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

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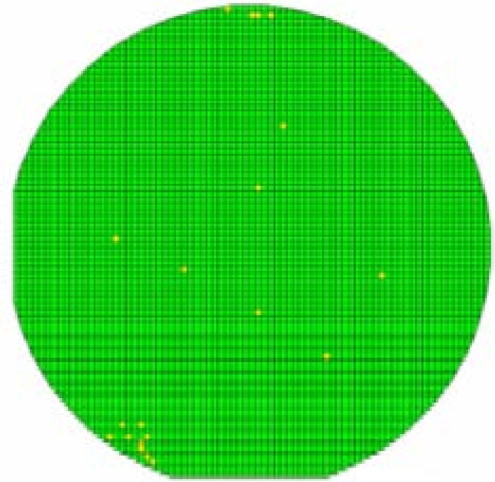
Outline

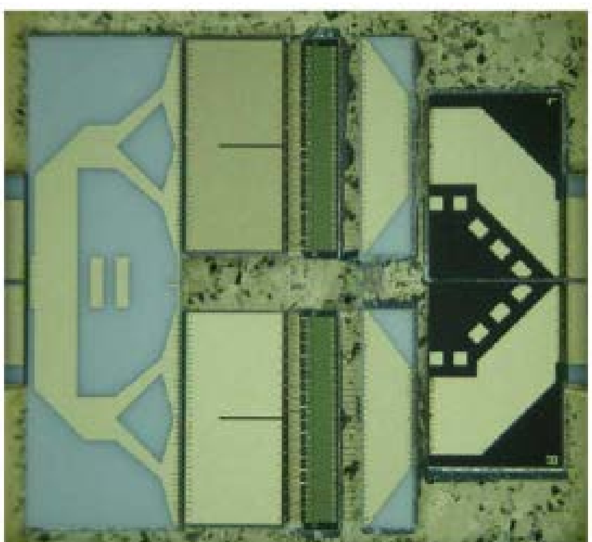
1. A few “universal” observations
2. Hypotheses for degradation mechanisms
3. Many questions…

GaN HEMT: breakthrough RF power technology

Counter-IED Systems (CREW)



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



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

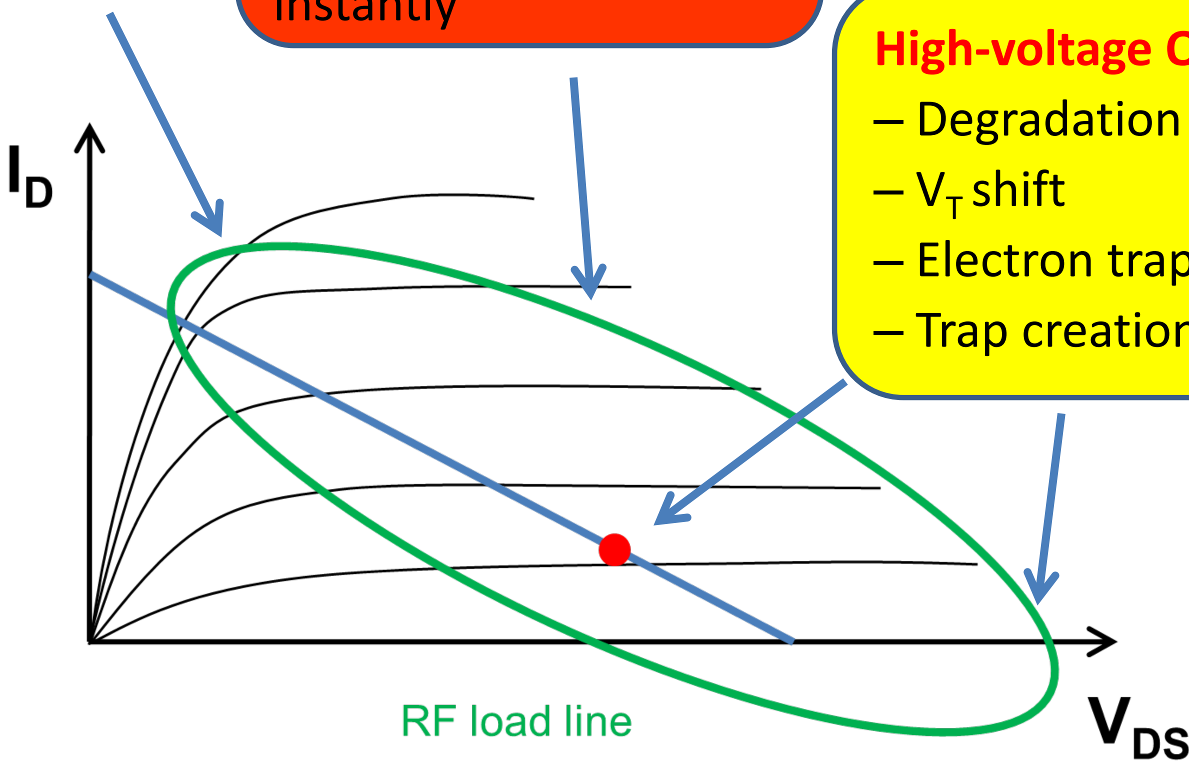
Sumitomo Remote Radio Head for Japanese Base Station

GaN HEMT: Electrical reliability concerns

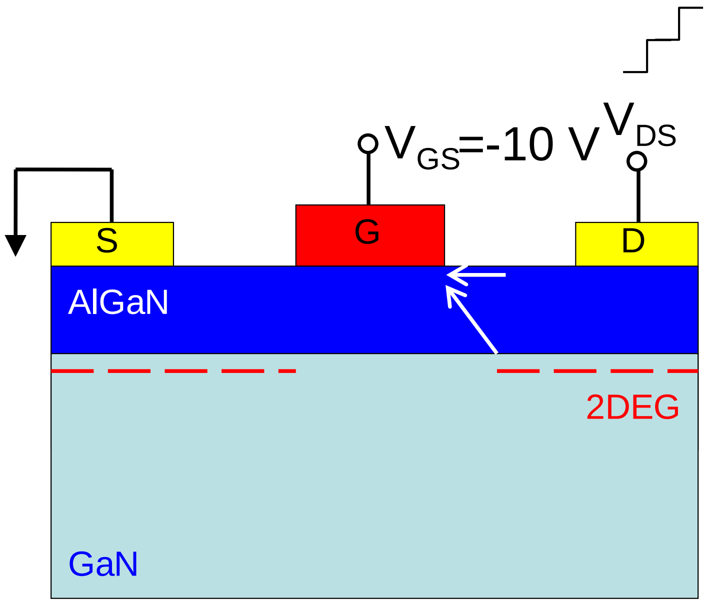
ON:
– Mostly benign

High-power:
– Not accessible to DC stress experiments
– Device blows up instantly

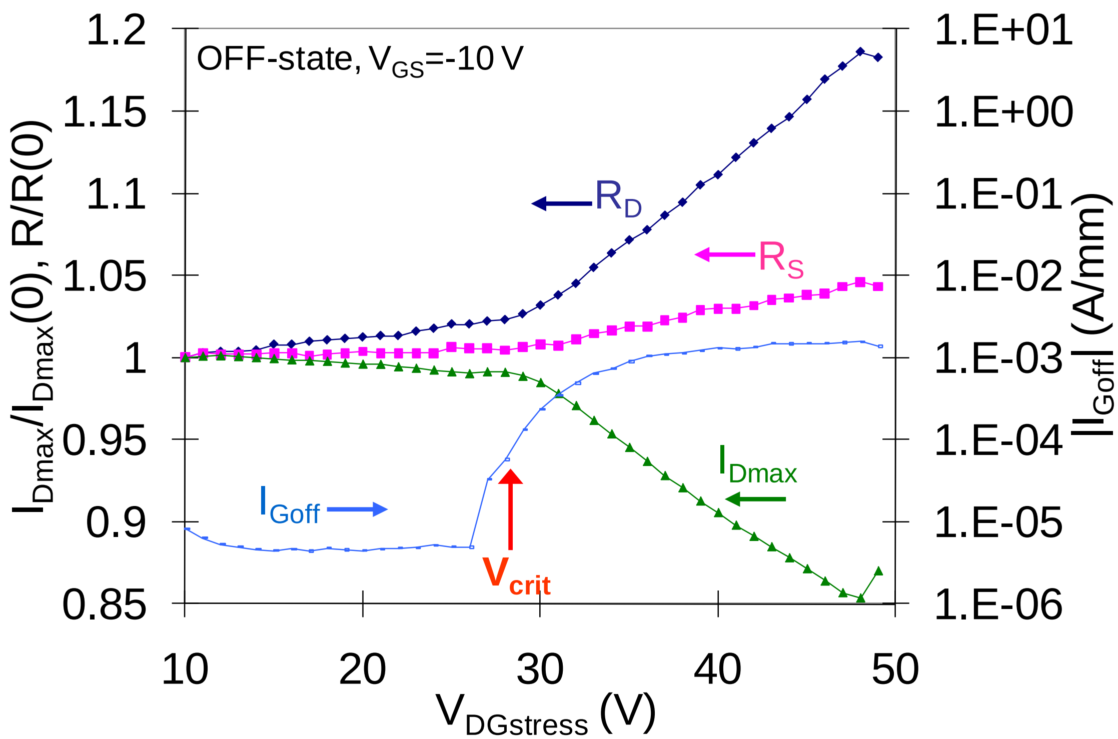
High-voltage OFF and semi-ON:
– Degradation of I_{Dmax}, R_D, I_{Goff}
– V_T shift
– Electron trapping
– Trap creation



