Strain and Temperature Dependence of Defect Formation at AlGaN/GaN High Electron Mobility Transistors on a Nanometer Scale

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Symposium G: Reliability and Materials Issues of III-V and II-VI Semiconductor Optical and Electron Devices and Materials II

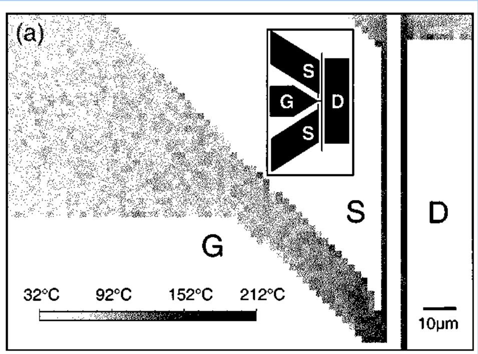
Outline

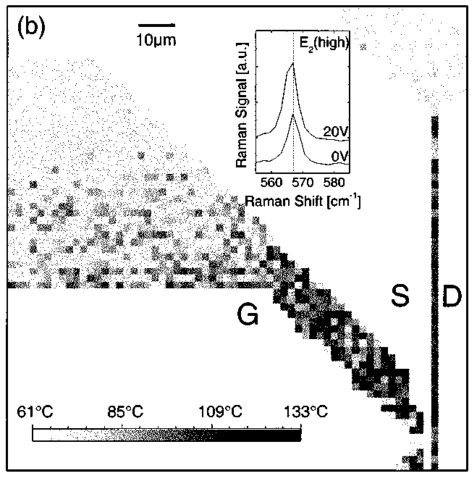
- **Background : AlGaN/GaN HEMT physical degradation mechanisms – Historical efforts**
- **Techniques: DRCLS, KPFM, I_D & I_{GOFF} vs. V_{DS}**
- **Device Conditions: ON-state vs. OFF-state stress**
- **Electric field vs. Thermal stress : Surface potential, leakage current, defect generation → Failure prediction**
- **Conclusions: (1) Dominant impact of V_{DS} vs. I_{DS} on device reliability**
  (2) Primary defects located *inside* AlGaN

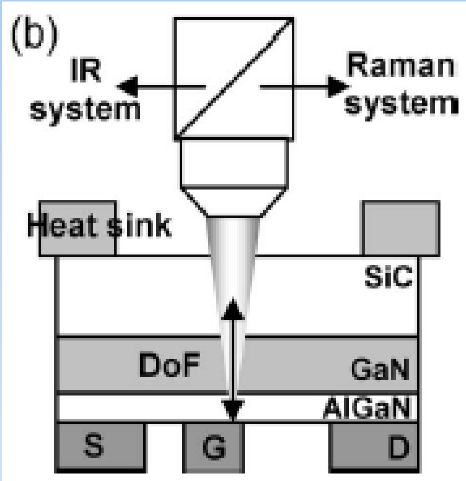
Motivation

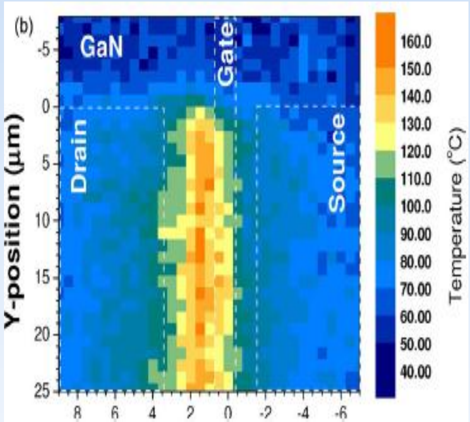
- **AlGaN/GaN HEMT: high power, RF, and high speed applications**
- **Reliability challenge: Hard to predict failure**
- **High current, piezoelectric material, & high field due to high bias → Defect generation**
- **Micro-CL, AFM, and KPFM: Follow evolution of potential, defects, and failure**

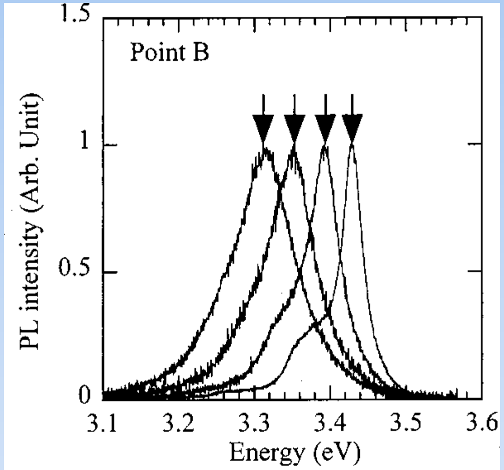
Background: All-Optical Methods

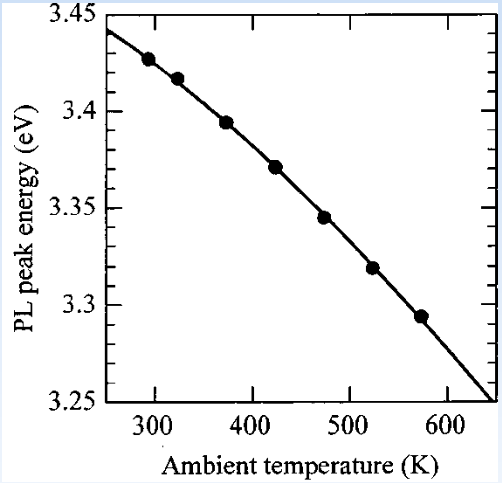












[1] M. Kuball *et al.* IEEE Electron Device Lett. **23**, 7 (2002)

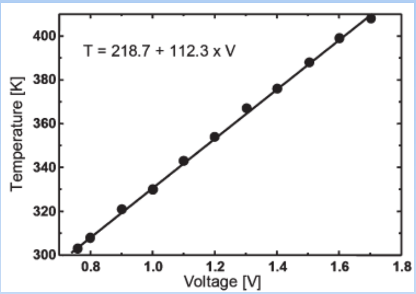
[2] A. Sarau *et al.* IEEE Trans. Electron Devices, **53**, 2438 (2006)

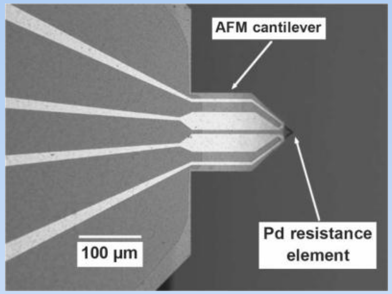
Raman/IR Technique

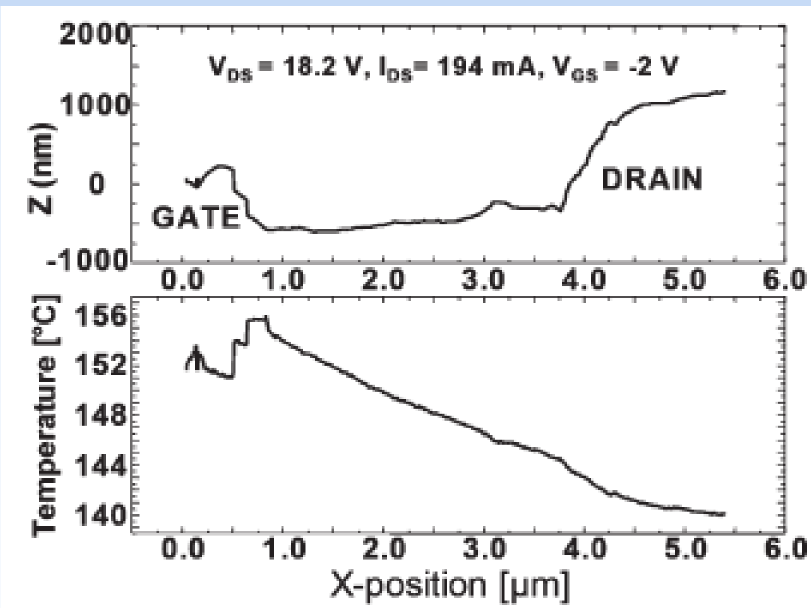
Shigekawa *et al.* J. Appl. Phys. **92**, 531 (2002)

