Recent Progress in Understanding the DC and RF Reliability of GaN High-Electron Mobility Transistors

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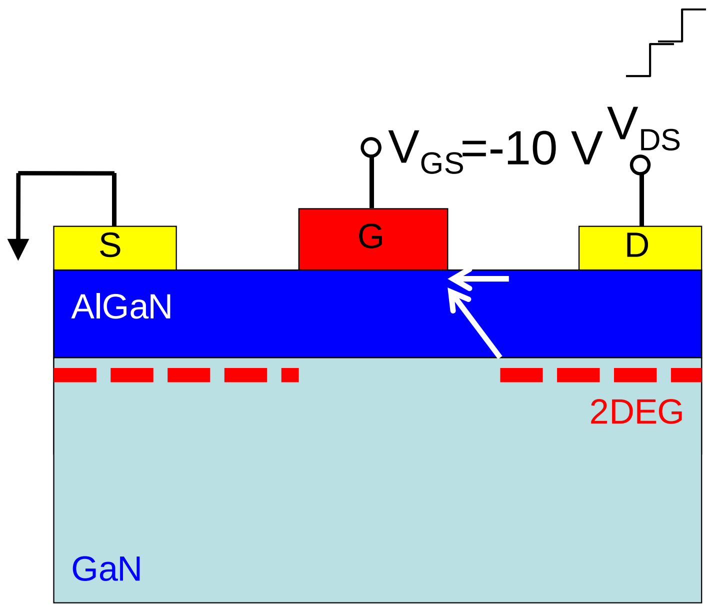
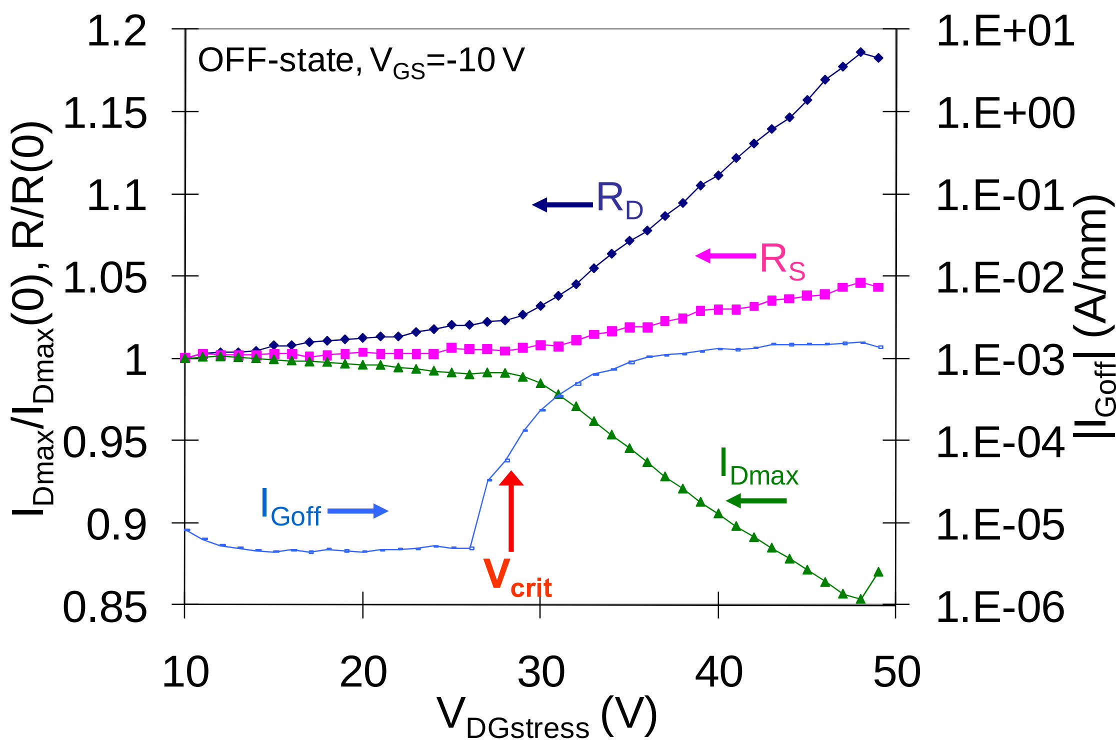
Outline

1. Critical voltage for GaN degradation
2. Structural degradation of GaN HEMTs
3. Time evolution of degradation
4. Discussion
5. Tentative new model for electrical degradation

Critical voltage for degradation of GaN HEMTs



Joh, EDL 2008

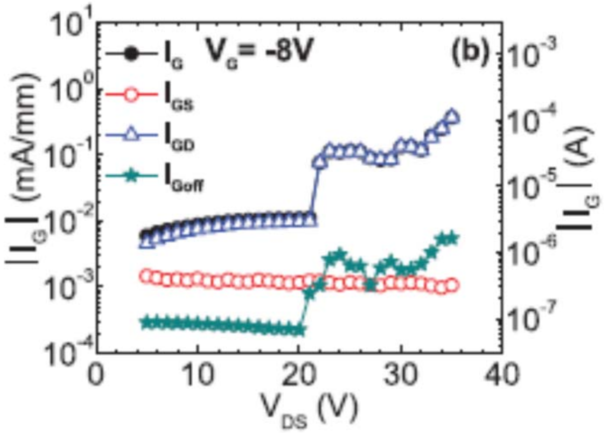


I_{Dmax}: V_{DS}=5 V, V_{GS}=2 V I_{Goff}: V_{DS}=0.1 V, V_{GS}=-5 V

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

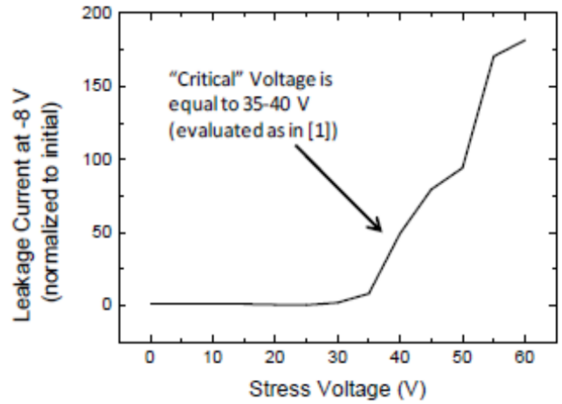
Critical voltage: a universal phenomenon?