Critical voltage for degradation in DC step-stress experiments



Joh, EDL 2008

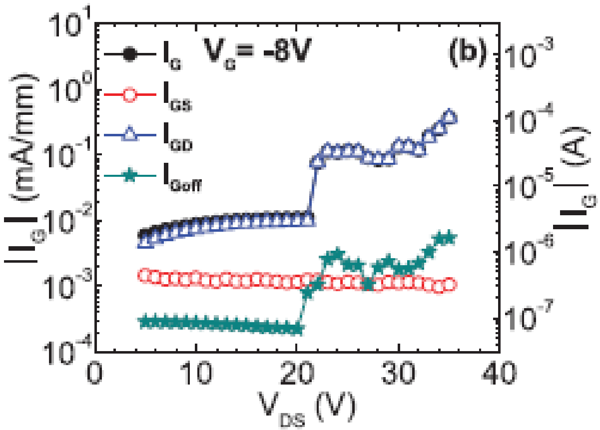


I_{Dmax}: V_{DS}=5 V, V_{GS}=2 V I_{Goff}: V_{DS}=0.1 V, V_{GS}=-5 V

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

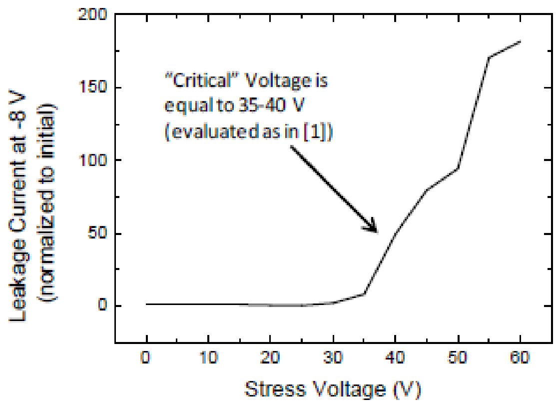
Critical voltage: a universal phenomenon

GaN HEMT on SiC



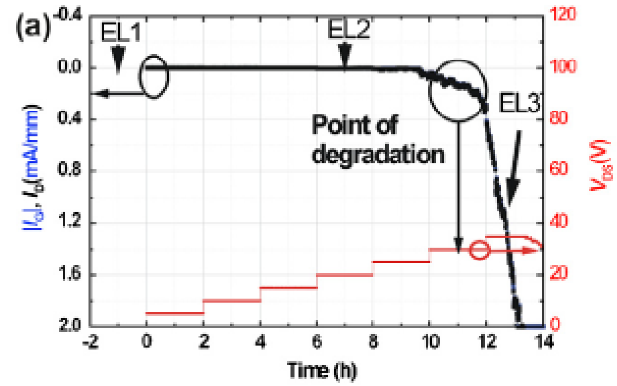
Liu, JVSTB 2011

GaN HEMT on SiC



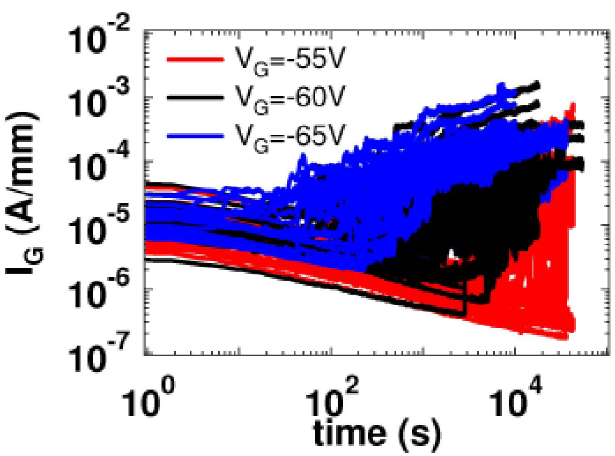
Meneghini, IEDM 2011

GaN HEMT on SiC



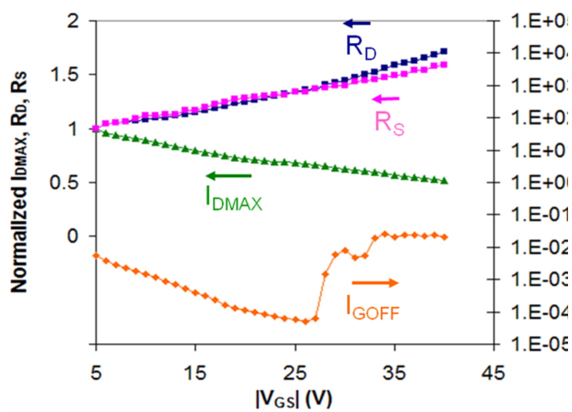
Ivo, MR 2011

GaN HEMT on Si



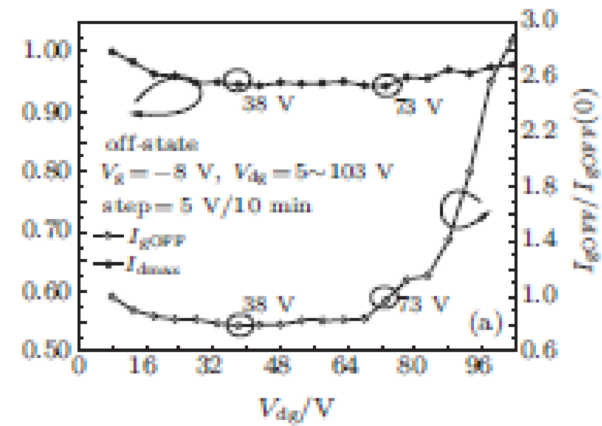
Marcon, IEDM 2010

GaN HEMT on Si



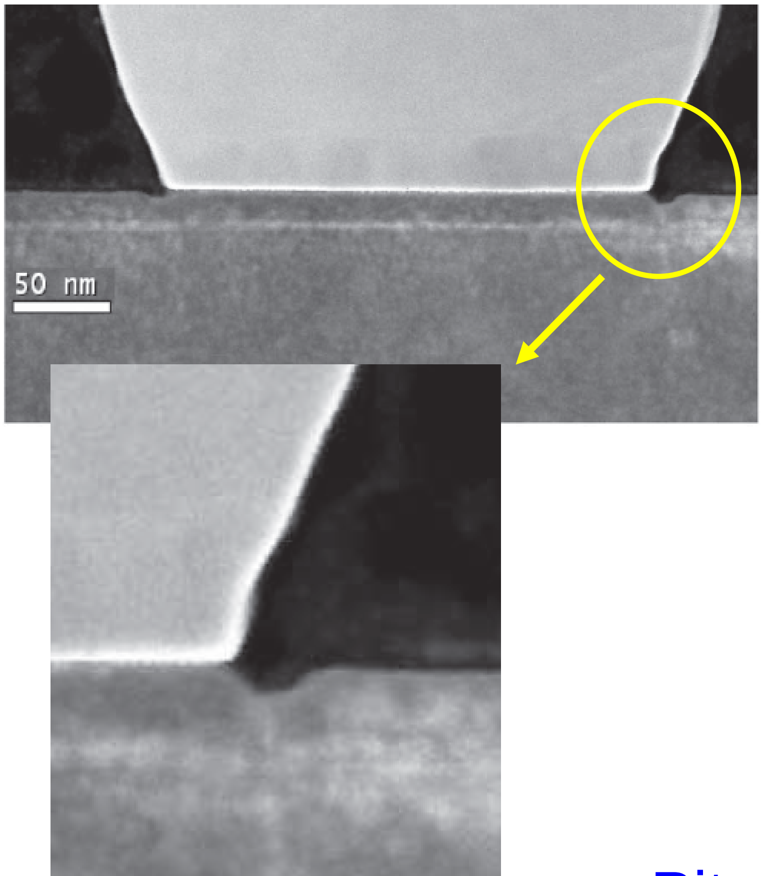
Demirtas, ROCS 2009

GaN HEMT on sapphire

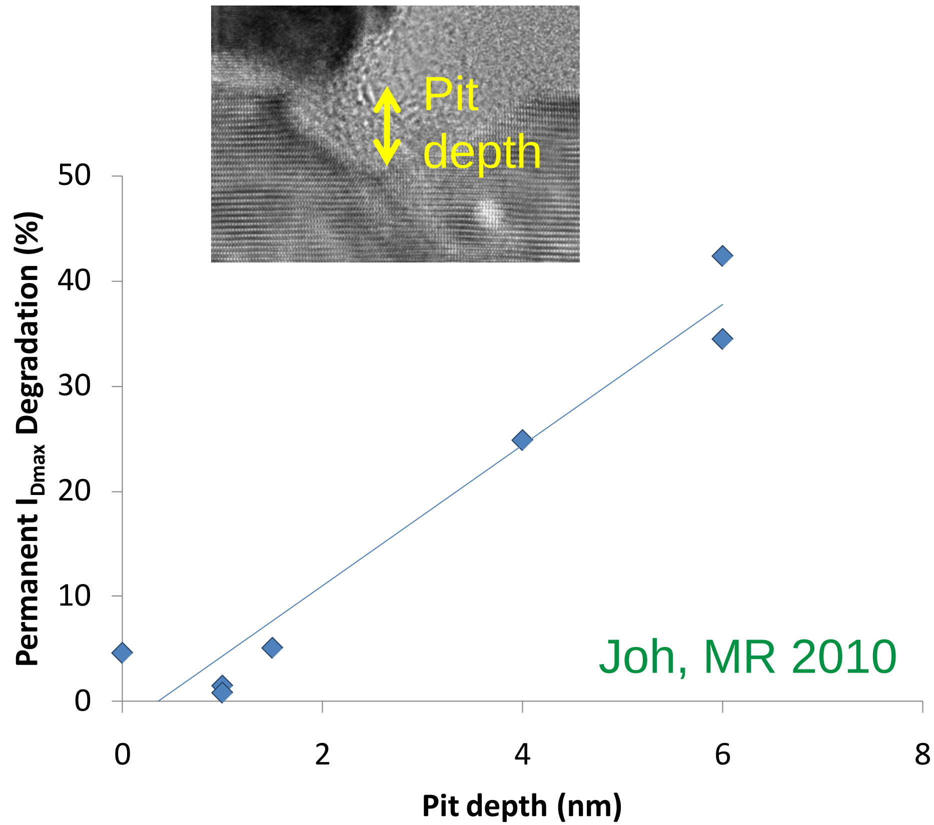


Ma, Chin Phys B 2011

Structural degradation; correlation with electrical degradation

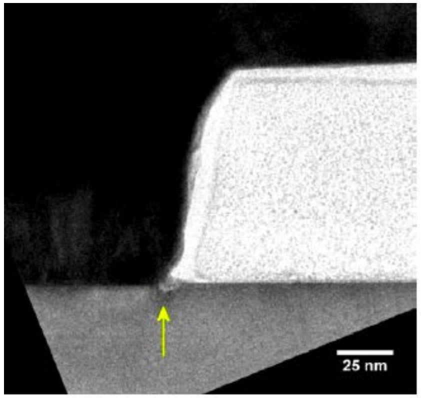


Chowdhury, EDL 2008

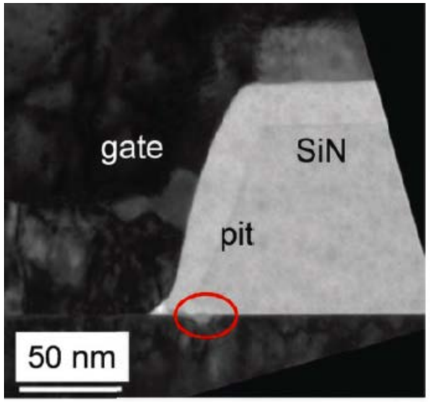


- Pit at edge of gate
- Pit depth and I_{Dmax} degradation correlate

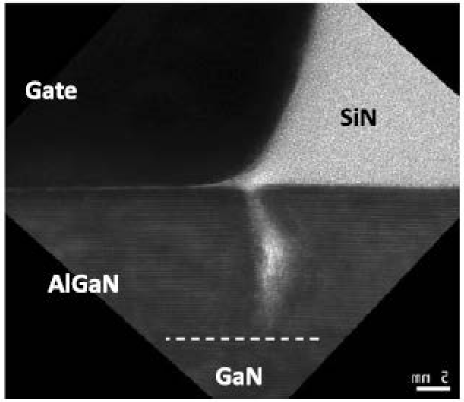
Structural damage at gate edge: a universal phenomenon