PL Technique

Background: Scanned Probe Methods



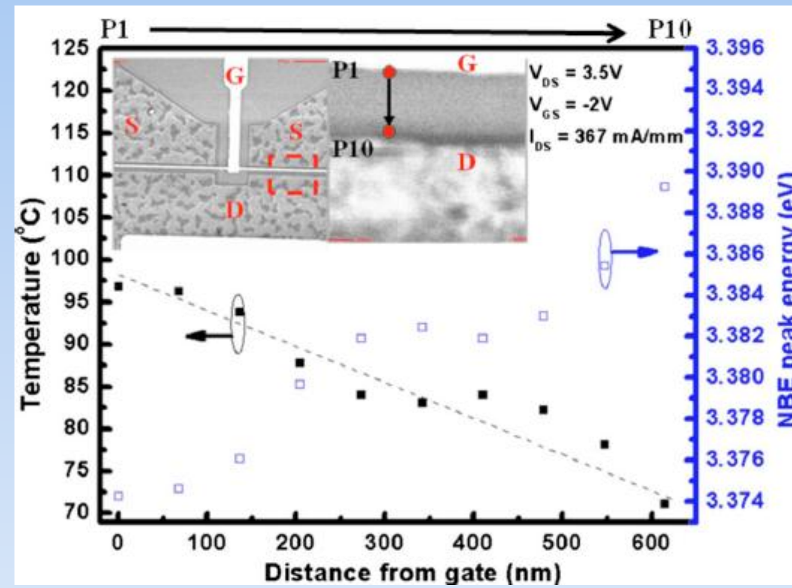




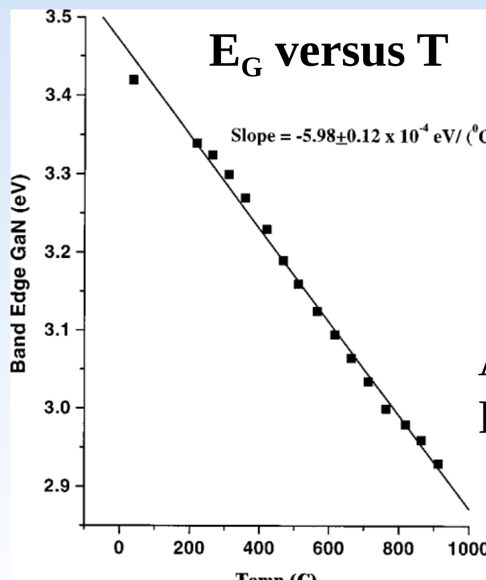
Aubry *et al.* IEEE Transactions on Electron Device, **54**, 385 (2007)

SThM Technique

T versus Gate-Drain Location



Lin *et al*. Appl. Phys. Lett., **95**, 033510 (2009)