GaN HEMT on SiC



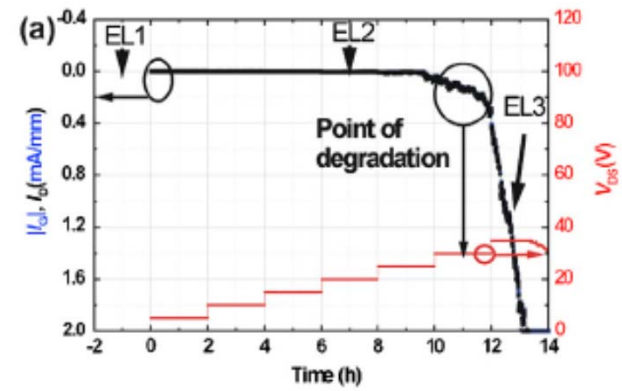
Liu, JVSTB 2011

GaN HEMT on SiC



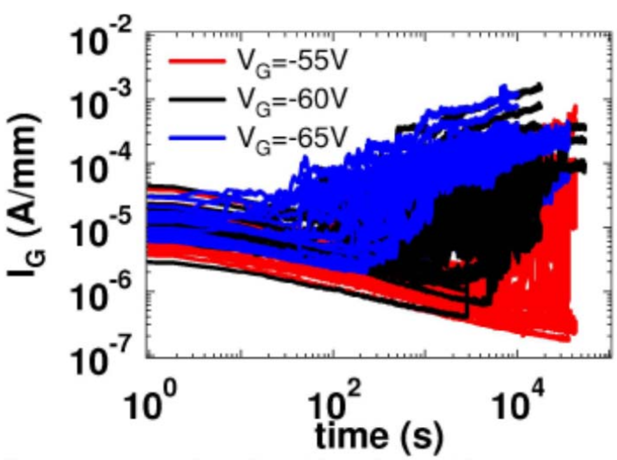
Meneghini, IEDM 2011

GaN HEMT on SiC



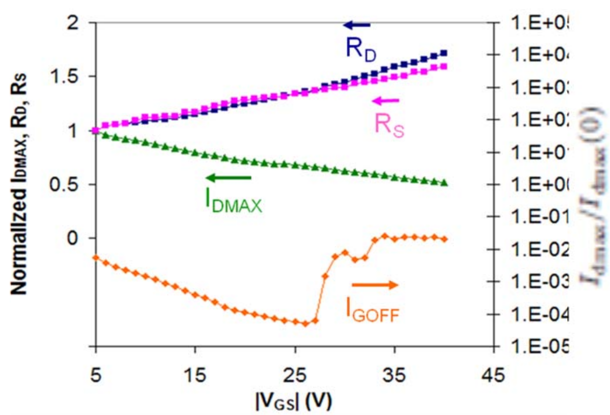
Ivo, MR 2011

GaN HEMT on Si



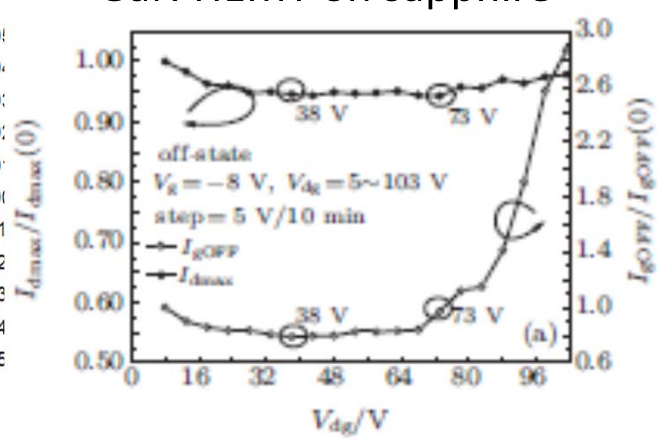
Marcon, IEDM 2010

GaN HEMT on Si



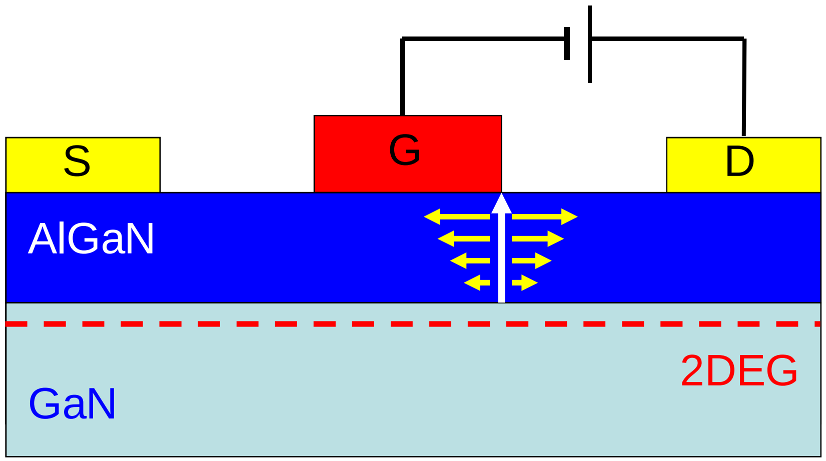
Demirtas, ROCS 2009

GaN HEMT on sapphire



Ma, Chin Phys B 2011

Initial hypothesis:
Inverse Piezoelectric Effect Mechanism



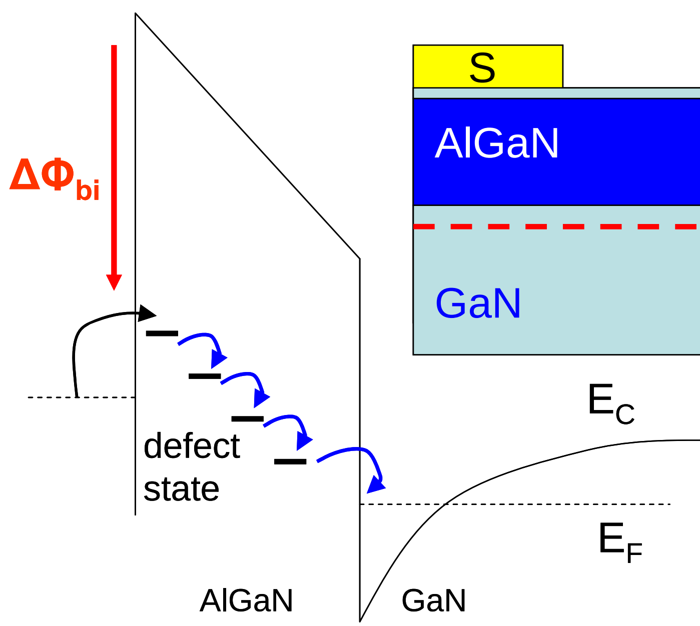
Strong piezoelectricity in AlGaN
→ $|V_{DG}|$↑ → tensile stress ↑
→ crystallographic defects beyond *critical elastic energy*

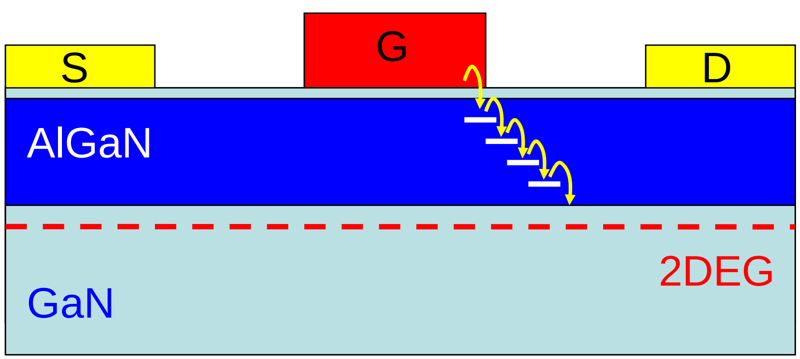
Defects:

Trap electrons
→ n_s↓ → R_D↑, I_D↓

Strain relaxation
→ I_D↓

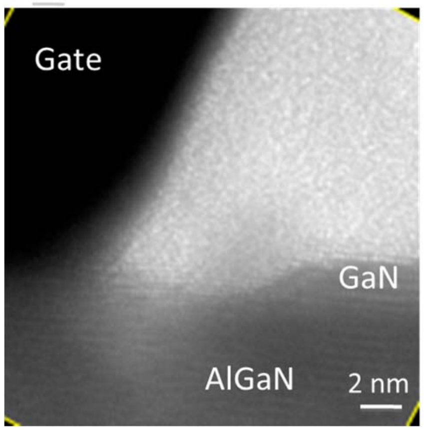
Provide paths for I_G
→ I_G↑



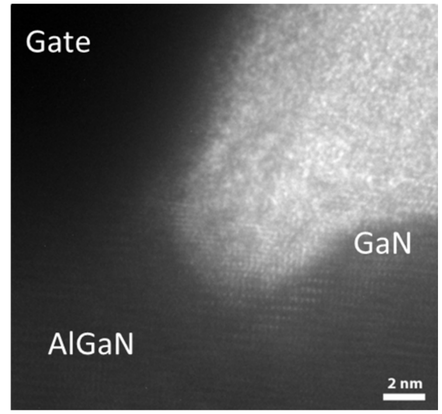


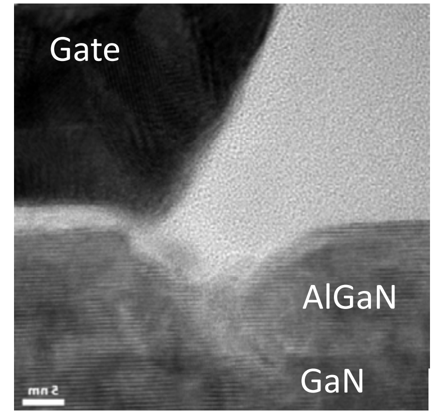
Joh, IEDM 2006
Joh, IEDM 2007
Joh, MR 2010b

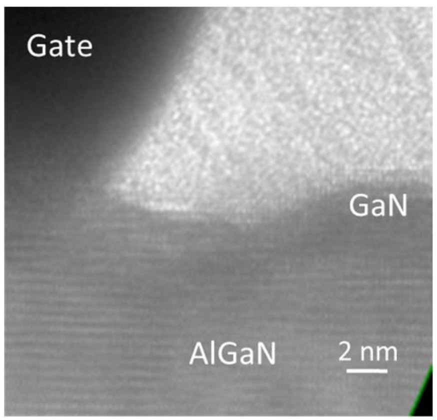
Structural degradation: cross section

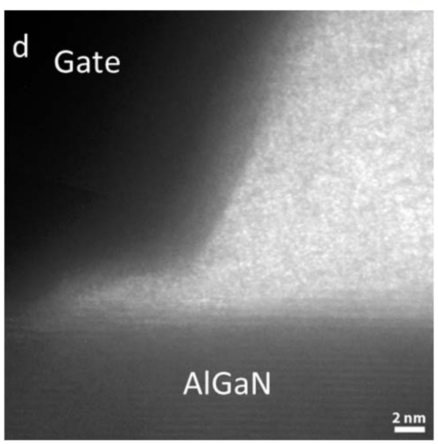


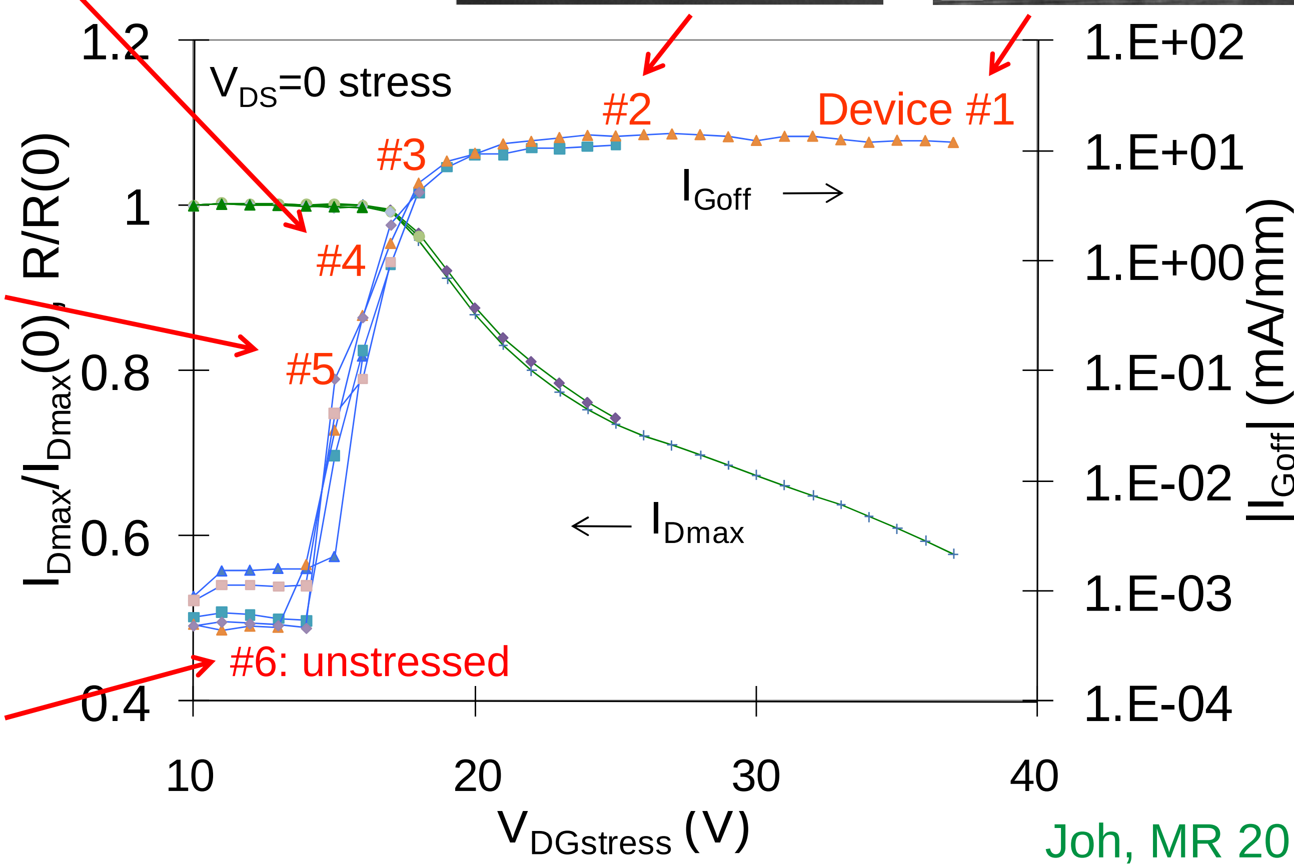
- Small dimple in early stages of I_G degradation;
- I_D degradation delayed