Barnes, CS-MANTECH 2012

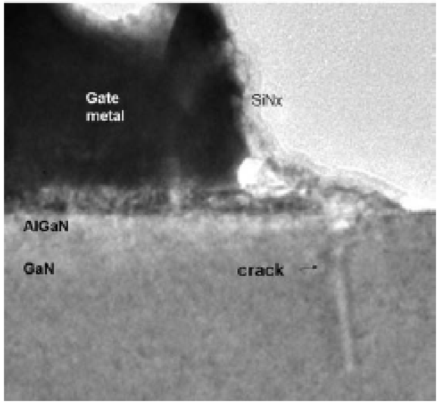


Dammann, IIRW 2011

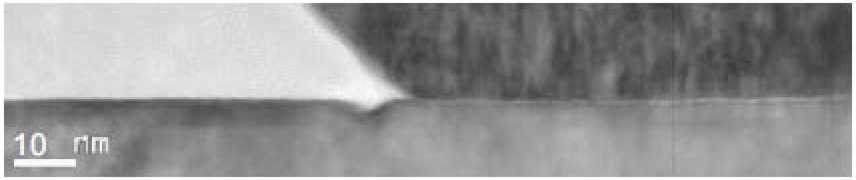


Marcon, MR 2010

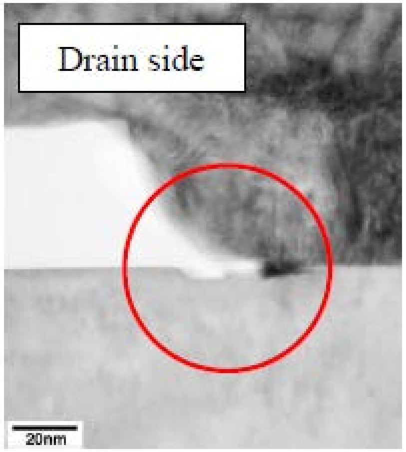
Cullen, TDMR 2013



Chang, TDMR 2011



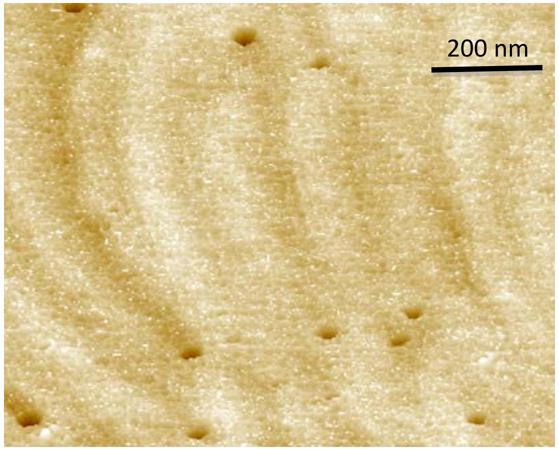
Liu, JVSTB 2011



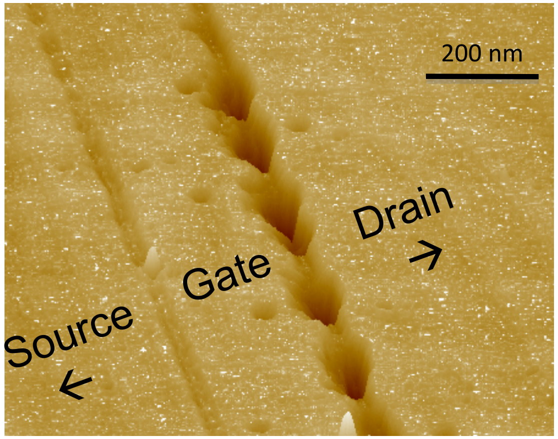
Christiansen, IRPS 2011

Structural degradation: planar view

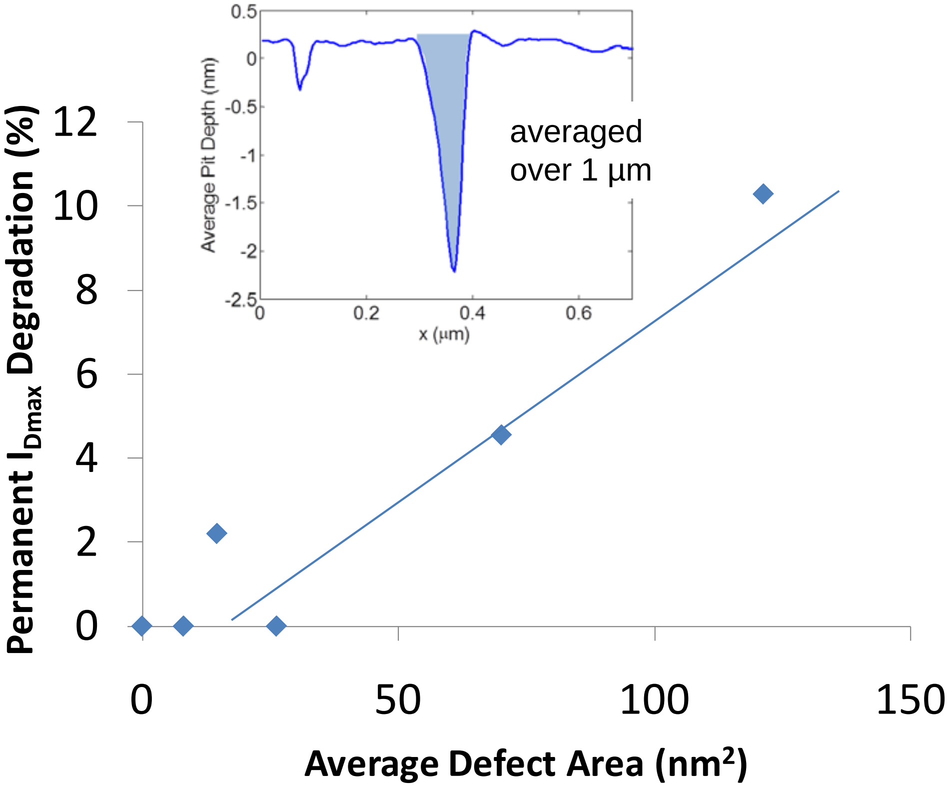
Unstressed



OFF-state stress:
V_{DG}=57 V, T_{base}=150 °C

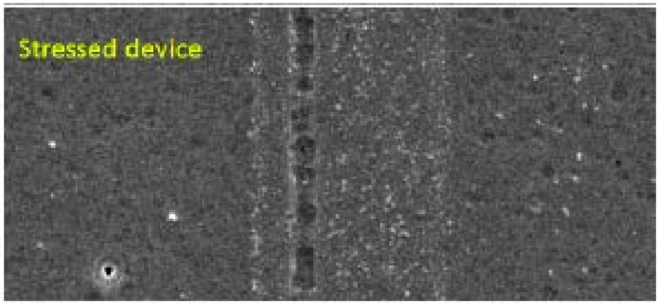


Makaram, APL 2010

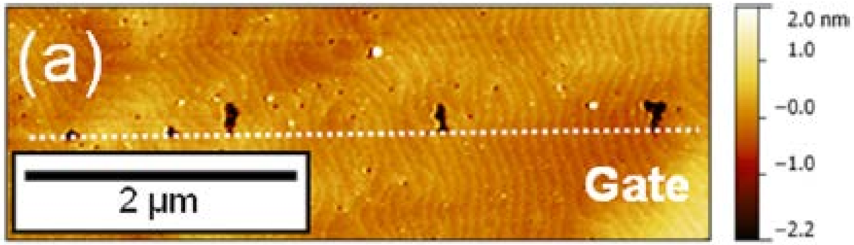


- V_{stress}>V_{crit}: pits along gate edge
- Pit cross-sectional area correlates with I_D degradation

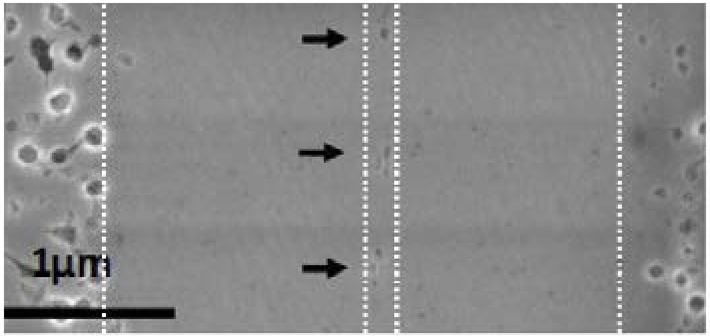
Structural damage at gate edge: a universal phenomenon



