Recent Progress in Understanding the Electrical Reliability of GaN High-Electron Mobility Transistors

J. A. del Alamo

Microsystems Technology Laboratories

Massachusetts Institute of Technology

IEEE Boston Reliability Chapter Meeting

MIT Lincoln Laboratory, Feb. 17, 2015

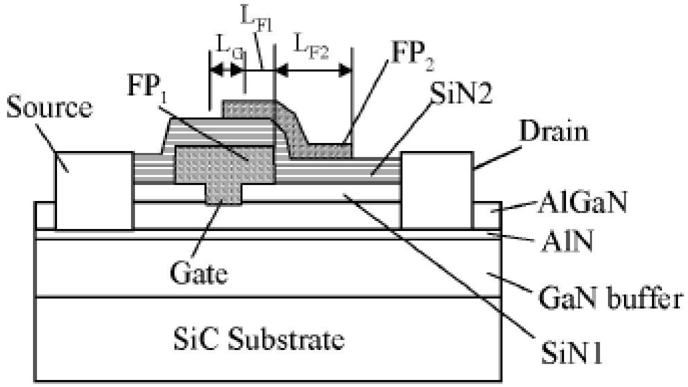
Acknowledgements:

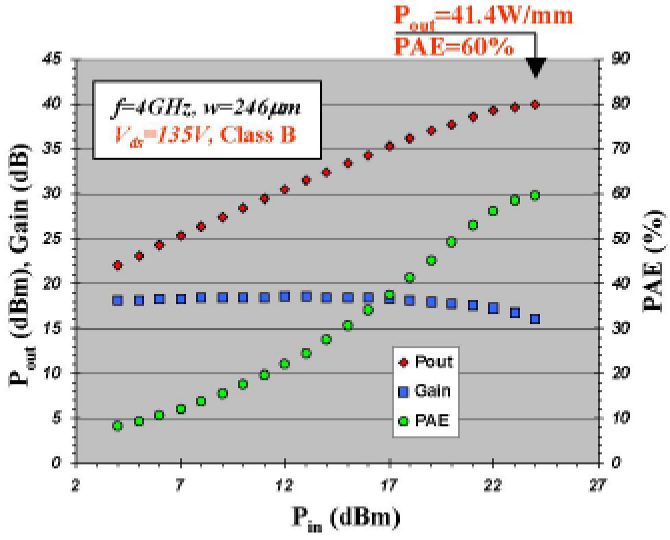
F. Gao, J. Jimenez, D. Jin, J. Joh, T. Palacios, C. V. Thompson, Y. Wu
ARL (DARPA-WBGS program), NRO, ONR (DRIFT-MURI program),

Outline

1. Motivation
2. Electrical and structural degradation of GaN HEMTs
3. Hypotheses for GaN HEMT degradation mechanisms
4. Paths for mitigation of GaN HEMT degradation

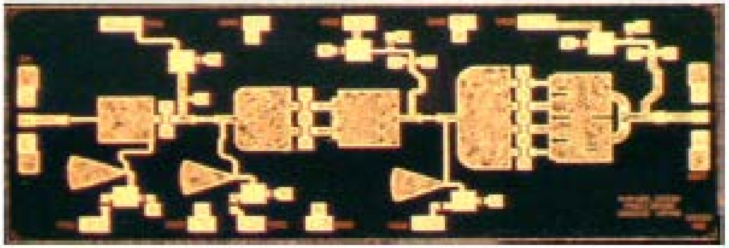
Breakthrough RF-µw-mmw power in GaN HEMTs





P_{out}>40 W/mm, over 10X GaAs!

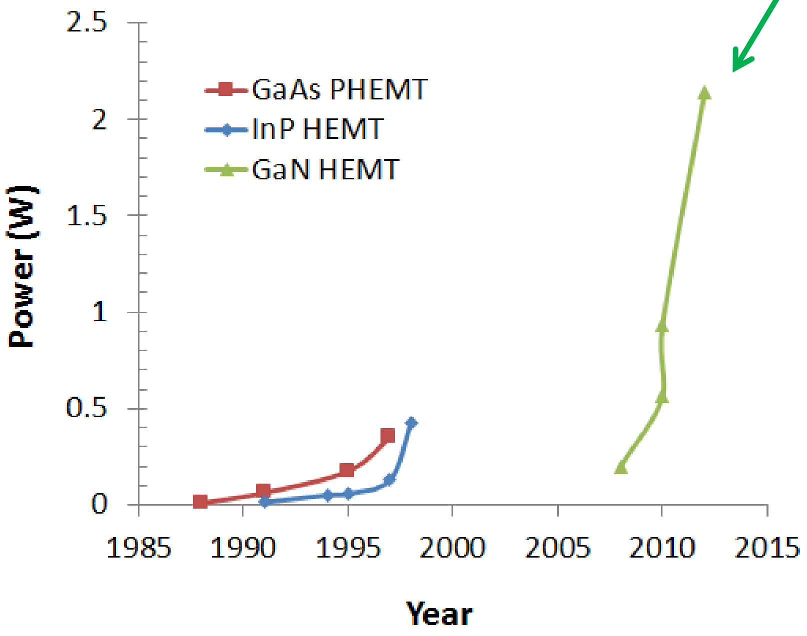
Wu, DRC 2006



Micovic, MTT-S 2010

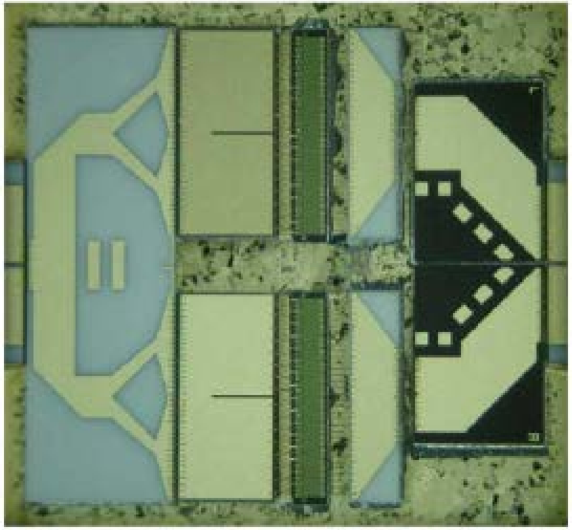
Micovic, MTT-S 2012

94-95 GHz MMIC PAs:



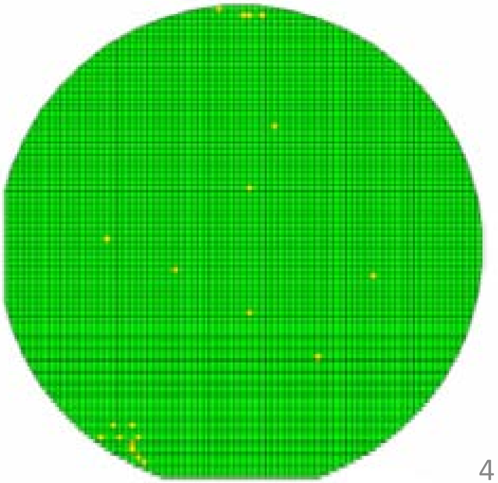
GaN HEMTs in the field

Counter-IED Systems (CREW)



200 W GaN HEMT for cellular base station
Kawano, APMC 2005

100 mm GaN-on-SiC volume manufacturing
Palmour, MTT-S 2010



GaN HEMT: Electrical reliability concerns

ON:

– Mostly benign

High-power:

– Not accessible to DC stress experiments

– Device blows up instantly

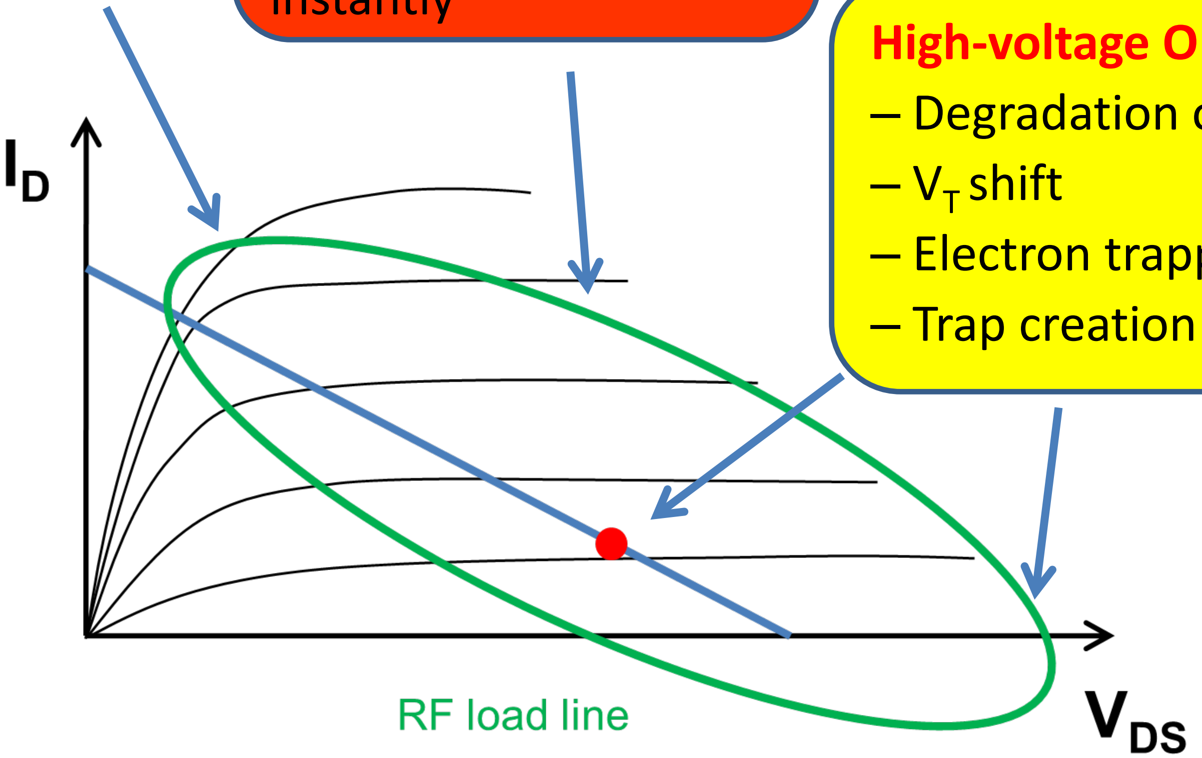
High-voltage OFF and semi-ON:

– Degradation of I_{Dmax}, R_D, I_{Goff}

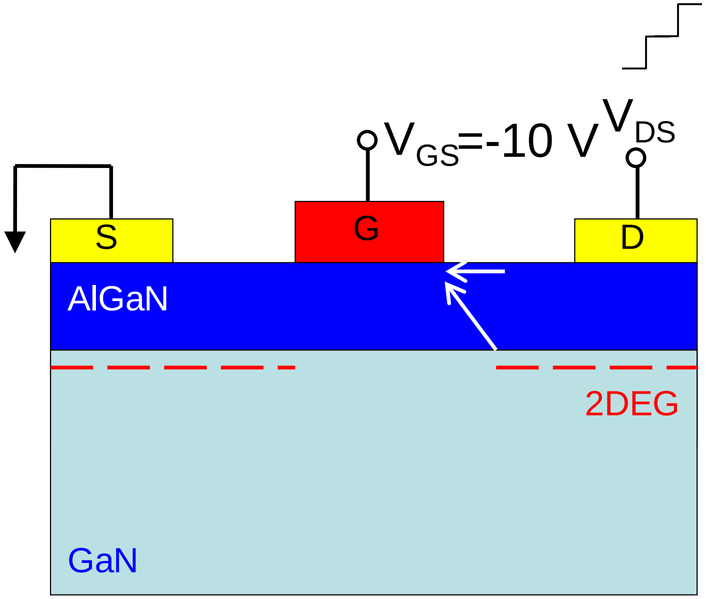
– V_T shift

– Electron trapping

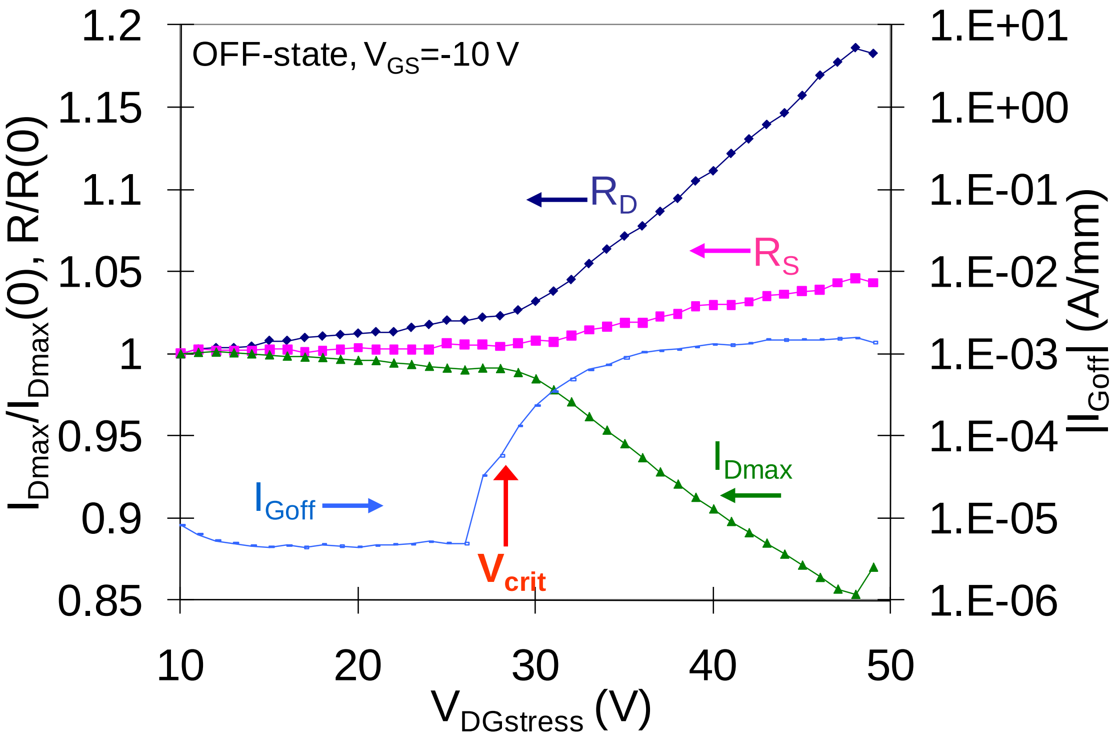
– Trap creation



Critical voltage for degradation in DC step-stress experiments



Joh, EDL 2008

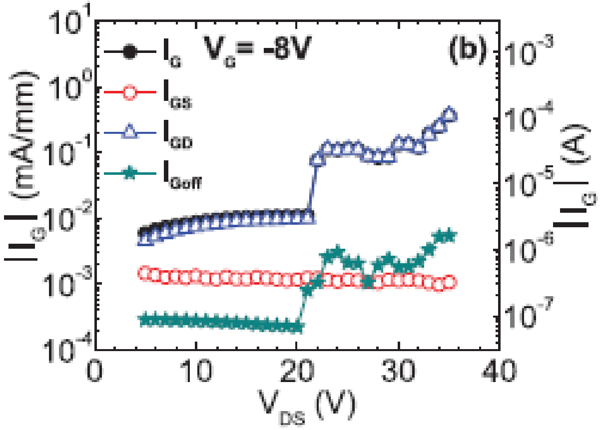


I_{Dmax}: V_{DS}=5 V, V_{GS}=2 V I_{Goff}: V_{DS}=0.1 V, V_{GS}=-5 V

I_D, R_D, and I_G start to degrade beyond *critical voltage* (V_{crit})
+ increased trapping behavior – current collapse

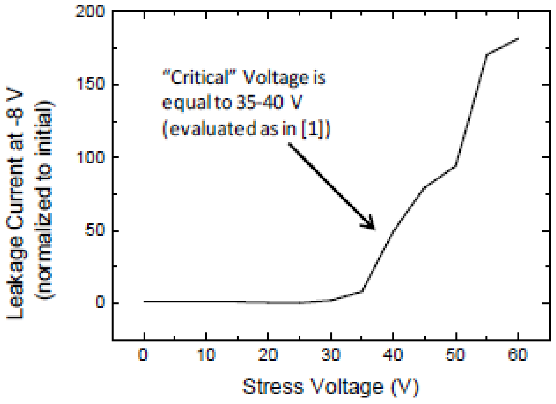
Critical voltage: a universal phenomenon