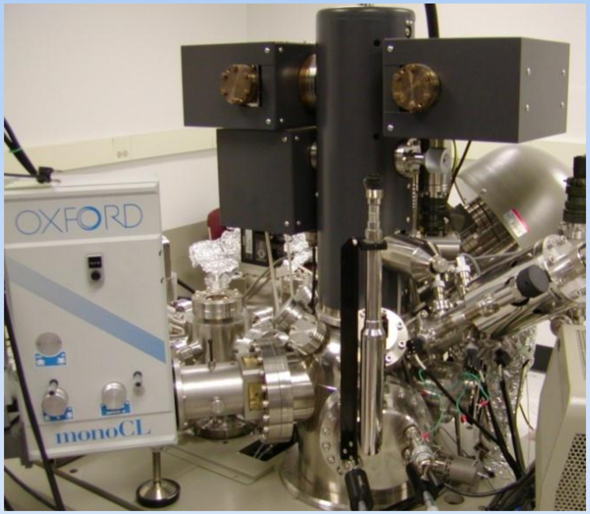


A. P. Young *et al*., Appl. Phys. Lett, **77**, 699 (2000)

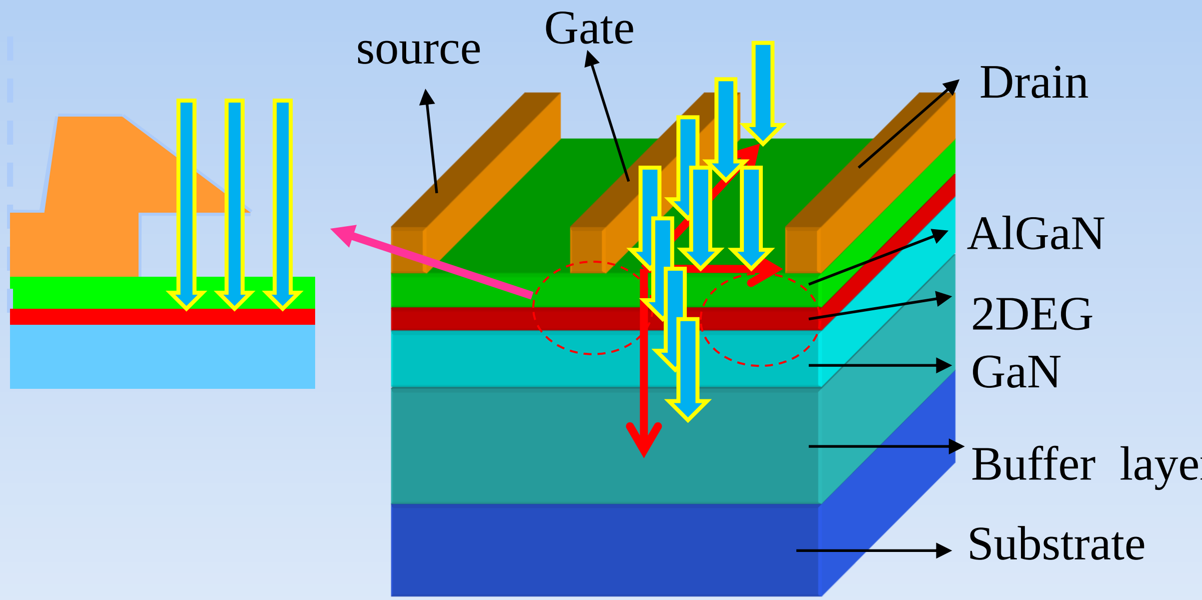
DRCLS Technique

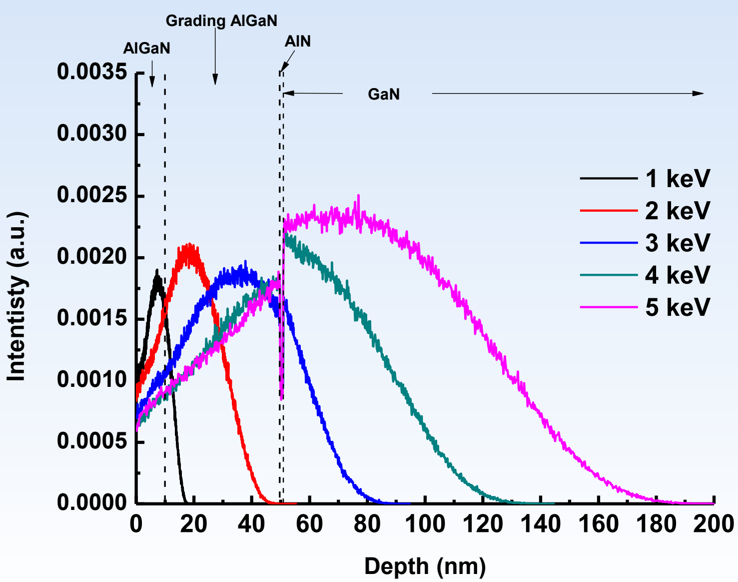
Depth and Laterally-Resolved CLS

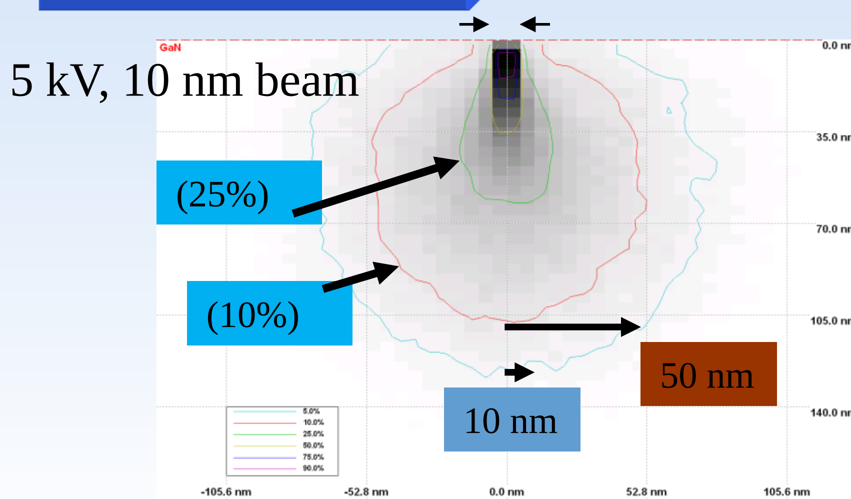
T, σ, defects, atomic composition



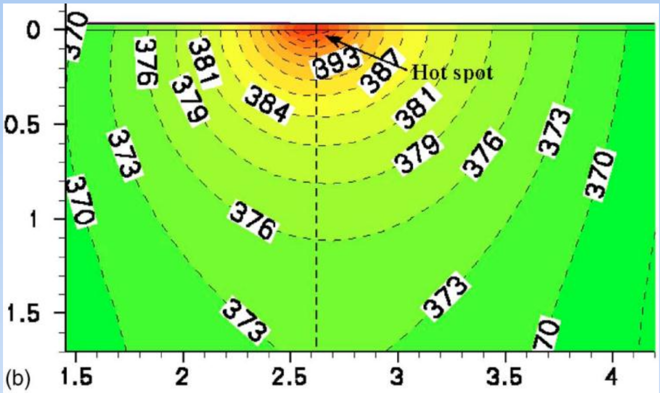
JEOL JAMP 7800F : SEM, Micro-CL



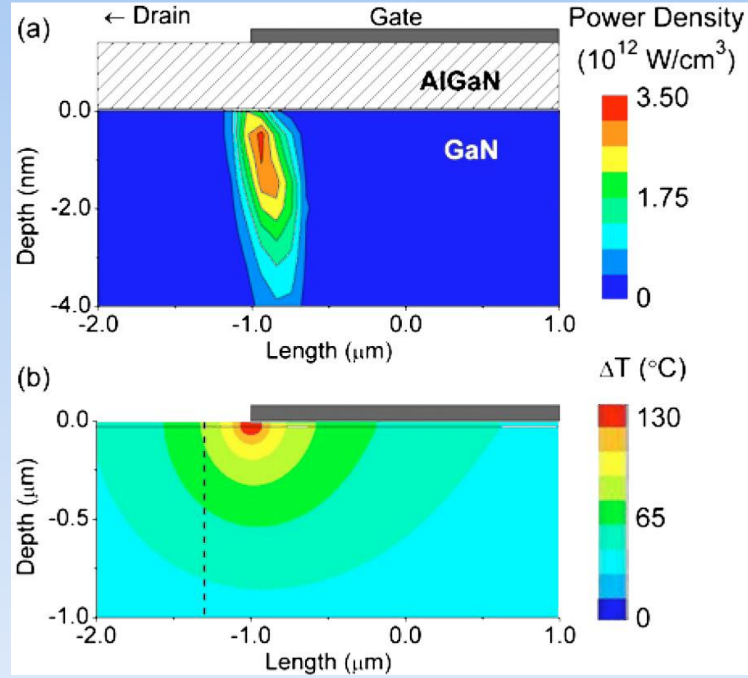




Background: Temperature Maps

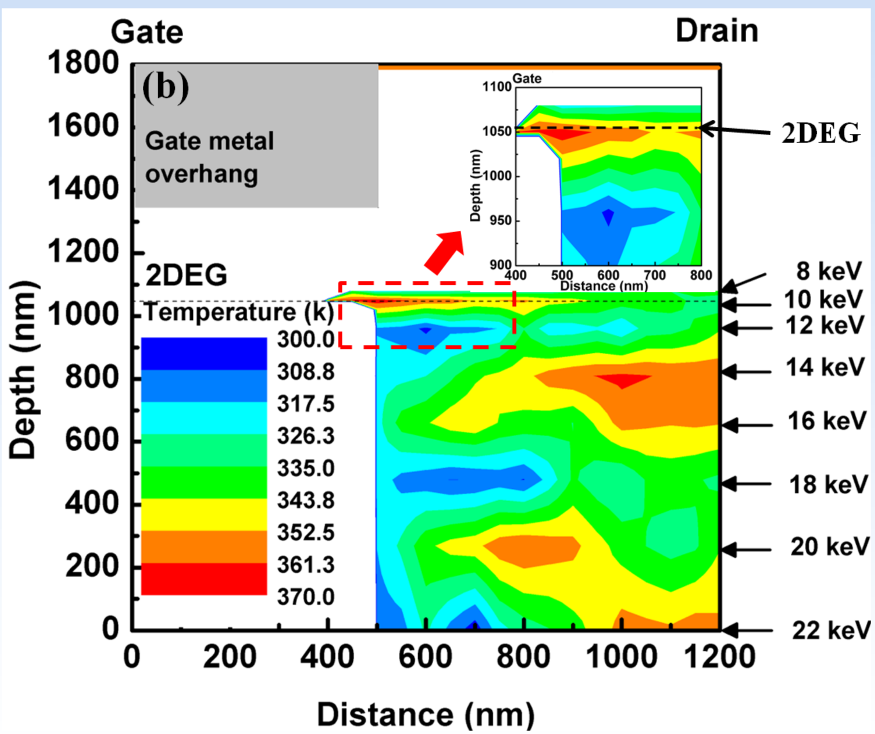


W.D. Hu *et al*. J. Appl. Phys. **100**, 074501 (2006)



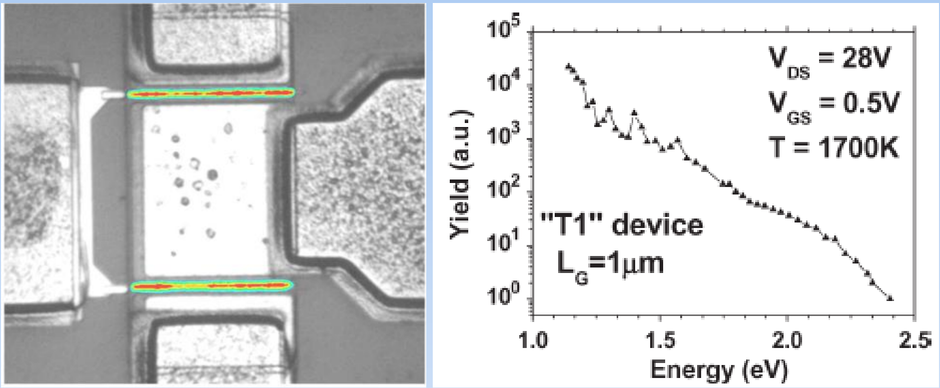
I. Ahmad *et al.* Appl. Phys. Lett. **86**, 173503 (2005)

- **Hottest spot at drain-side gate edge**
- **Hot spots *also* inside GaN buffer**

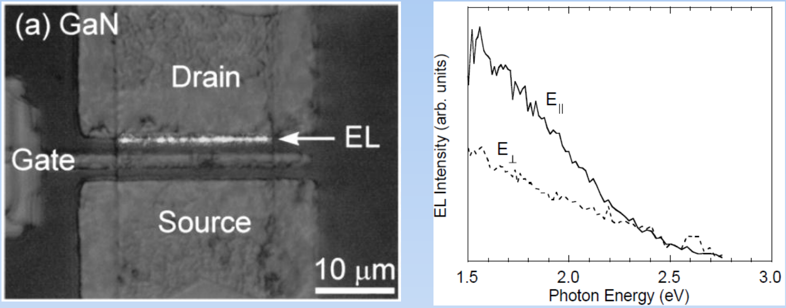


C.-H. Lin *et al*, IEEE Trans. Electron Devices

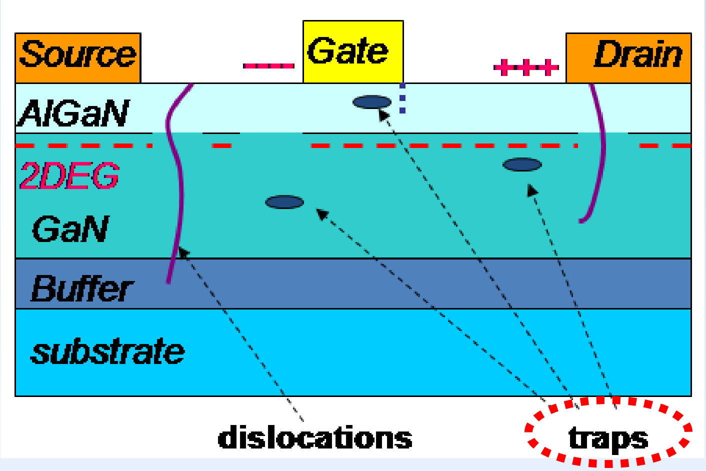
Electroluminescence Results: Gap States

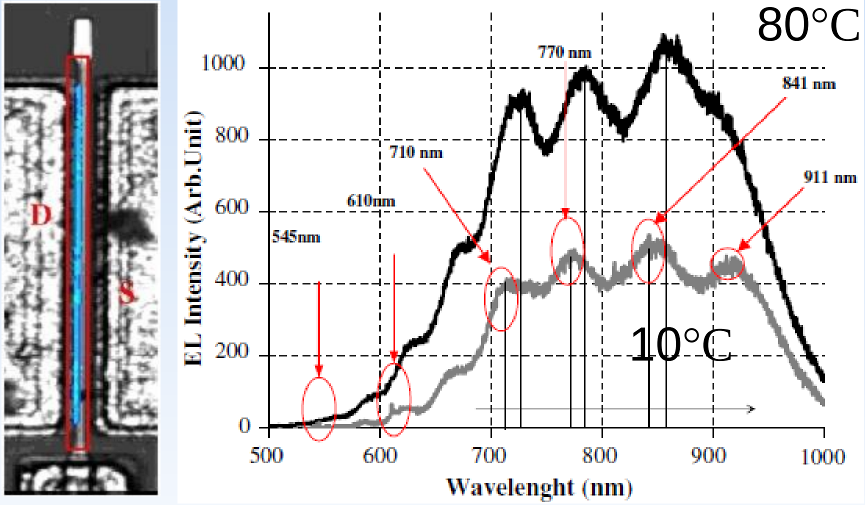


Meneghesso *et al*. IEEE Tran. Device Mater. Rel., **8**, 332 (2008)