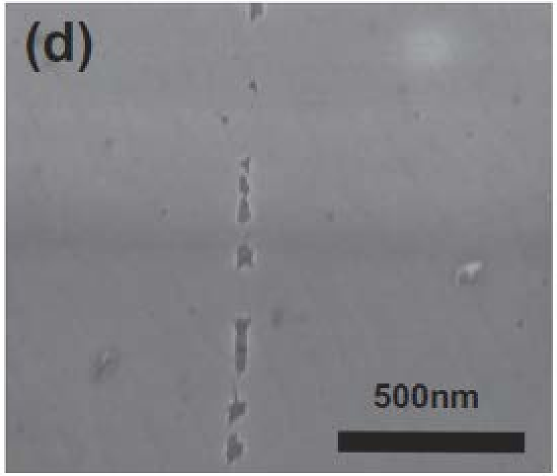
Barnes, CS-MANTECH 2012



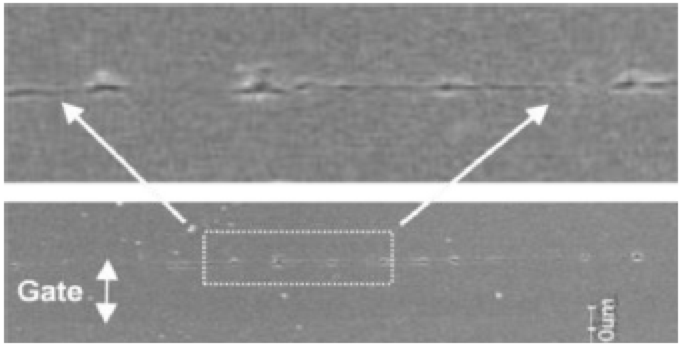
Monte Bajo, APL 2014



Holzworth, ECST 2014

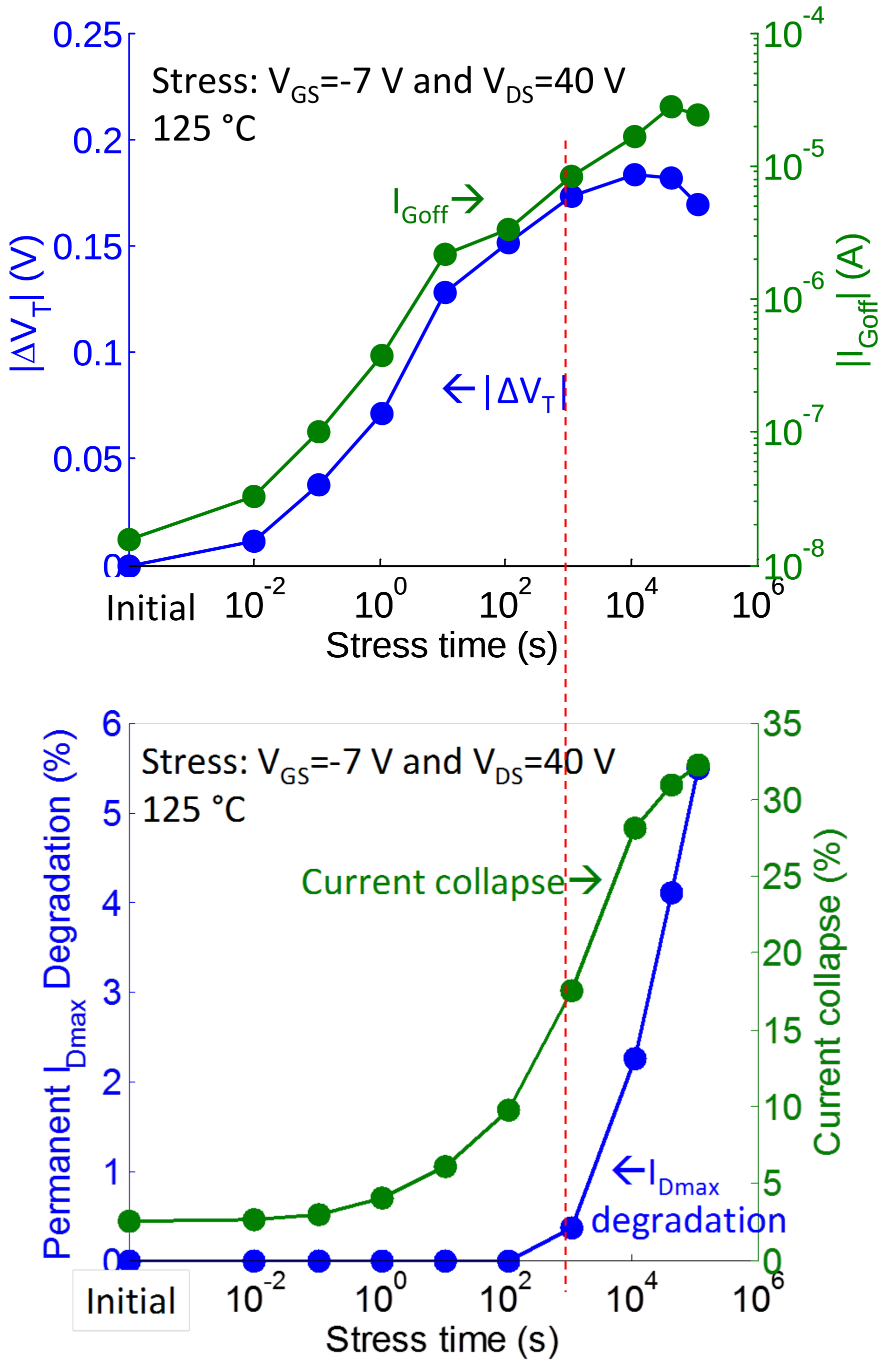


Whiting, MR 2012



Brunel, MR 2013

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



I_{Goff} and V_T degradation:

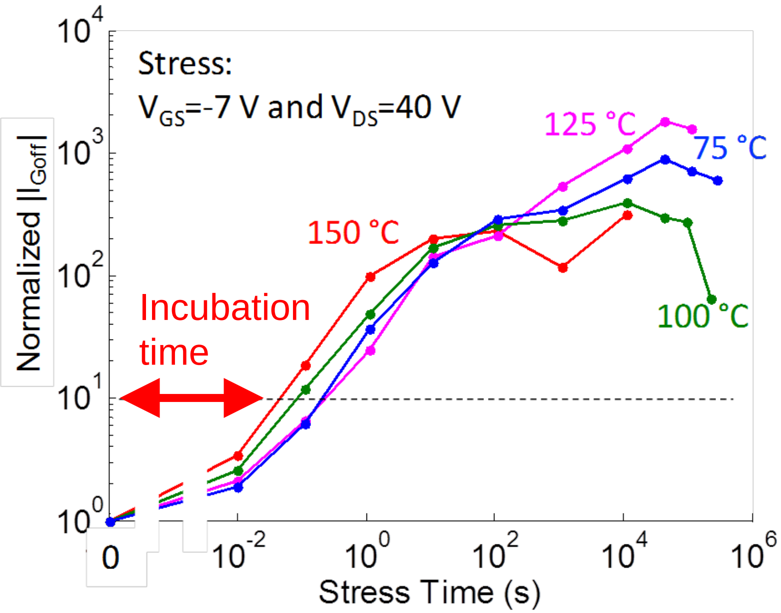
- fast (<10 ms)
- saturate after 10^4 s

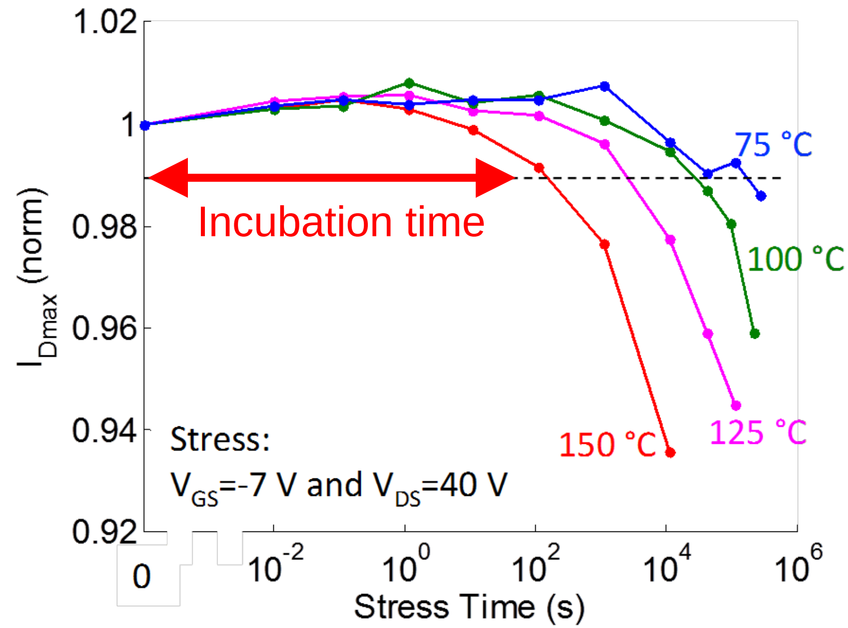
Permanent I_{Dmax} degradation:

- much slower
- does not saturate with time

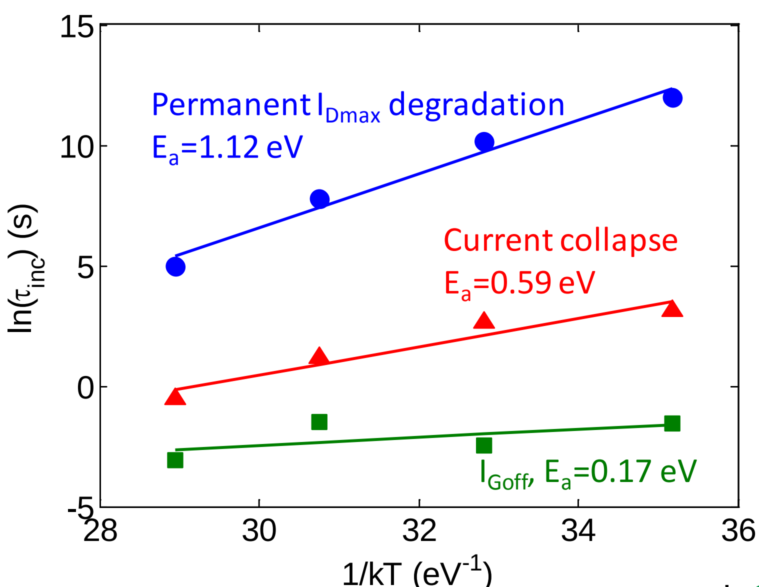
Joh, IRPS 2011

The role of temperature in time evolution





Joh, IRPS 2011



Different degradation physics:

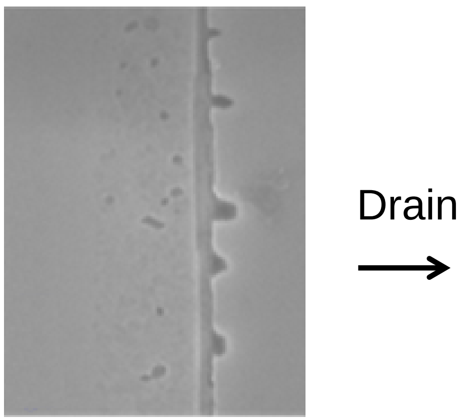
- I_G: weak T dependence
- I_{Dmax}: T activated, E_a similar to life-test data*