GaN HEMT on SiC



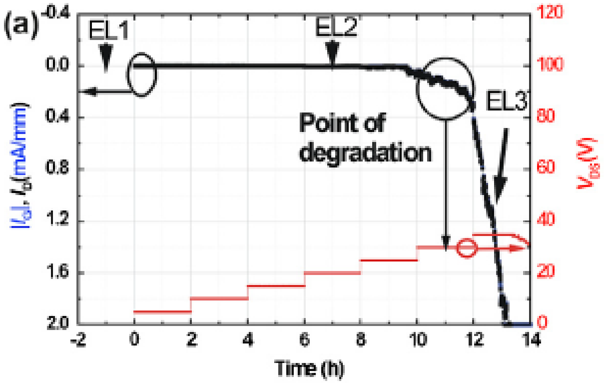
Liu, JVSTB 2011

GaN HEMT on SiC



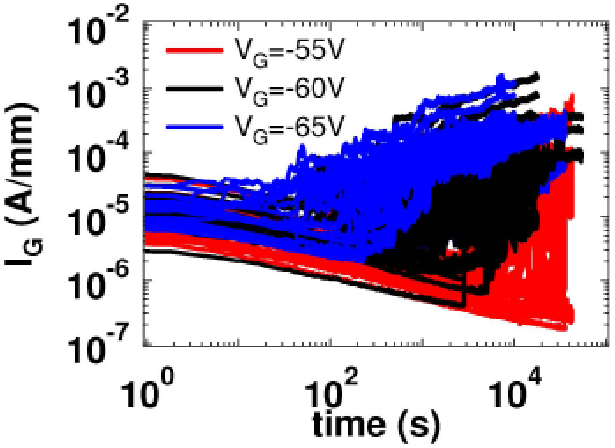
Meneghini, IEDM 2011

GaN HEMT on SiC



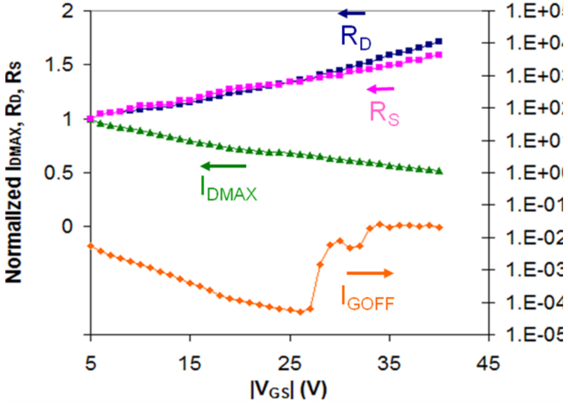
Ivo, MR 2011

GaN HEMT on Si



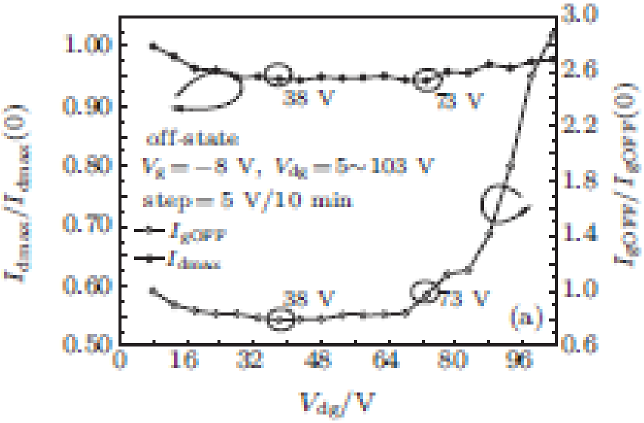
Marcon, IEDM 2010

GaN HEMT on Si



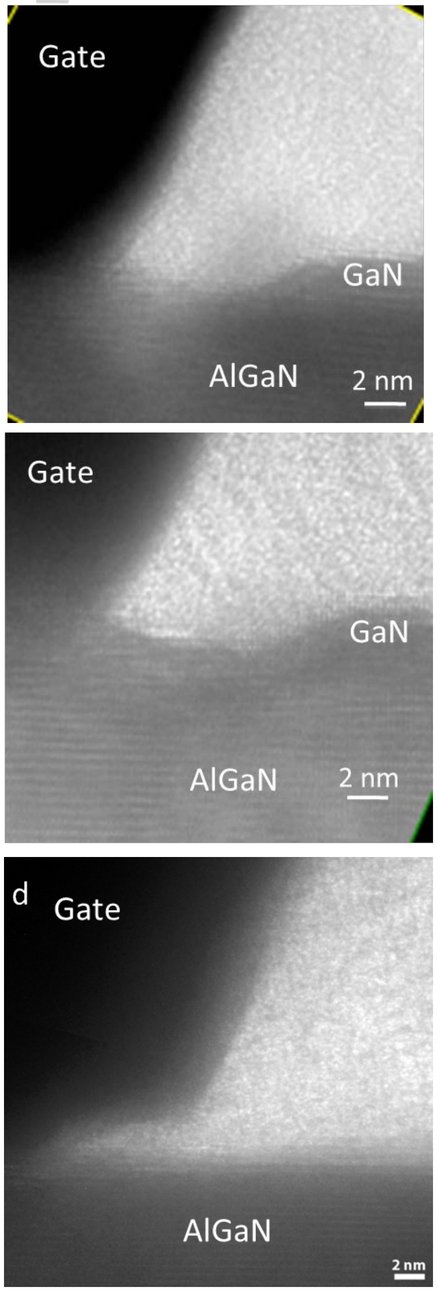
Demirtas, ROCS 2009

GaN HEMT on sapphire

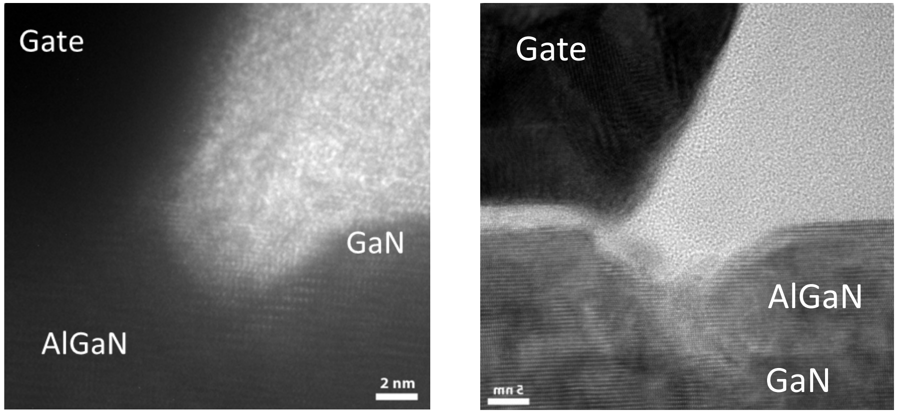


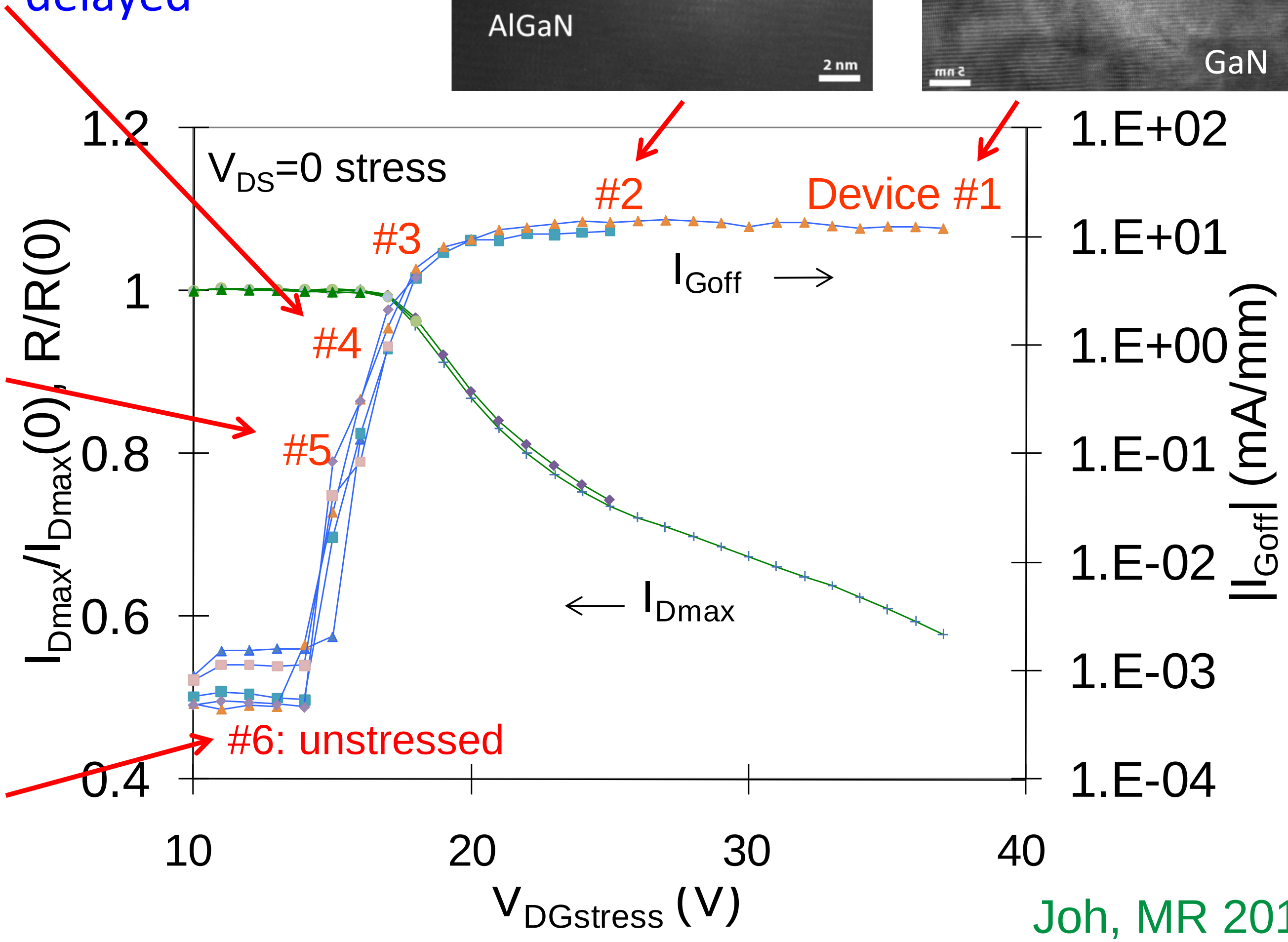
Ma, Chin Phys B 2011

Structural degradation: cross section



- Small dimple in early stages of I_G degradation;
- I_D degradation delayed

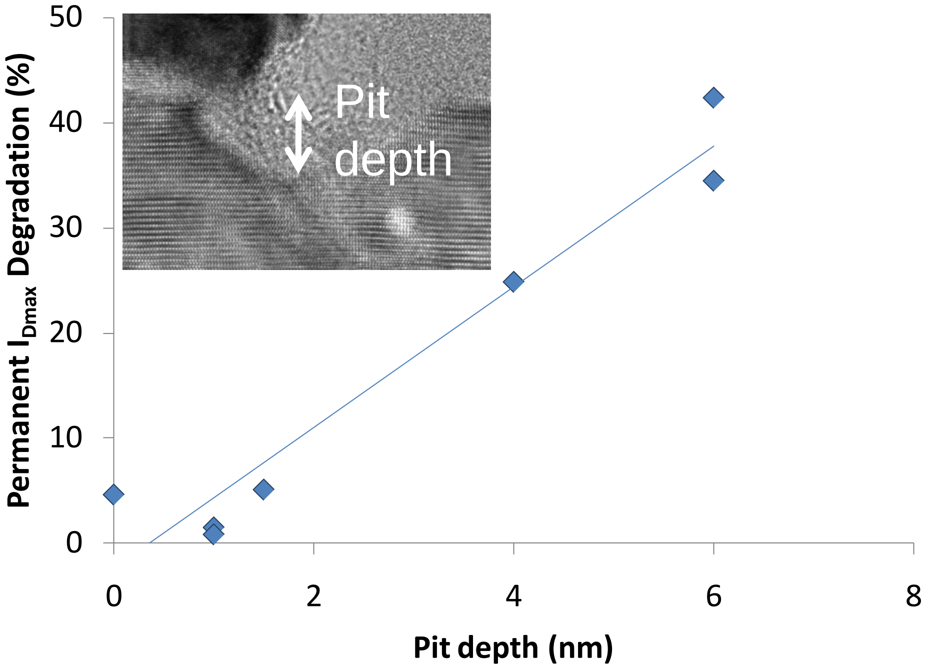


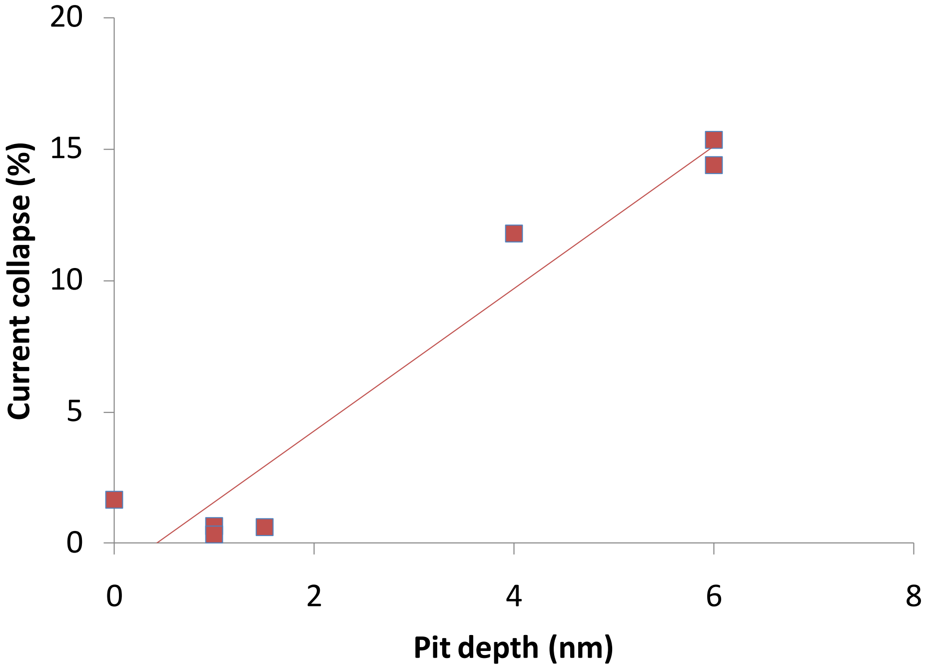


Joh, MR 2010

Correlation between pit geometry and I_{Dmax} degradation

Joh, MR 2010

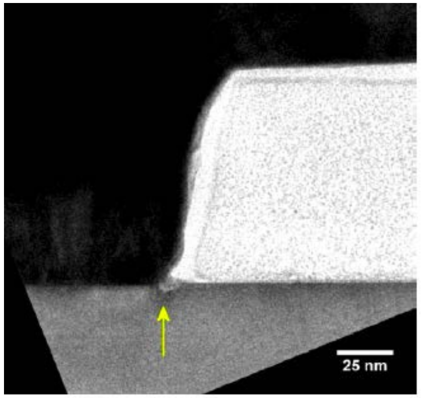




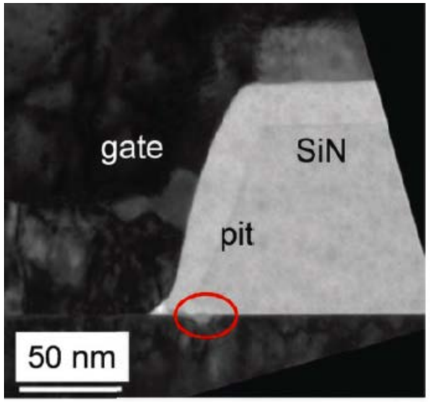
Pit depth and I_{Dmax} degradation correlate:

→ both permanent degradation and current collapse (CC)

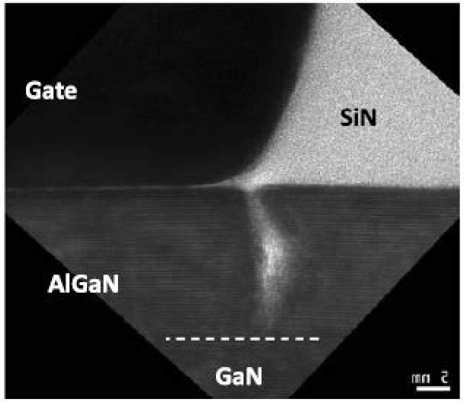
Structural damage at gate edge: a universal phenomenon



