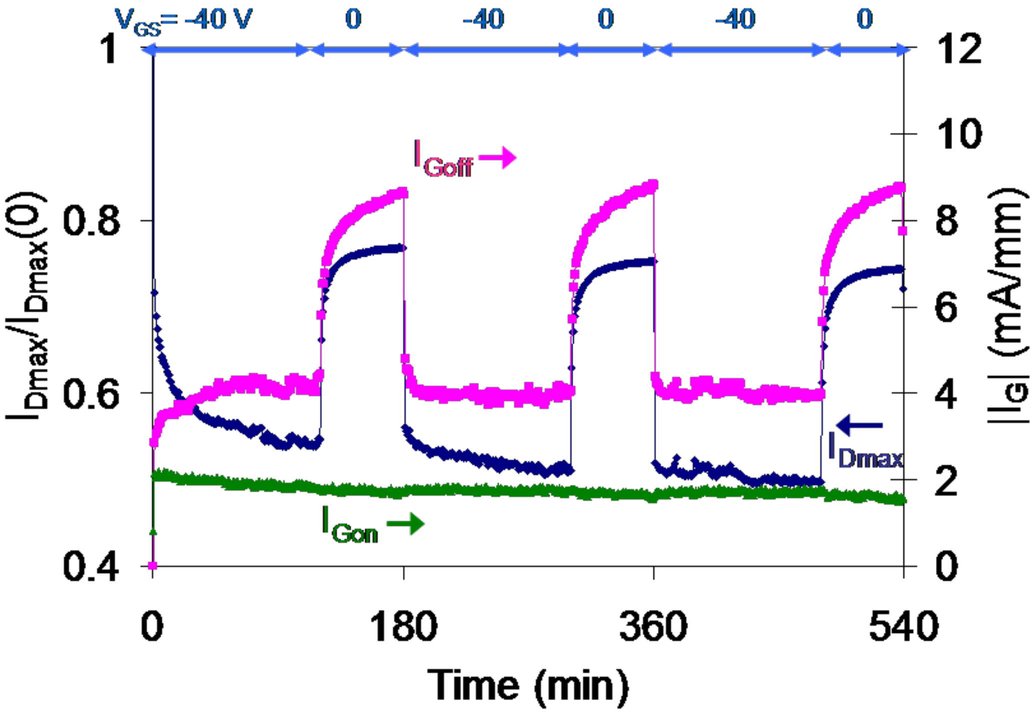
→ Current is not accelerating factor

Trapping in stressed devices

V_{DS}=0 stress-recovery experiment; V_{GS}=-40 V (beyond V_{crit})



Joh, IEDM 2007

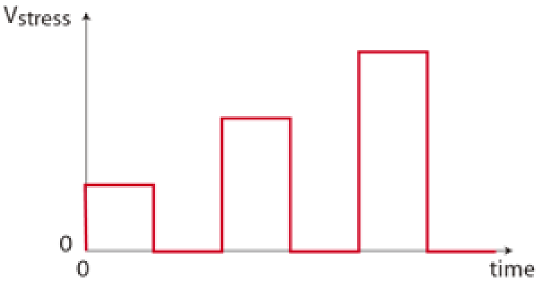


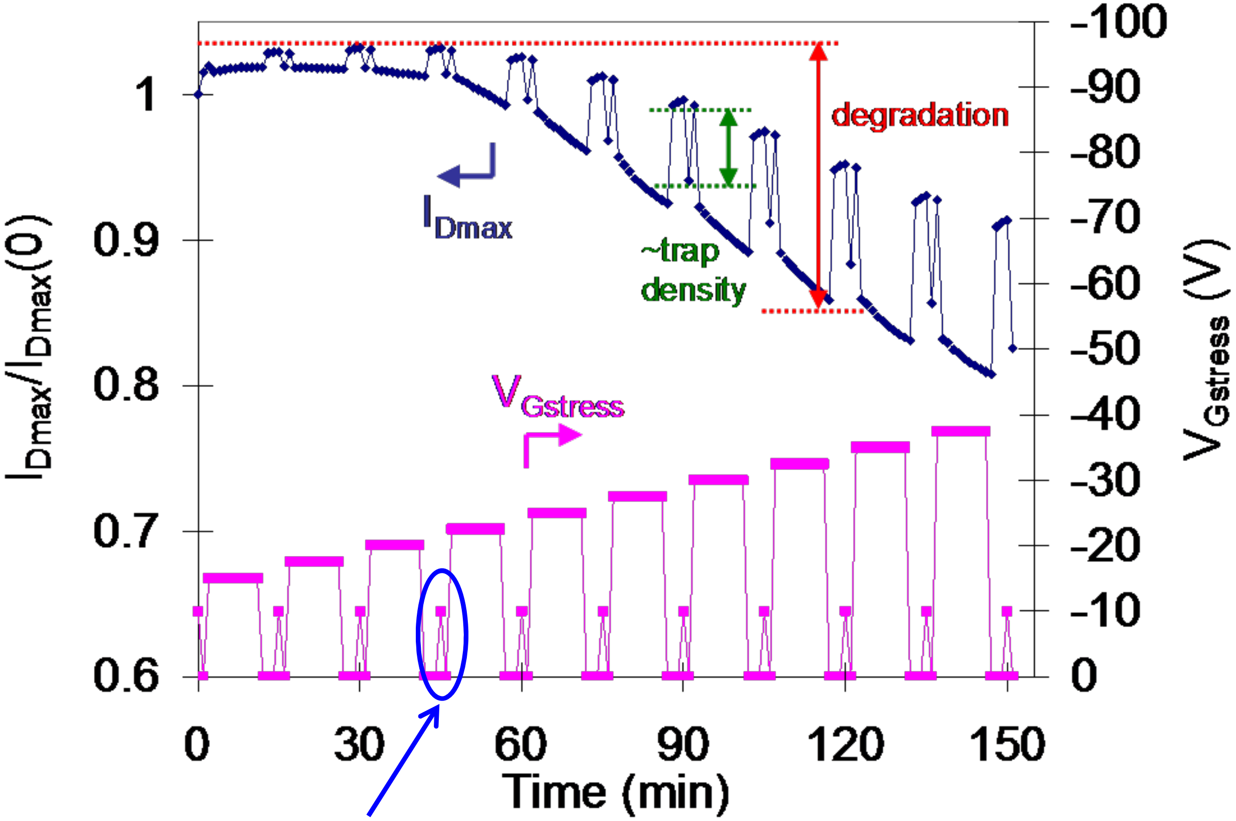
- I_G follows same trapping behavior as I_D

  → common physical origin for I_G and I_D degradation
- In recovery phase: I_{Dmax}↑, I_{Goff}↑ → trapped electrons block I_G
- I_{Gon} steady → traps not accessible from channel?

Are traps also generated at V_{crit}?

- V_{DS}=0 step-stress-recovery experiment with *diagnostic pulse*
  - *10 min step, 5 min recovery, 2.5 V/step*
- Under light to speed up recovery