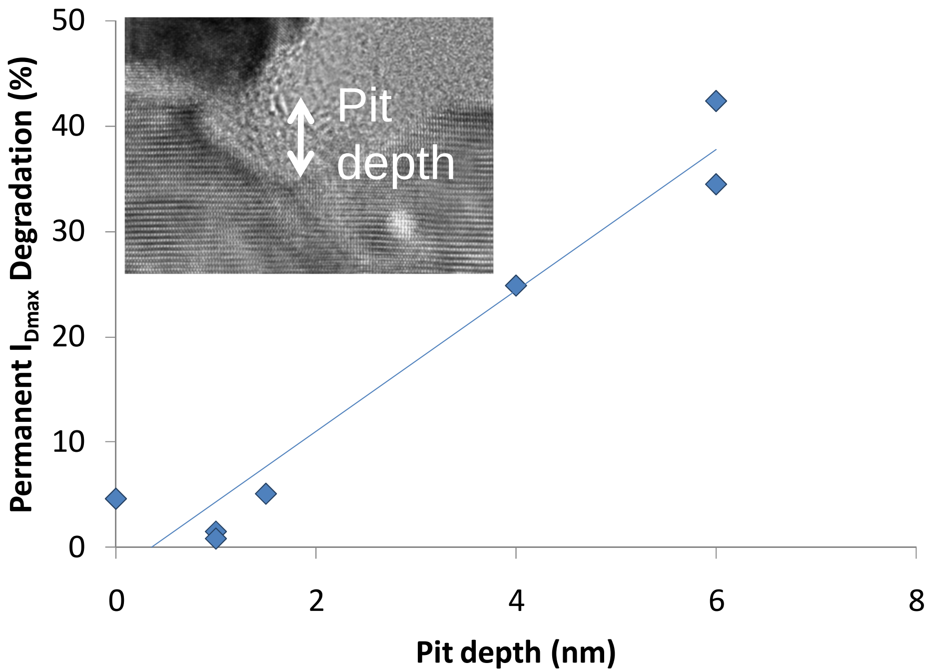


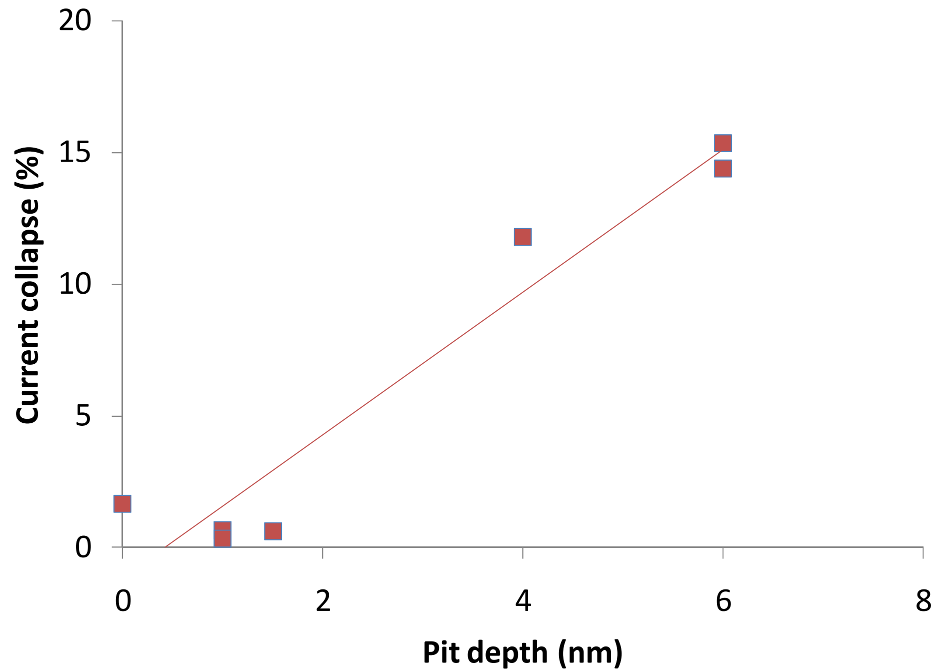


Joh, MR 2010

Correlation between pit geometry and I_{Dmax} degradation

Joh, MR 2010





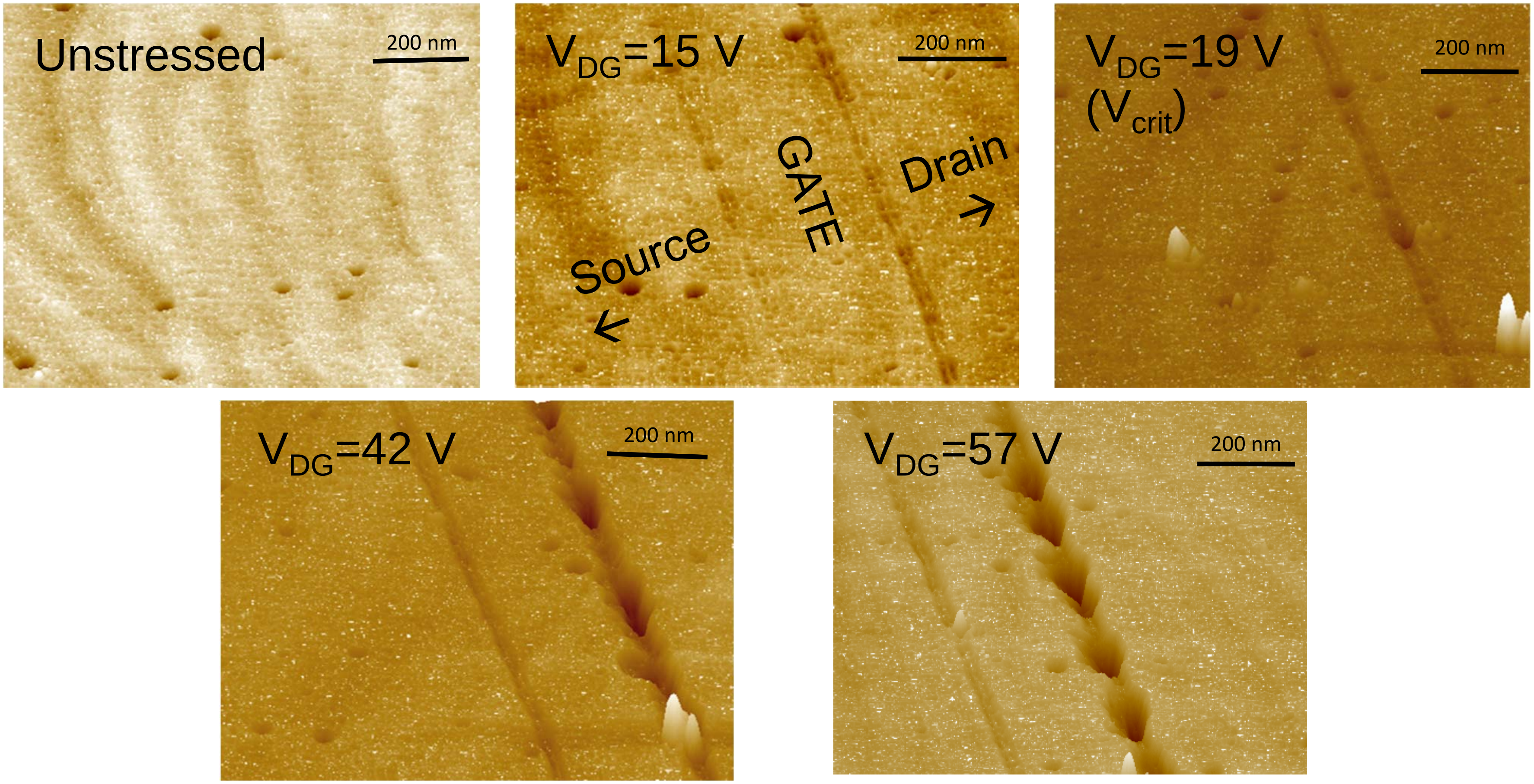
Pit depth and I_{Dmax} degradation correlate:

→ both permanent degradation and current collapse (CC)

Structural degradation: planar view

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

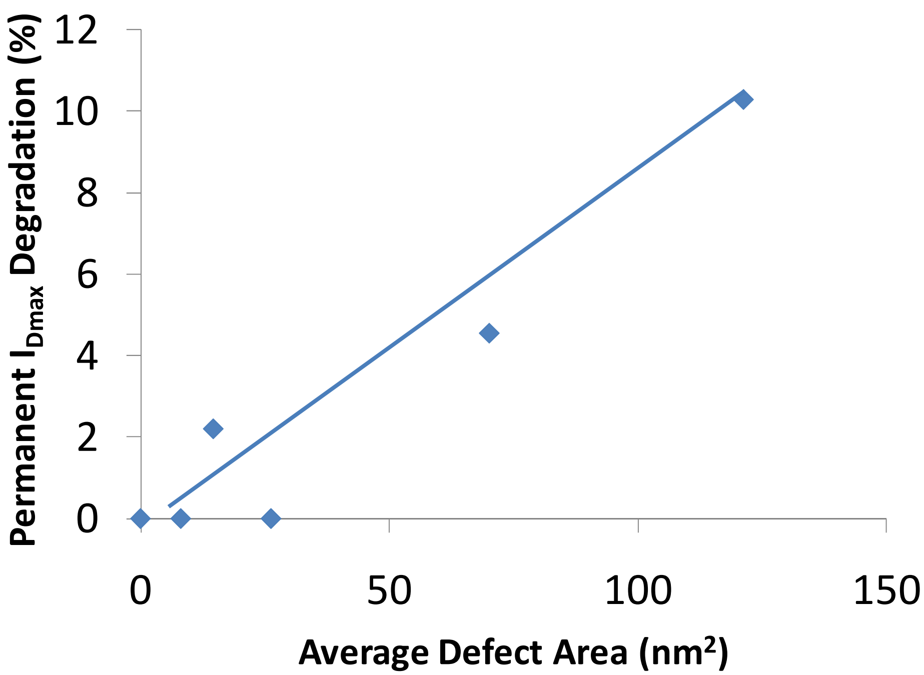
Makaram, APL 2010

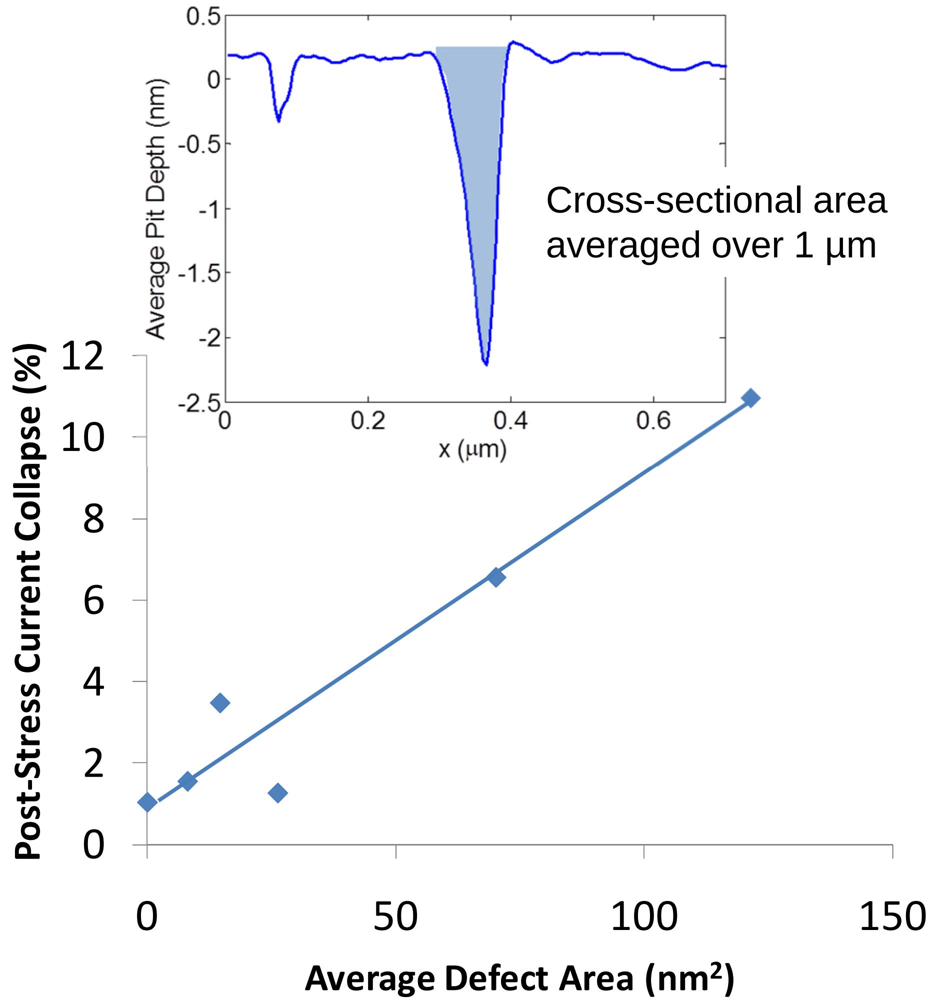


- Continuous groove appears for V_{stress}<V_{crit}
- Deep pits formed along groove for V_{stress}>V_{crit}