Barnes, CS-MANTECH 2012

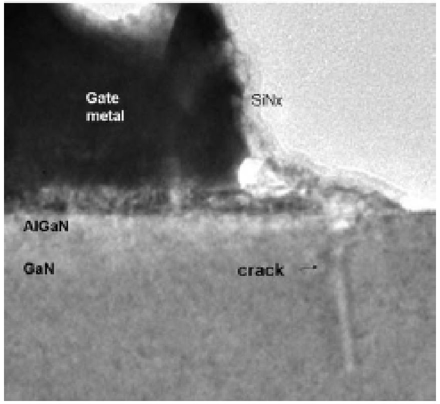


Dammann, IIRW 2011

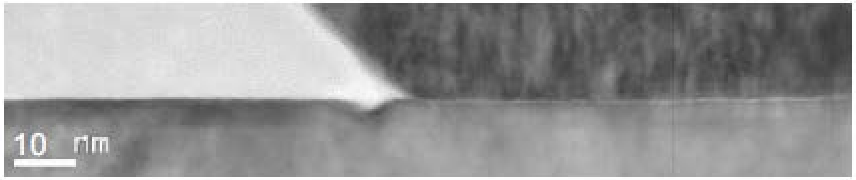


Marcon, MR 2010

Cullen, TDMR 2013

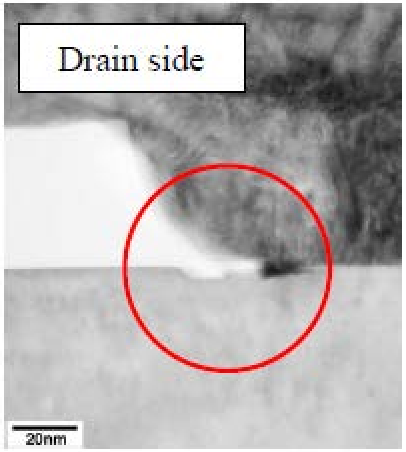


Chang, TDMR 2011



Liu, JVSTB 2011

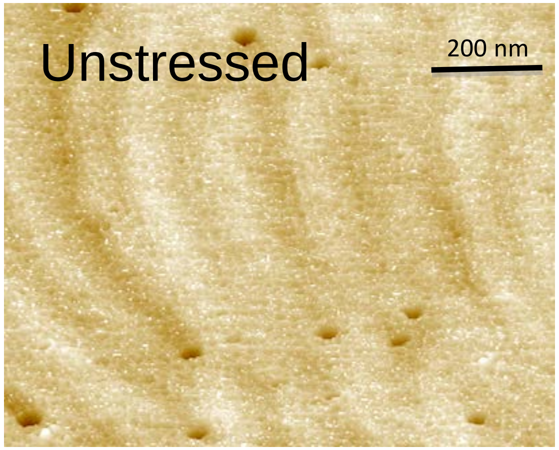
Christiansen, IRPS 2011

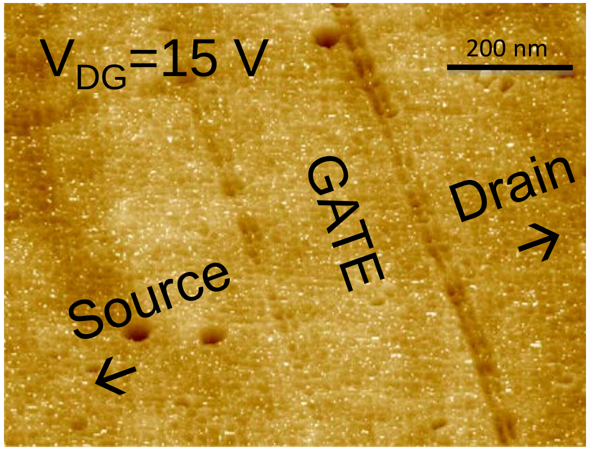


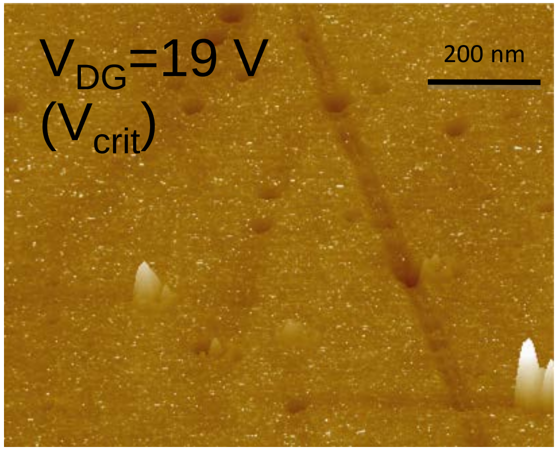
Structural degradation: planar view

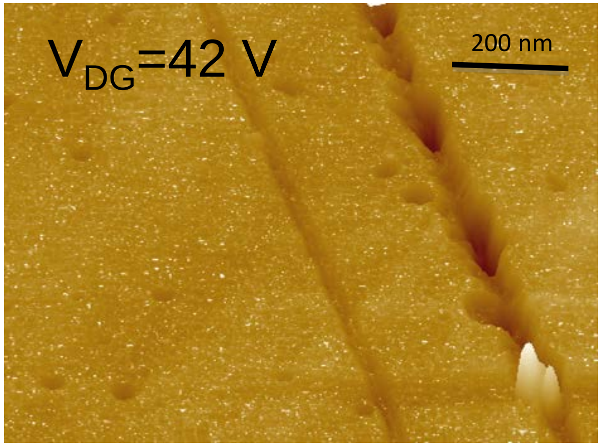
OFF-state step-stress, V_{GS}=-7 V, T_{base}=150 °C

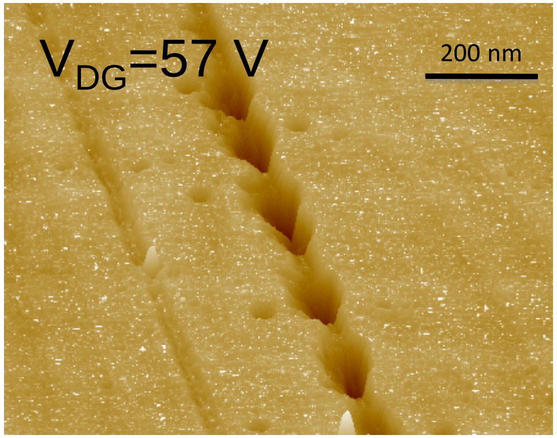
Makaram, APL 2010







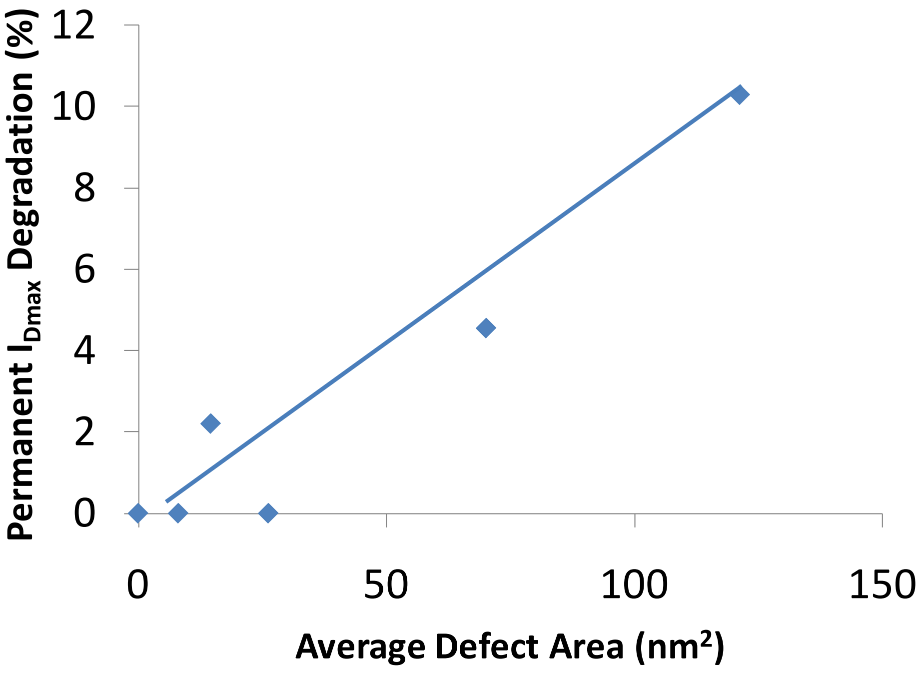


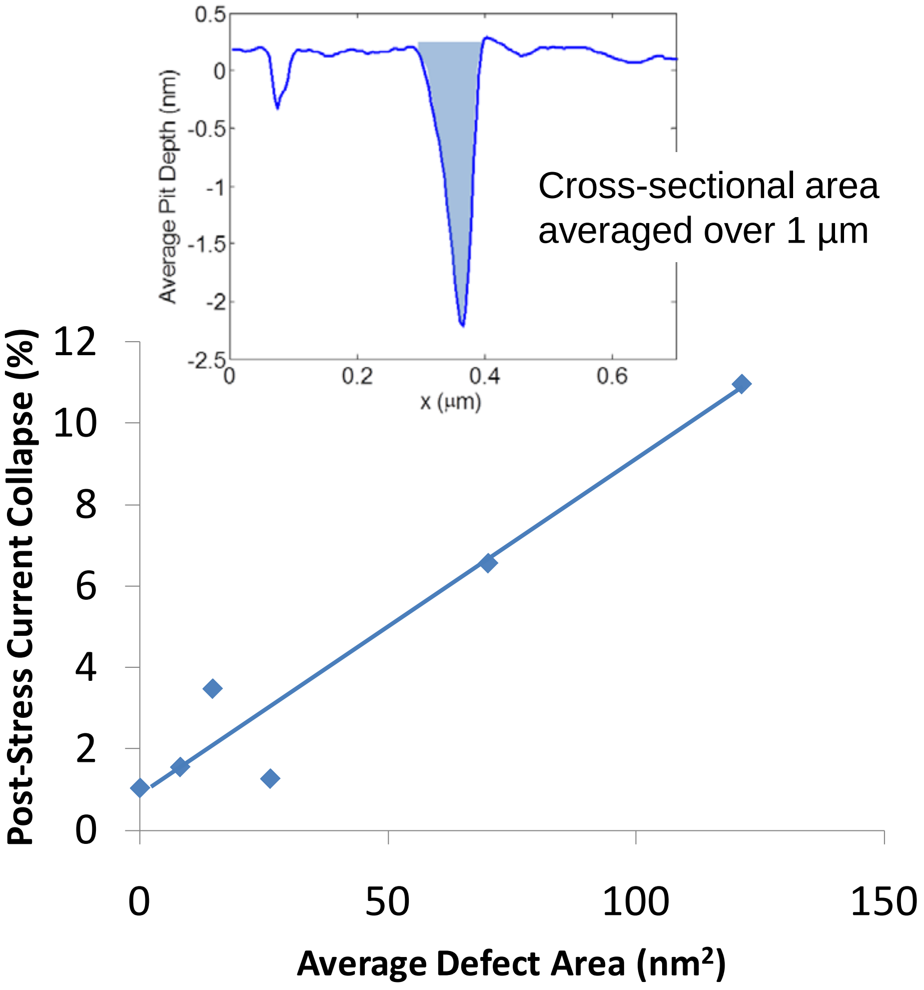


- Continuous groove appears for V_{stress}<V_{crit}
- Deep pits formed along groove for V_{stress}>V_{crit}

Correlation between pit geometry and I_{Dmax} degradation

Makaram, APL 2010





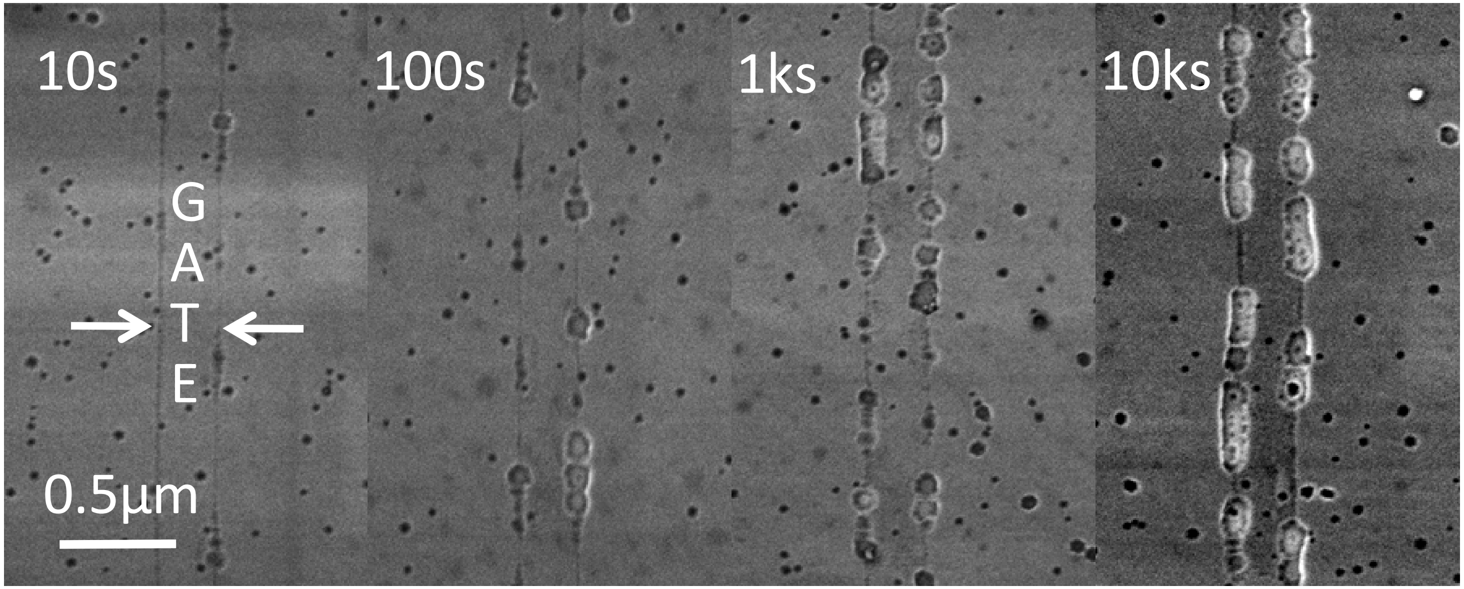
Cross-sectional area averaged over 1 µm

I_{Dmax} degradation and pit cross-sectional area correlate

Planar degradation: the role of time

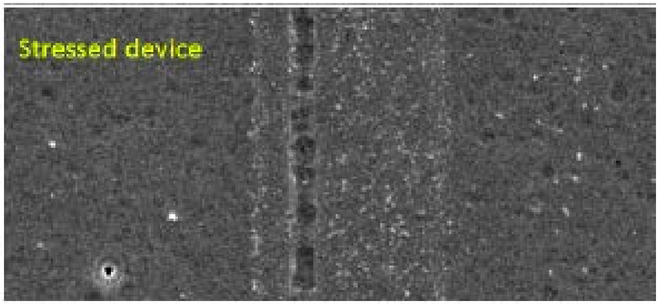
V_{DS}=0, V_{GS}=-40 V, T_{base}=150 °C

Joh, IWN 2010

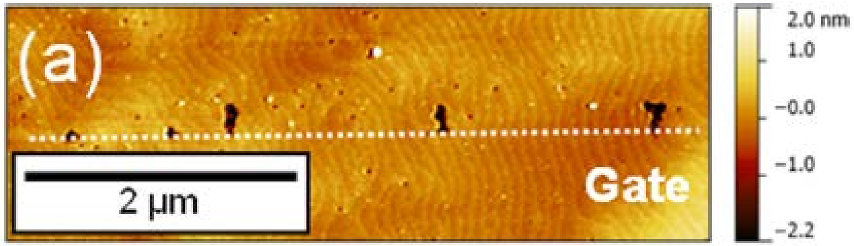


- Very fast groove formation (within 10 s)
- Delayed pit formation
- Pit density/size increase with time
- Good correlation between I_{Dmax} degradation and pit area

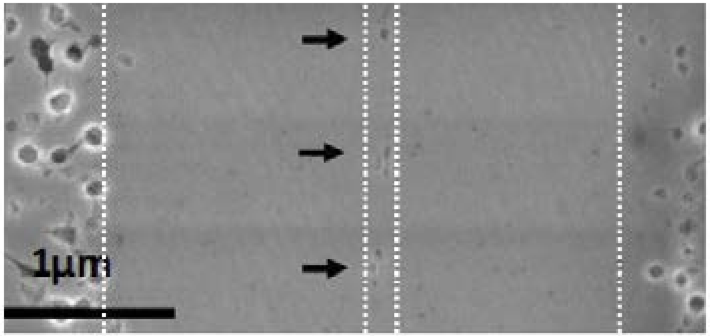
Structural damage at gate edge: a universal phenomenon