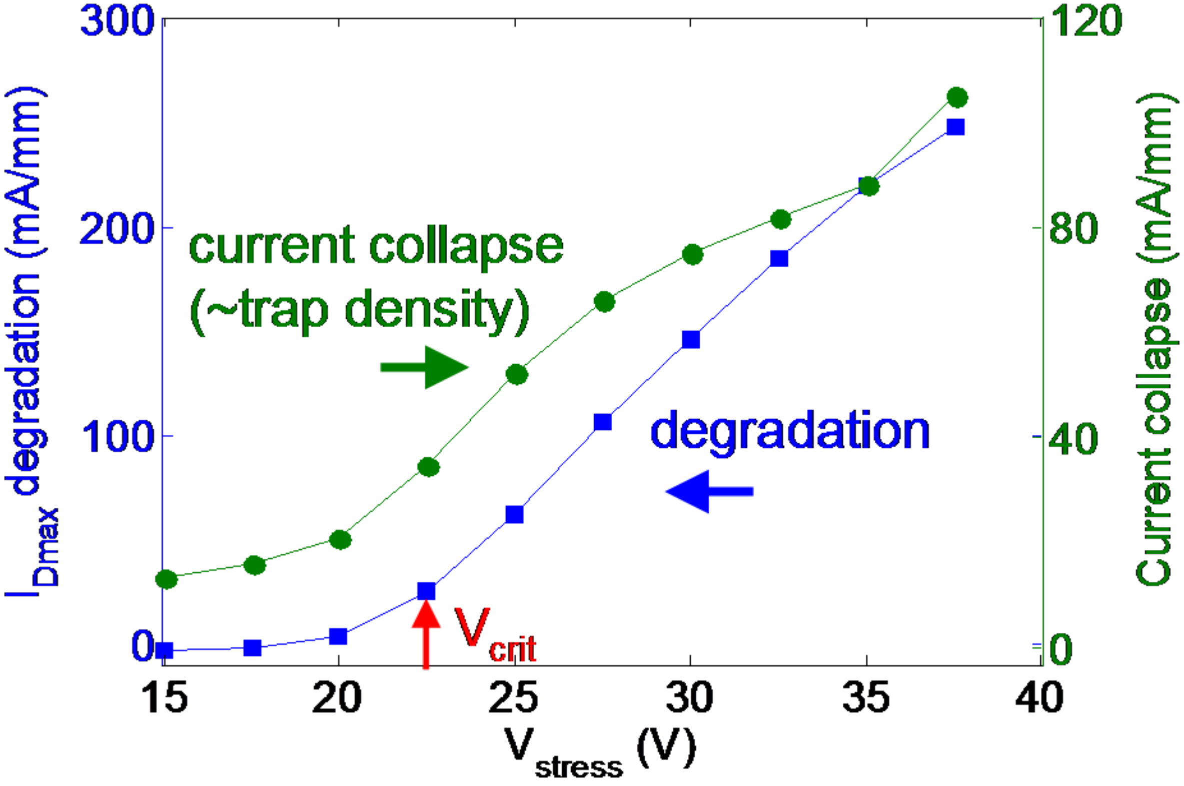




Joh, IEDM 2006

10 V diagnostic pulse

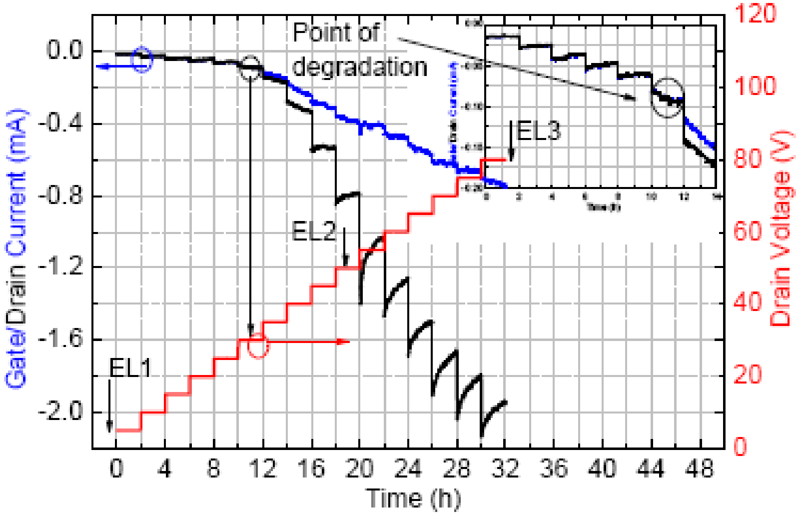
Trap density vs. damage in GaN HEMT



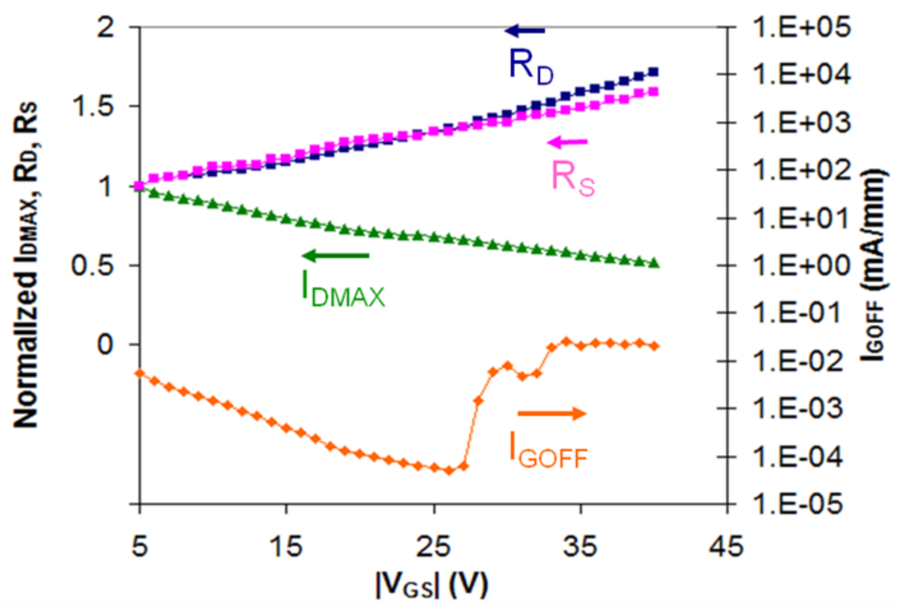
Joh, IEDM 2006

V_{crit}: onset of I_G, I_D, R_S, R_D degradation *and* trap formation

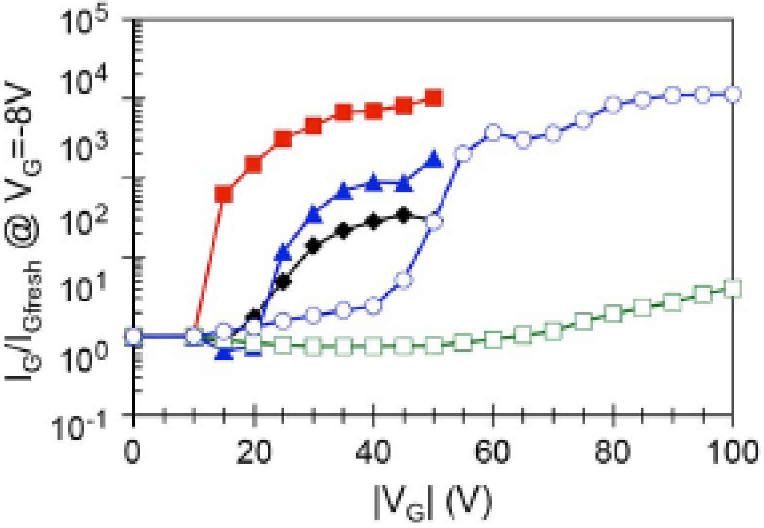
Other Reports of Critical Voltage Behavior



V_{crit}=30-60 V; Ivo, IRPS 2009



GaN HEMT on Si, V_{crit}=10-75 V
Demirtas, ROCS 2009

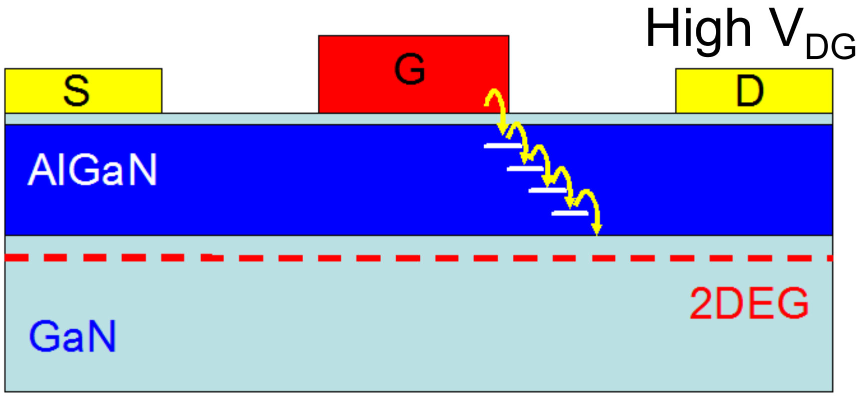


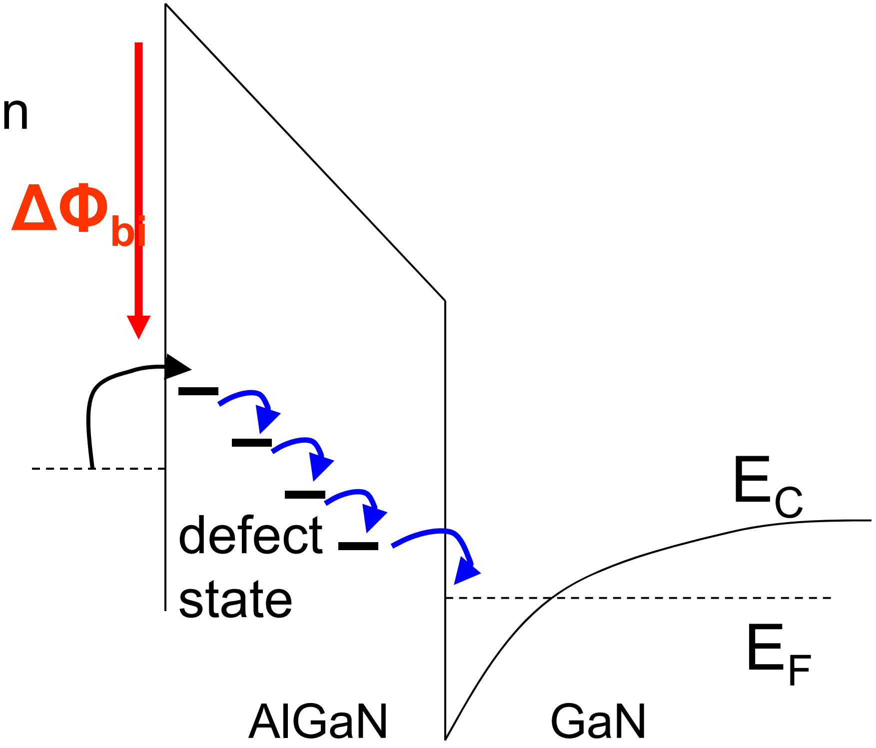
V_{crit}=10-80 V; Zanoni, EDL 2009

4. Hypothesis for high-voltage degradation mechanism

1. Defects in AlGaN

- provide path for reverse I_G ($I_{Goff}\uparrow$)
- electron trapping → $n_s\downarrow$ → $I_{Dmax}\downarrow$, $R_D\uparrow$
- transient effects
- additional non-transient degradation