Nakao *et al*. Jpn. J. Appl. Phys., **41**, 1990 (2002)

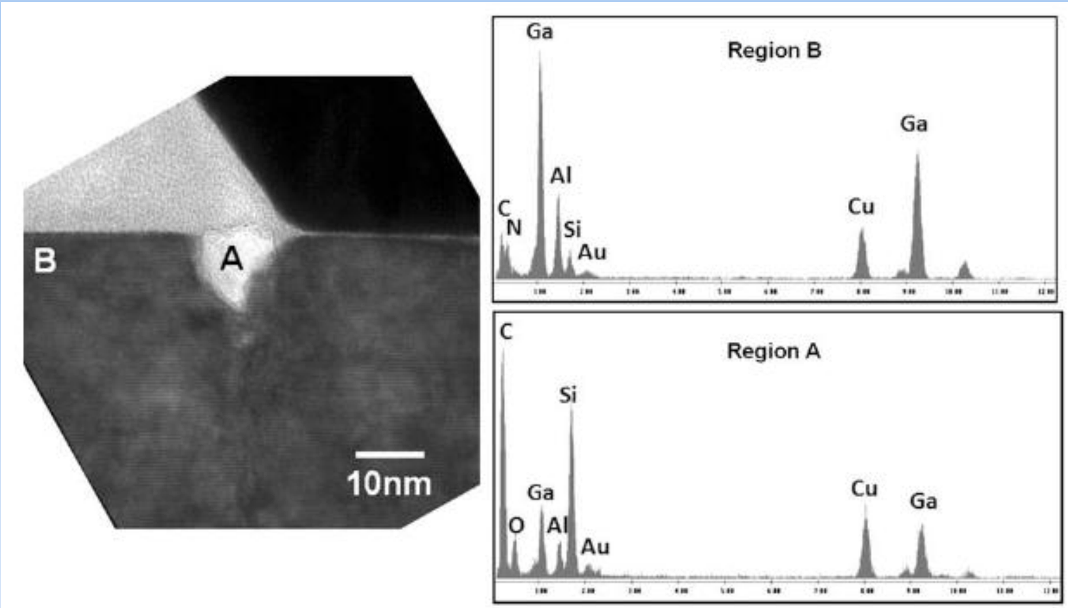




Bouya *et al*. Microelectron. Reliab., **48**, 1366 (2008)

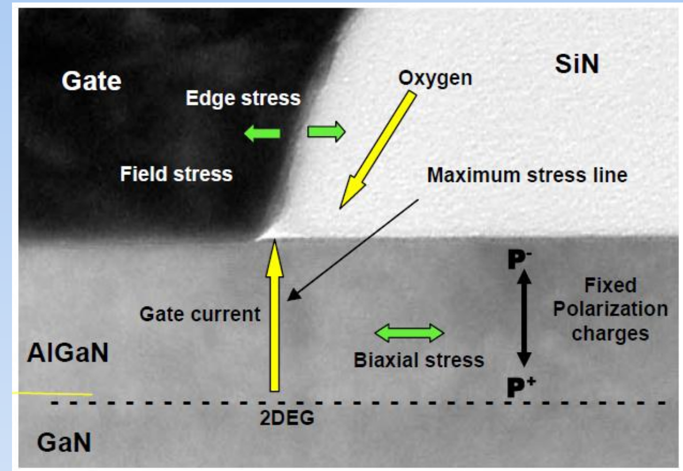
Electroluminescence detects gap states forming inside HEMT during operation

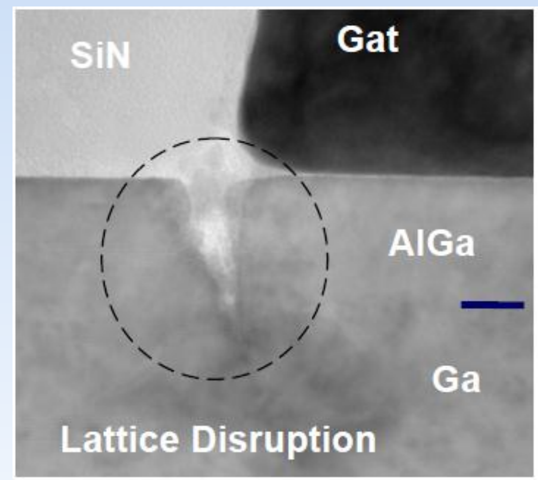
Electrochemically-Produced Defects



Park *et al*. Microelectron. Reliab., **49**, 478 (2009)

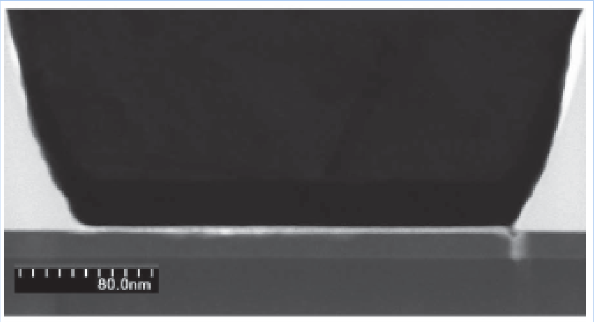
- High C, O, and Si concentrations at gate foot "lattice disruption" area
- Gate leakage current promotes electrochemical reaction