* Saunier, DRC 2007; Meneghesso, IJMWT 2010

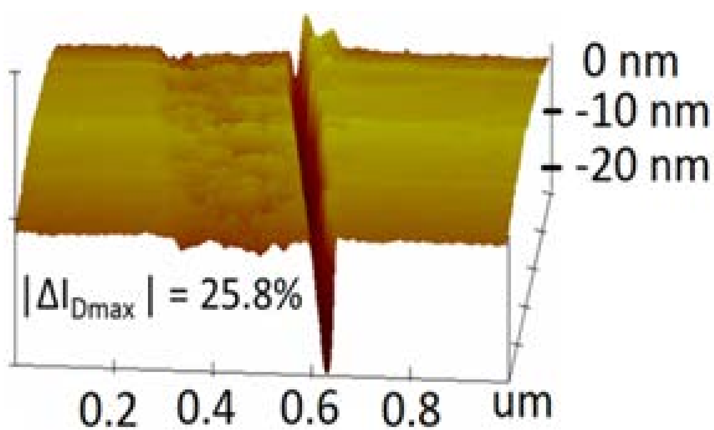
DC semi-ON stress experiments

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

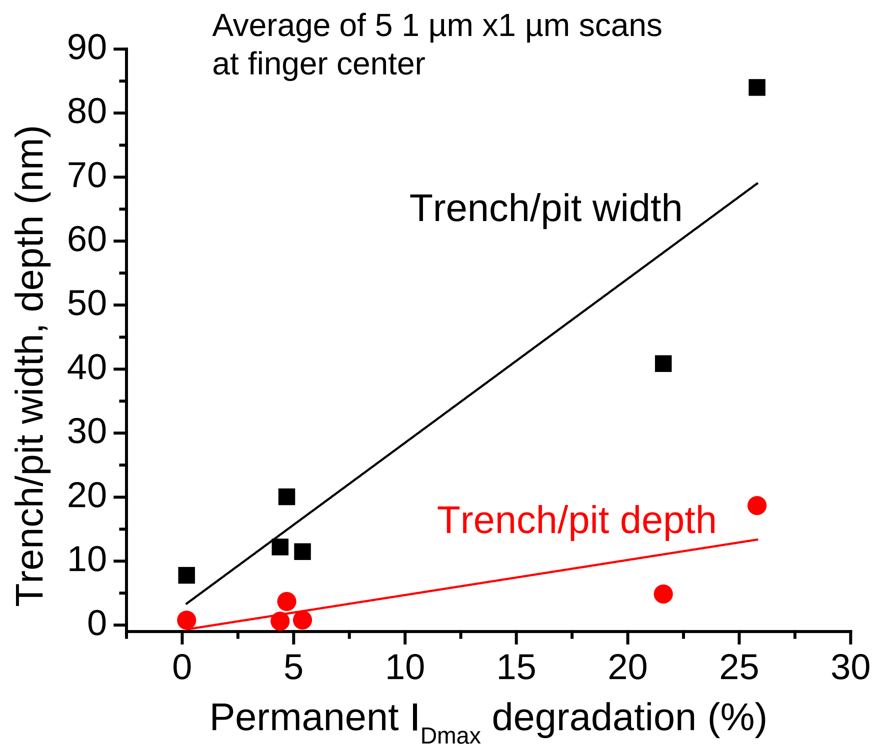
SEM



AFM

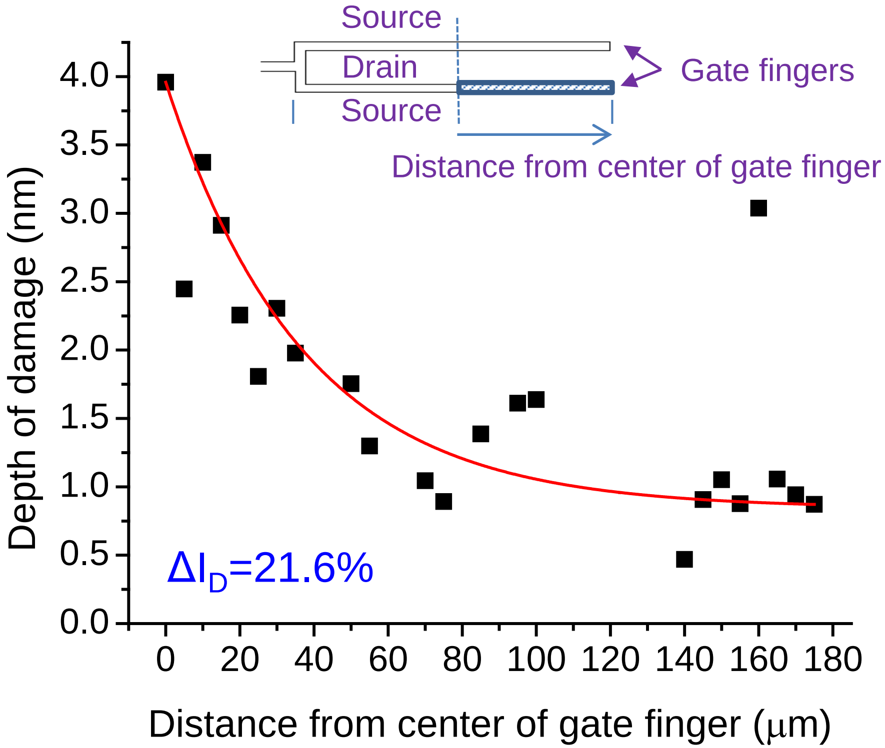


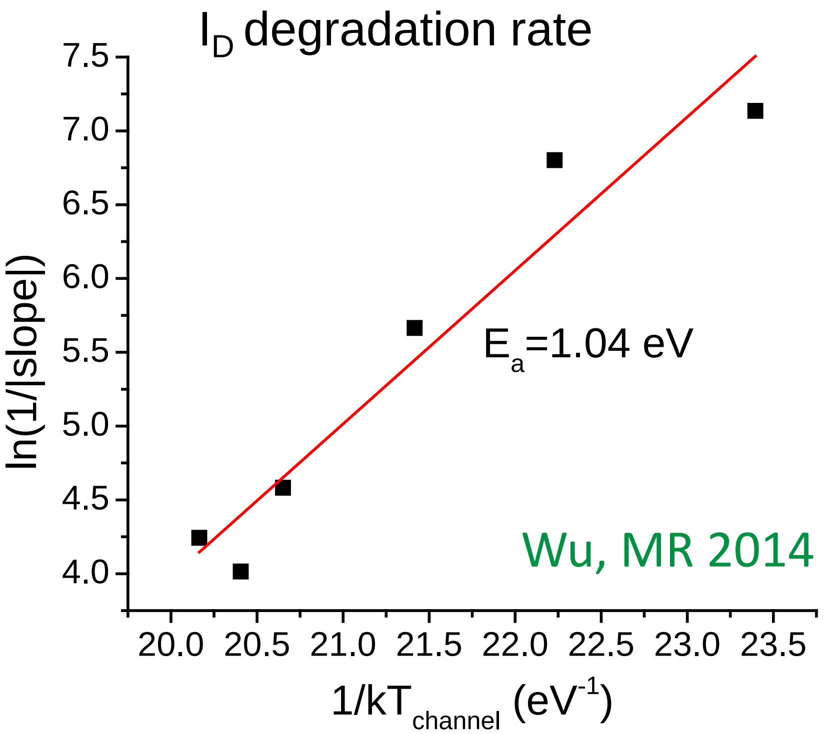
Wu, JAP 2015



- Pits and trenches under gate edge on drain side
- Trench/pit depth and width correlate with I_{Dmax} degradation

Thermally activated degradation





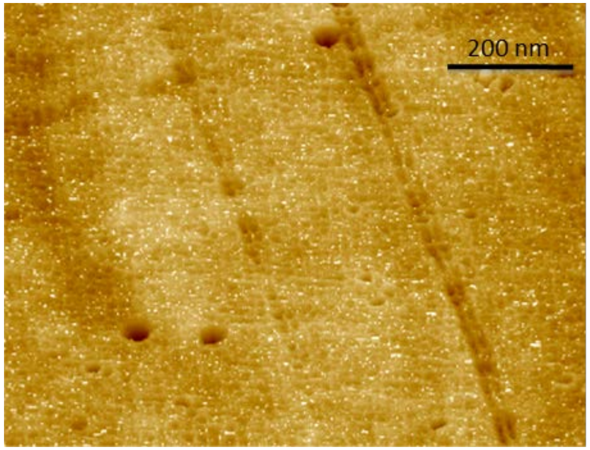
- Pit/trench depth increase towards center of gate finger
  → self heating + thermally activated process
- Permanent I_{Dmax} degradation thermally activated with E_a~1.0 eV

Summary of electrical and structural degradation under OFF and Semi-ON bias

1. I_G degradation

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

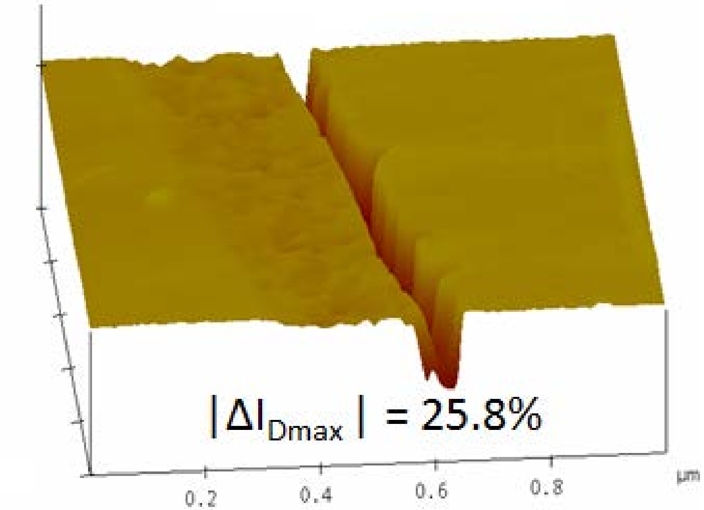
Correlates with appearance of shallow *groove* and *small pits*