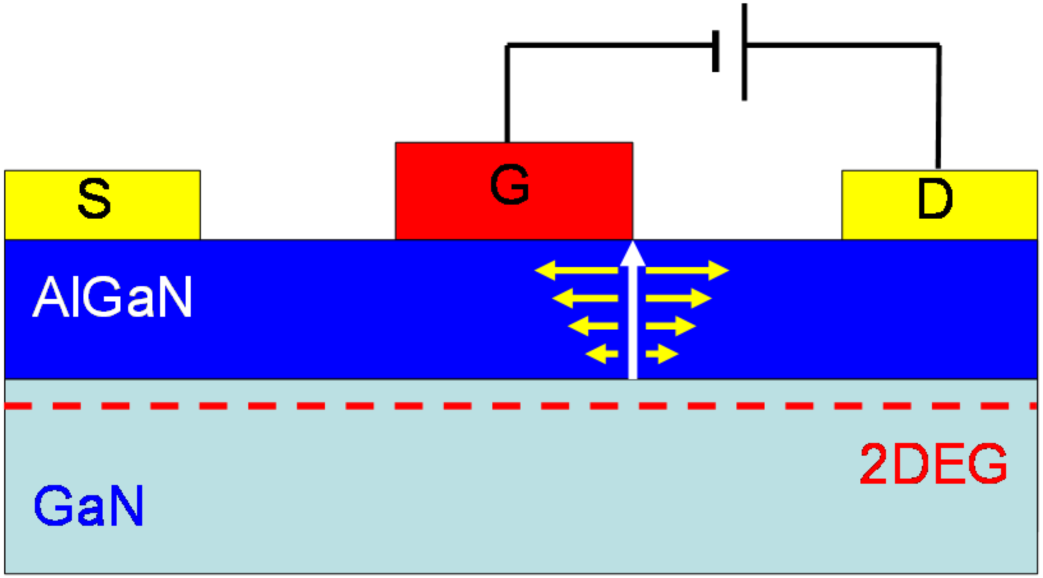




Hypothesis for high-voltage degradation mechanism

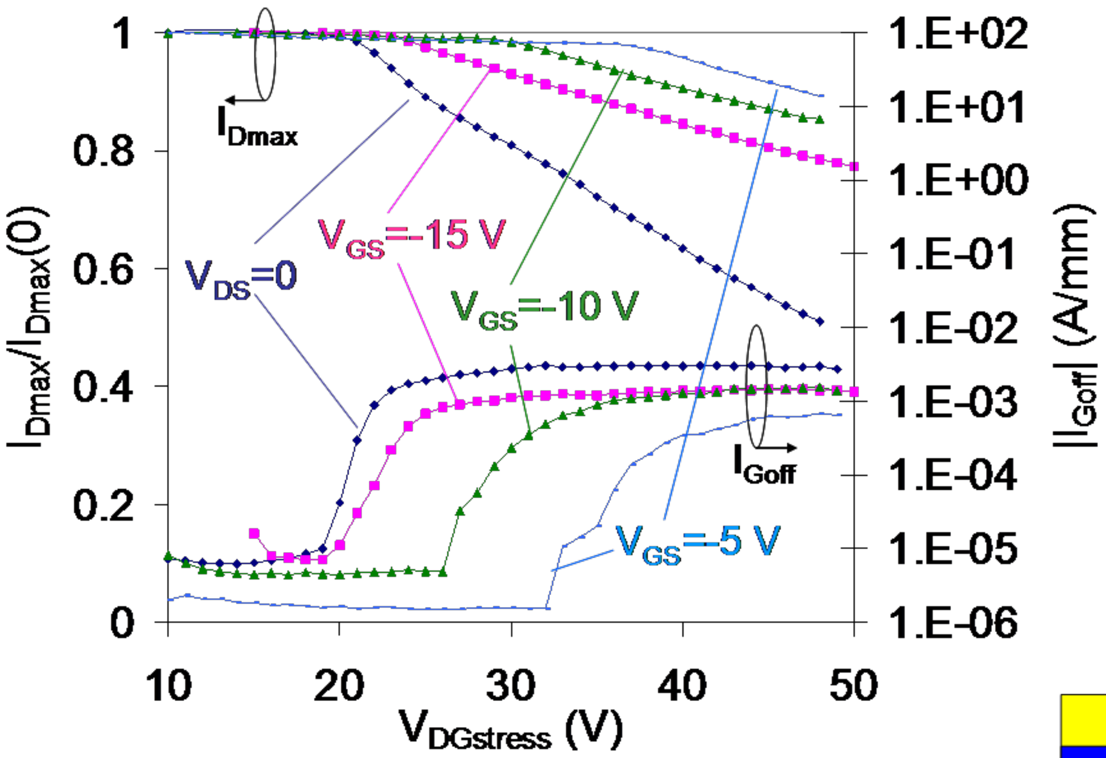
2. Defects originate from excessive mechanical stress

- introduced by high electric field through inverse piezoelectric effect
- concentrated at gate edge
- builds on top of lattice mismatch stress between AlGaN and GaN
- when elastic energy density in AlGaN exceeds critical value



Role of V_{GS}

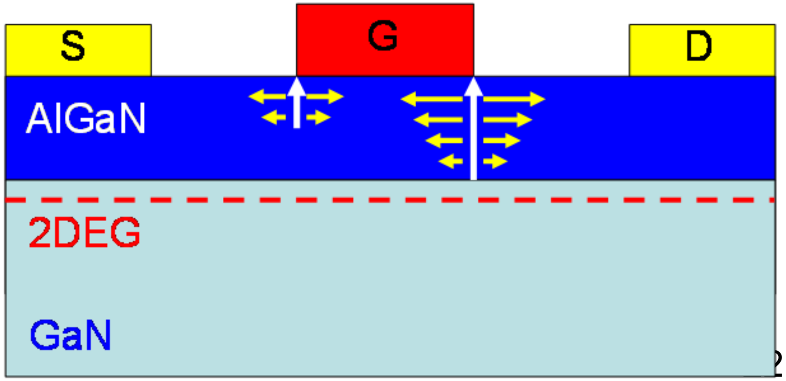
OFF-state step-stress experiments at different V_{GS}:



Joh, IEDM 2007

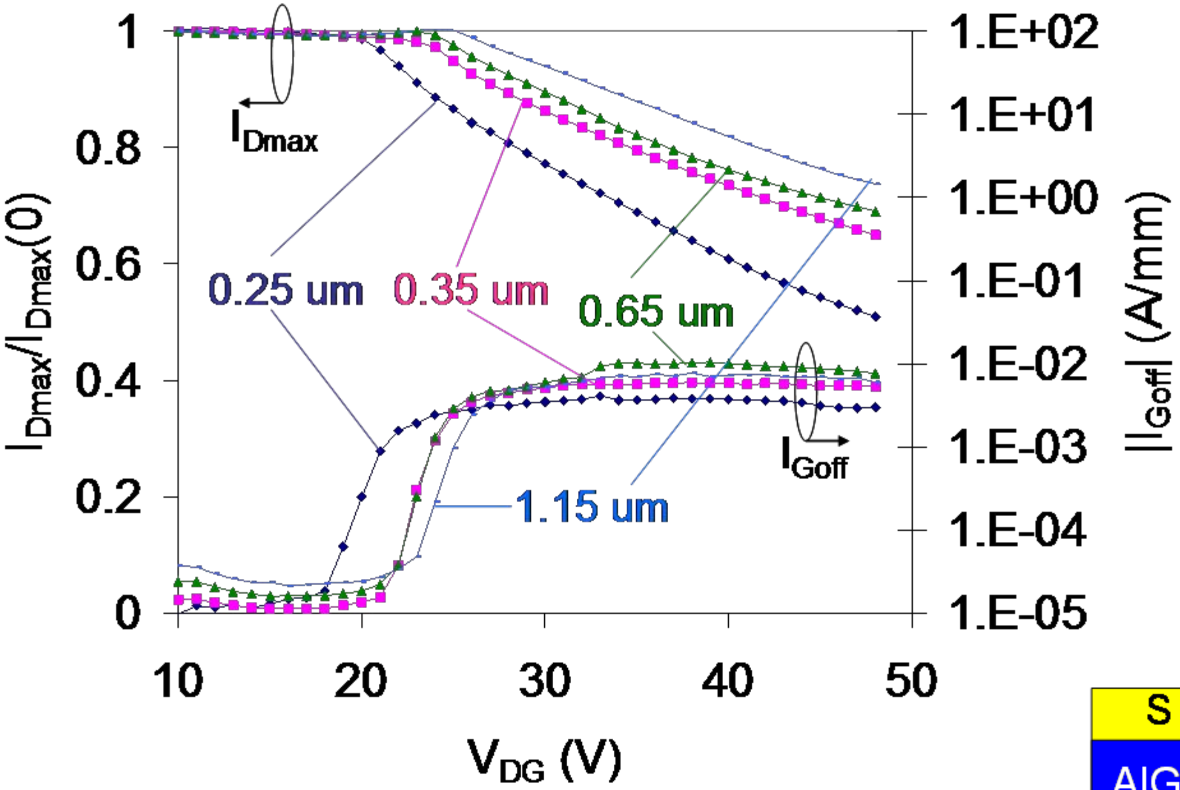
High-field on source side adds to stress on drain side

$|V_{GS}| \downarrow \rightarrow V_{crit} \uparrow$



Role of Gate Length

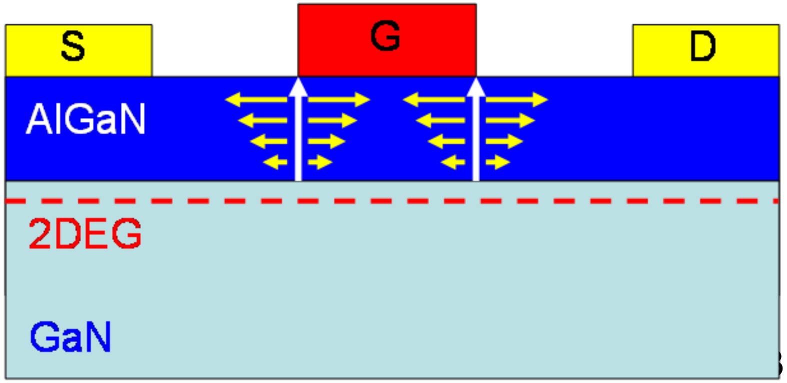
V_{DS}=0 step-stress experiments for different L_G