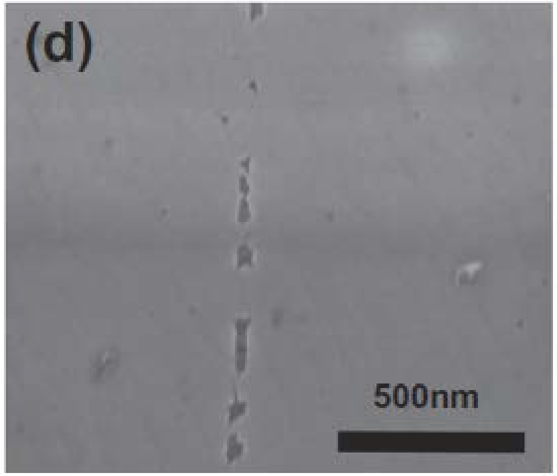
Barnes, CS-MANTECH 2012



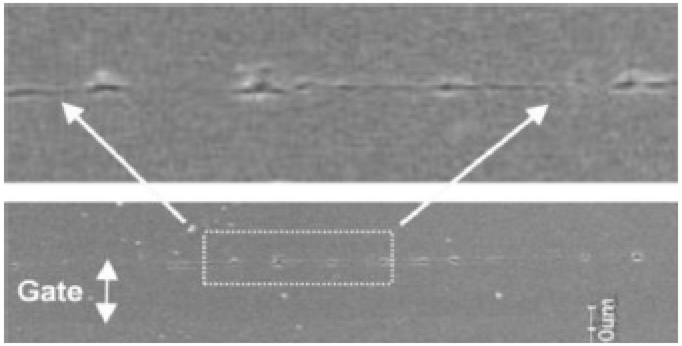
Monte Bajo, APL 2014



Holzworth, ECST 2014

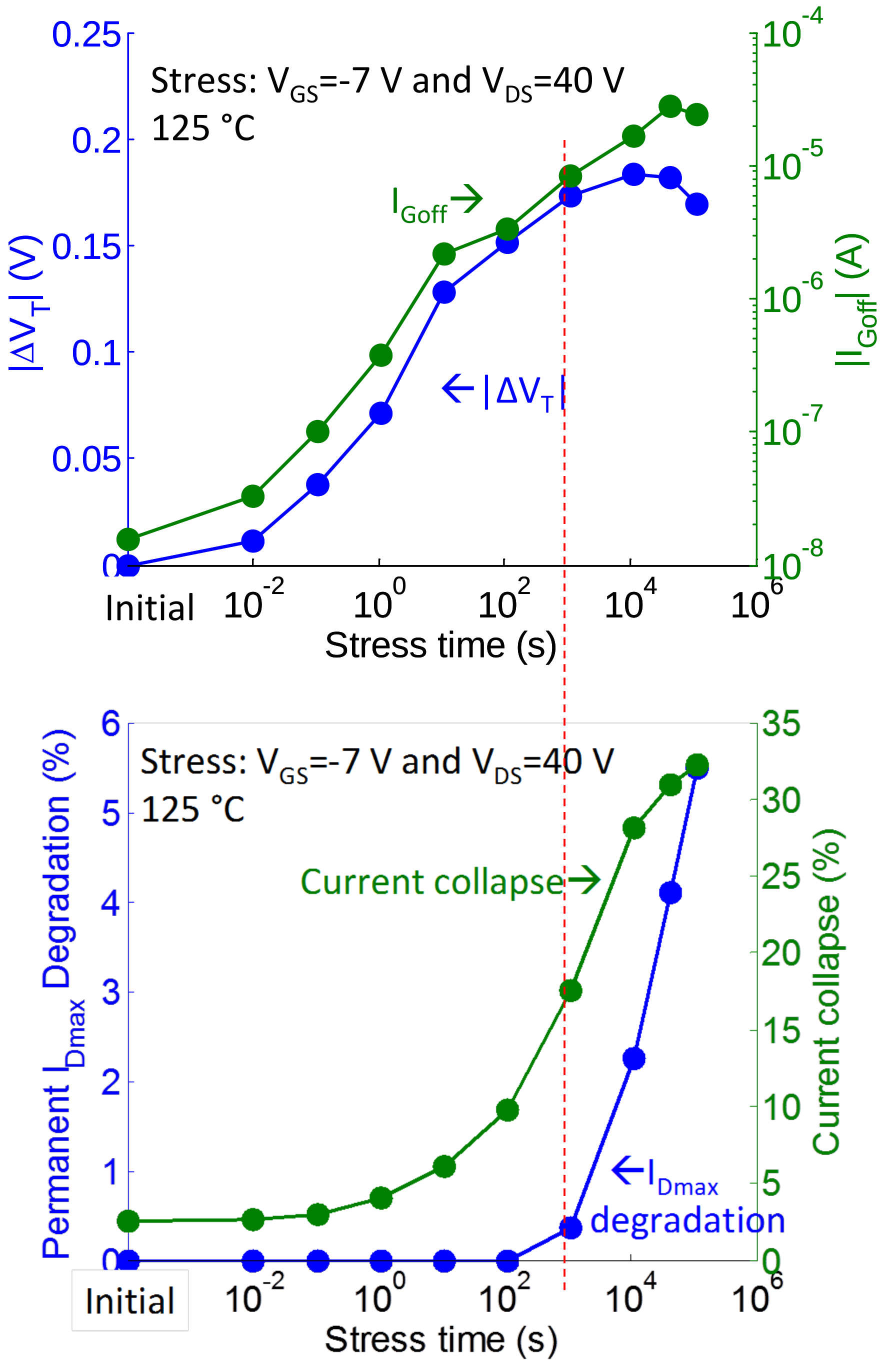


Whiting, MR 2012



Brunel, MR 2013

Time evolution of degradation for constant $V_{stress} > V_{crit}$



I_{Goff} and V_T degradation:

- fast (<10 ms)
- saturate after 10^4 s

CC degradation:

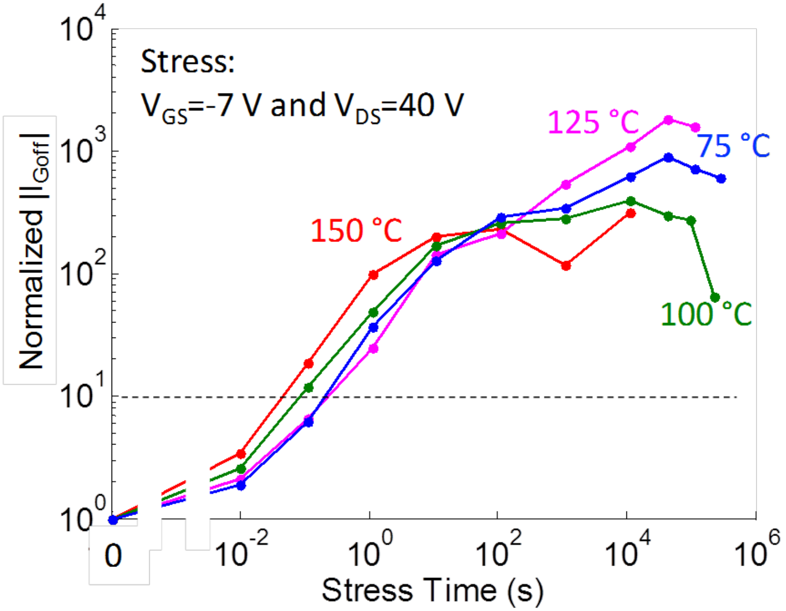
- slower
- hint of saturation for long time

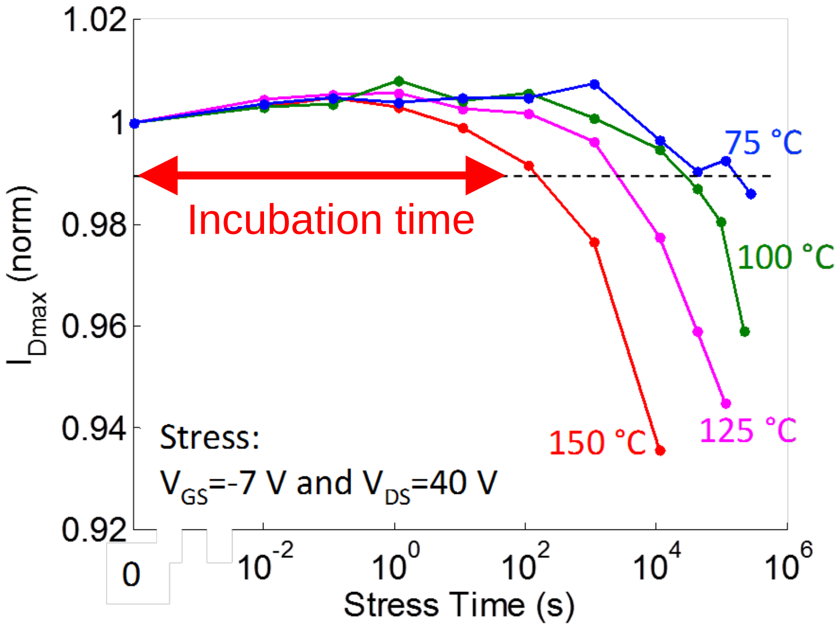
Permanent I_{Dmax} degradation:

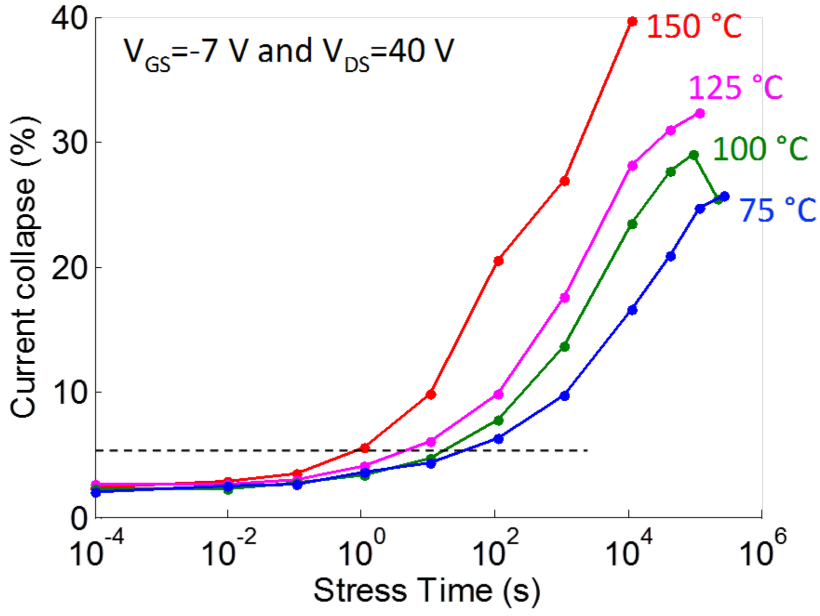
- much slower
- does not saturate with time

Joh, IRPS 2011

The role of temperature in time evolution



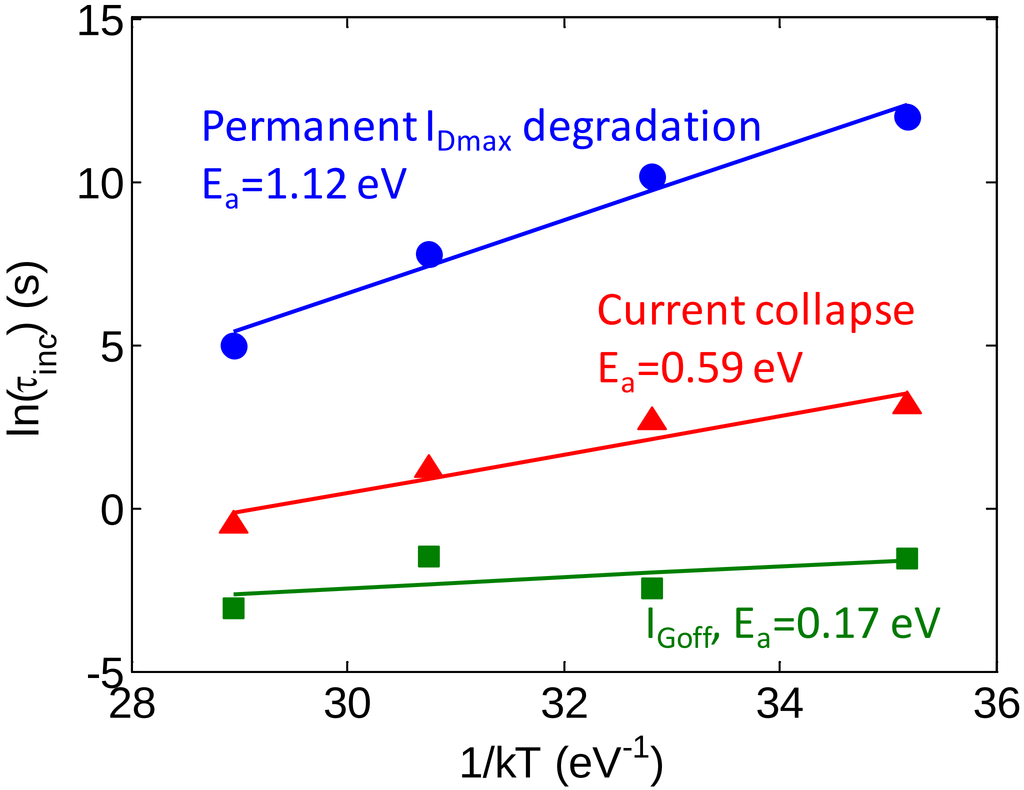




- I_G: weak T dependence
- CC, I_{Dmax}: T activated

Joh, IRPS 2011

Temperature acceleration of incubation time



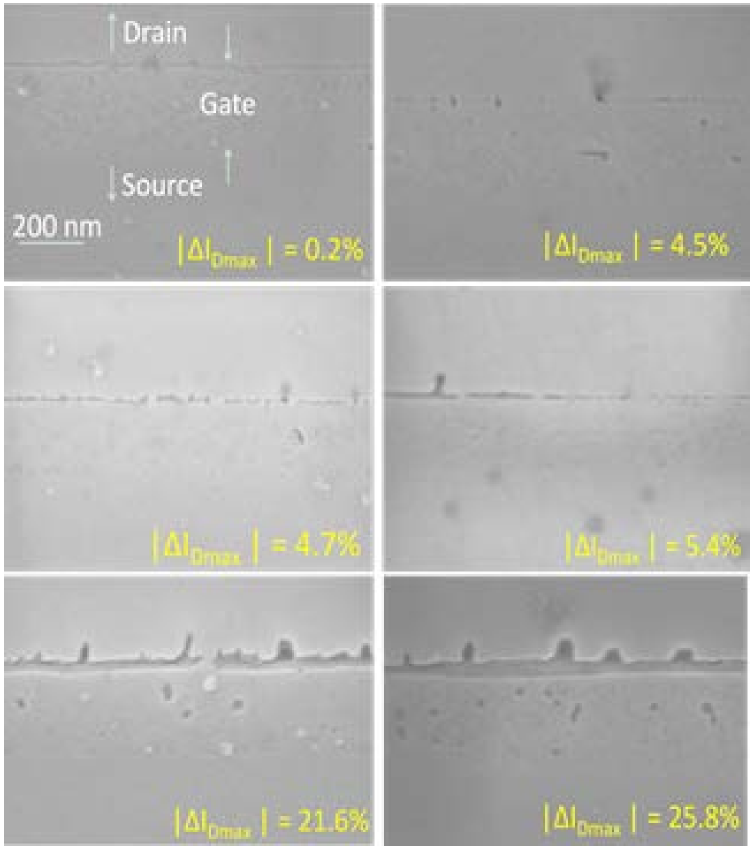
- Different E_a for I_{Goff}, CC, I_{Dmax} reveal different degradation physics
- E_a for permanent I_{Dmax} degradation similar to life test data*

* Saunier, DRC 2007; Meneghesso, IJMWT 2010

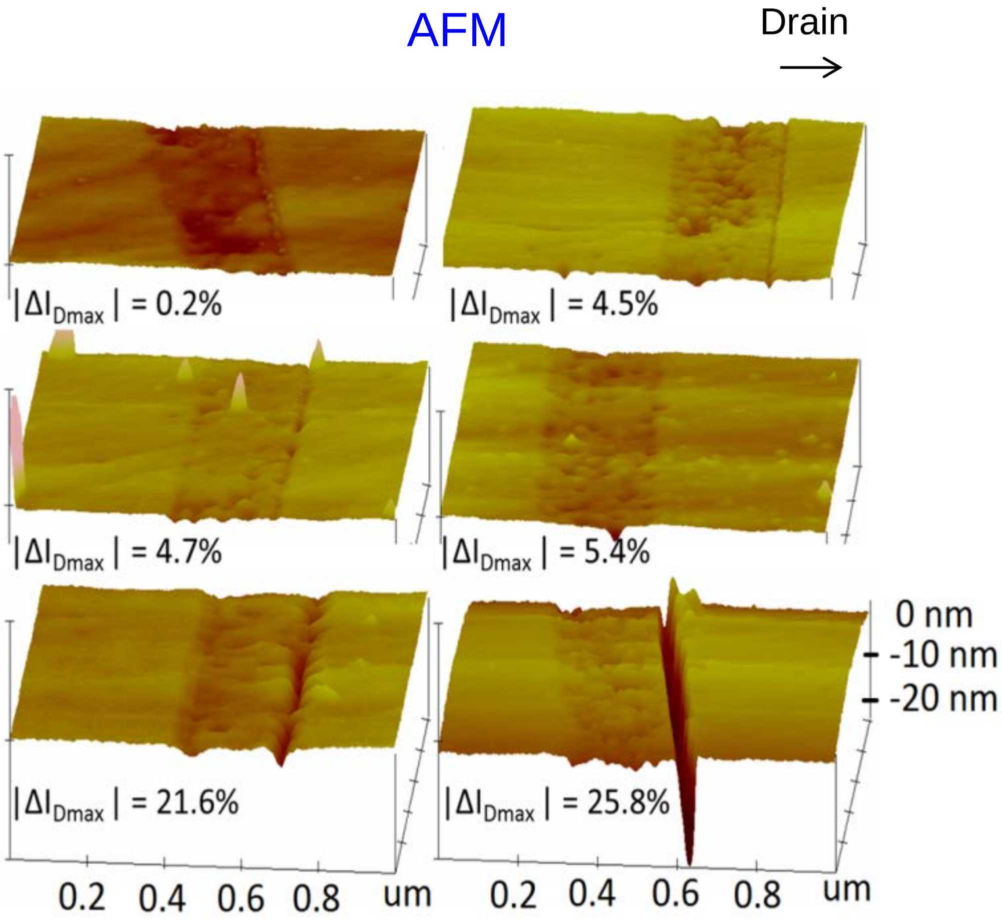
DC semi-ON stress experiments

Stress conditions:
I_D=100 mA/mm,
V_{DS}=40 or 50 V
Step-T experiments: 50<T_a<230^{o}C
(T$_j$~110-330^{o}C)