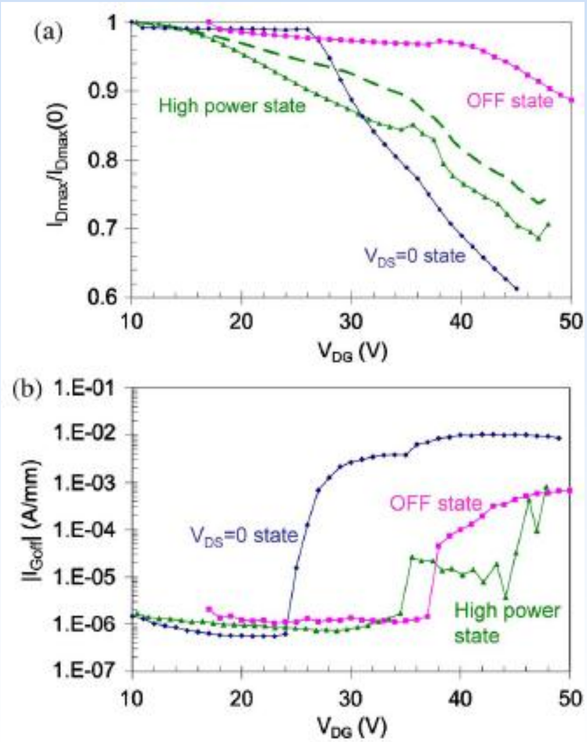


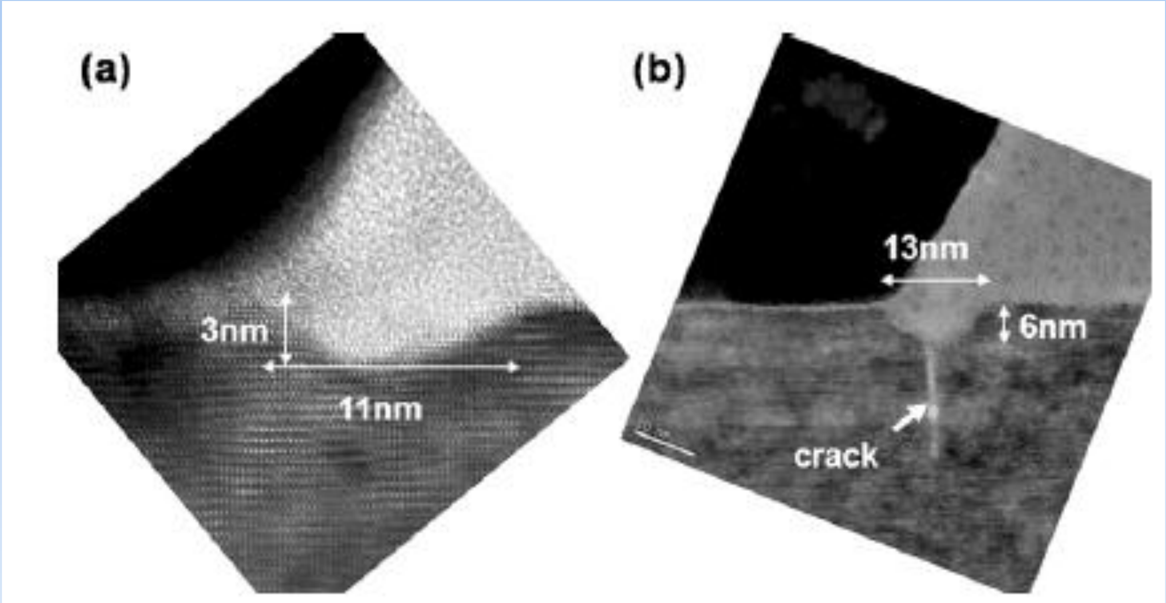
Smith *et al*. ECS Transactions, **19**, 113 (2009)

Impact of Structural Defects

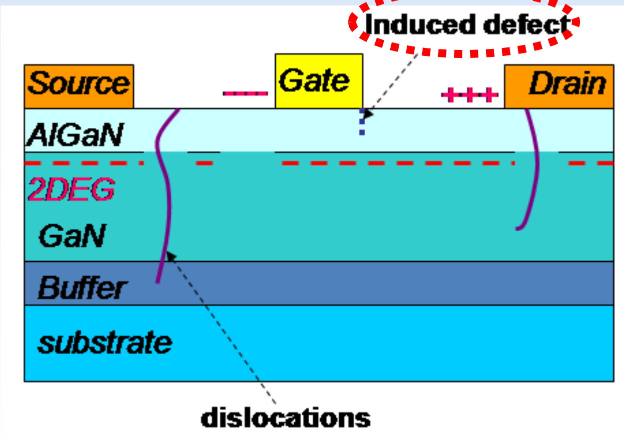


Chowdhury *et al*. IEEE Electron Device Lett. **29**, 1098 (2008)





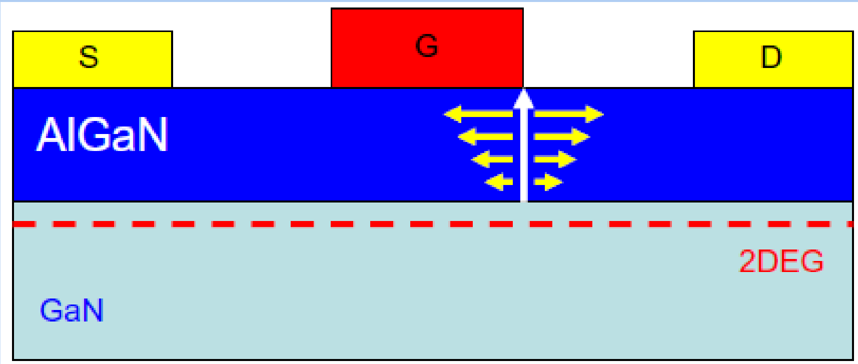
Park *et al*. Microelectron. Reliab. **49**, 478 (2009)

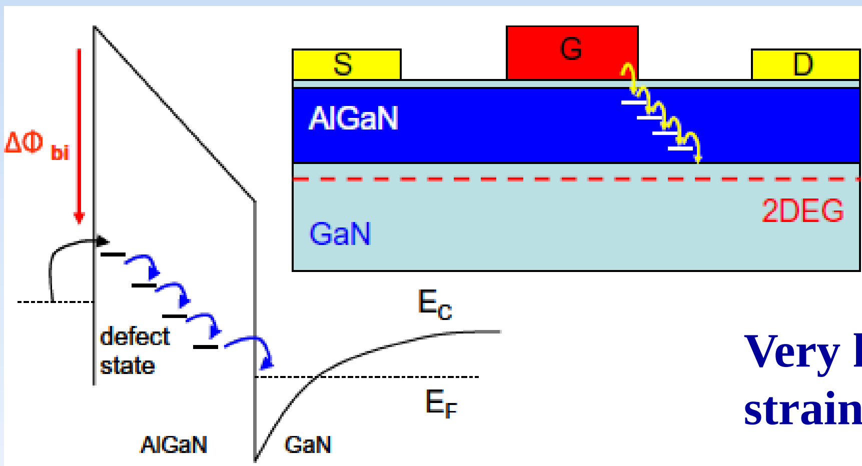


Joh *et al*. IEEE Electron Dev. Lett. **29**, 287 (2008)

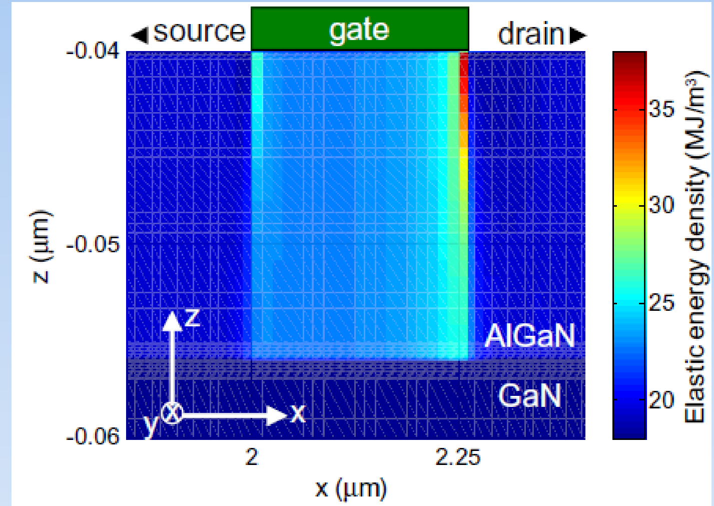
High field at drain - side gate can form structural defects that affect $I_{G\text{-}OFF}$ & I_D

Inverse Piezoelectric Effect and Defects



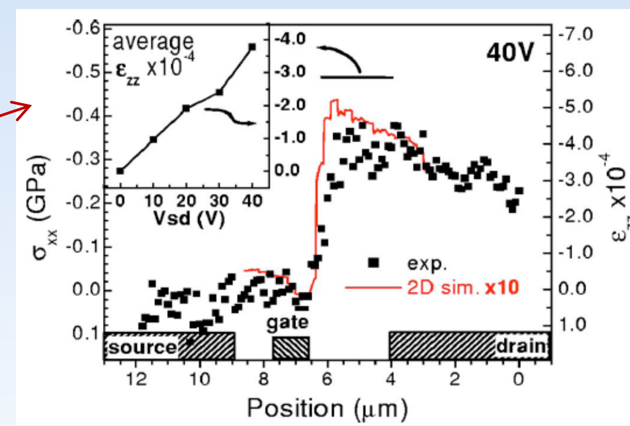


del Alamo *et al*. Microelectron. Reliab., **49**, 1200 (2009)



Joh et al. Microelectron. Reliab., **50**, 767 (2010)

Very high local strain fields

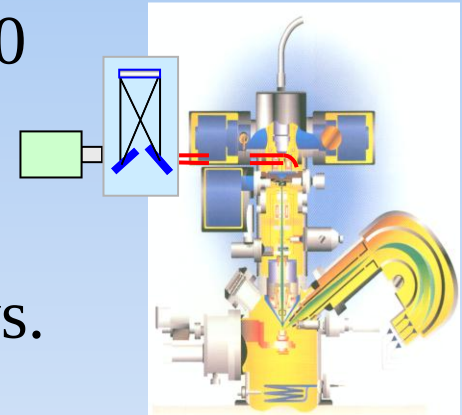


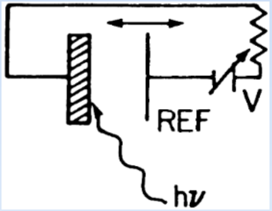
Sarua *et al*. Appl, Phys. Lett., **88**, 103502 (2006)