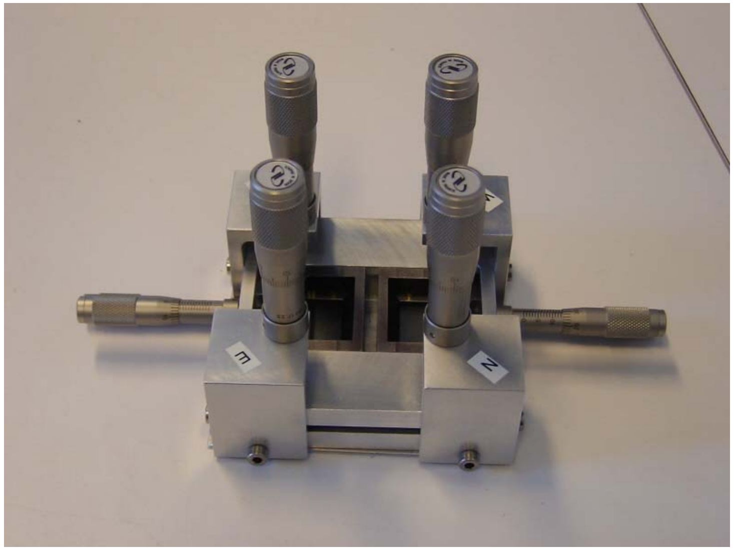
L_G↑ → V_{crit}↑

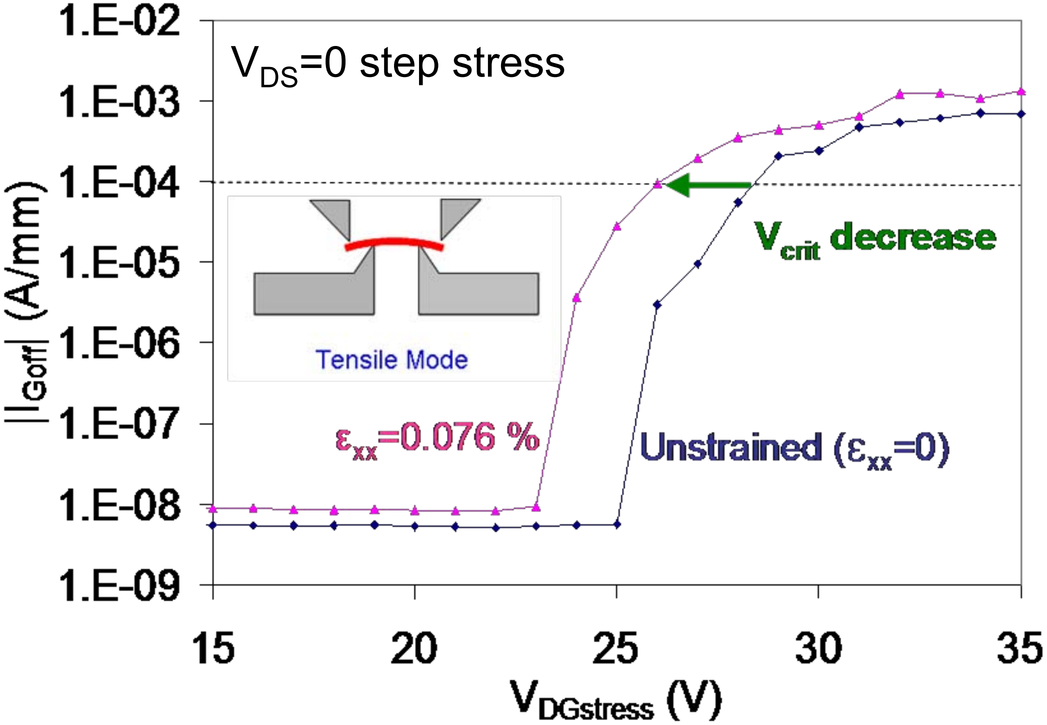
Joh, IEDM 2007

L_g↑ → less cumulative stress at edges



Role of Mechanical Strain





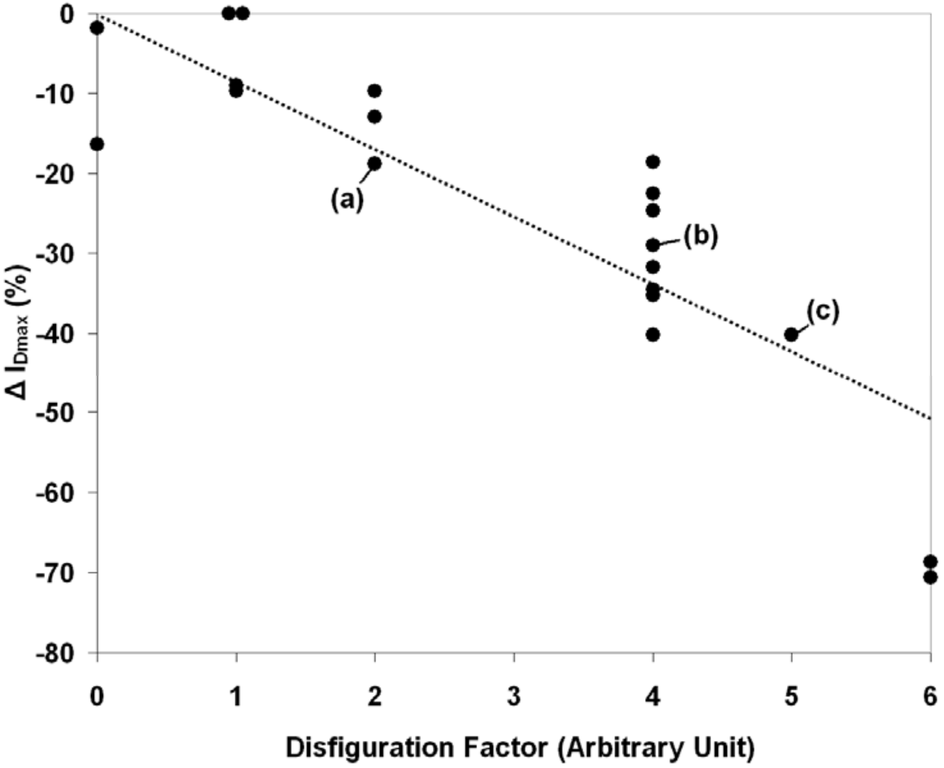
Joh, IEDM 2007

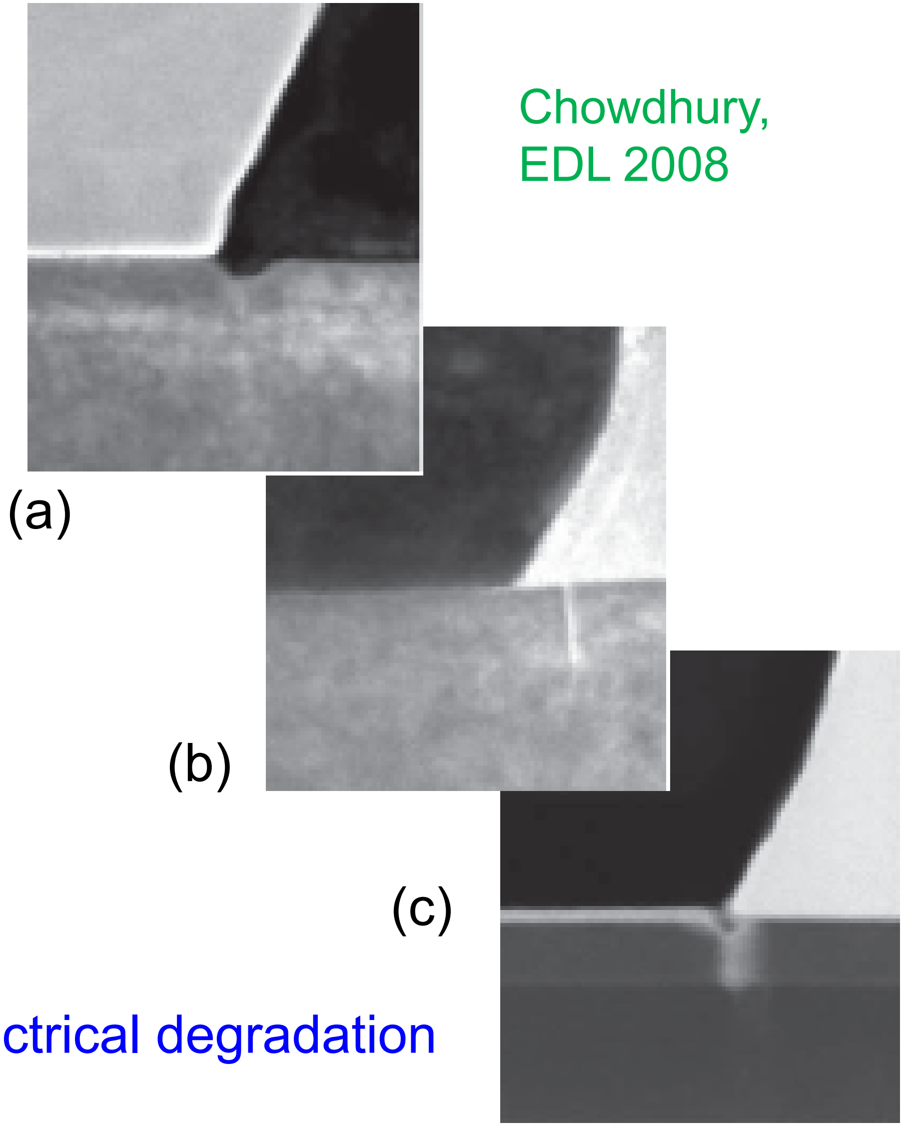
External tensile strain ↑ → V_{crit} ↓

→ reveals mechanical origin of degradation

Crack and pits in stressed GaN HEMTs

ON-state degradation at 40 V, I_D=250 mA/mm, T_a=112 C

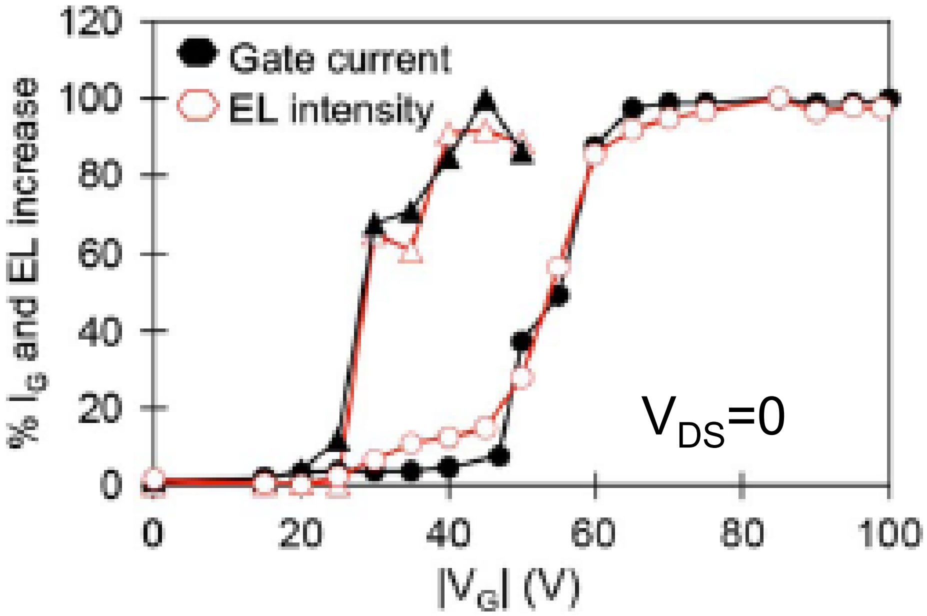




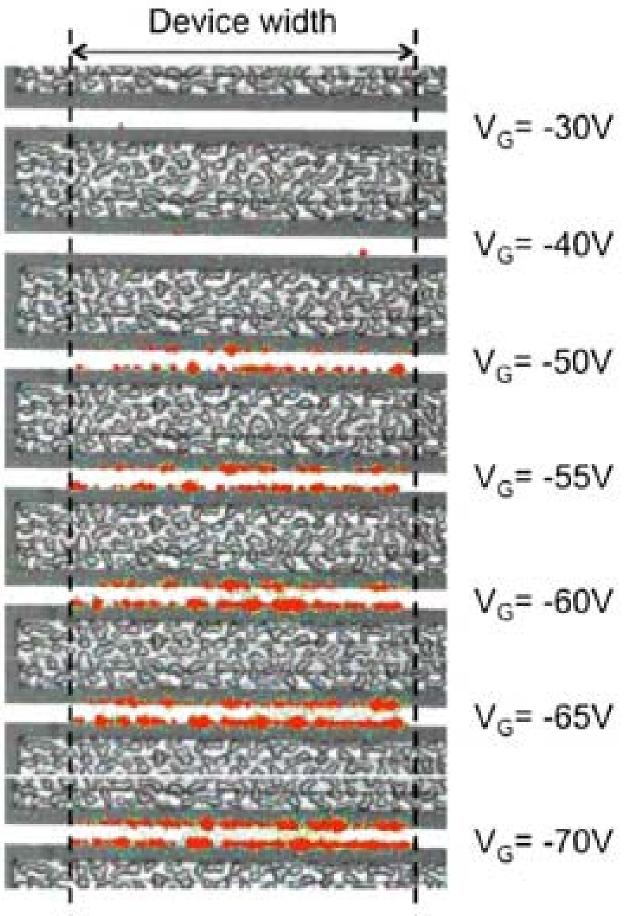
Chowdhury, EDL 2008

Physical degradation correlates with electrical degradation

Other observations of damage at edges of gate



Zanoni, EDL 2009

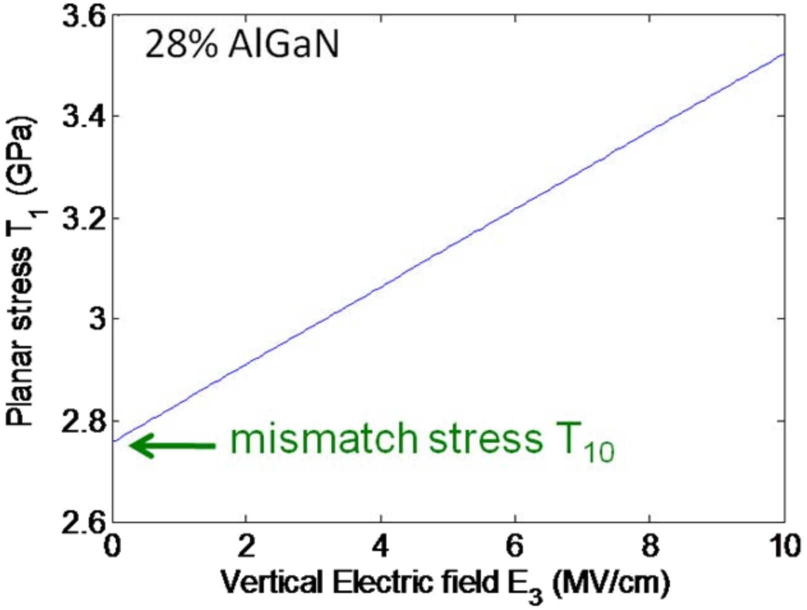