SEM



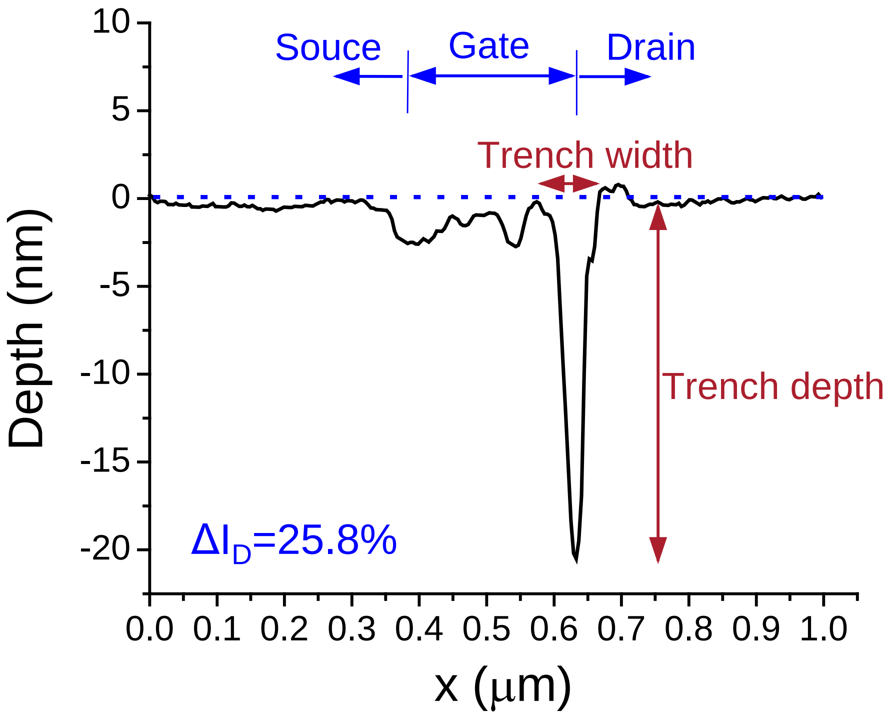
AFM

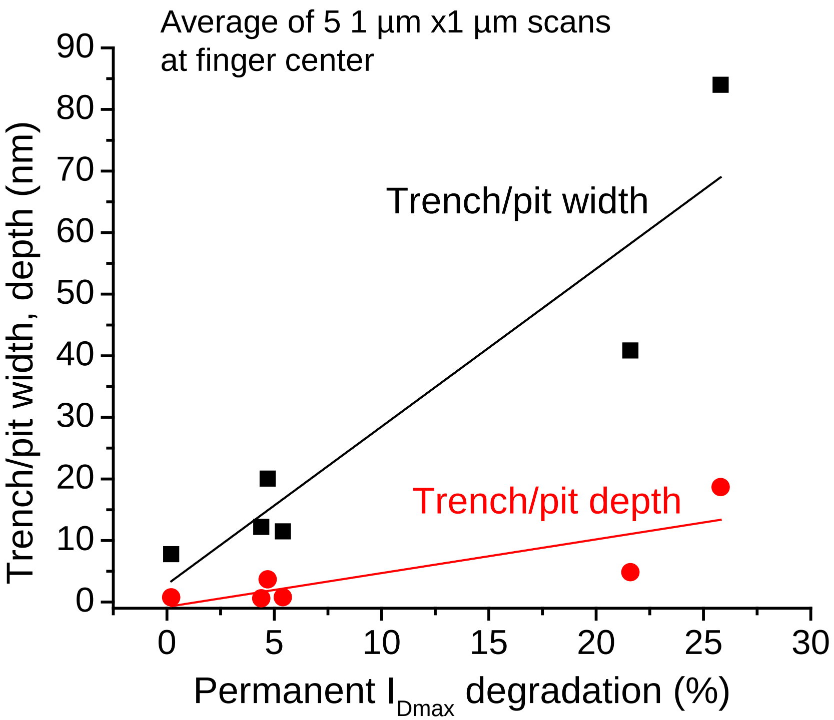


Prominent pits and trenches under gate edge on drain side

Wu, JAP 2015

Structural vs. electrical degradation

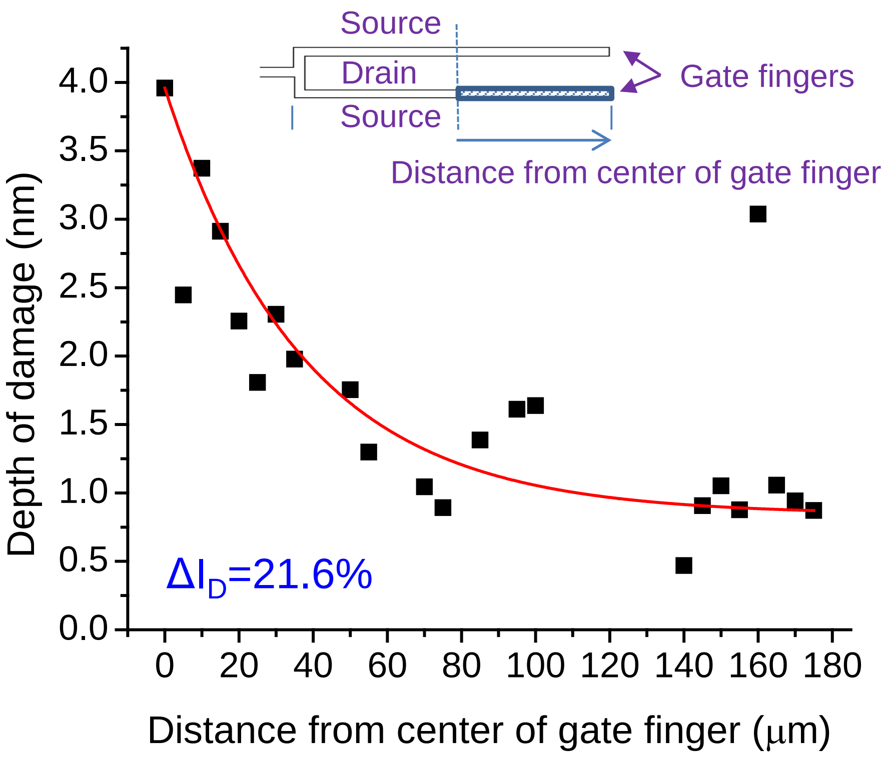


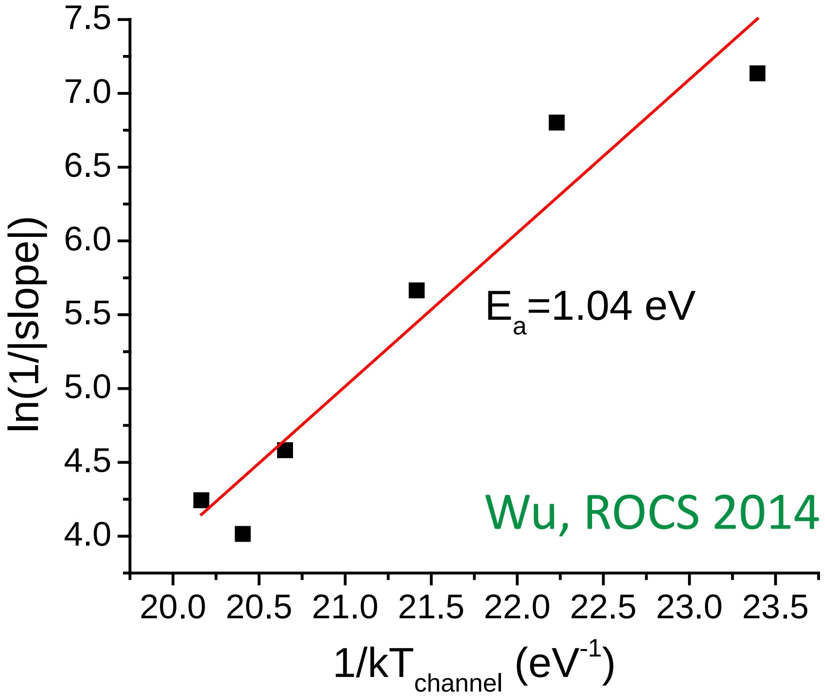


Trench/pit depth and width correlate with I_{Dmax} degradation

Wu, JAP 2015

Thermally activated degradation



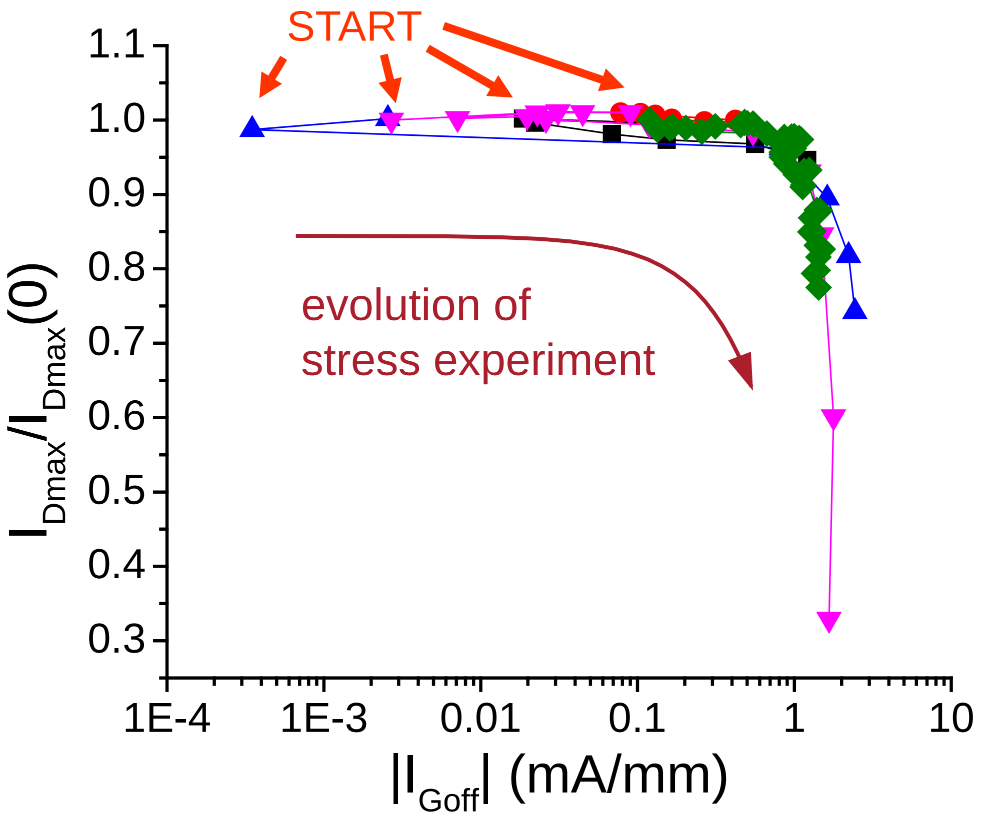


Wu, ROCS 2014

- Pit/trench depth increase towards center of gate finger
  → self heating + thermally activated process
- Permanent I_{Dmax} degradation is thermally activated with E_a~1.0 eV

Sequential I_G and I_D degradation

Stress conditions:
I_D=100 mA/mm,
V_{DS}=40 or 50 V
Step-Temperature: $50<T_a<230^oC$



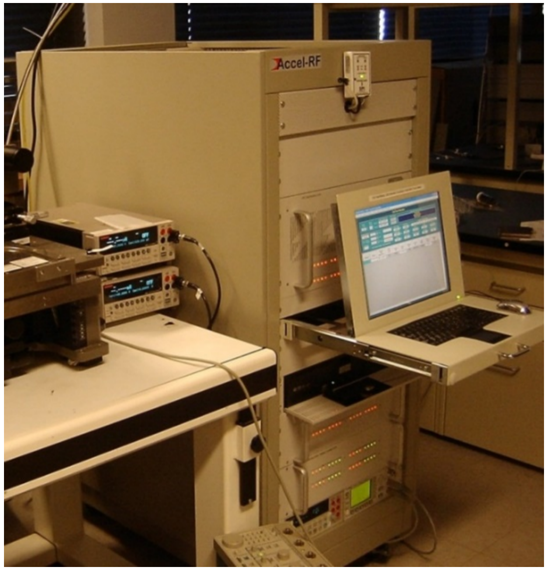
Wu, ROCS 2014

Wu, MR 2014

"Universal degradation" pattern:

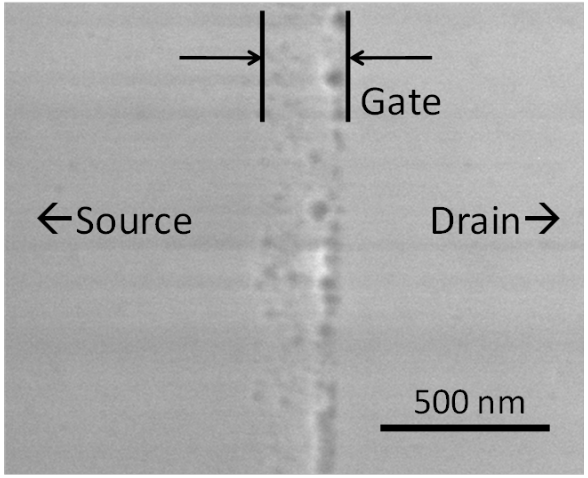
- I_G degradation takes places first without I_D degradation
- I_D degradation takes place next without further I_G degradation

RF power degradation

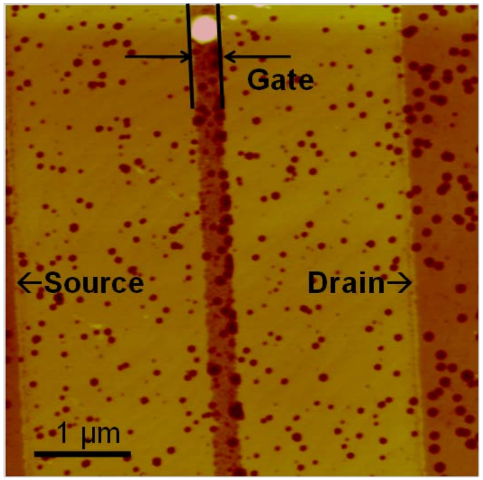


	HV OFF-state DC	RF power
I_{Dmax}	↓ beyond V_{crit}	↓ beyond $P_{in\text{-}crit}$
R_D	↑ beyond V_{crit}	↑ beyond $P_{in\text{-}crit}$
R_S	small increase	small increase
I_{Goff}	↑ beyond V_{crit}	↑ beyond $P_{in\text{-}crit}$
Current Collapse	↑ beyond V_{crit}	↑ beyond $P_{in\text{-}crit}$
Permanent I_{Dmax}	↓ beyond V_{crit}	↓ beyond $P_{in\text{-}crit}$
Pits under drain end of gate	Yes	Yes
Pits under source end of gate	No	No

SEM



AFM



- RF power degradation pattern matches that of OFF-state DC stress
- But not always…

Joh, IEDM 2010
Joh, ROCS 2011
Joh, MR 2012

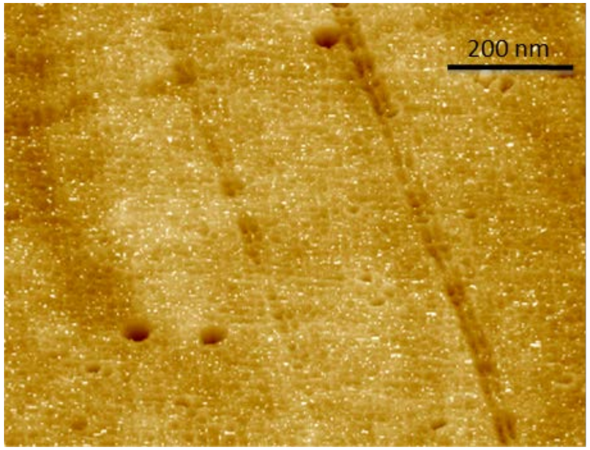
Summary of electrical and structural degradation

1. I_G degradation

- Fast
- Electric-field driven
- Little temperature sensitivity (E_a~0.2 eV)
- Tends to saturate

Correlates with appearance of shallow *groove* and *small pits*

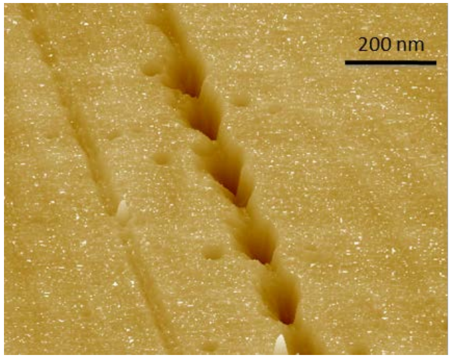
- On S and D side (bigger on D side)
- Groove/small pits appear for $V_{stress} < V_{crit}$



Summary of electrical and structural degradation

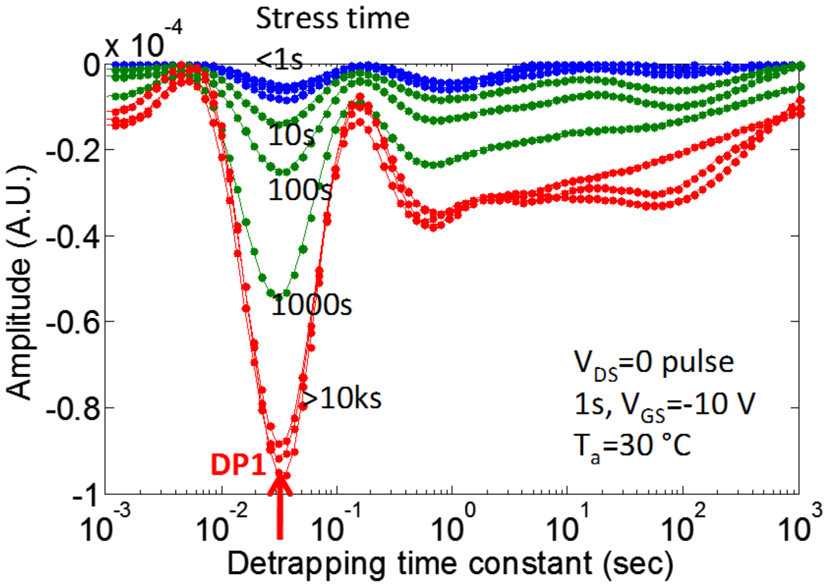
2. Current-collapse degradation (trapping)