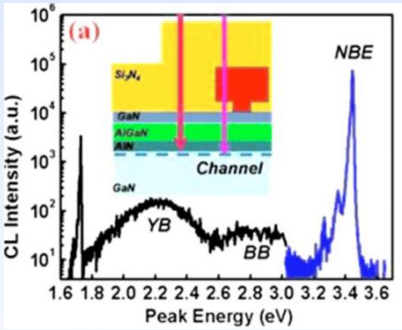
V_{DS} + V^{inv}_{piezo} → strain energy
→ exceed elastic energy of crystal
→ form defects at gate foot

Measurement Strategy

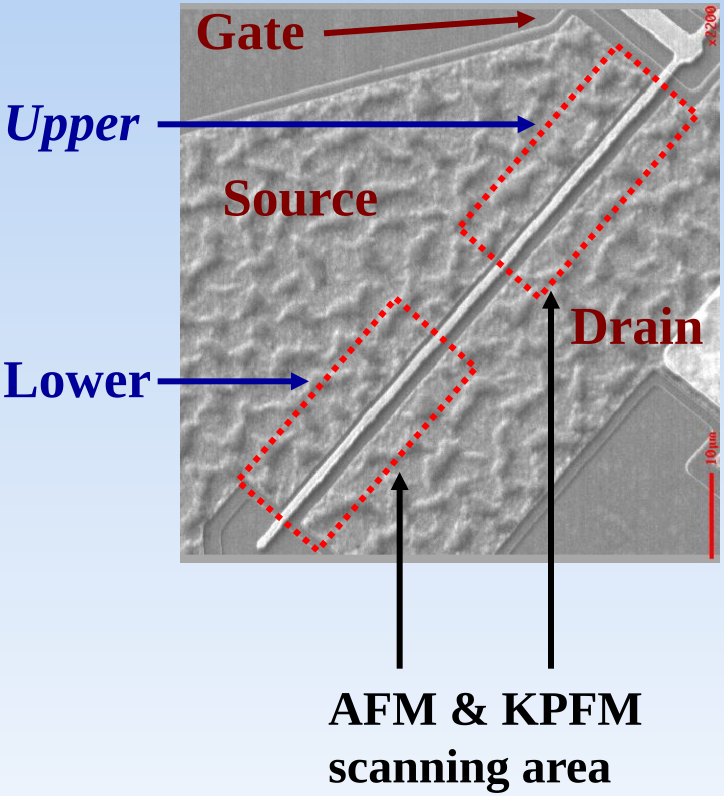
- **Thermal Mapping**: DRCLS NBE laterally (<10 nm) & in depth (nm's to μm's)
  - Obtain T vs. I_{DS}; locate "hot" spots
- **Stress Mapping**: DRCLS NBE near gate foot vs. V_{DS} with I_{DS} OFF (*no heating*)
- **Potential Mapping**: Kelvin work function vs. V_{DS} with I_{DS} OFF (*no heating*)
- **Device testing**: Step-wise ON & OFF-state I_{DMAX} and I_{GOFF} vs. V_{DS}
- **Defect Generation**: CLS defect peak intensities vs. thermal and electrical stress
- **Defect Localization:** DRCLS intensities vs. depth







Stress Conditions



- **Reference:** No stress
- **ON-state stress**: high I_D, low V_{DS}

  (I_D = 0.75 A/mm, V_{DS} = 6 V, V_G = 0 V)

- **OFF-state stress** : low I_D, high V_{DS}

  (I_D = $5*10^{-6}$ A/mm, V_{DS} = 10 ~ 30 V

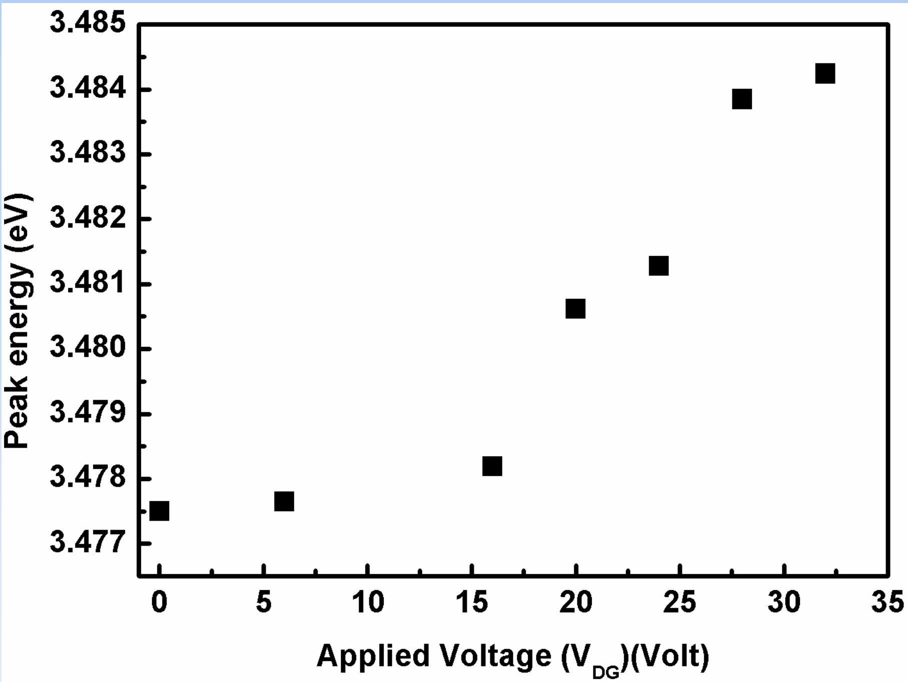
  V_G = -6 V)

- I_{GOFF} taken at V_{DS} = 0.5 V, V_{GS} = -6 V

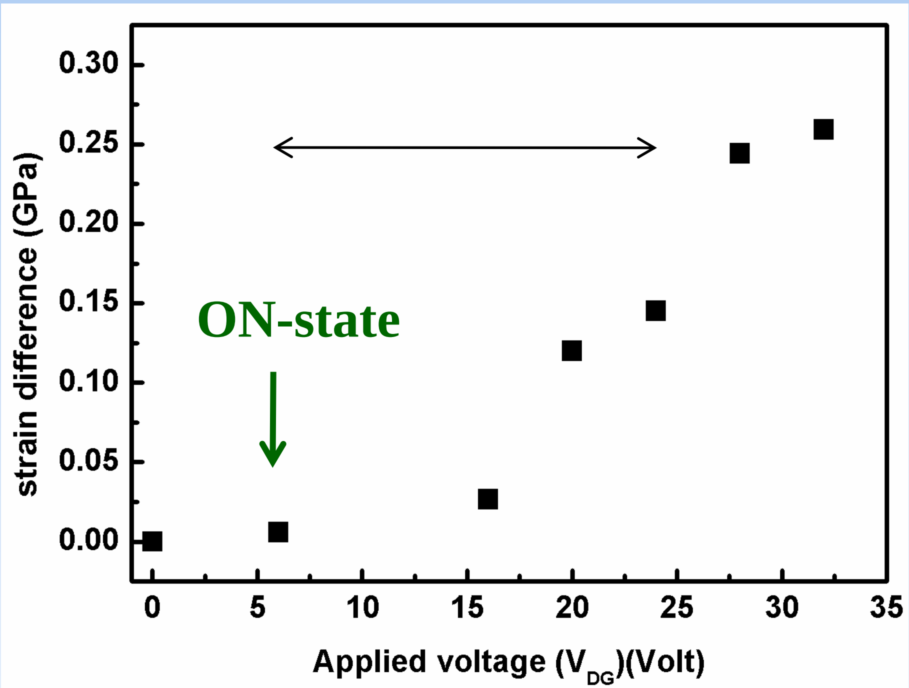
Aim: Test electric field-induced strain vs. current-induced (e.g., heating) mechanism