Correlation between pit geometry and I_{Dmax} degradation

Makaram, APL 2010



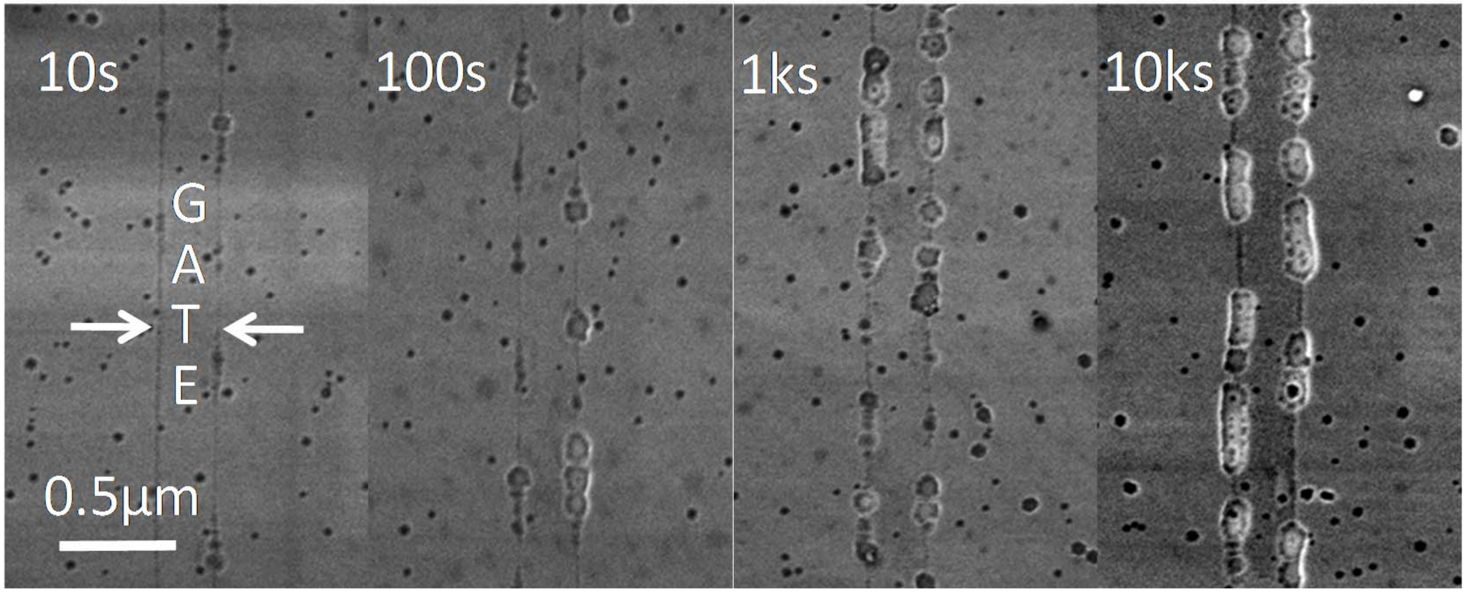


I_{Dmax} degradation and pit cross-sectional area correlate

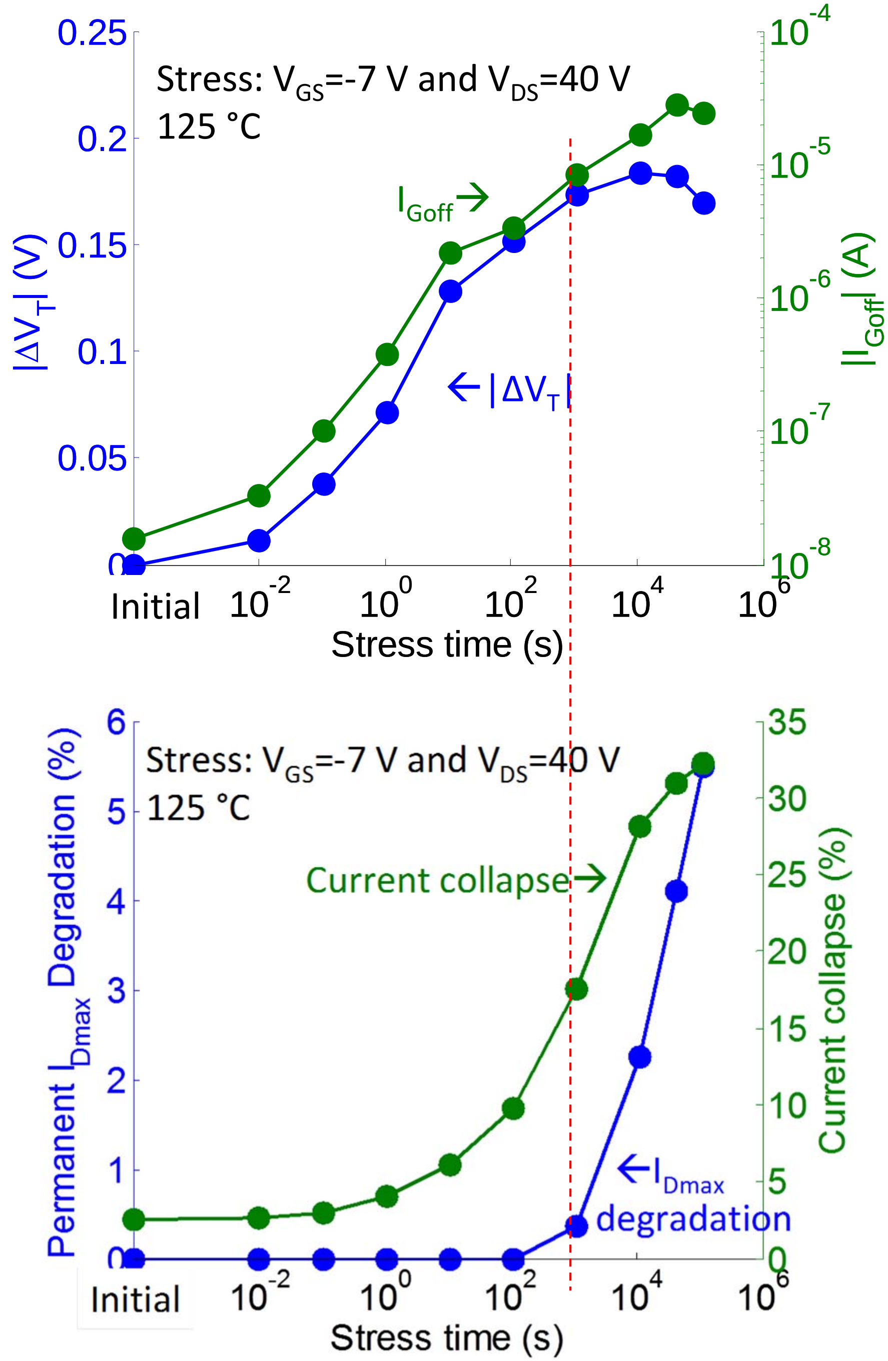
Planar degradation: the role of time

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



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:

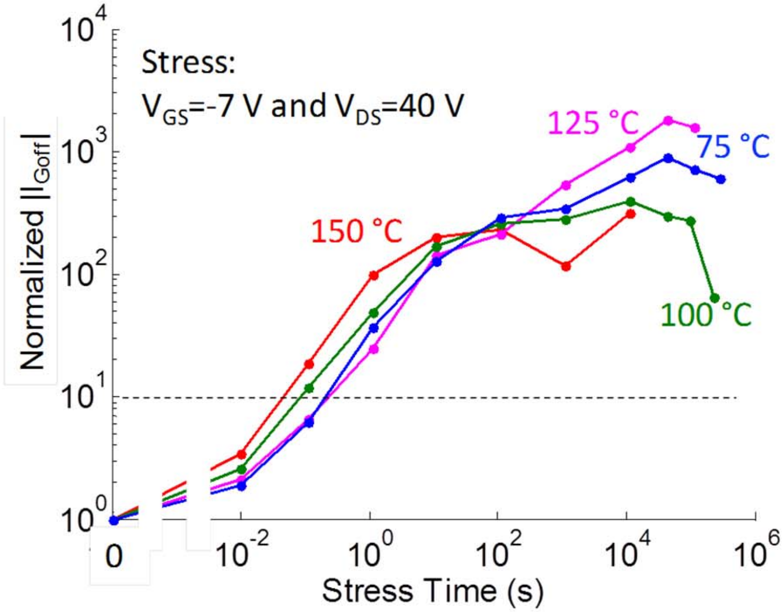
- slower
- hint of saturation for long time

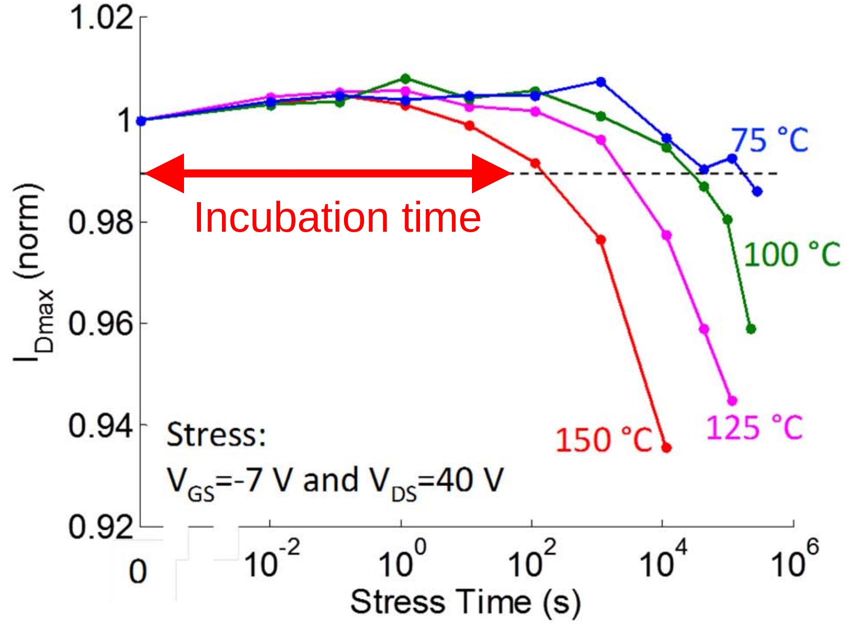
Permanent I_{Dmax} degradation:

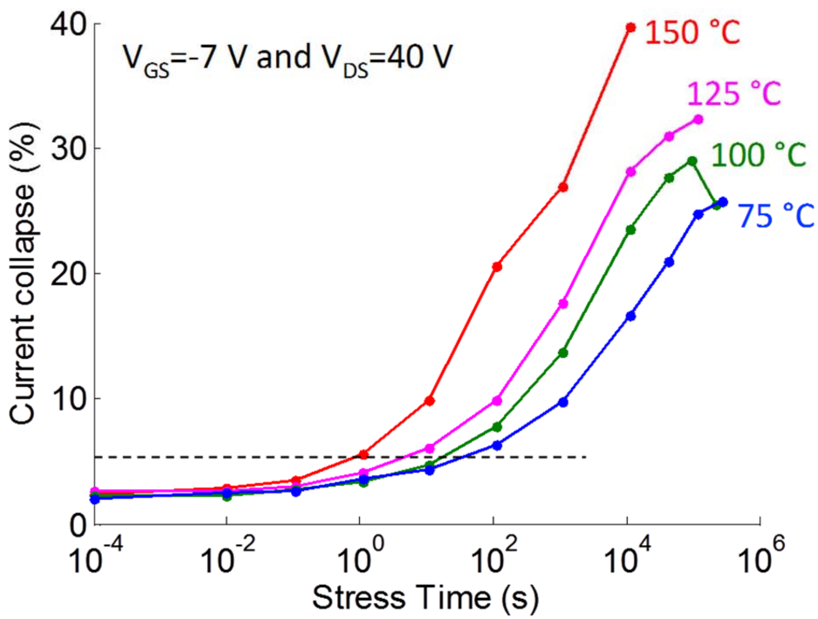
- much slower
- does not saturate with time

Joh, IRPS 2011

The role of temperature in time evolution



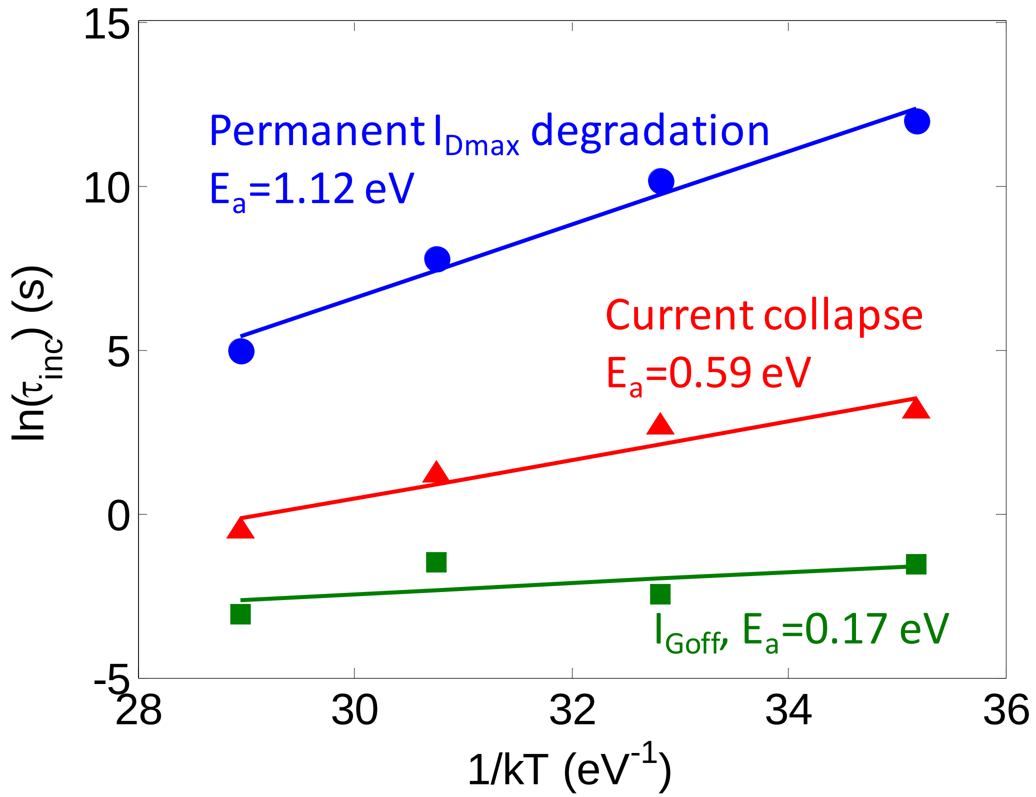




- I_G: weak T dependence
- CC, I_{Dmax}:
  strongly T activated

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

Summary of degradation after OFF-state stress for $V_{stress} > V_{crit}$

1. I_G degradation

- Fast
- Voltage enhanced
- Little temperature sensitivity
- Tends to saturate

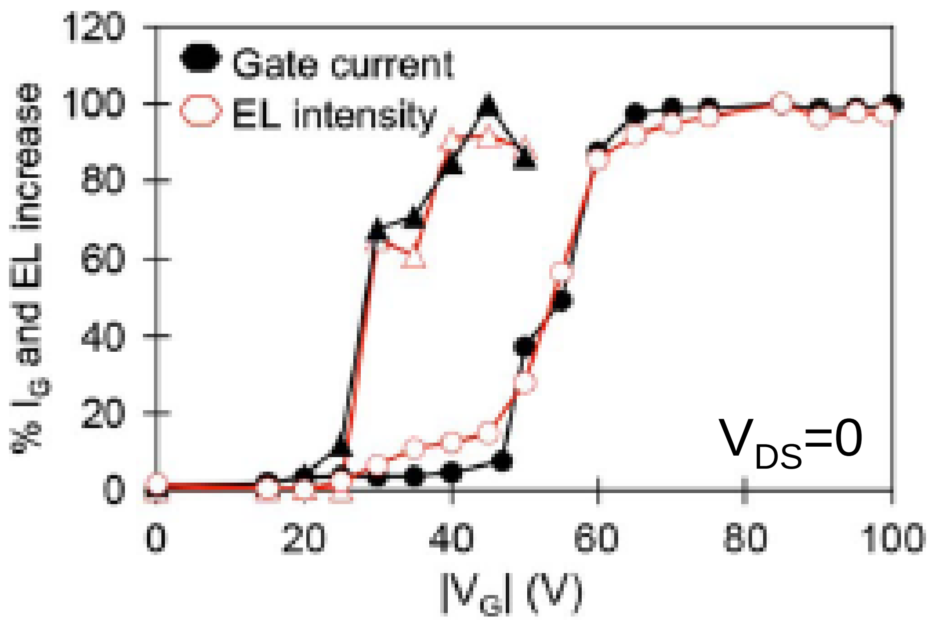
Correlates with shallow *groove*

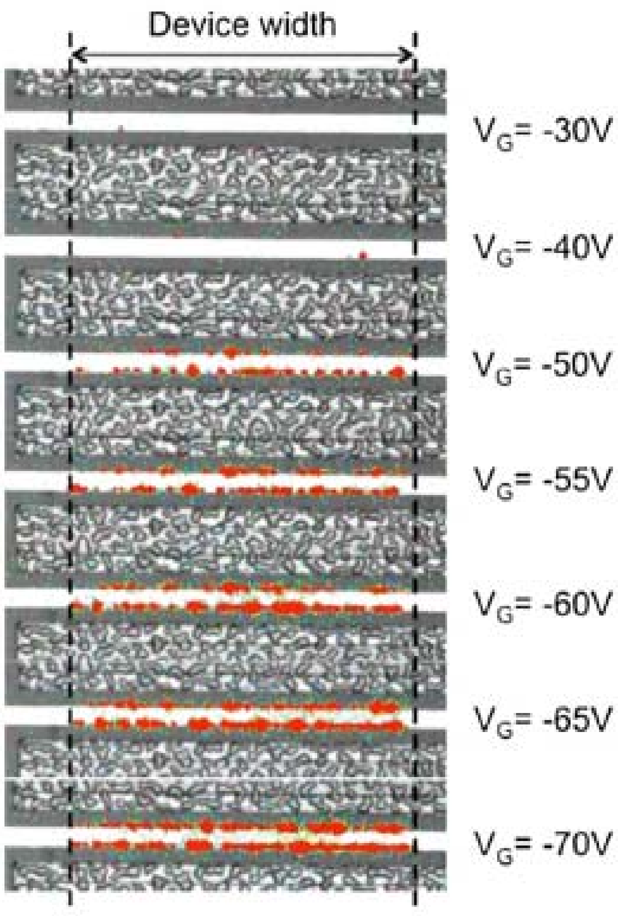
- Groove continuous; on S and D side
- Groove appears for $V_{stress} < V_{crit}$

Mechanisms:

- Groove: reduction of interfacial oxide at drain end of gate → field-induced oxidation?
- I_G rise: hopping through defects? Lower ϕ_B due to gate interface reconstruction?