- Slower
- Enhanced by temperature, electric field
- Tends to saturate for very long times



Correlates with *pit growth*:

- Pits randomly located on drain side
- Pits grow with V_{stress}, time and temperature
- Pits eventually merge



Dominant trap created by stress *already present in virgin sample*, E_a=0.56 eV

Joh, IRPS 2011

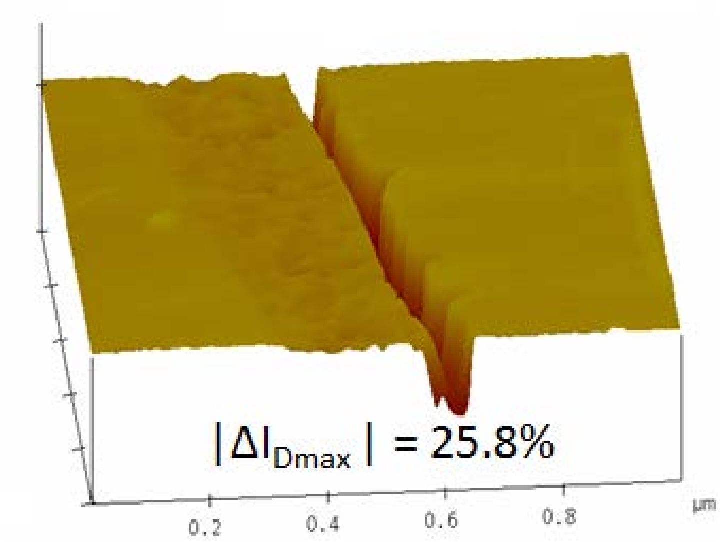
Summary of electrical and structural degradation

3. I_{Dmax}, R_D degradation

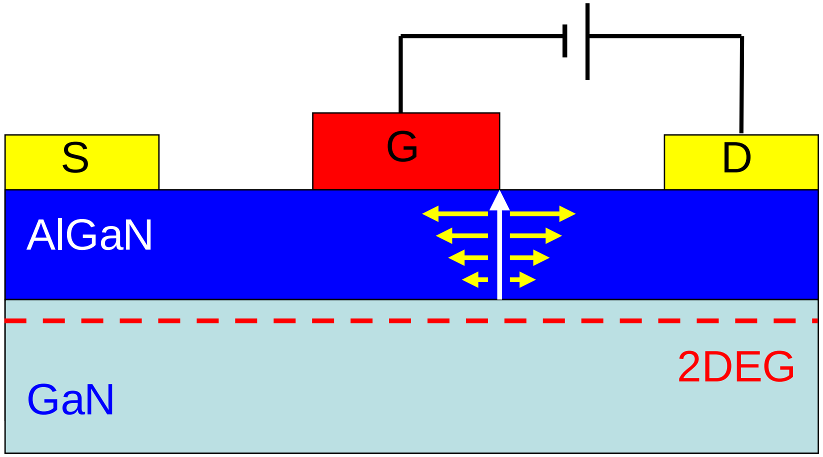
- Much slower
- Temperature activated (E_a~1 eV)
- Electric-field driven
- Does not saturate

Correlates with geometry of *pits* and *trench*

- Pits grow larger and merge into trench
- Trench grows deeper



Initial hypothesis: Inverse Piezoelectric Effect Mechanism



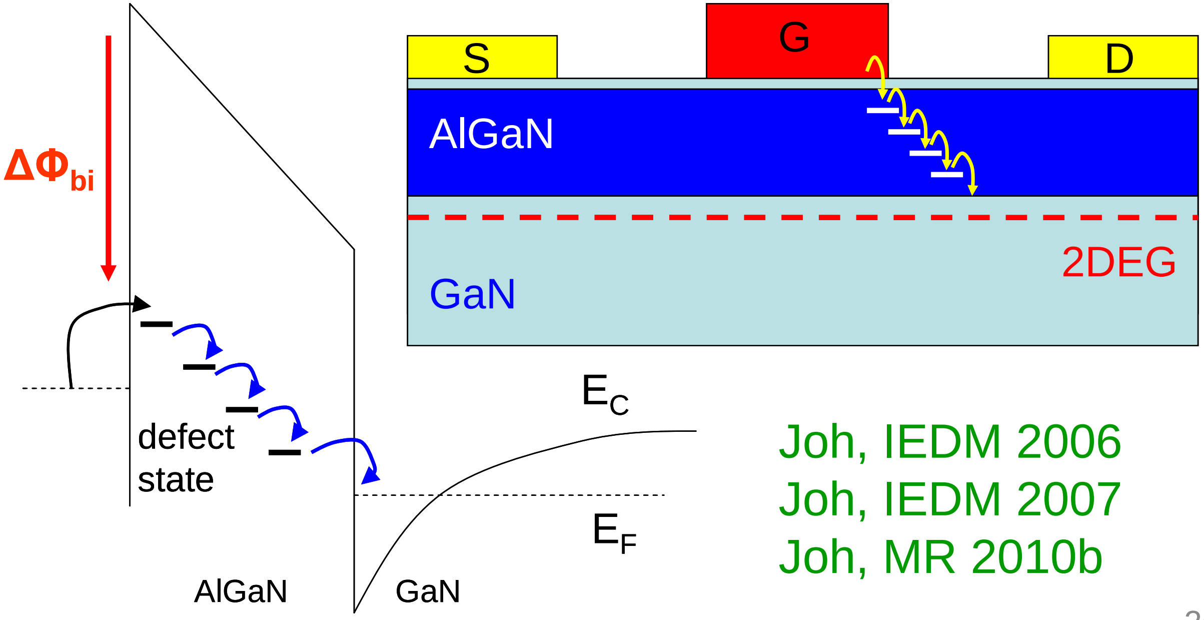
Strong piezoelectricity in AlGaN
→ $|V_{DG}|$↑ → tensile stress ↑
→ crystallographic defects beyond *critical elastic energy*

Defects:

Trap electrons
→ n_s↓ → R_D↑, I_D ↓

Strain relaxation
→ I_D ↓

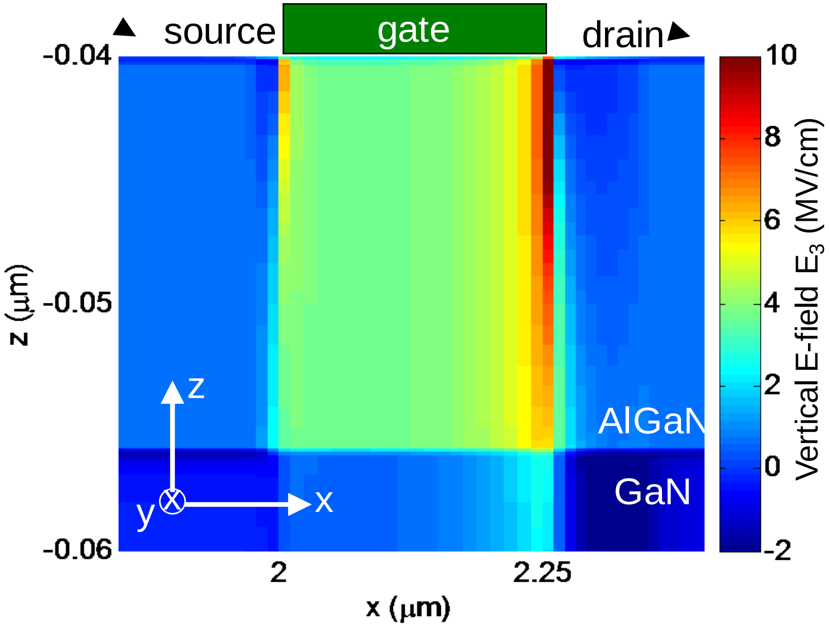
Provide paths for I_G
→ I_G↑

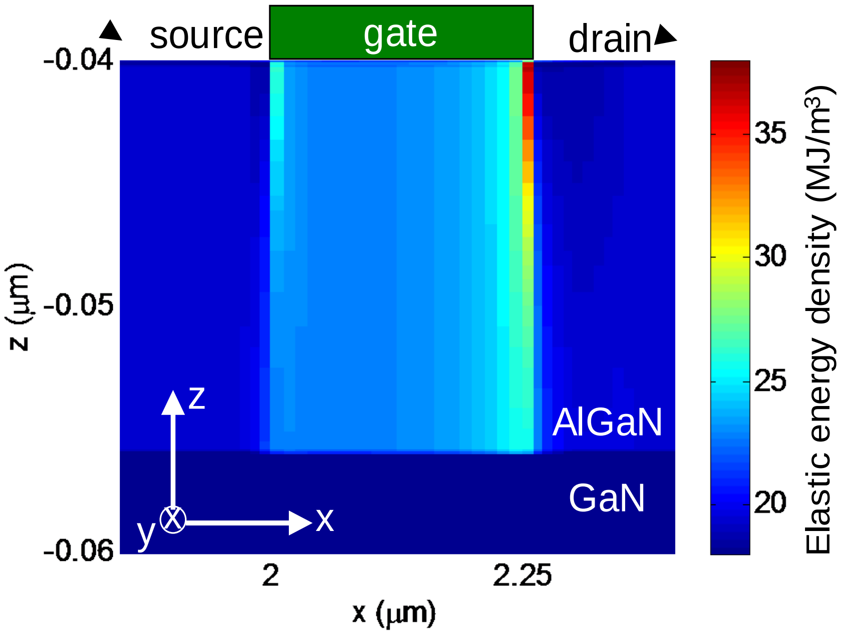


Joh, IEDM 2006
Joh, IEDM 2007
Joh, MR 2010b

Model for critical voltage

V_{GS}=-5 V, V_{DS}=33 V
16nm 28% AlGaN





$$T_1 = \boxed{(C_{11}+C_{12}-2\frac{C_{13}^{2}}{C_{33}})S_{10}} + \boxed{(\frac{C_{13}e_{33}}{C_{33}} - e_{31})E_3}$$

Mismatch stress

Inverse piezoelectric stress

$$W = \frac{C_{33}}{C_{11}C_{33}-2C_{13}^{2}+C_{12}C_{33}}T_1^{2}$$
$$\propto (T_{10}+aE_3)^2$$

Joh, MR 2010

Predictions of Inverse Piezoelectric Effect model borne out by experiments

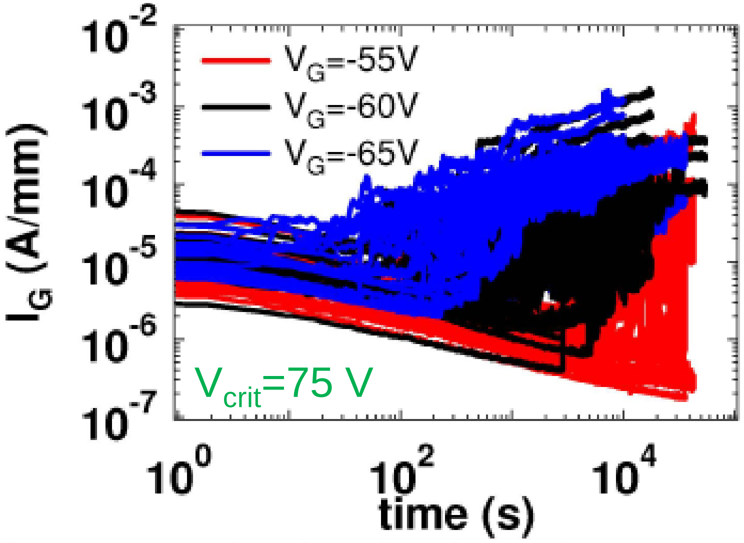
To enhance GaN HEMT reliability:

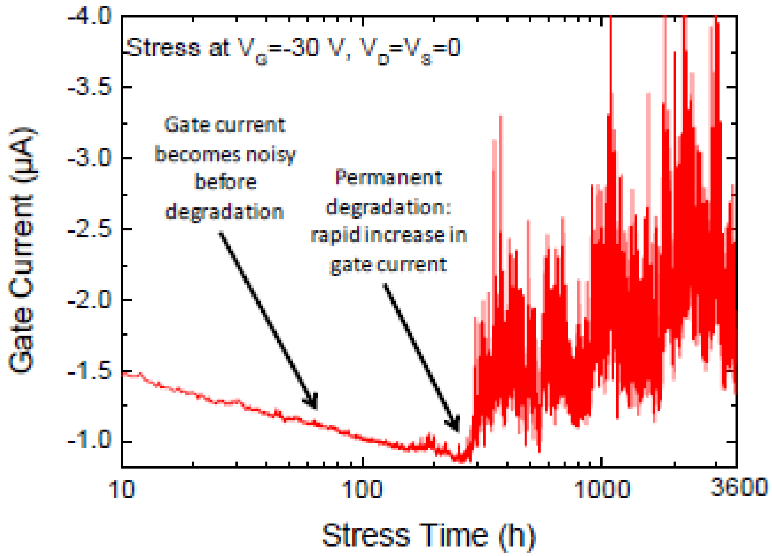
- Reduce AlN composition of AlGaN barrier (Jimenez, ESREF 2011)
- Thin down AlGaN barrier (Lee, EL 2005)
- Use thicker GaN cap (Ivo, IRPS 2009; Jimenez, ESREF 2011)
- Use InAlN barrier (Jimenez, ESREF 2011)
- Use AlGaN buffer (Joh, IEDM 2006; Ivo, MR 2011)
- Electric field management at drain end of gate (many)

Can't explain:

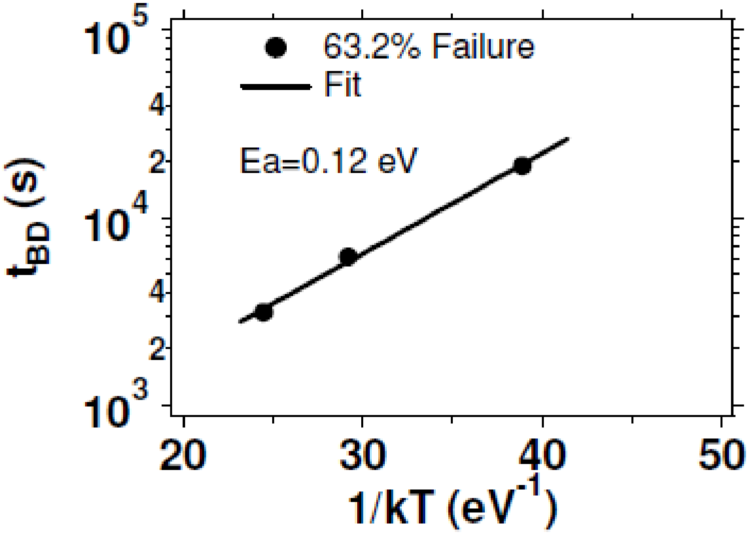
- Groove formation/I_G degradation below critical voltage
- Presence of oxygen in groove/pit
- Role of atmosphere during stress
- Role of surface chemistry