Strain Measurements: Drain-side Gate Foot

Band Gap vs. V_{DG}



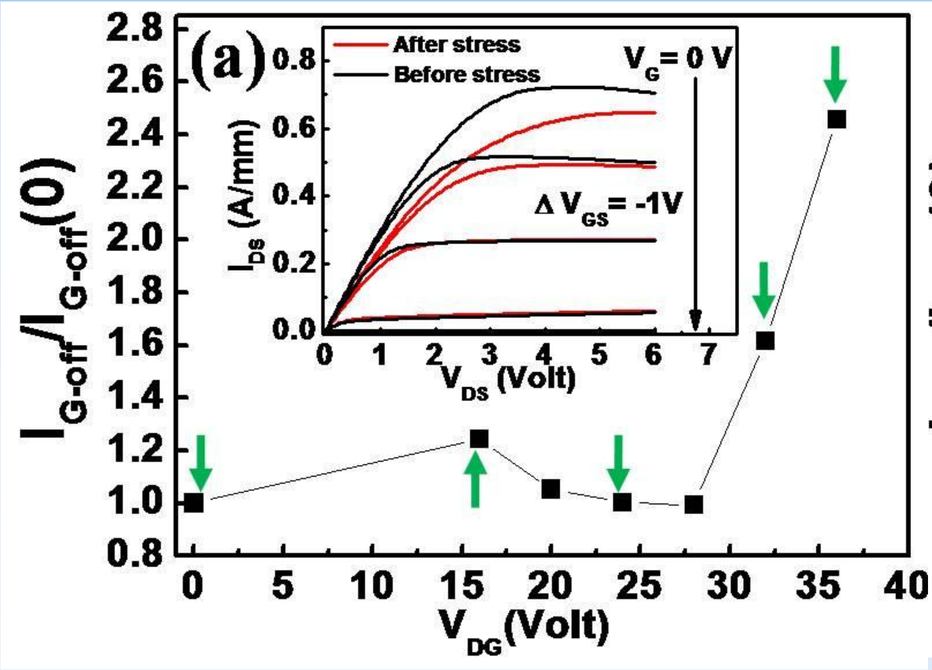
Strain vs. V_{DG}



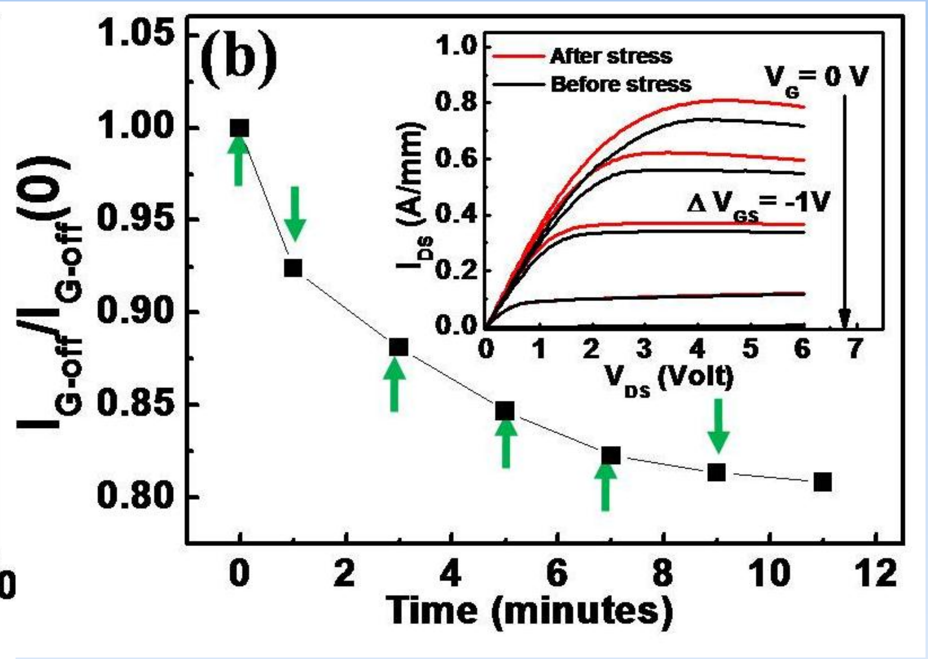
- **Applied voltage blue-shifts band gap, increases mechanical strain at drain-side gate foot**
- **26 meV CL shift = 1 GPa ; V_{DG} = 32 V → 0.27 GPa**

C.H. Lin *et al.* Appl. Phys. Lett. **97**, 223502 (2010)

I_{DMAX}, $I_{G\text{-}OFF}$ vs. Time & Applied Voltage



OFF-state

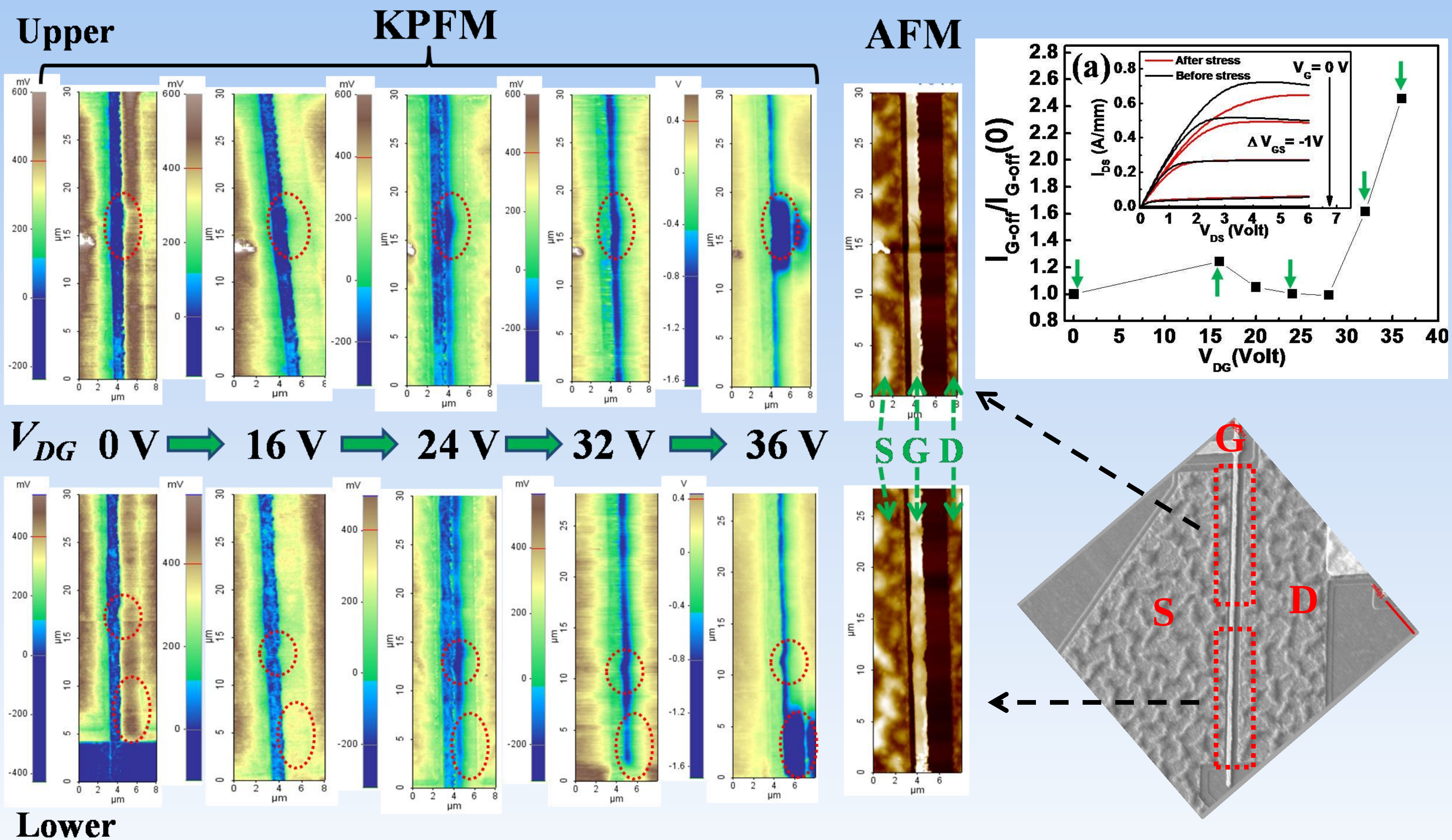


ON-state

- OFF-state $I_{G\text{-}Off}$ rises sharply at threshold V_{DG}
- ON-state $I_{G\text{-}OFF}$ *decreases* vs. time

  → device degradation with external stress

Surface Potential Evolution (OFF-state)