Gate current degradation correlates with elecroluminescence from gate edges

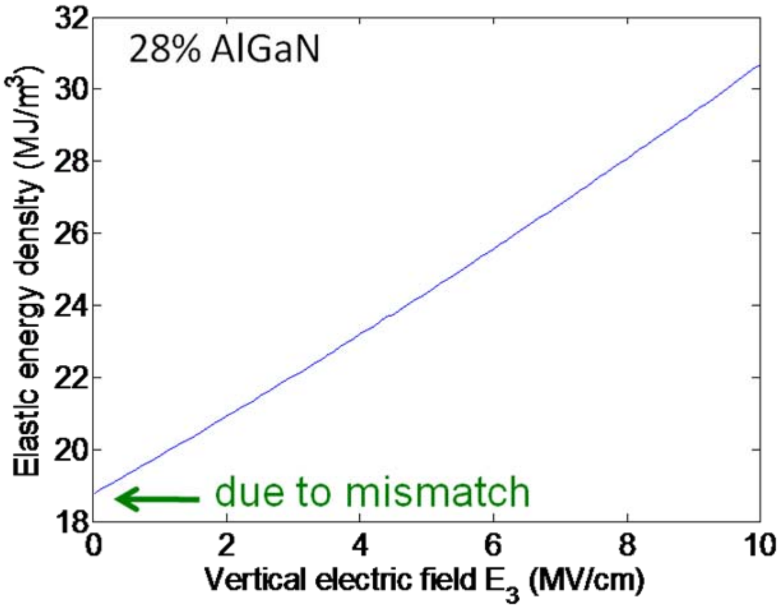
5. First-order model for V_{crit}

- Key assumption: at V_{crit}, elastic energy density in AlGaN reaches critical value
  - Electrical model: 2D electrostatic simulator (Silvaco Atlas)
  - Mechanical model: analytical formulation of stress and elastic energy vs. electric field

Joh, ROCS 2009



Planar stress linear on vertical electric field

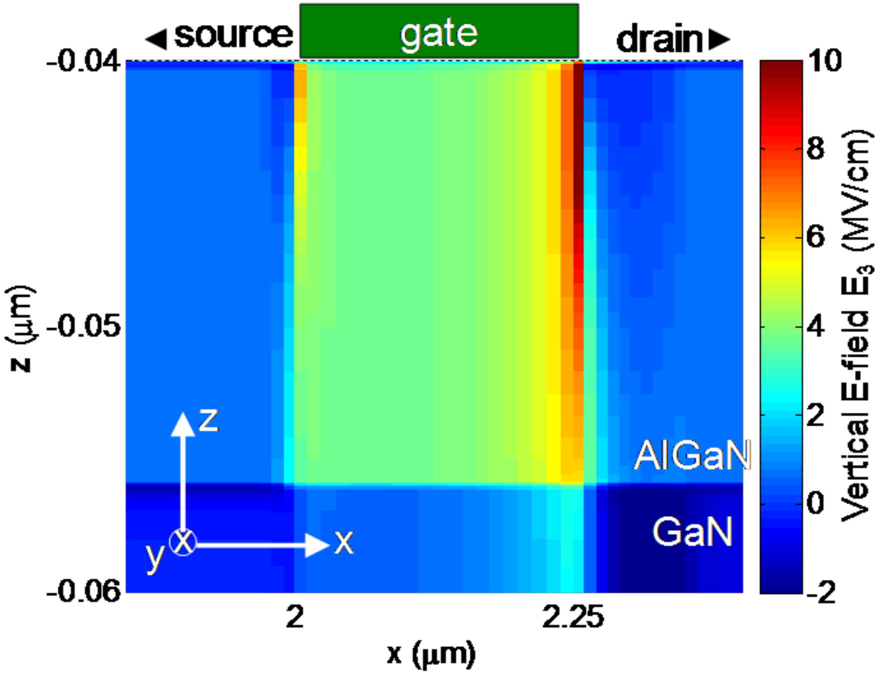


Elastic energy density superlinear on vertical electric field

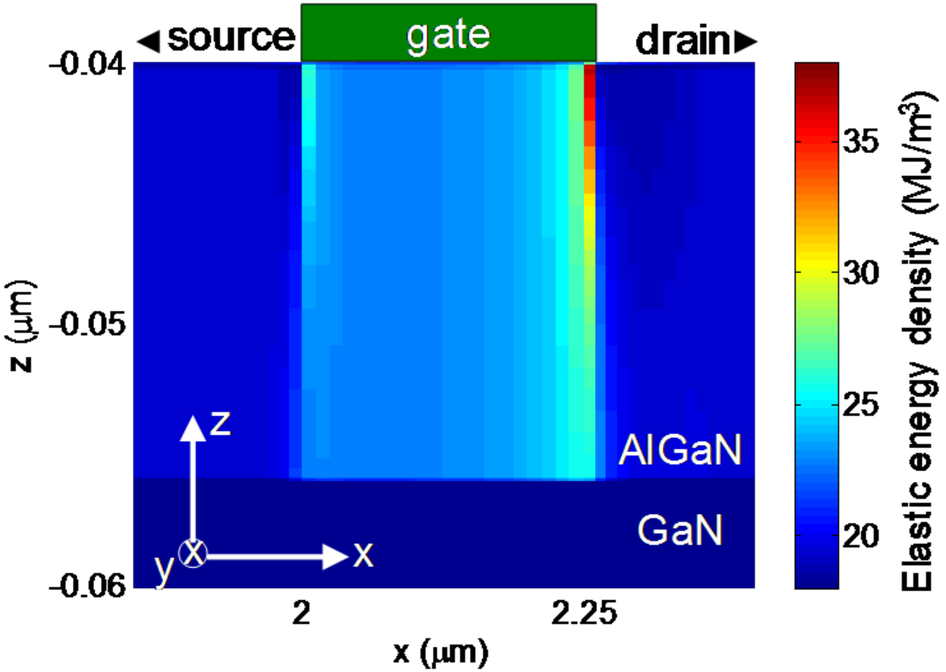
First-order model for V_{crit}

- Example: 16 nm thick AlGaN with x=28%
- V_{crit} condition in OFF-state (V_{GS}=-5 V, V_{DS}=33 V)