Electroluminescence correlates with I_G degradation





Zanoni, EDL 2009
Meneghini, IEDM 2011

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

Summary of degradation after OFF-state stress for $V_{stress} > V_{crit}$

2. Current collapse degradation (trapping)

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

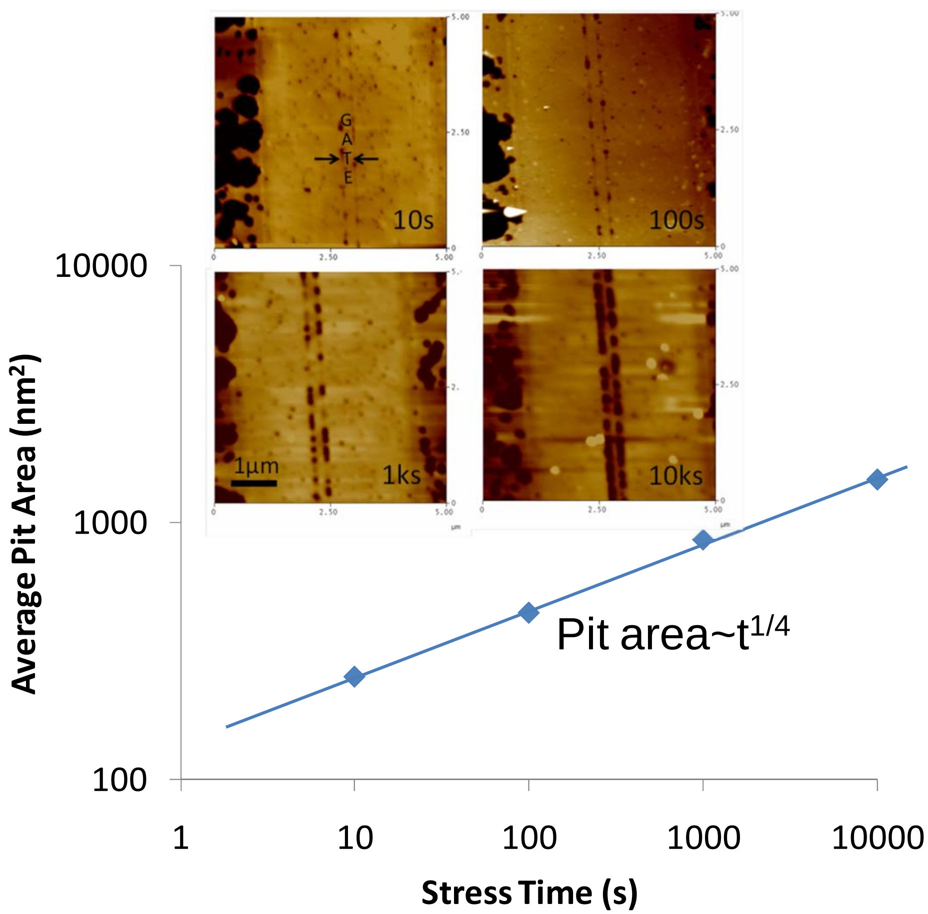
Correlates with *pits*:

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

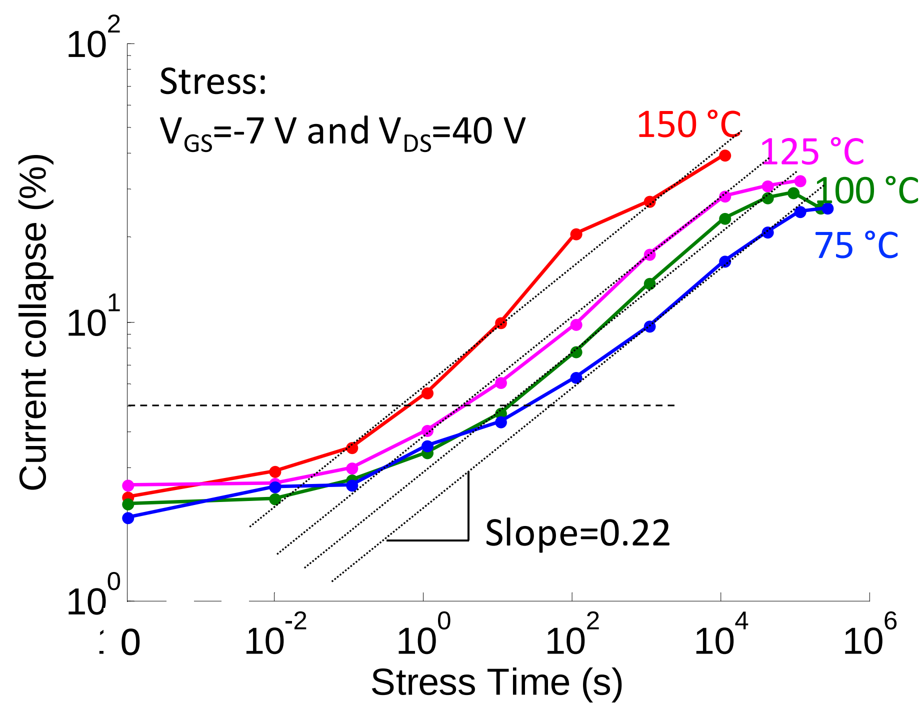
Mechanism:

- Pits: relieve mechanical stress arising from inverse piezoelectric effect (but detailed process?); electrochemical oxidation?
- CC: trapping associated with facets of pits?

Time evolution of pit growth and CC



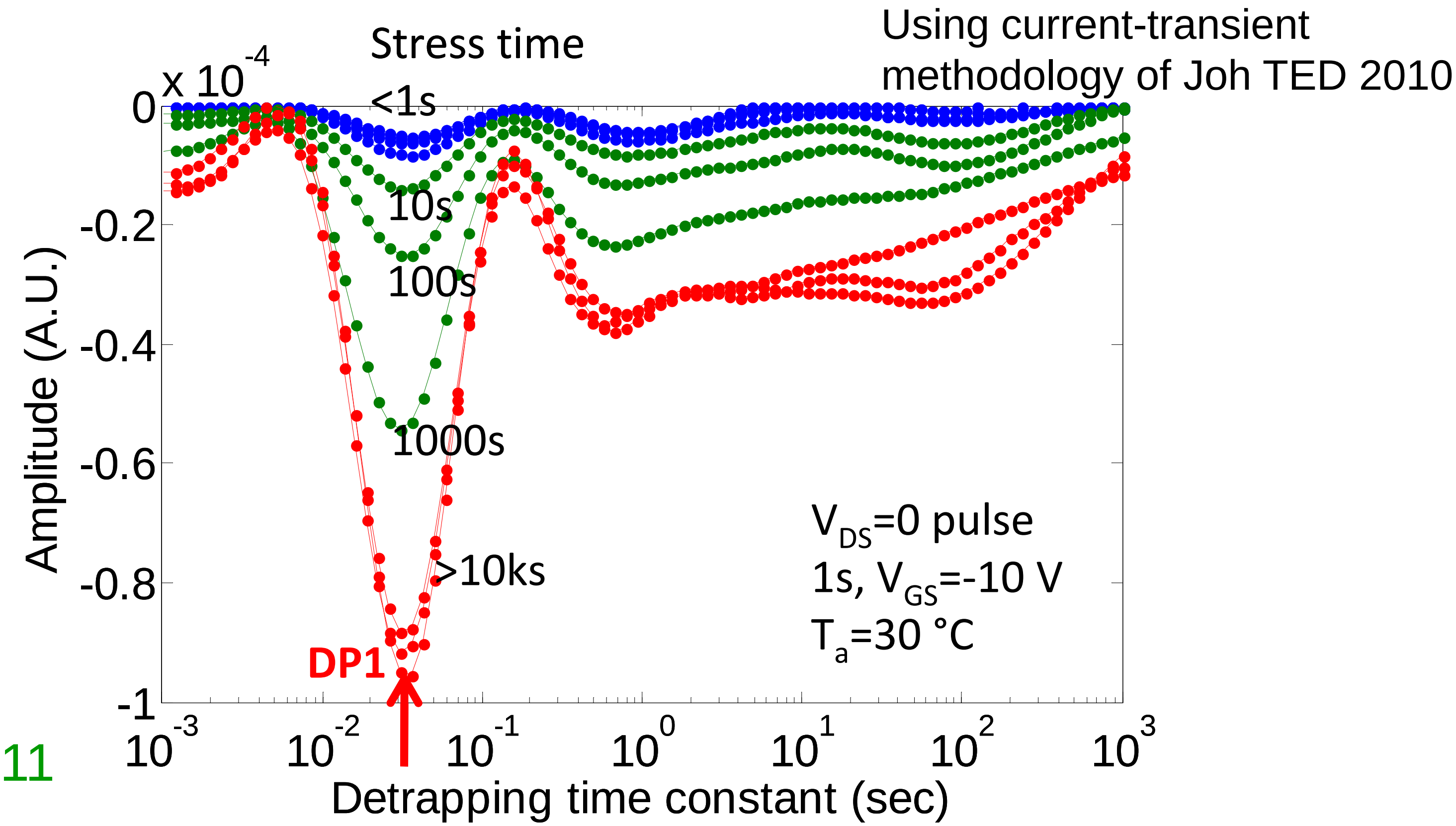
Joh, IWN 2010



Joh, IRPS 2011

Similar time dependence in current collapse and pit formation

Current collapse time-constant spectrum



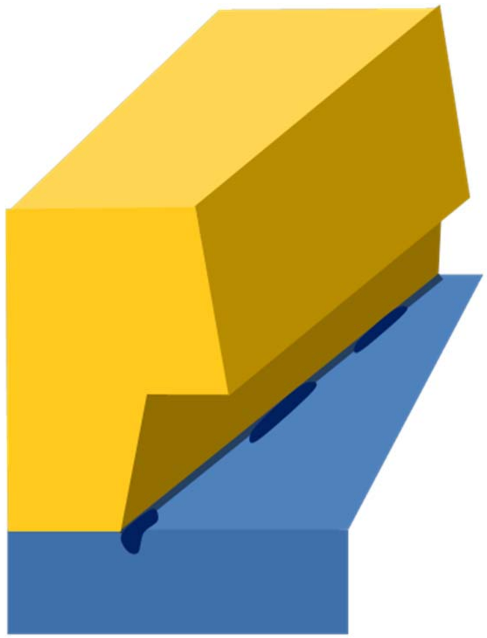
Joh, IRPS 2011

- Dominant trap created by stress already present in virgin sample, E_a=0.56 eV
- CC associated with surface (?) (pit creates new surfaces right next to gate edge!)

Summary of degradation after OFF-state stress for $V_{stress} > V_{crit}$

3. I_{Dmax}, R_D degradation

- Much slower
- Temperature activated
- Voltage enhanced
- Does not saturate

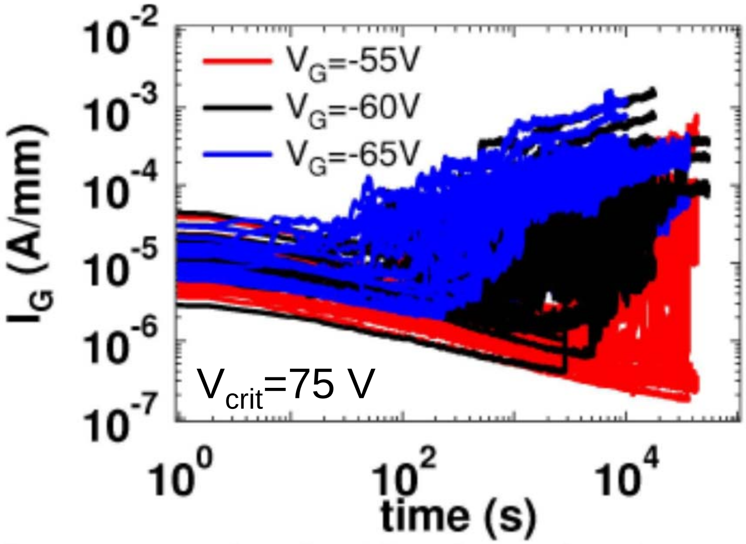


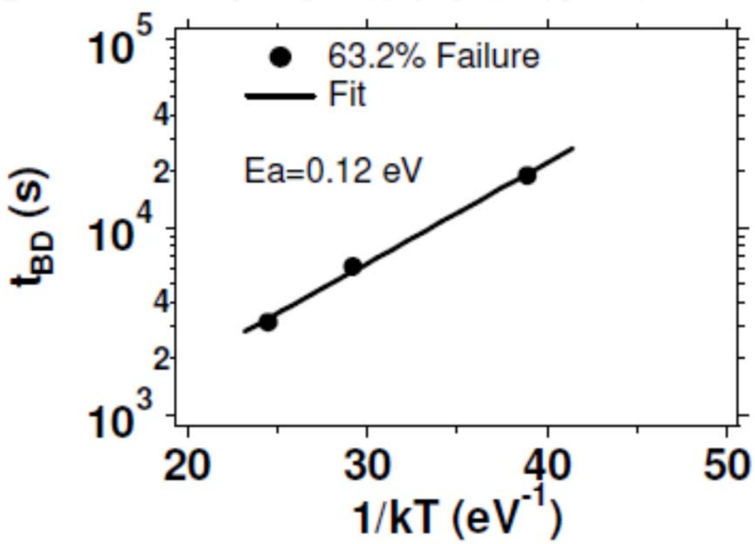
Correlate with *pits*

Mechanism:

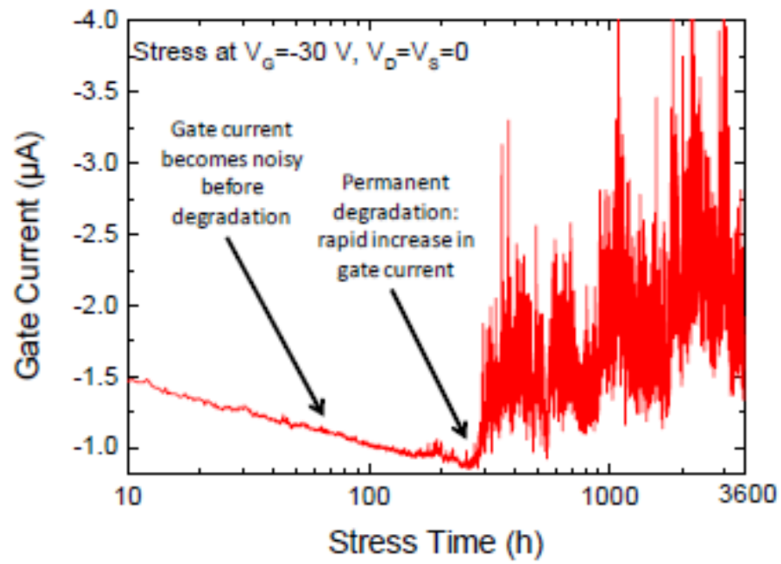
- Pit depletes electron concentration in channel below
- Current loss associated with pit depth?

Can degradation occur for $V_{stress} < V_{crit}$?





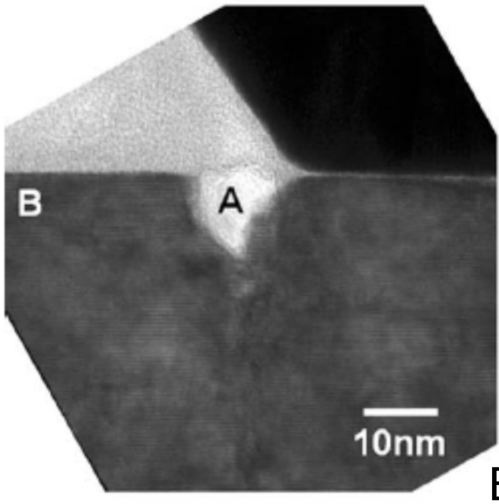
Marcon, IEDM 2010



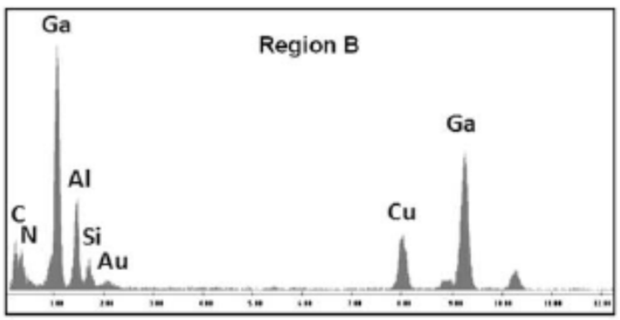
Meneghini, IEDM 2011

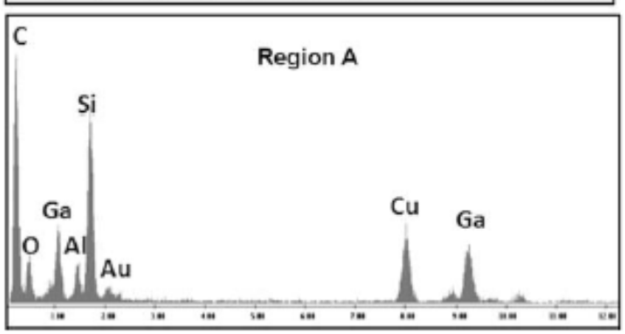
- Sudden irreversible increase in I_G, enhanced by V_{stress}
- No reported I_D degradation
- Appearance of I_G noise, EL hot-spots
- E_a=0.12 eV
- Consistent with groove formation?

Oxygen inside pit



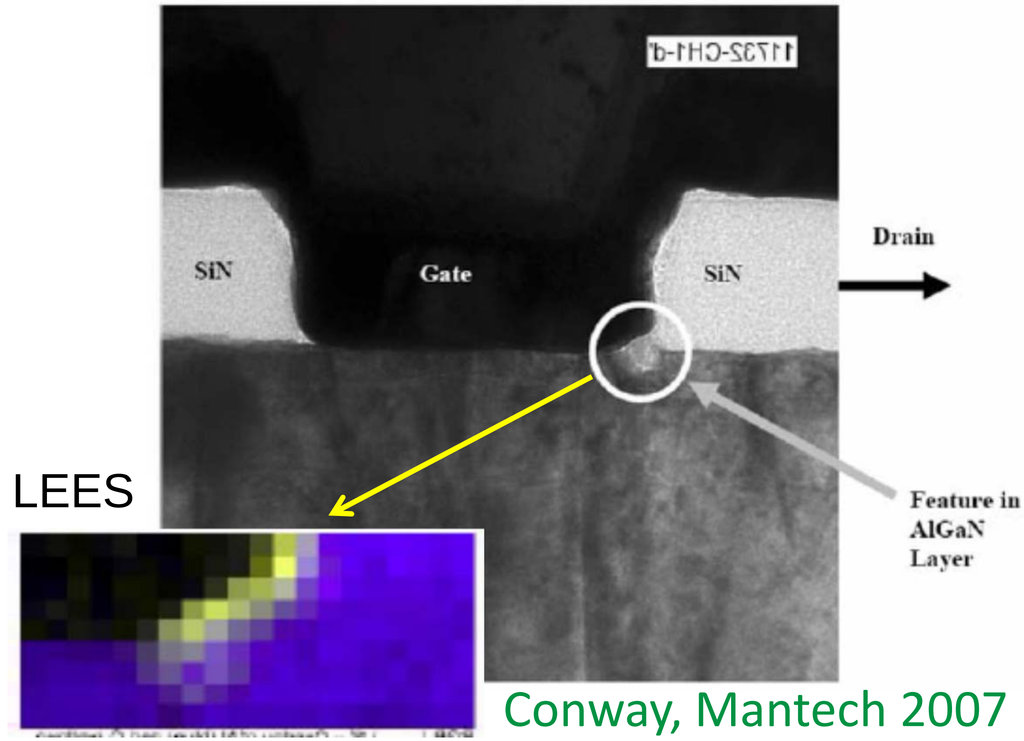
EDX





Park, MR 2009

LEES

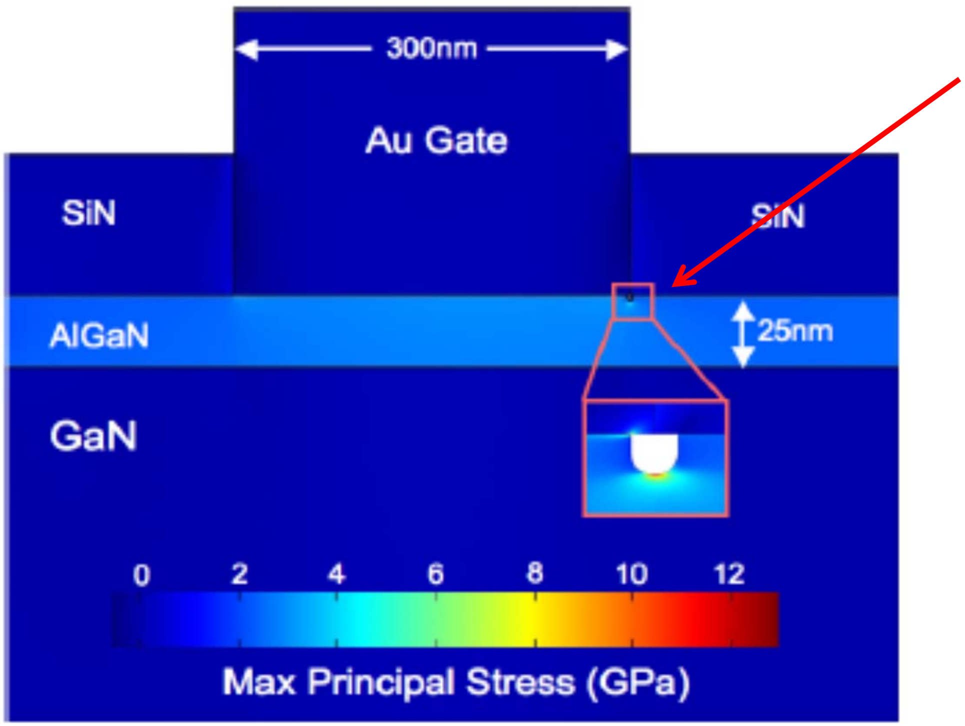


Conway, Mantech 2007

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

Groove: essential for pit formation?