I_G degradation for $V_{stress} < V_{crit}$





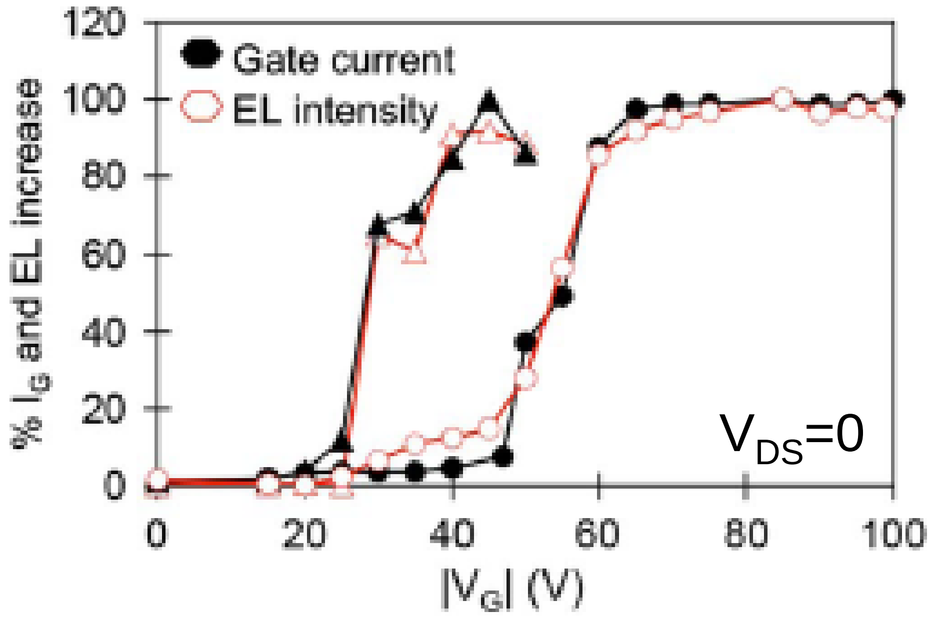
Meneghini, IEDM 2011



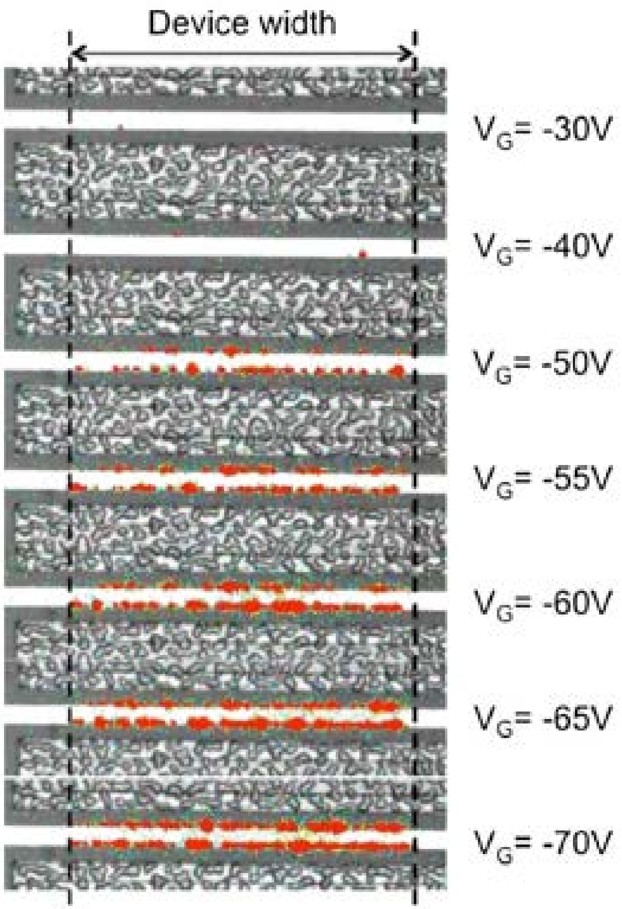
Marcon, IEDM 2010

- Sudden irreversible increase in I_G
- Enhanced by V_{stress}
- Preceded by onset of I_G noise
- Weakly temperature enhanced (E_a=0.12 eV)

I_G degradation correlates with electroluminescence hot spots



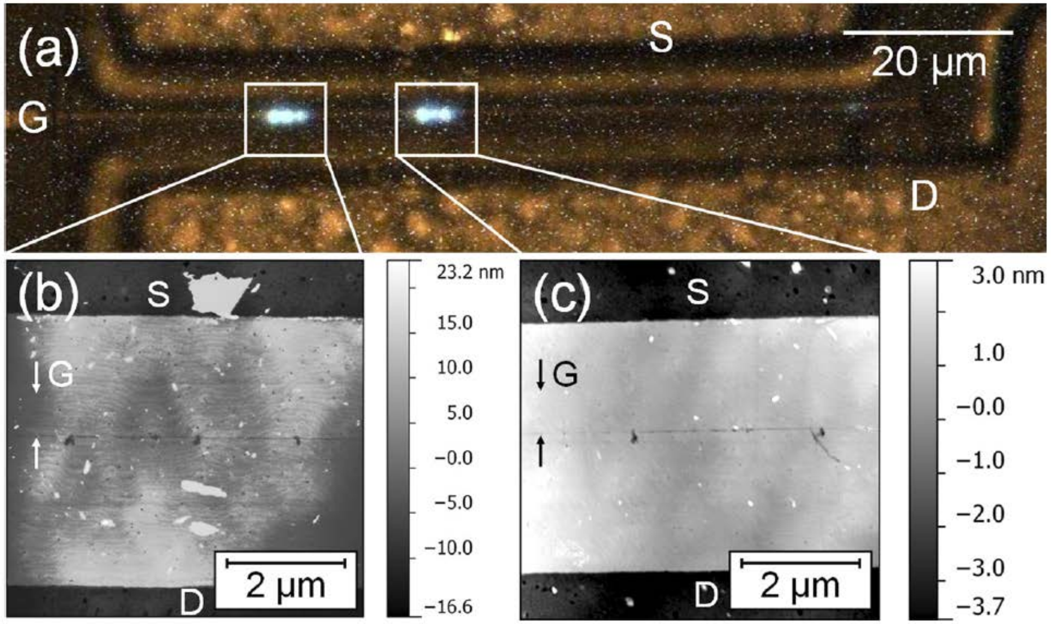
Zanoni, EDL 2009
Meneghini, IEDM 2011



- Gate current electrons produce EL in GaN substrate
- EL spots tend to merge into a continuous line

EL hot spots correlate with pits, pits are conducting

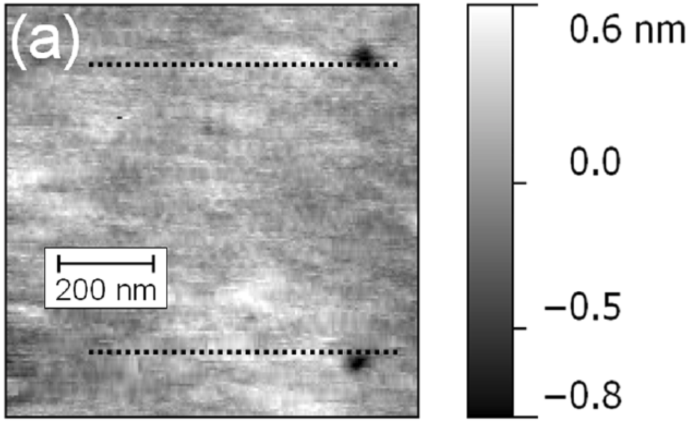
EL picture



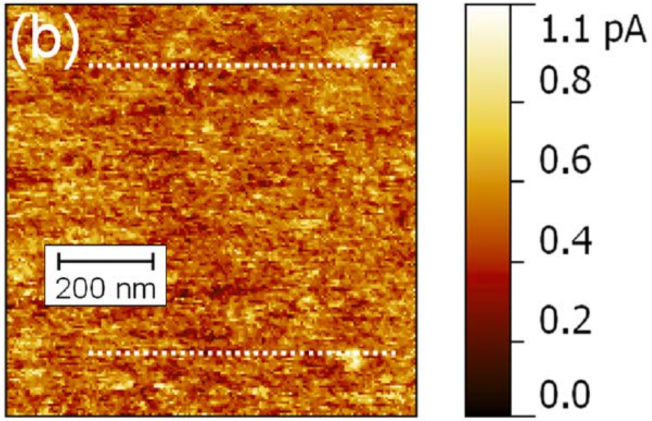
AFM topography

Montes Bajo, APL 2012

Normal AFM



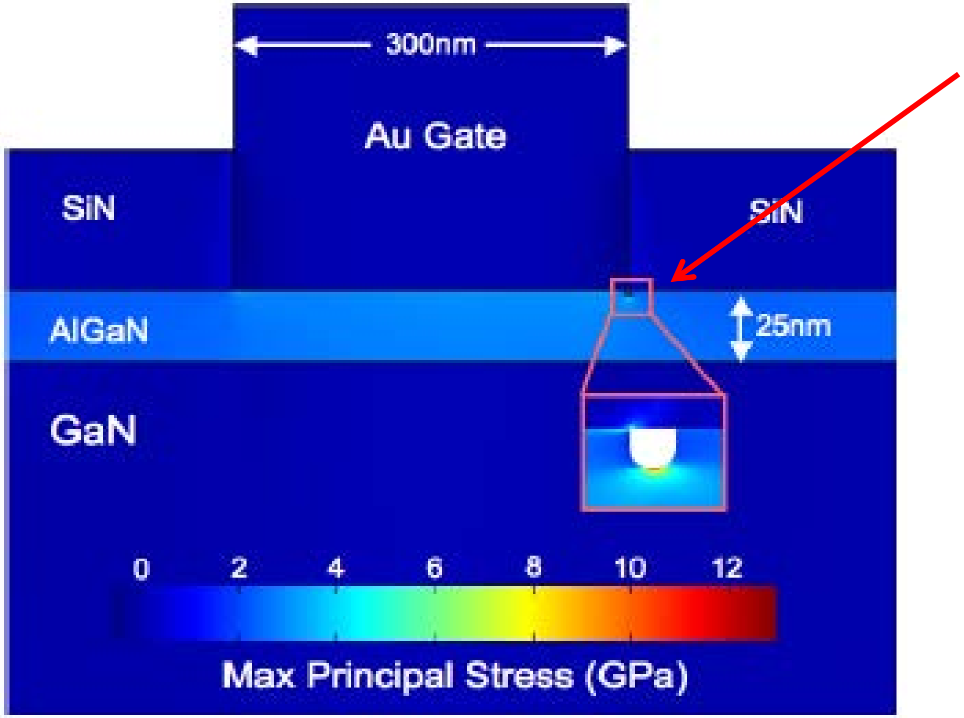
Conducting AFM



Shallow pits and groove responsible for I_G degradation

Pits/Groove increase mechanical stress

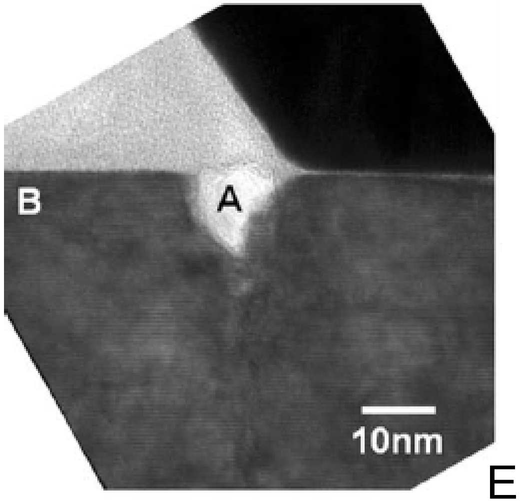
Pit/groove increases mechanical stress due to inverse piezoelectric effect at drain end of gate



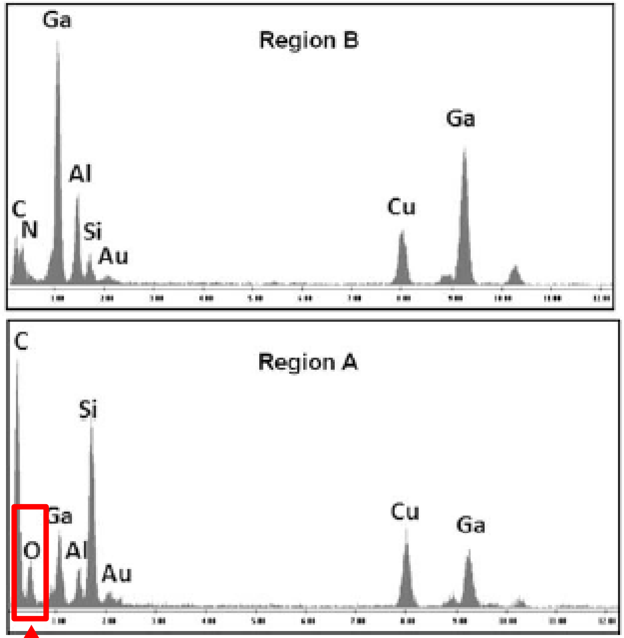
- 2 nm x 3 nm groove increases mechanical stress in AlGaN from 4.6 GPa to 13 GPa
- Groove has little effect in current underneath
- Pit formation brings major loss of current

Ancona, JAP 2012

Oxygen inside pit

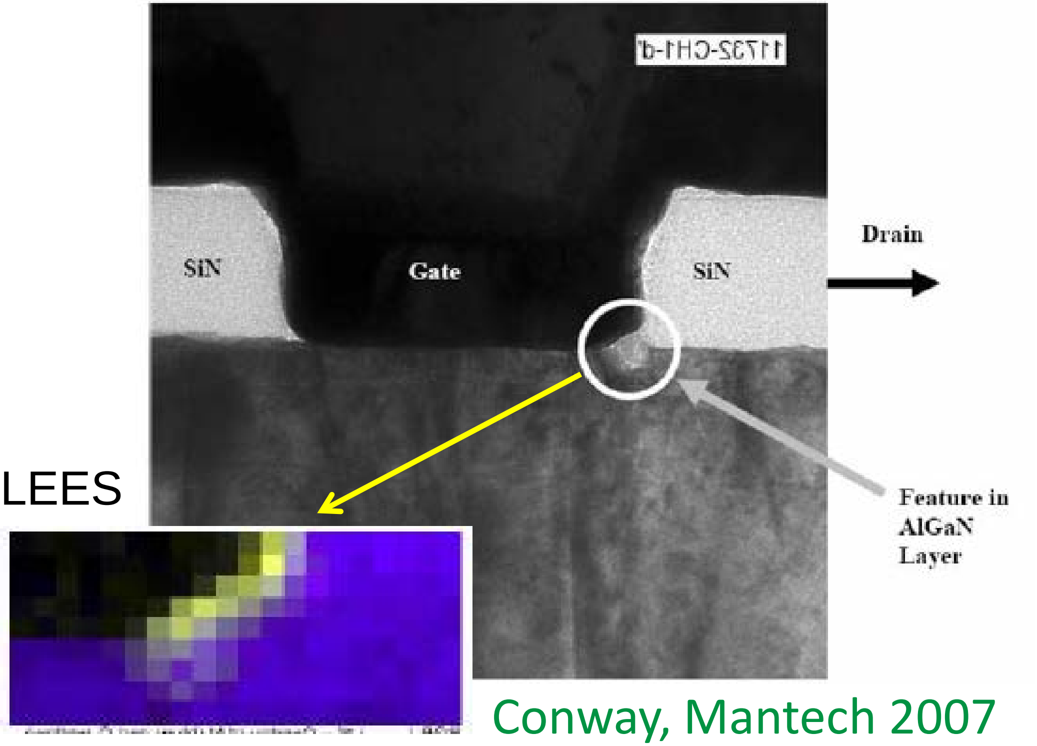


EDX



Park, MR 2009

LEES



Conway, Mantech 2007

- O, Si, C found inside pit
- Anodization mechanism for pit formation? (Smith, ECST 2009)
- Electrical stress experiments under N_2 inconclusive

Role of atmosphere on structural degradation

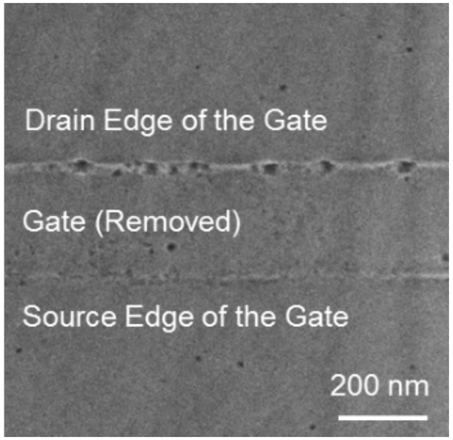
Off-state stress: V_{ds}=43 V, V_{gs}=-7 V for 3000 s in dark at RT