Vertical electric field



Elastic energy density

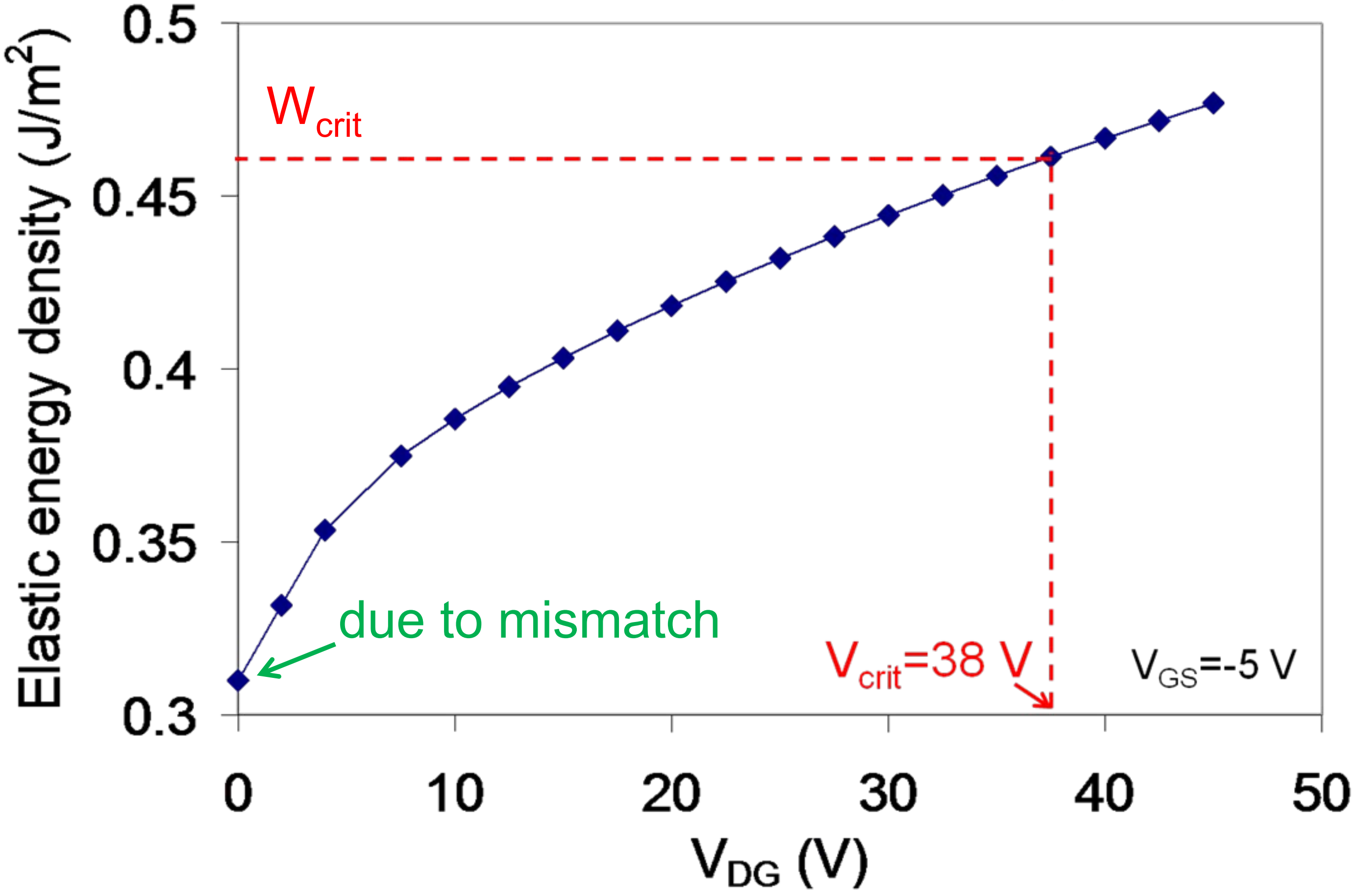


Large peak of electric field and elastic energy density under gate edge on drain side

Joh, ROCS 2009

Elastic energy density in AlGaN vs. V_{DG}

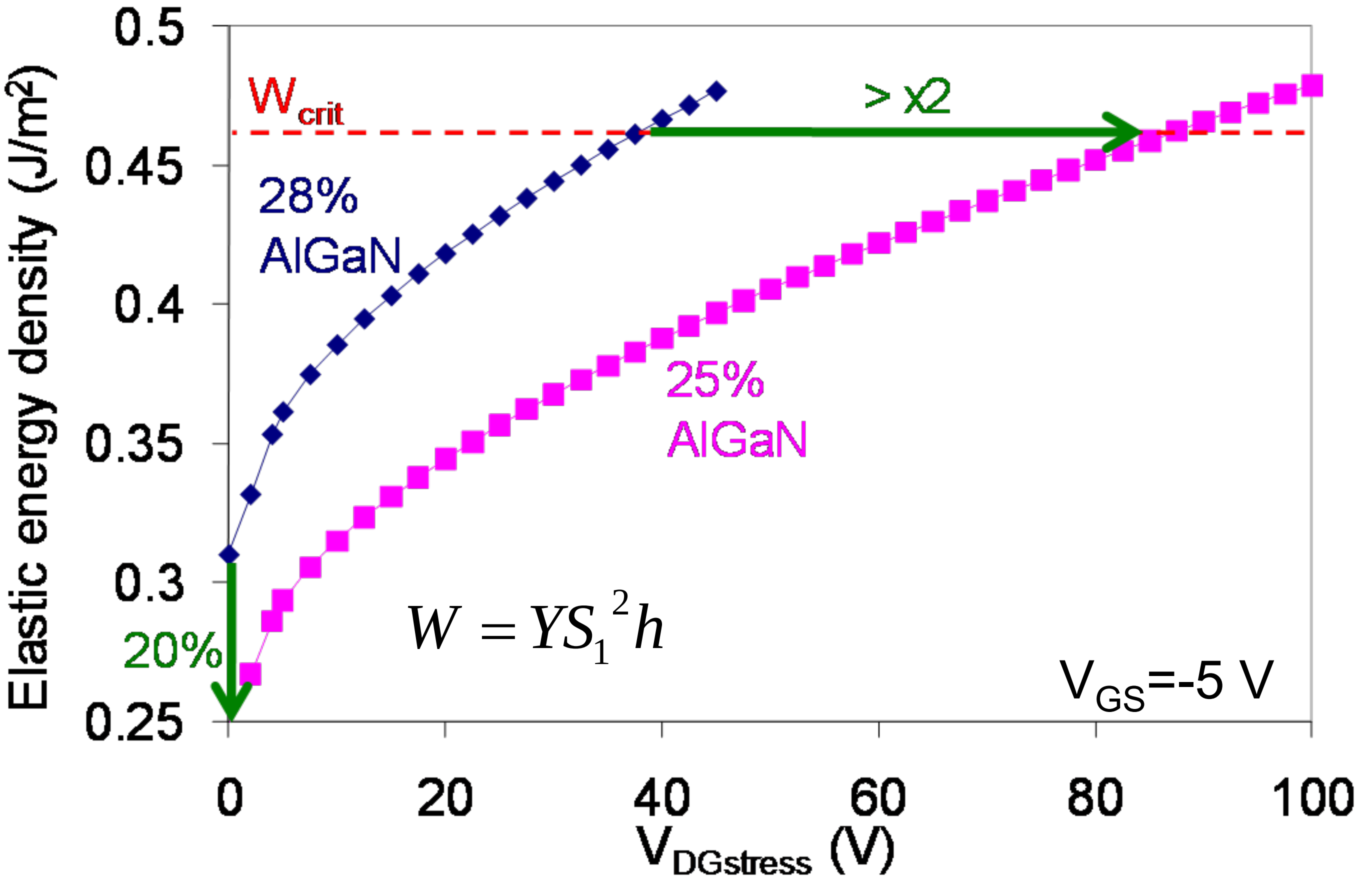
Joh, ROCS 2009



W_{crit} corresponding to V_{crit} consistent with value for onset of relaxation of AlGaN/GaN heterostructures