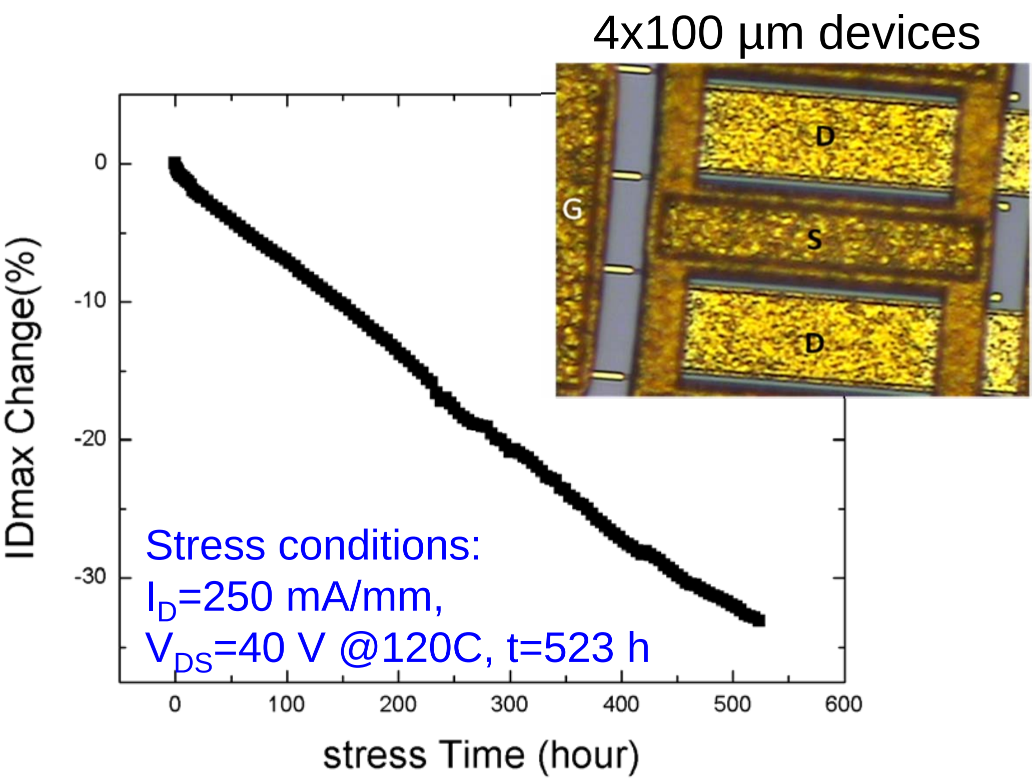
Appearance of groove increases mechanical stress due to inverse piezoelectric effect at drain end of gate



- 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, SISPAD 2011

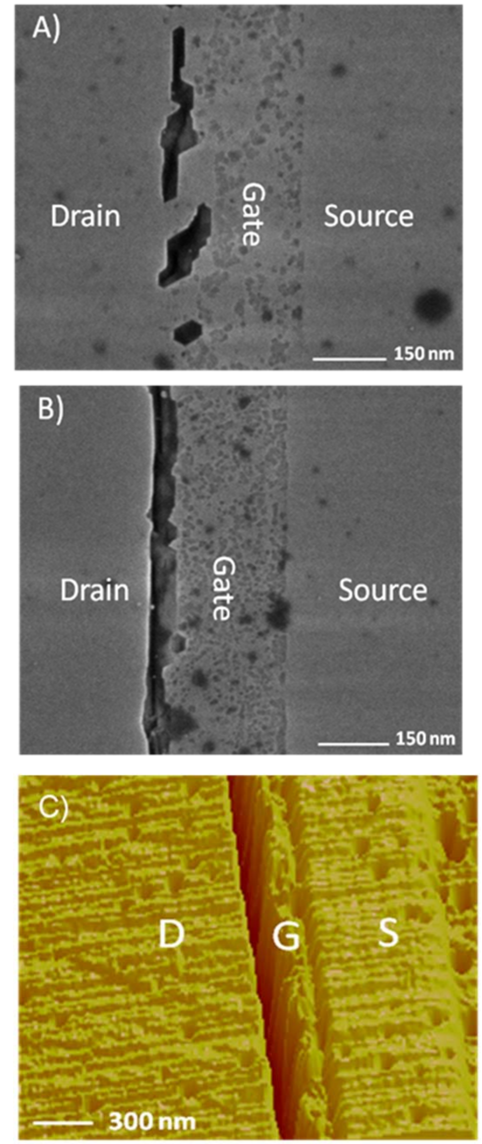
2D distribution of structural degradation under high-power stress



SEM: finger end

SEM: finger center

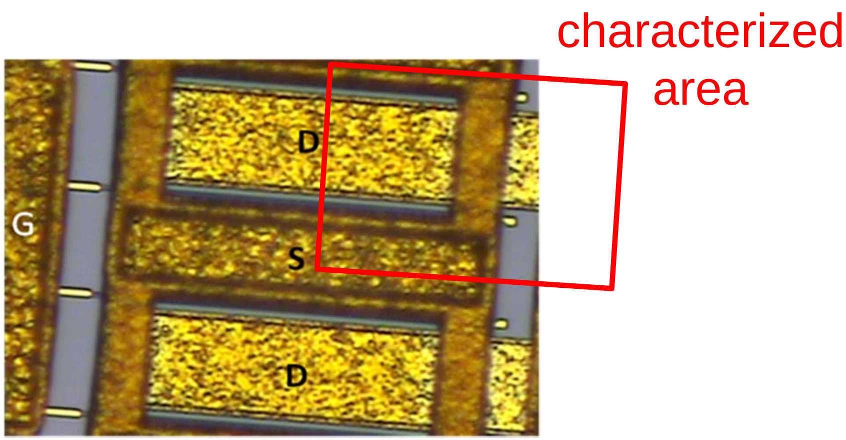
AFM

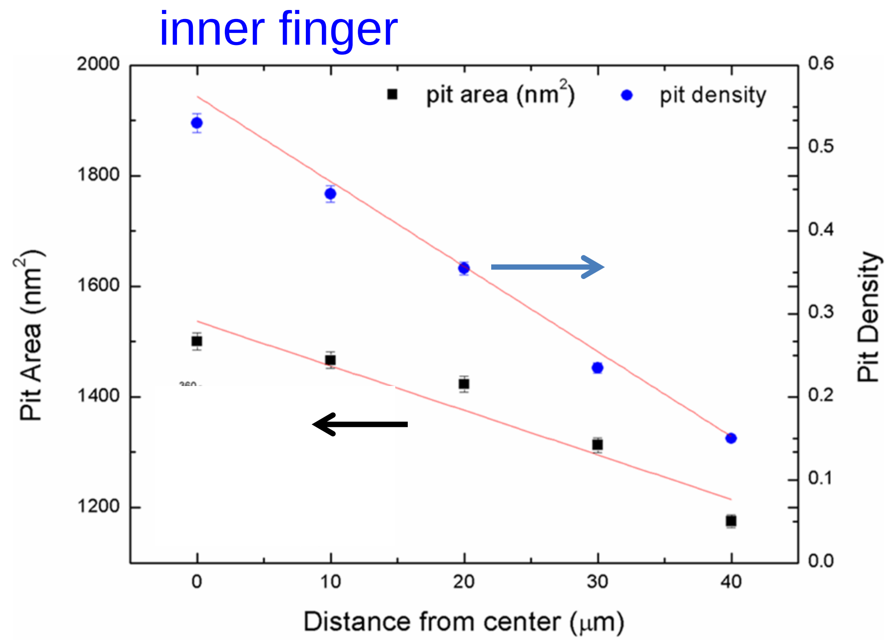


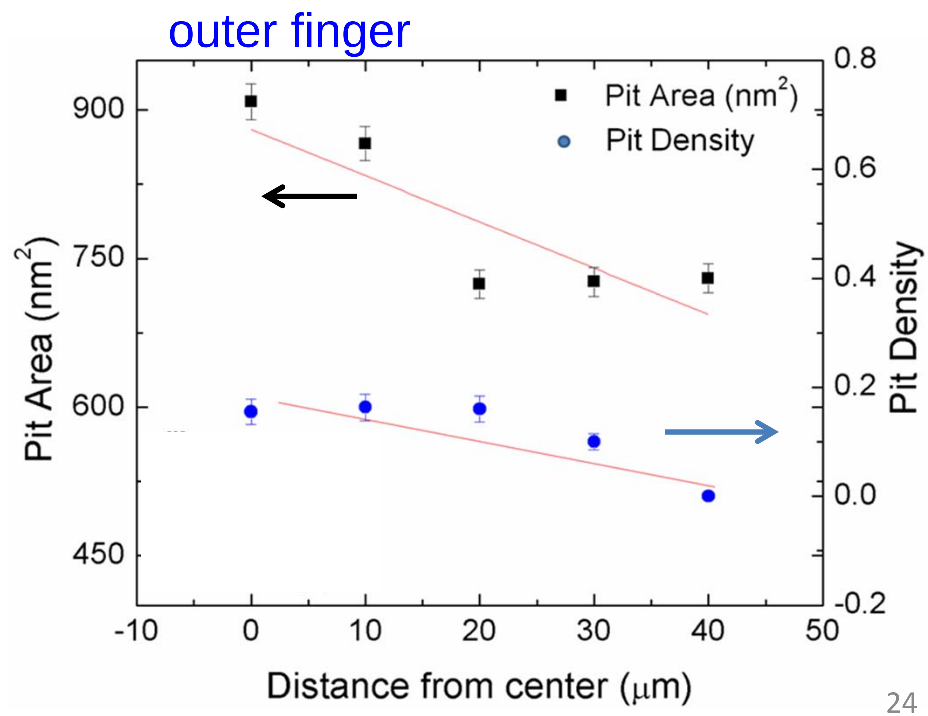
- Prominent pits under gate edge on drain side
- Pits more prominent towards center of finger
- Typical pit: 50 nm wide, 8 nm deep

Lin, APL 2012

2D distribution of pits







- Pits evaluated along 10 μm segments
- Pit cross sectional area and density increase towards center of device
- Consistent with local T activating pit formation

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 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)

Surprises:

- Role of oxygen
- Role of surface chemistry
- Groove formation below critical voltage

Tentative new IPE model for GaN HEMT electrical degradation

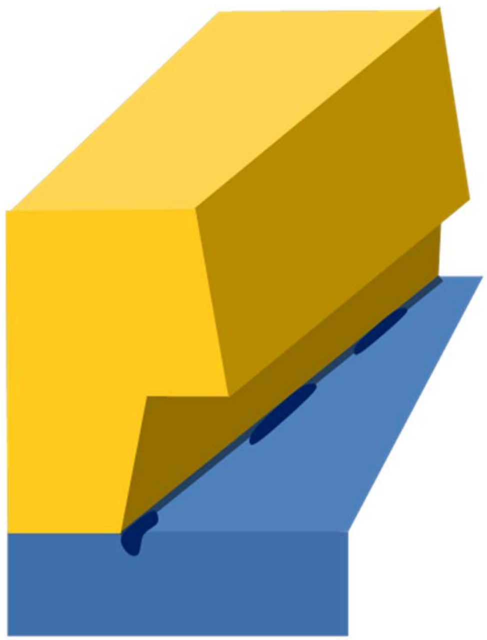
Step 1: electrochemical (?) formation of continuous groove in cap

- I_G↑ through leakage path created around groove (?)

Step 2: random seeding of pits as AlGaN barrier exposed

Step 3: growth of pits through AlGaN and along gate edge to relieve mechanical stress

- CC↑ due to new surfaces (?)
- I_{Dmax}↓ as electron concentration under gate edge reduced



Model very sensitive to cap design, interface treatments, residual O, and passivation