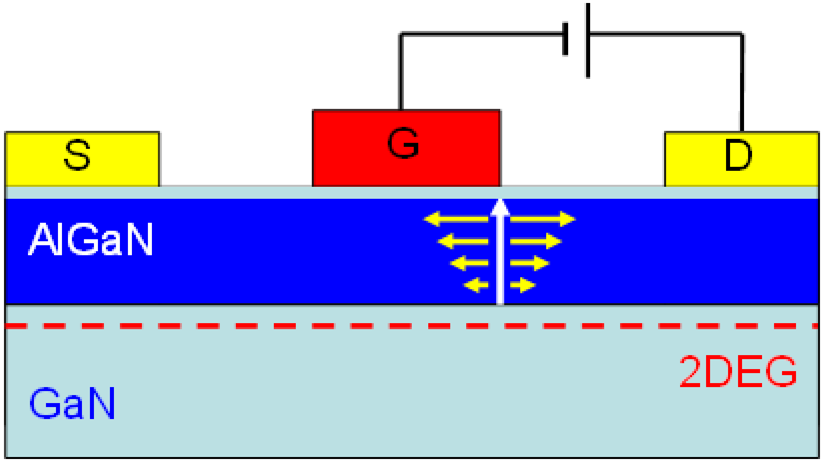
2. I_{Dmax} degradation

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

Correlates with growth of *pits* and merging into *trenches*



Initial hypothesis:
Inverse Piezoelectric Effect Mechanism



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

Defects:

Trap electrons

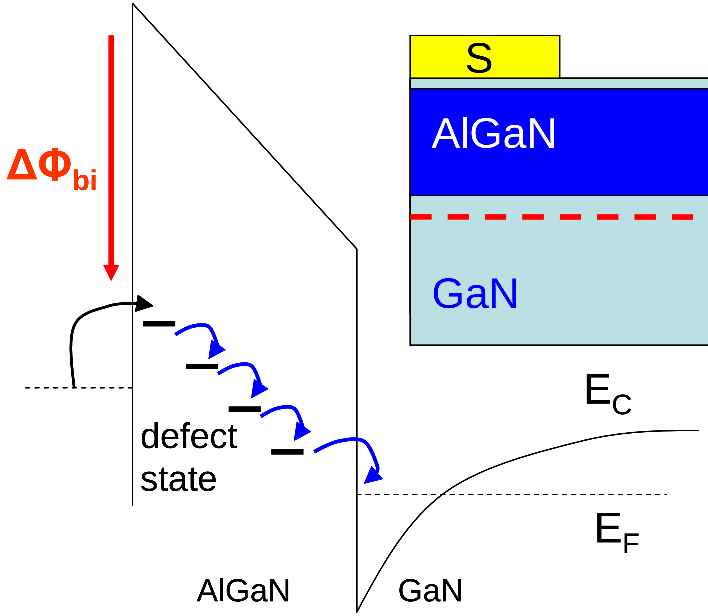
→ n_s↓ → R_D↑, I_D↓

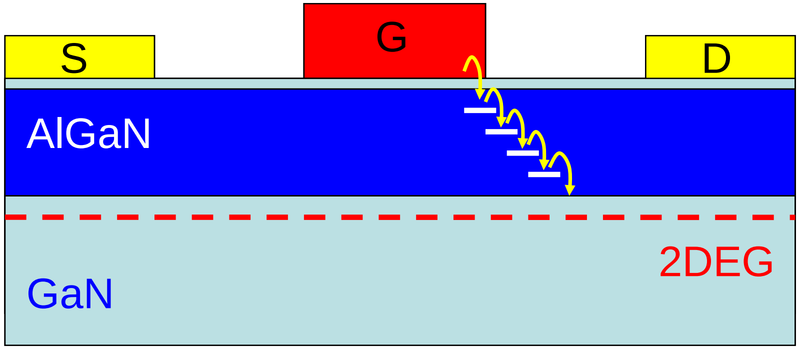
Strain relaxation

→ I_D↓

Provide paths for I_G

→ I_G↑





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

Predictions of Inverse Piezoelectric Effect model borne out by experiments

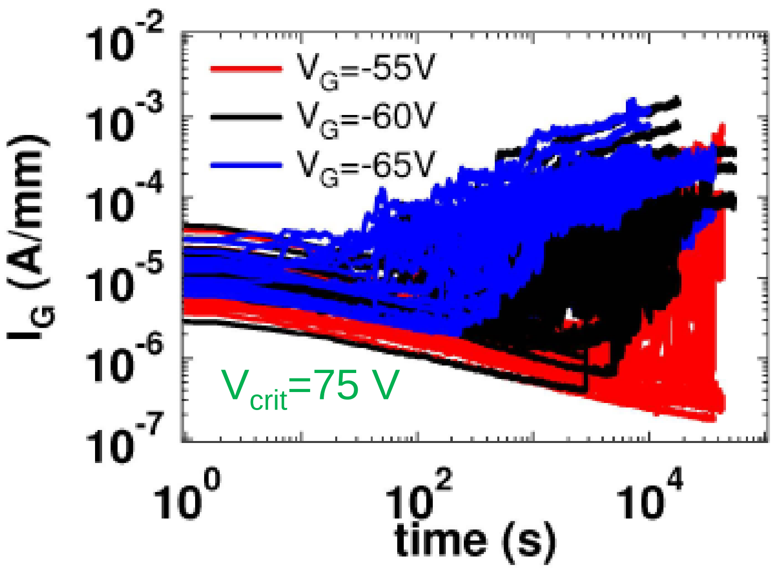
To enhance GaN HEMT reliability:

- 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)

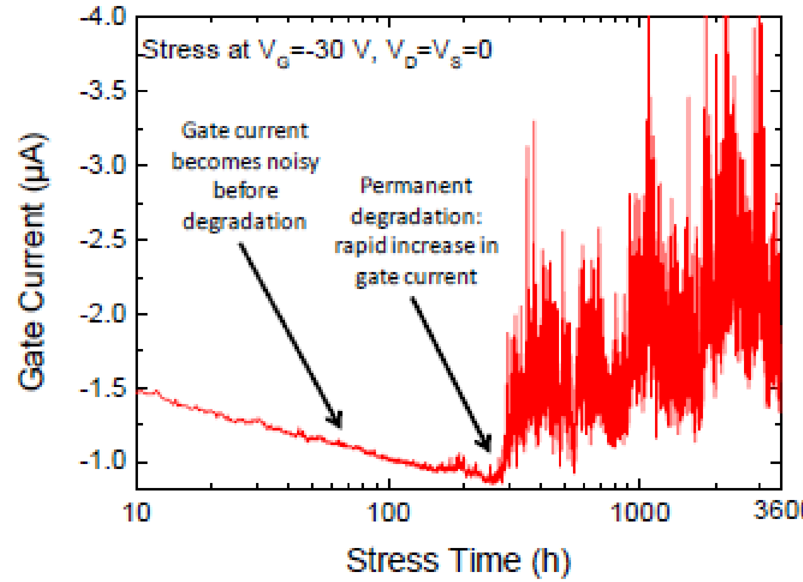
Can't explain:

- Groove formation/I_G degradation below critical voltage
- Sequential nature of I_G and I_D degradation
- Presence of oxygen in pit
- Role of atmosphere during stress

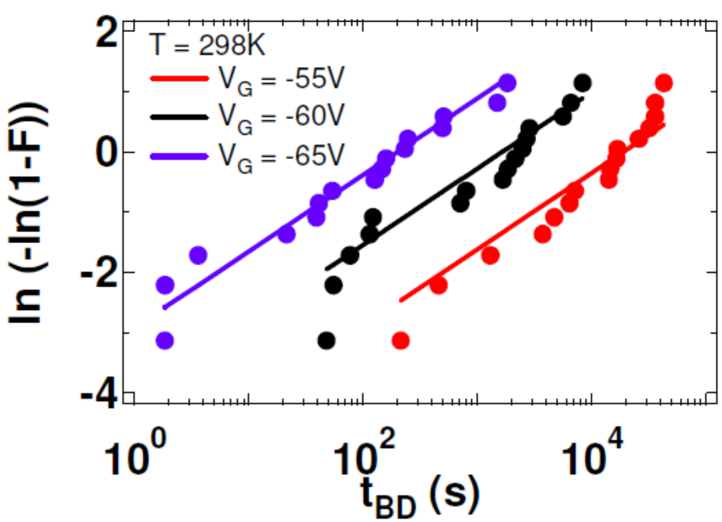
I_G degradation not critical; TDDB*-like



Marcon, IEDM 2010



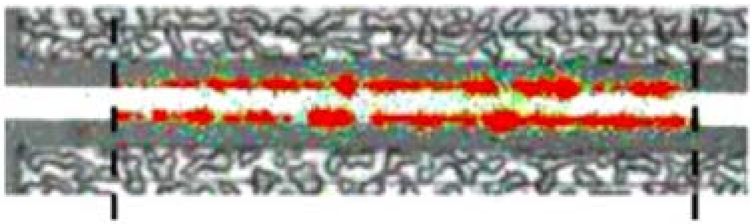
Meneghini, IEDM 2011



- I_G starts increasing for V_{stress}<V_{crit}
- Onset enhanced by V_{stress}
- Weibull distribution
- Preceded by onset of I_G noise

* TDDB = Time-Dependent Dielectric Breakdown

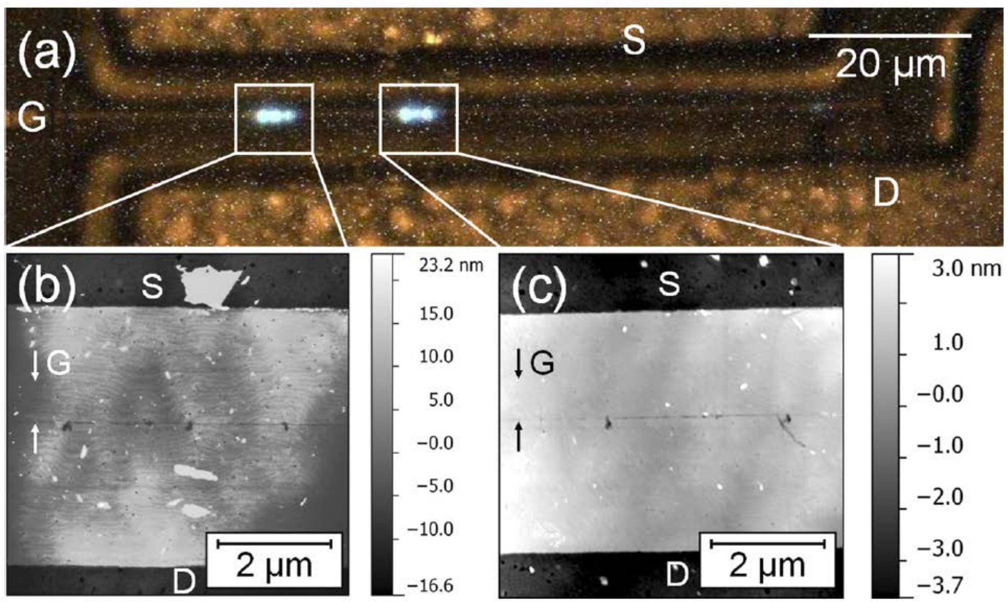
I_G correlates with EL; EL hot spots correlate with pits, pits are conducting