Impact of AlGaN composition on V_{crit}

Joh, ROCS 2009



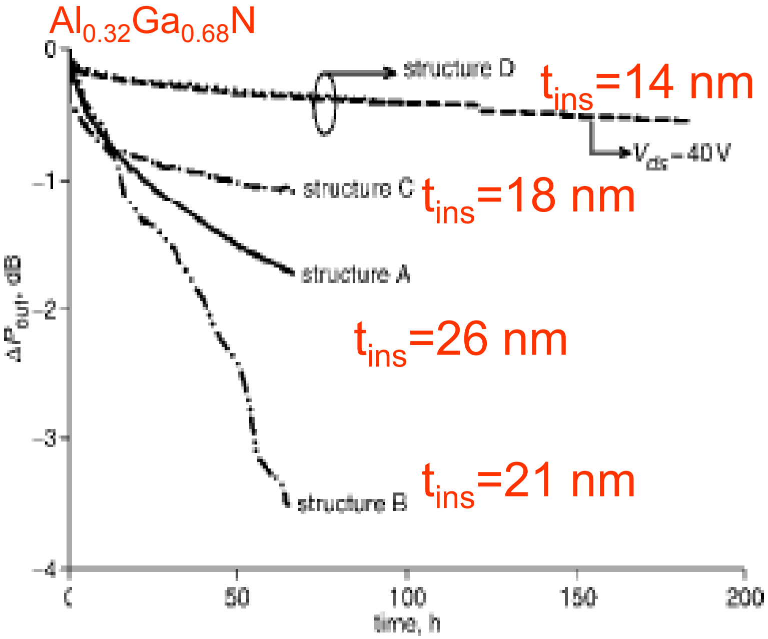
$$W = YS_1^{\ 2}h$$

x(AlN) ↓ → initial elastic energy ↓ → V_{crit} ↑↑

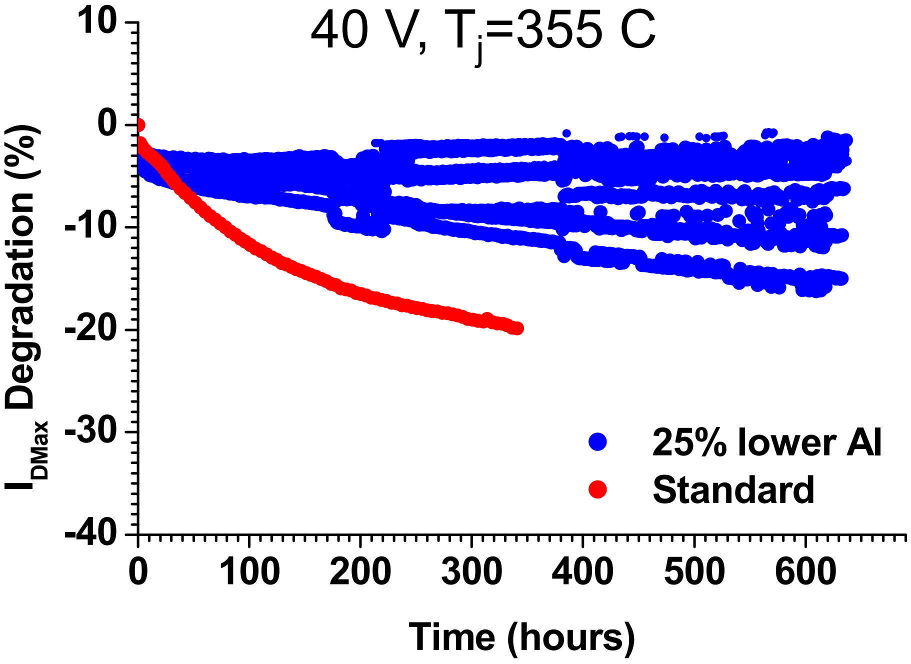
Consequences:
HEMT reliability improved if…

1. Elastic energy density in AlGaN barrier is minimized:

- Thinner AlGaN barrier [Lee 2005]
- AlGaN with lower AlN composition [Gotthold 2004, Valizadeh 2005, Jimenez 2009]



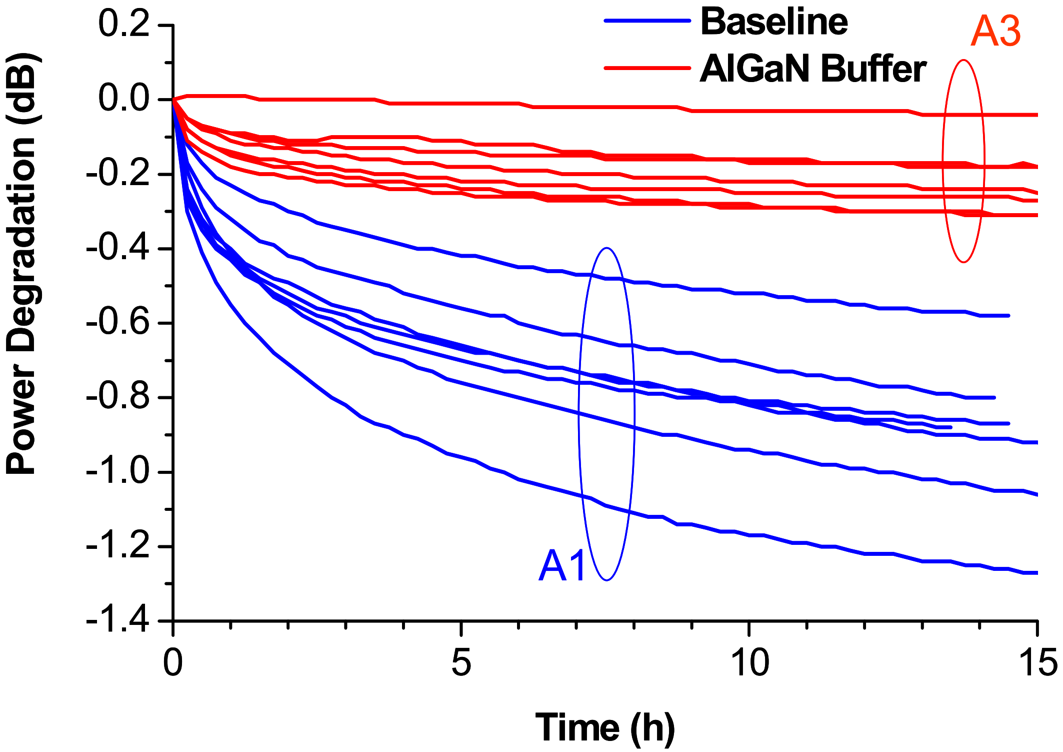
Lee, TED 2005



Jimenez, TWHM 2009

1. Elastic energy density in AlGaN barrier is minimized (cont.):

- AlGaN buffer layer [Joh 2006]
- No AlN spacer [ref?]

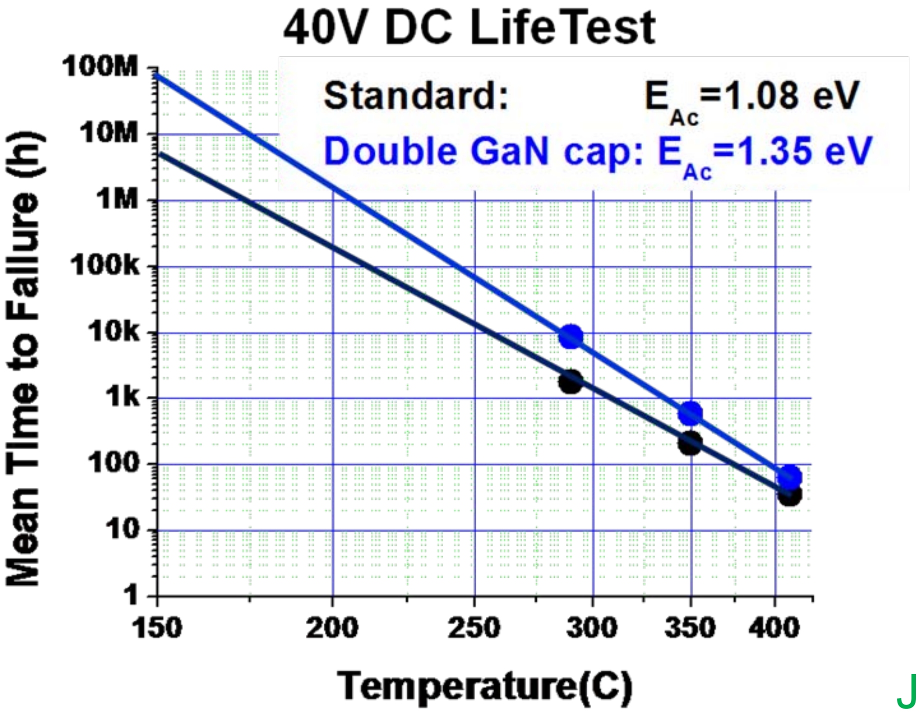


Joh, IEDM 2006

Consequences:
HEMT reliability improved if…

2. AlGaN barrier is mechanically strengthened:

- GaN cap [Gotthold 2004, Ivo 2009, Jimenez 2009]
- SiN passivation [Mittereder 2003, Edwards 2005, Derluyn 2005, Marcon 2009]