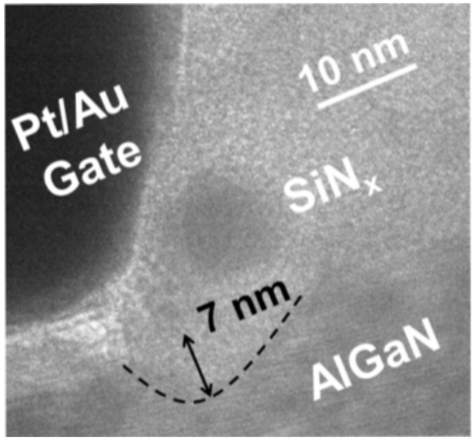
SEM Top View

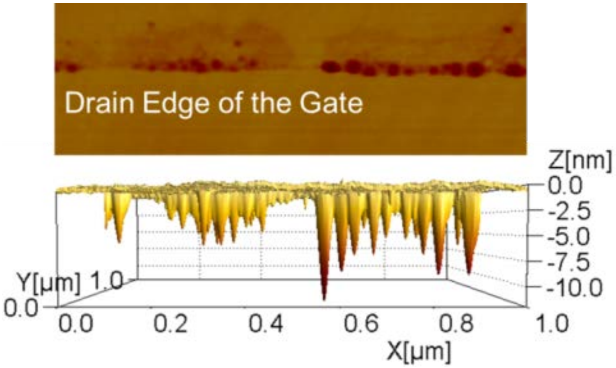
TEM Cross Section

AFM Depth Profile

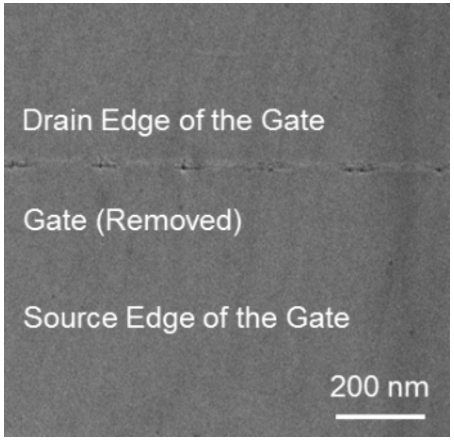
Stressed in ambient air ΔI_D=5.0%

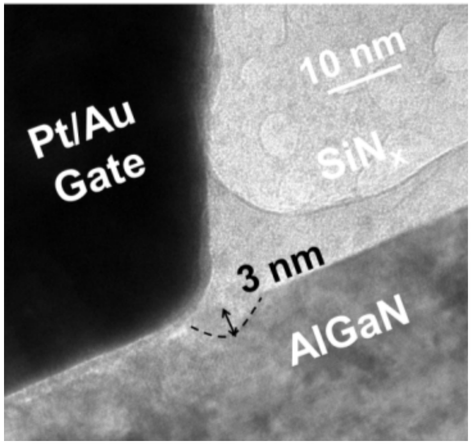


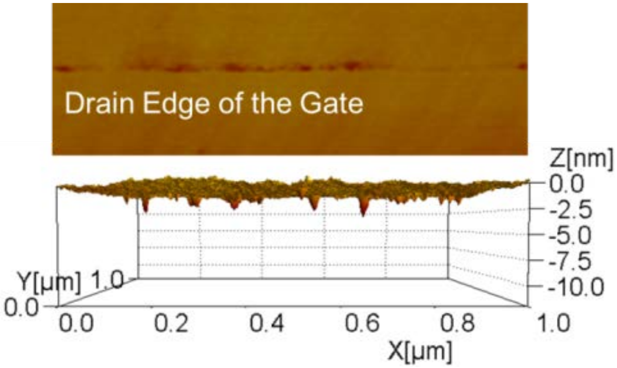




Stressed in vacuum of 10^{-7} Torr ΔI_D=0.5%







Gao, TED 2014

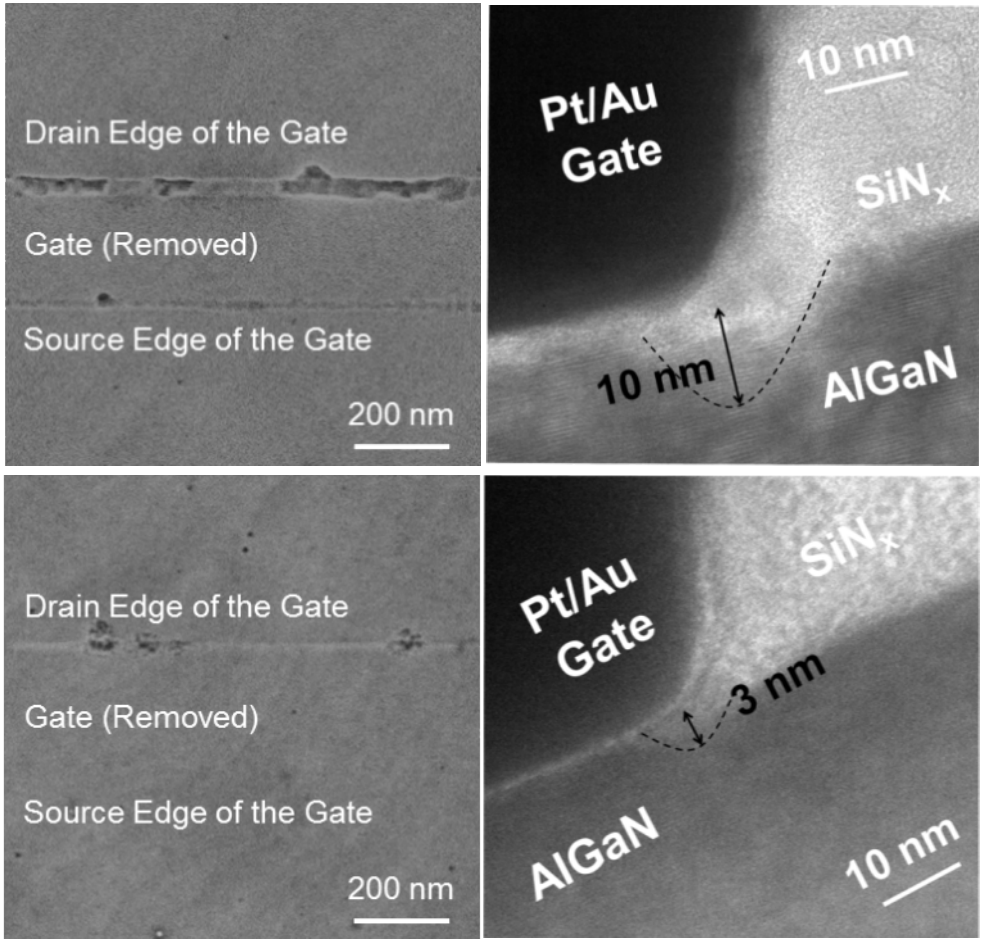
Surface pitting significantly reduced in vacuum

Impact of Moisture on Surface Pitting

Off-state stress:
V_{ds} = 43 V, V_{gs} = -7 V
for 3000 s in dark at RT

SEM Top View

TEM Cross Section



Stressed in water-saturated gas (Ar)
ΔI_D=28.8%

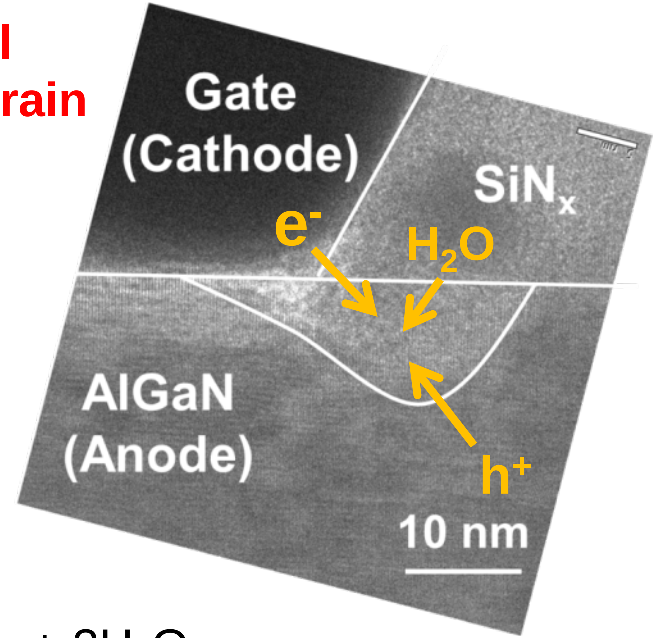
Stressed in dry gas (Ar)
ΔI_D=0.3%

Gao, TED 2014

- Moisture enhances surface pitting
- Results reproduced with dry/wet O_2, N_2, CO_2 and air

New hypothesis:
AlGaN corrosion at edge of gate

Electrochemical cell formed at drain edge of gate



- Reduction of water:

$2H_2O + \mathbf{2e^-} \leftrightarrow 2OH^- + H_2$

- Anodic oxidation of AlGaN:

$2Al_xGa_{1-x}N + \mathbf{6h^+} \leftrightarrow 2xAl^{3+} + 2(1-x)Ga^{3+} + N_2$

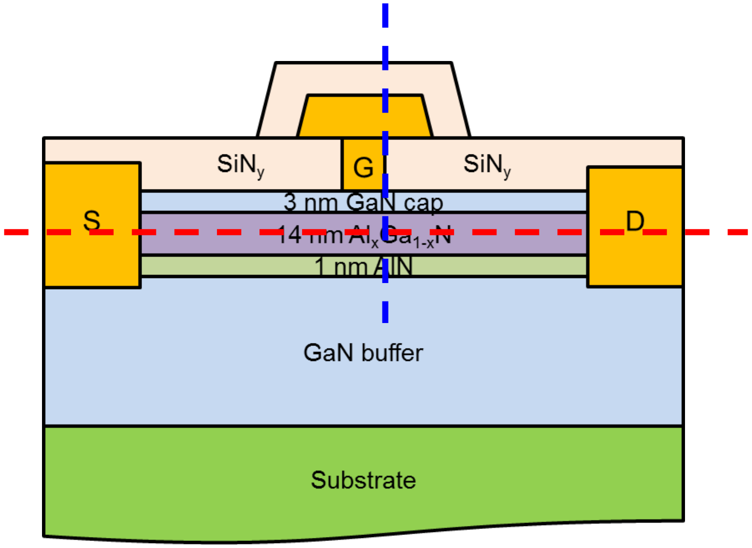
$2xAl^{3+} + 2(1-x)Ga^{3+} + 6OH^- \leftrightarrow xAl_2O_3 + (1-x)Ga_2O_3 + 3H_2O$

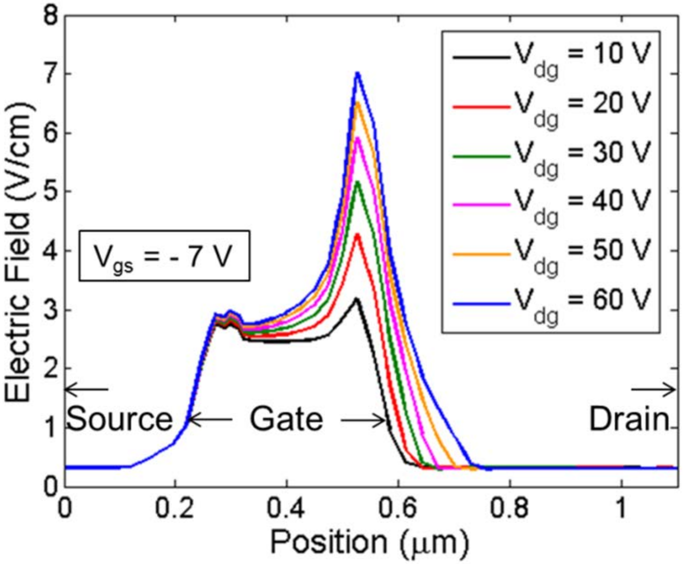
- Complete redox electrochemical reaction:

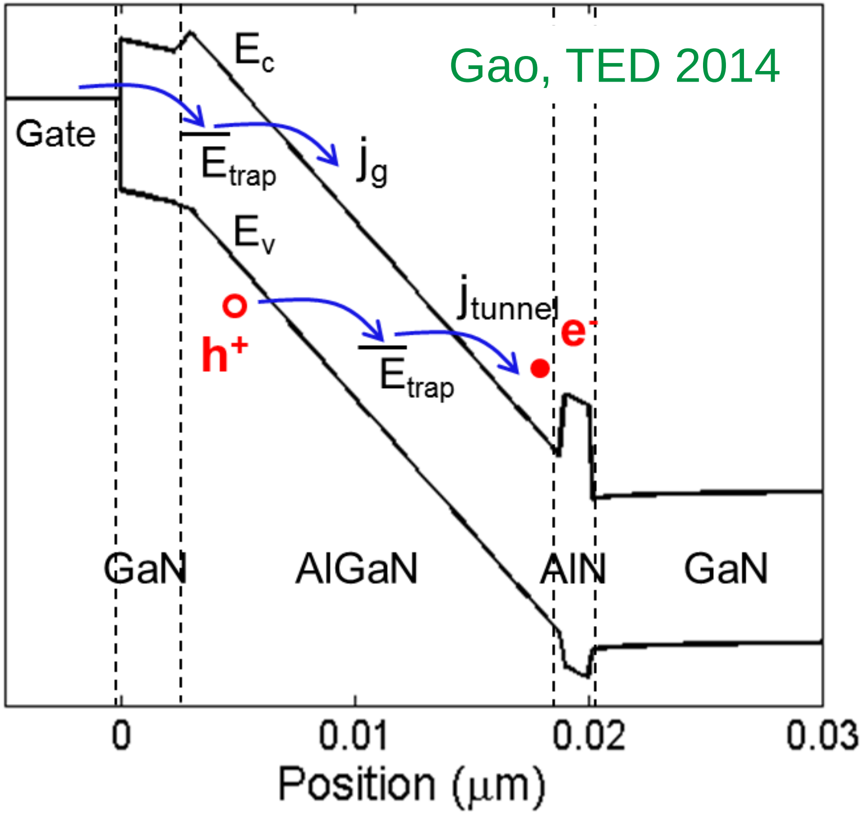
$\mathbf{2Al_xGa_{1-x}N + 3H_2O \leftrightarrow xAl_2O_3 + (1-x)Ga_2O_3 + N_2 + H_2}$

Gao, TED 2014

Source of holes: trap-assisted tunneling







Gao, TED 2014

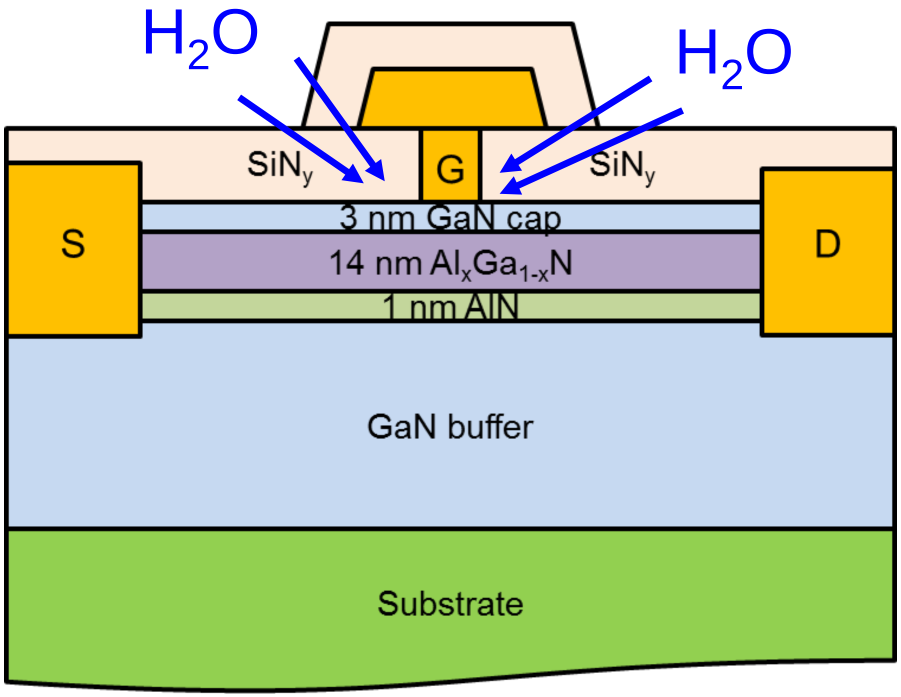
High electric field under gate edge

→ trap-assisted BTBT electron tunneling

→ hole generation at AlGaN surface

Source of water: diffusion through SiN

Gao, TED 2014



- Water-vapor transmission rate (WVTR) through 100 nm of PECVD SiN:

  $0.01\sim0.1\ g/m^2/day$

- Gao's estimate of necessary WVTR to cause pits:

  $0.05\sim0.1\ g/m^2/day$

Tentative new model for GaN HEMT electrical degradation

Step 1: formation of shallow pits/continuous groove in cap

- Pits/groove conducting: I_G↑

Step 2: growth of pits through anodic oxidation of AlGaN

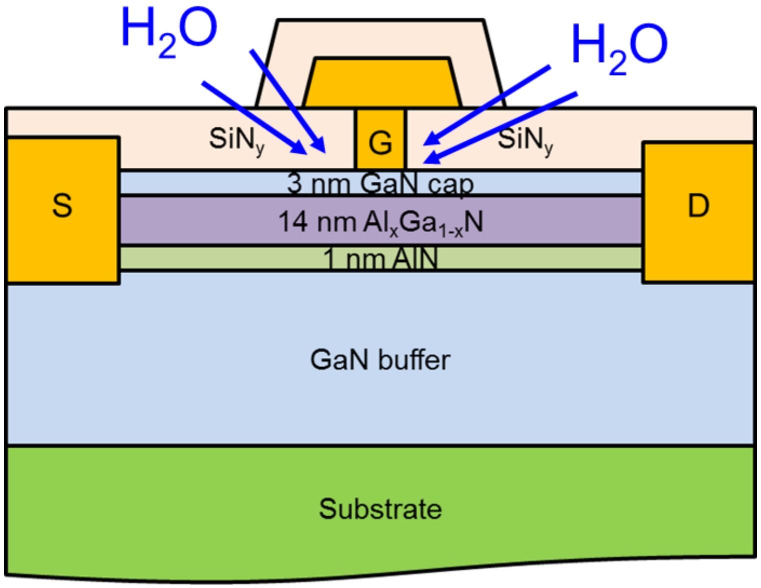
- I_{Dmax}↓ as electron concentration under gate edge reduced
- CC↑ due to new traps

Exponential dependence of tunneling current on electric field

→ *"critical voltage" behavior*

Paths for mitigation

1. Reduce hole production
   - Mitigate electric field at gate edge:
     - gate edge design
     - field plate design
   - Mitigate traps in AlGaN:
     - optimize growth conditions
     - reduce AlN composition
     - thin down AlGaN
     - mitigate mechanical stress



2. Reduce water around gate edge
   1. Reduce SiN permeability
   2. Mitigate trapped moisture during process
   3. Hermetic package

Many questions…

- I_G degradation:
  - Detailed physics of onset of pits/groove? Also of electrochemical nature?
  - Why weak temperature activation?
  - Why does I_G degradation saturate?
  - Detailed mechanism for electrical conduction of pits?
- Trap formation:
  - Why traps introduced during degradation have similar dynamic signature as virgin traps?
- Mechanical stress:
  - Does mechanical stress and inverse piezoelectric effect still play role in degradation?
- Large variability in reliability:
  - Why? Also need effective screening process for virgin devices
- High-power RF stress
  - Is there a pulsed stress mode that faithfully emulates high-power RF stress?