Zanoni, EDL 2009

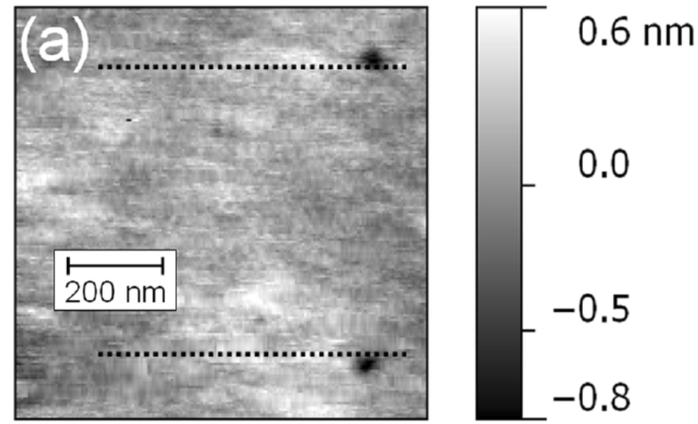
EL picture

Montes Bajo, APL 2012

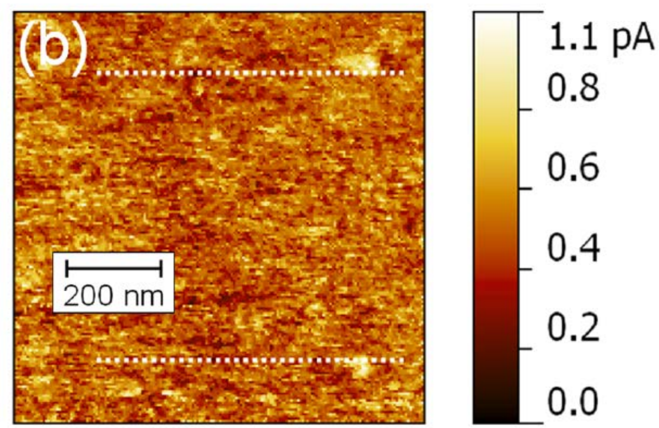


AFM topography

Normal AFM



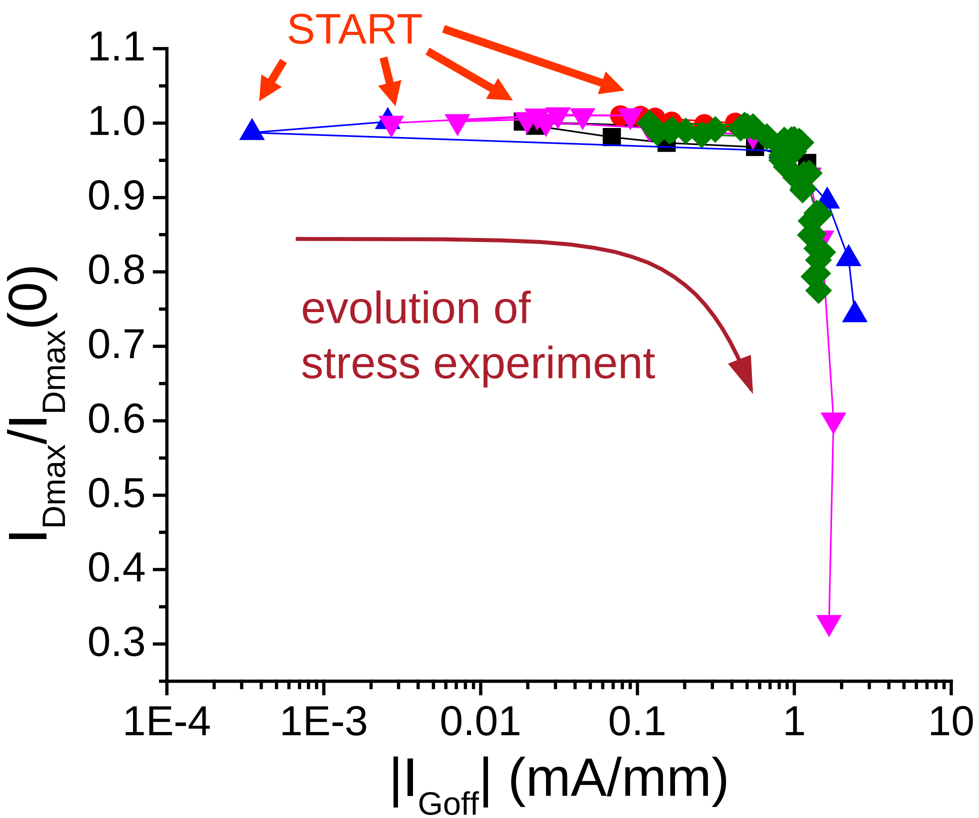
Conducting AFM



Shallow pits responsible for I_G degradation

Sequential I_G and I_D degradation

Semi-ON stress:
I_D=100 mA/mm,
V_{DS}=40 or 50 V
Step-Temperature: 50<T_a<230°C



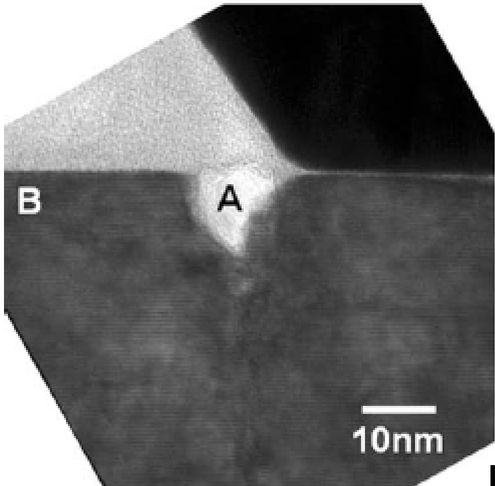
Wu, ROCS 2014

Wu, MR 2014

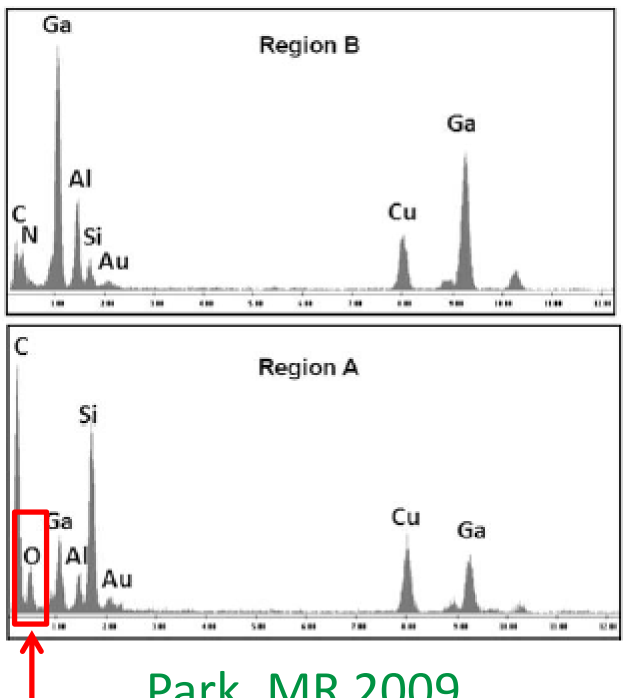
"Universal" degradation pattern:

- I_G degradation first without I_D degradation
- I_D degradation next without further I_G degradation
- "Corner" of I_G and I_D same for all samples

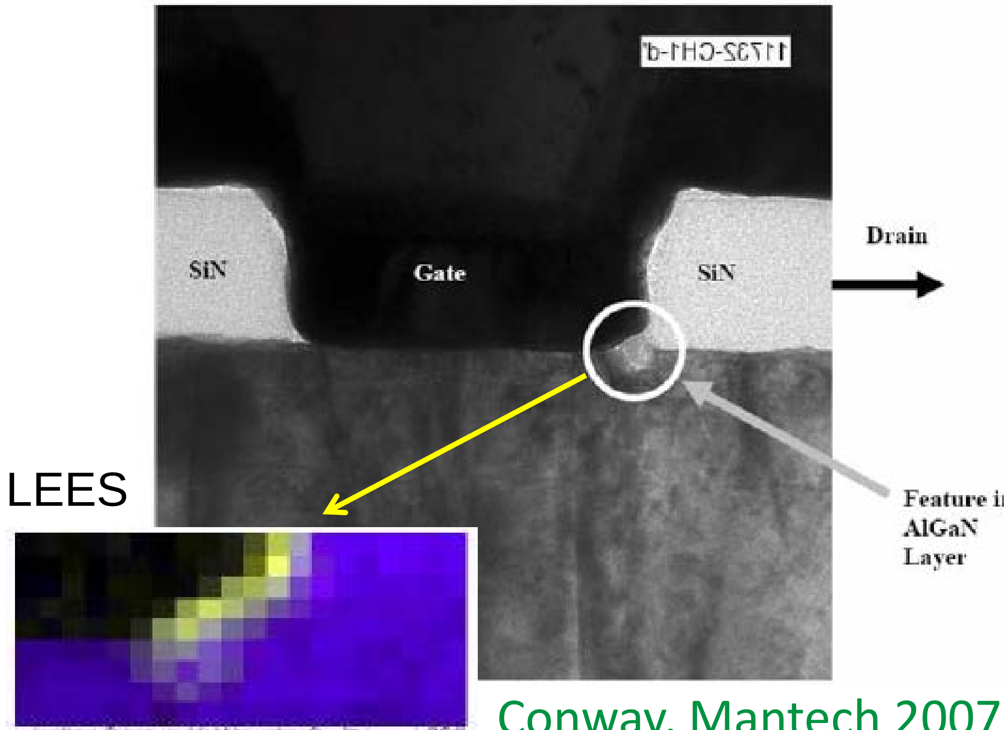
Oxygen inside pit



EDX



Park, MR 2009



Conway, Mantech 2007

- O, Si, C found inside pit
- Anodization mechanism for pit formation? (Smith, ECST 2009)