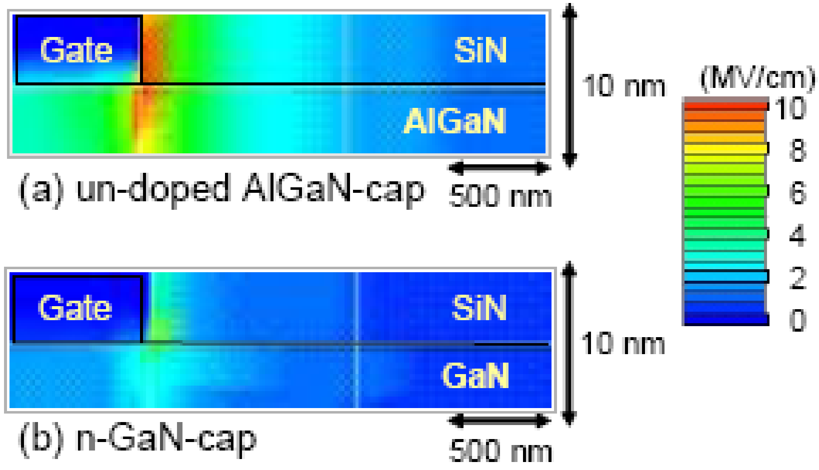


Jimenez, TWHM 2009

Consequences:
HEMT reliability improved if…

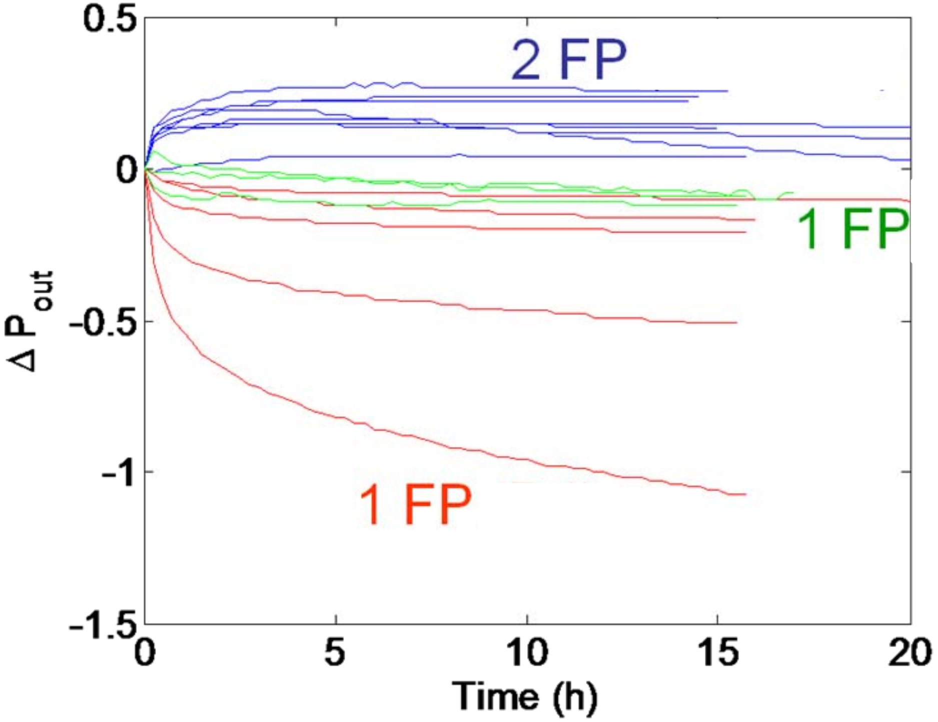
3. Electric field across AlGaN at gate edge is minimized:

- Field plate [Lee 2003, Jimenez 2006]
- Longer gate-drain gap [Valizadeh 2005]
- Add GaN cap [Ivo 2009, Ohki 2009]
- Rounded gate edge [ref?]



Ohki, IRPS 2009

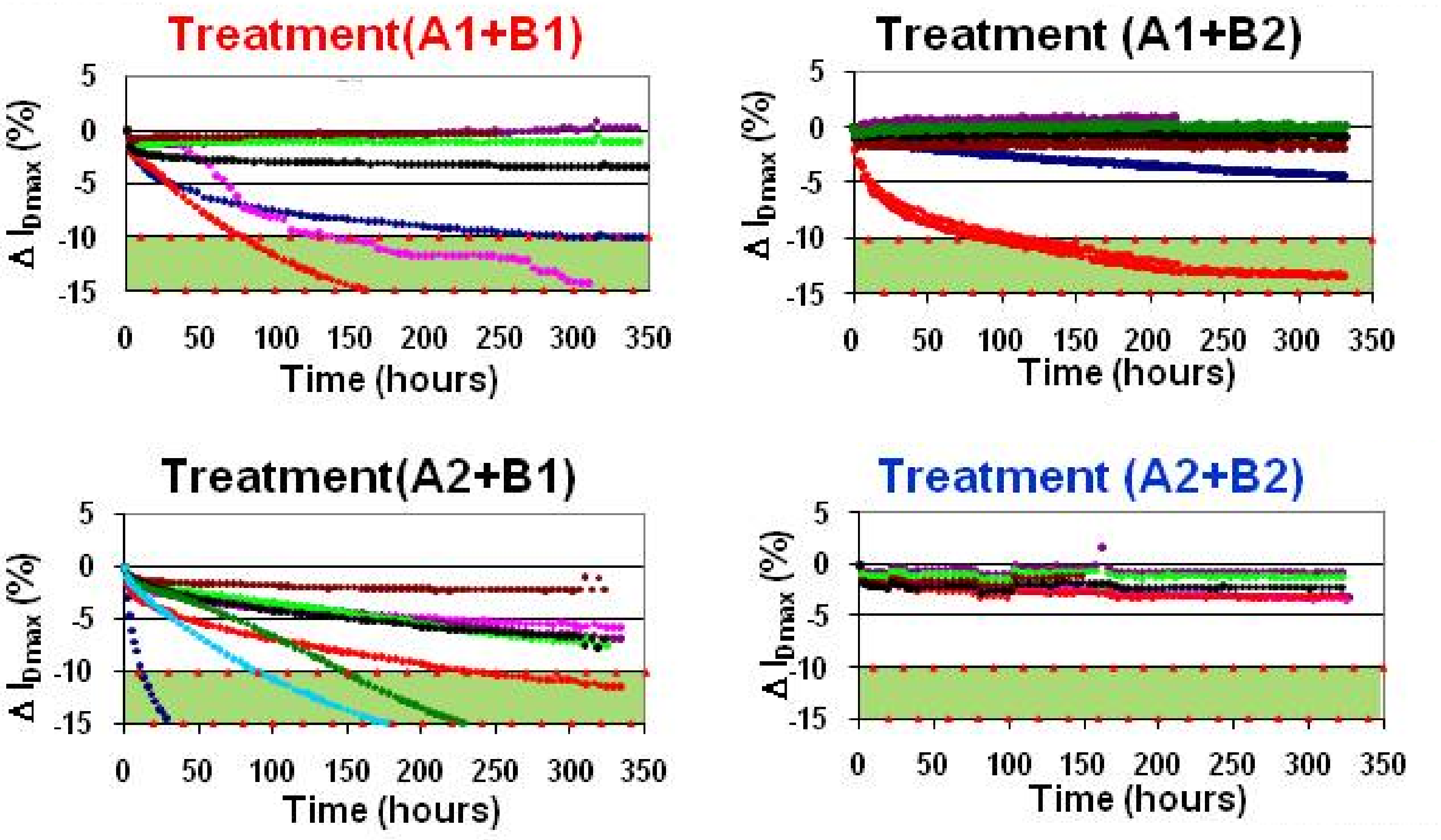
Jimenez, ROCS 2006



Many unknowns

- What is the detailed nature of the defects at the gate edge?
  - Crack?
  - Metal diffusion down crack?
  - Aggregation of dislocations?
  - Other crystalline defects
- Role of stress gradient?
- Role of time?
- Role of temperature?
- Hot electron damage in high-power state?
- Are these mechanisms relevant under large RF drive?
- Why spatial variations?
- Role of buffer?
- Role of surface and surface treatments?

The surface matters…



Surface treatments prior to ohmic metal deposition and gate evaporation impact reliability

Jimenez, TWHM 2009

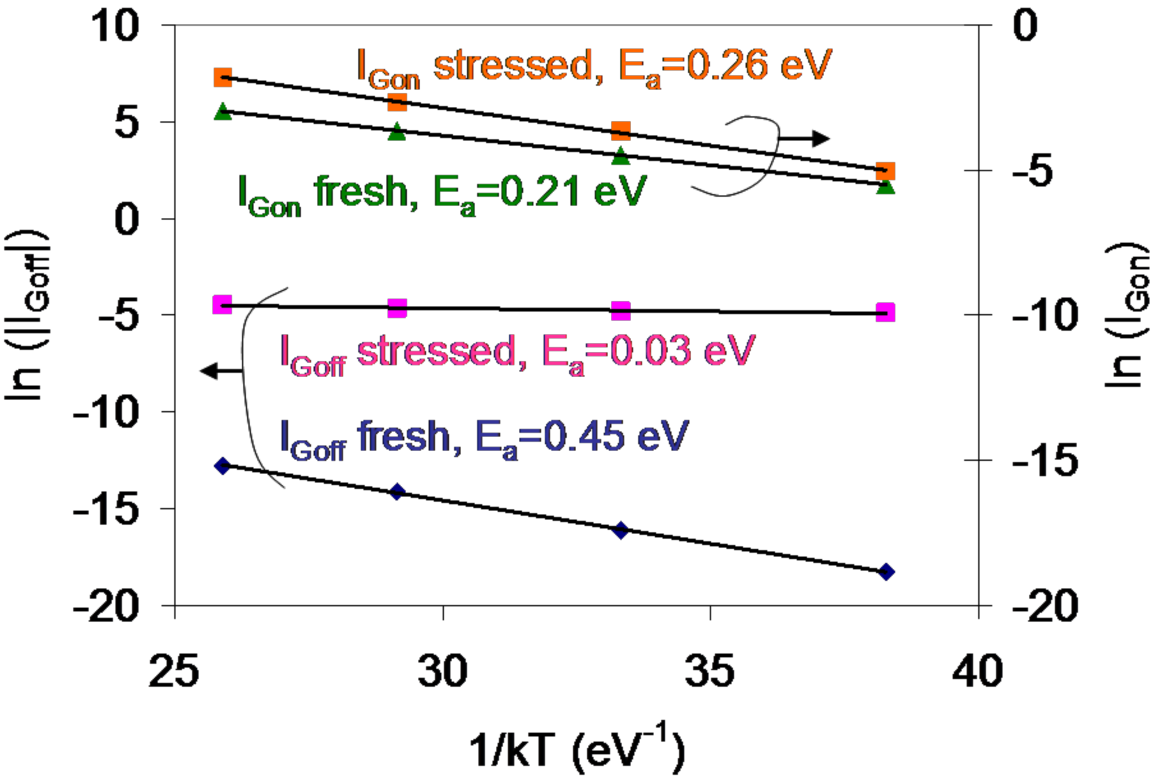
6. Conclusions

- Unique degradation aspects of AlGaN/GaN HEMTs with relevance to degradation
- Need fundamental research to provide understanding
- Many opportunities to improve reliability
- Not obvious today how to accelerate degradation to provide accurate estimation of MTTF
- Optimistic about long-term prospects of reliable GaN HEMTs

More materials

V_{DS}=0 Degradation

V_{DS}=0 step-stress; V_{DG}: 10 to 50 V, 1 V/step, 1 min/step



Joh, IEDM 2007

$E_a(I_{Goff})\downarrow$

$E_a(I_{Gon})$ unchanged