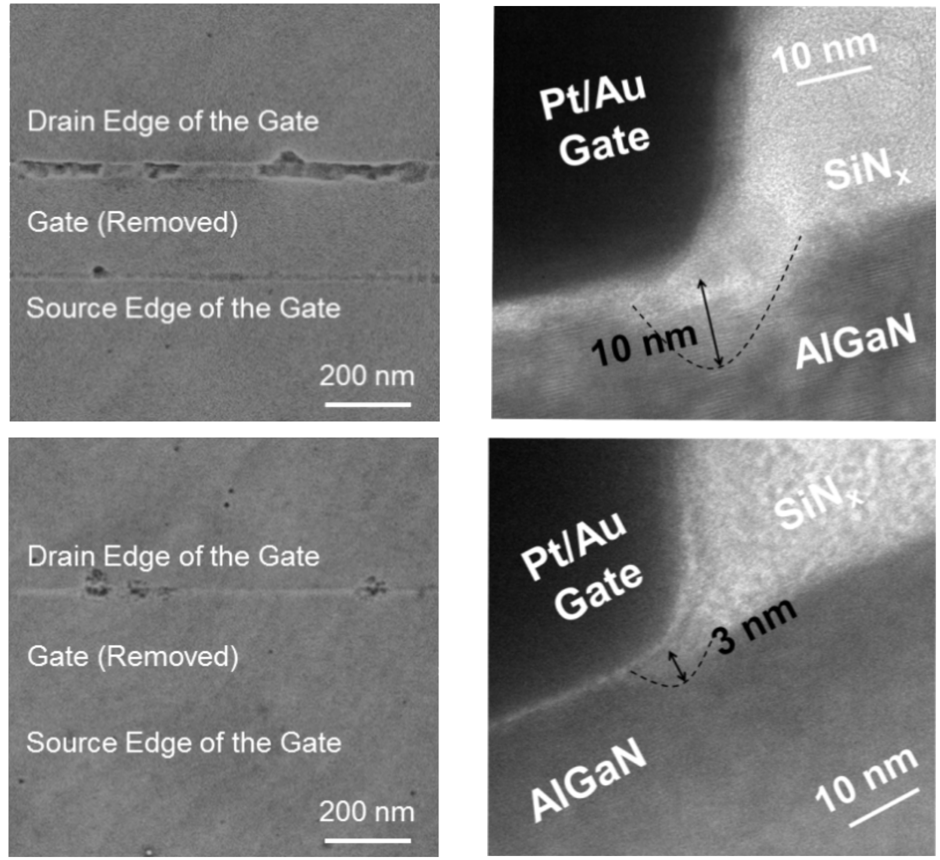
Role of atmosphere on structural degradation

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

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

Stressed in dry gas (Ar)
ΔI_D=0.3%

SEM Top View | TEM Cross Section

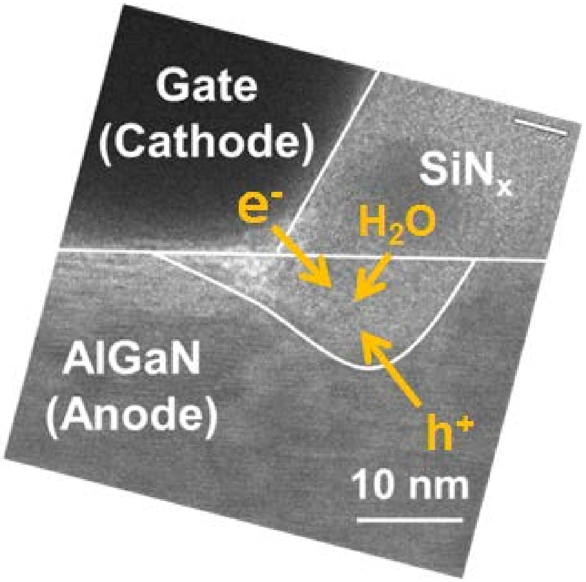


Gao, TED 2014

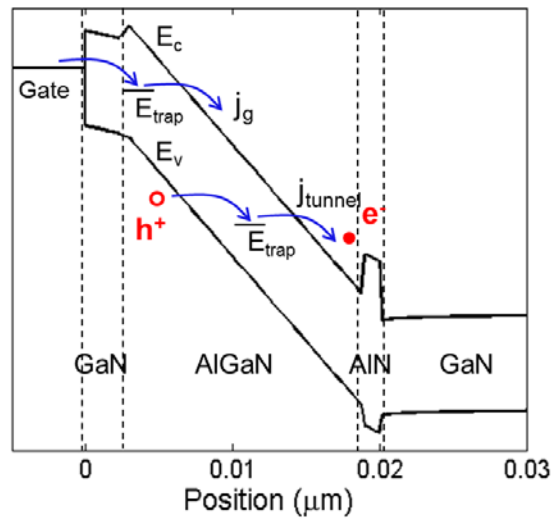
- Moisture enhances surface pitting
- Results reproduced with dry/wet O_2, N_2, CO_2, air and vacuum

New phenomenon: AlGaN corrosion

Electrochemical cell formed at drain edge of gate



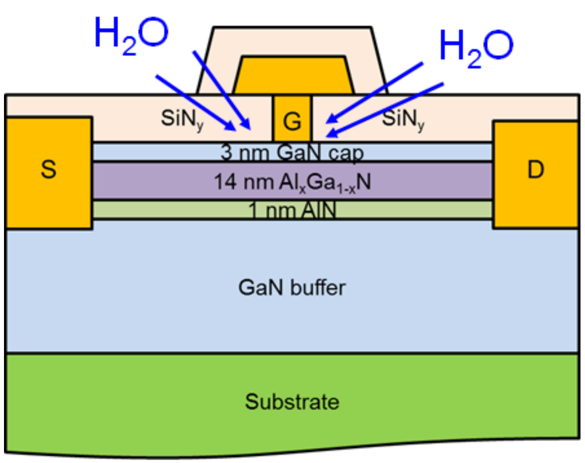
Source of holes: trap-assisted BTBT



Source of water: diffusion through SiN

Electrochemical reaction (requires holes):

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



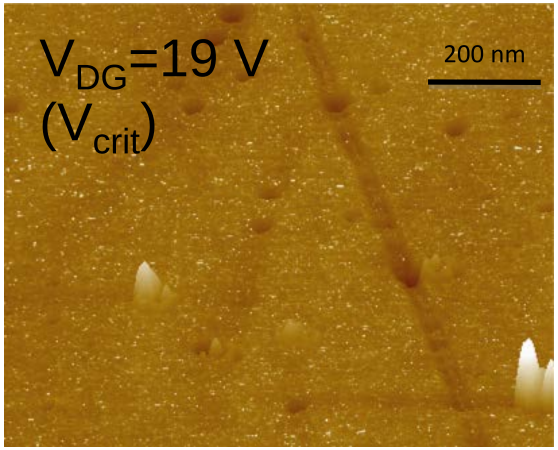
Gao, TED 2014

Tentative complete model?

Makaram, APL 2010

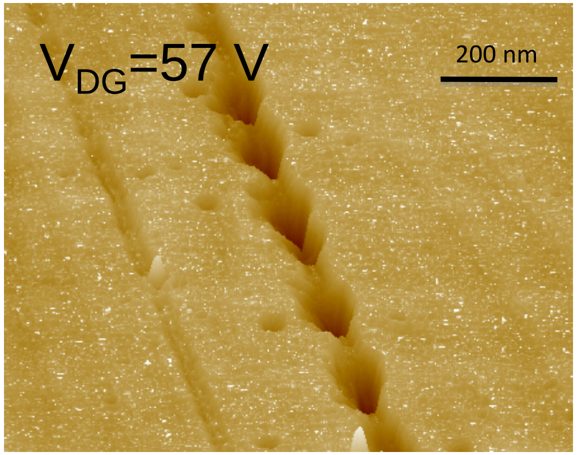
Step 1: formation of shallow pits/continuous groove in cap

- TDDB-like formation of small conducting paths: $I_G\uparrow$



Step 2: growth of pits through anodic oxidation of AlGaN

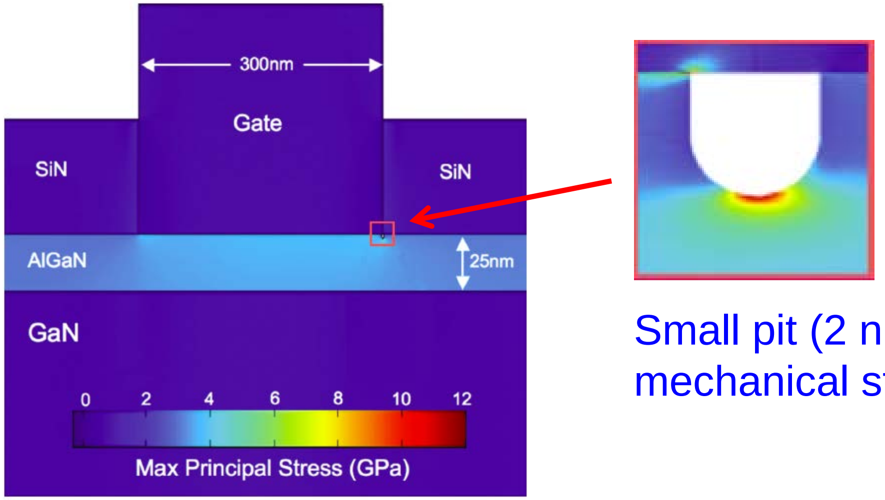
- $I_{Dmax}\downarrow$ as electron concentration under gate edge reduced



Exponential dependence of tunneling current on electric field → origin of *"critical voltage" behavior?*

Many questions…

- Why weak temperature activation of I_G degradation?
- Why does I_G degradation tend to saturate?
- Why does I_D degradation start as I_G degradation saturates?
- Does mechanical stress and inverse piezoelectric effect play role?



Ancona, JAP 2012

Small pit (2 nm x 3 nm) increases mechanical stress in AlGaN by 3X

- Why large variability in reliability?
- Is this all relevant under RF power conditions?