Low potential regions appear and expand with increasing applied stress V_{DG}

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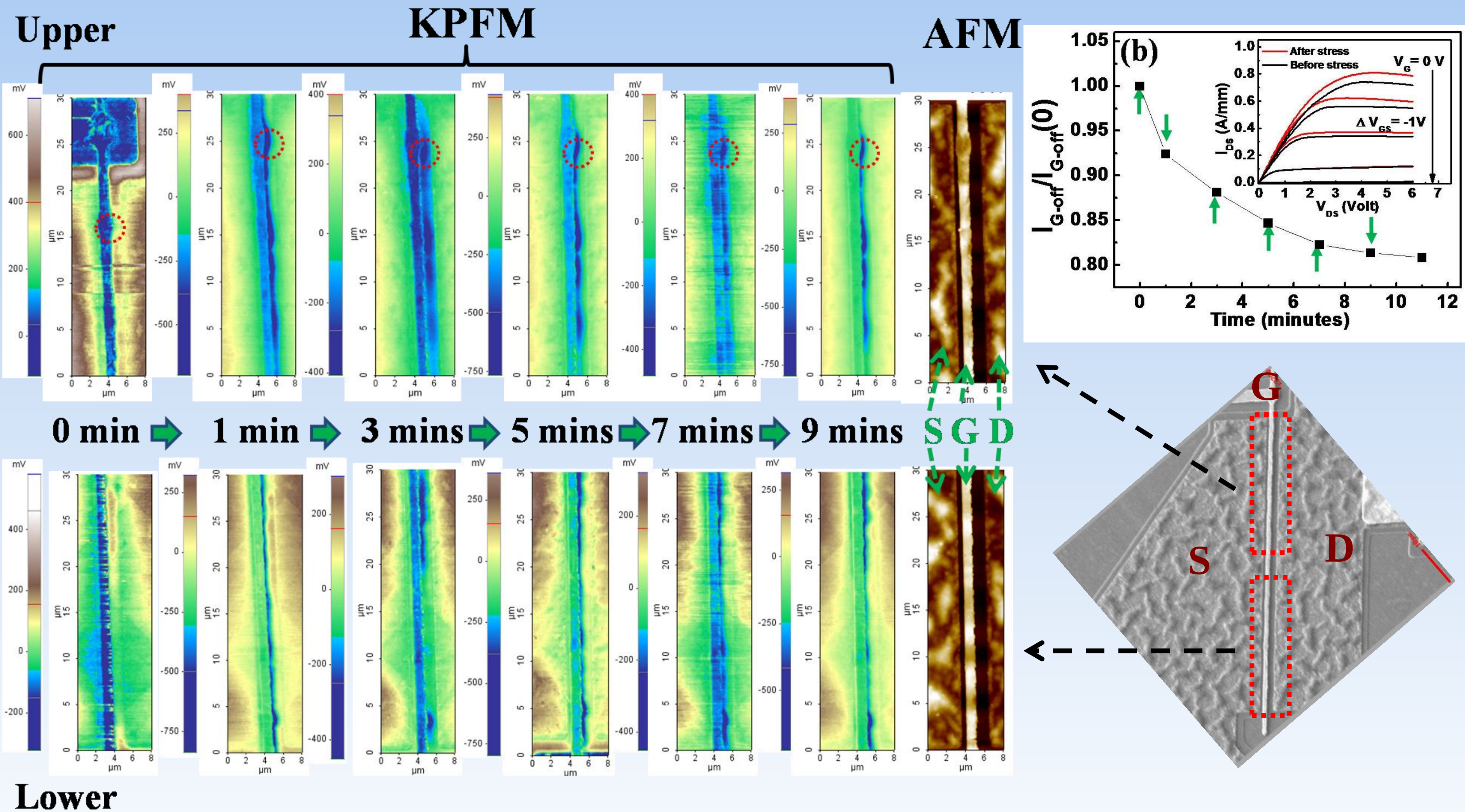
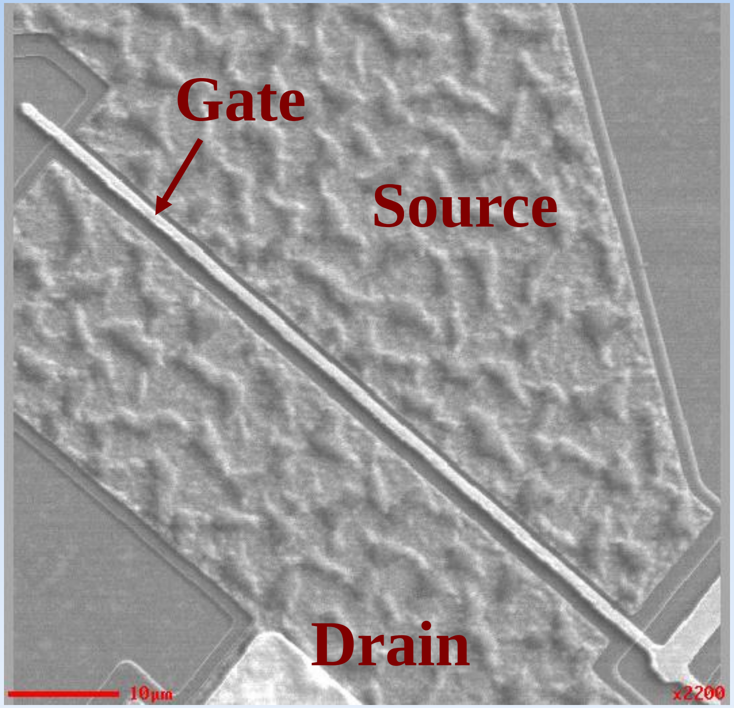
Surface Potential Evolution (ON-state)



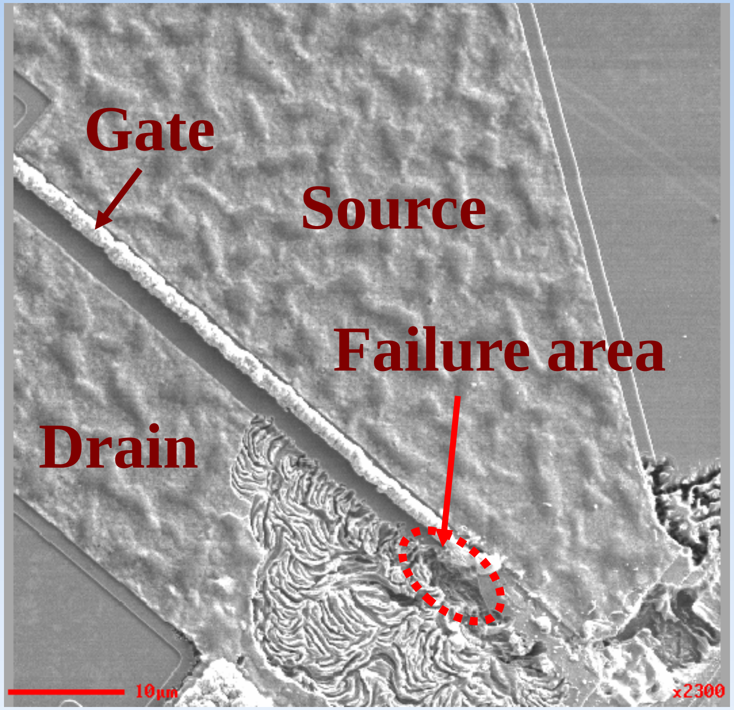
Current stress seems to degrade device in a different way

Device Failure under OFF-state Stress

Before failure



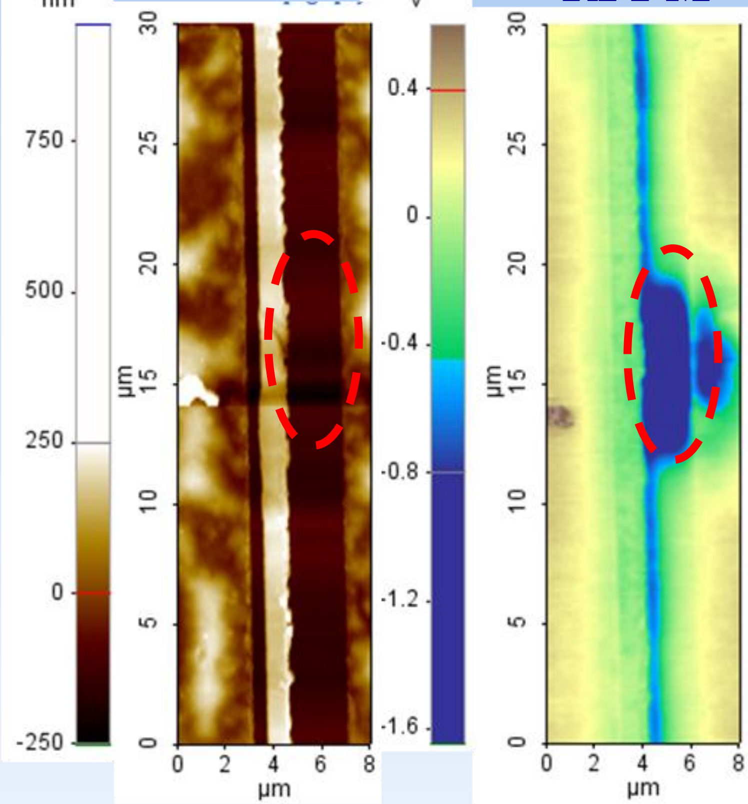
After failure



- Device failure occurs as V_{DG} increases further
- Large, cratered failure area appears; morphology of drain metal exhibits huge change

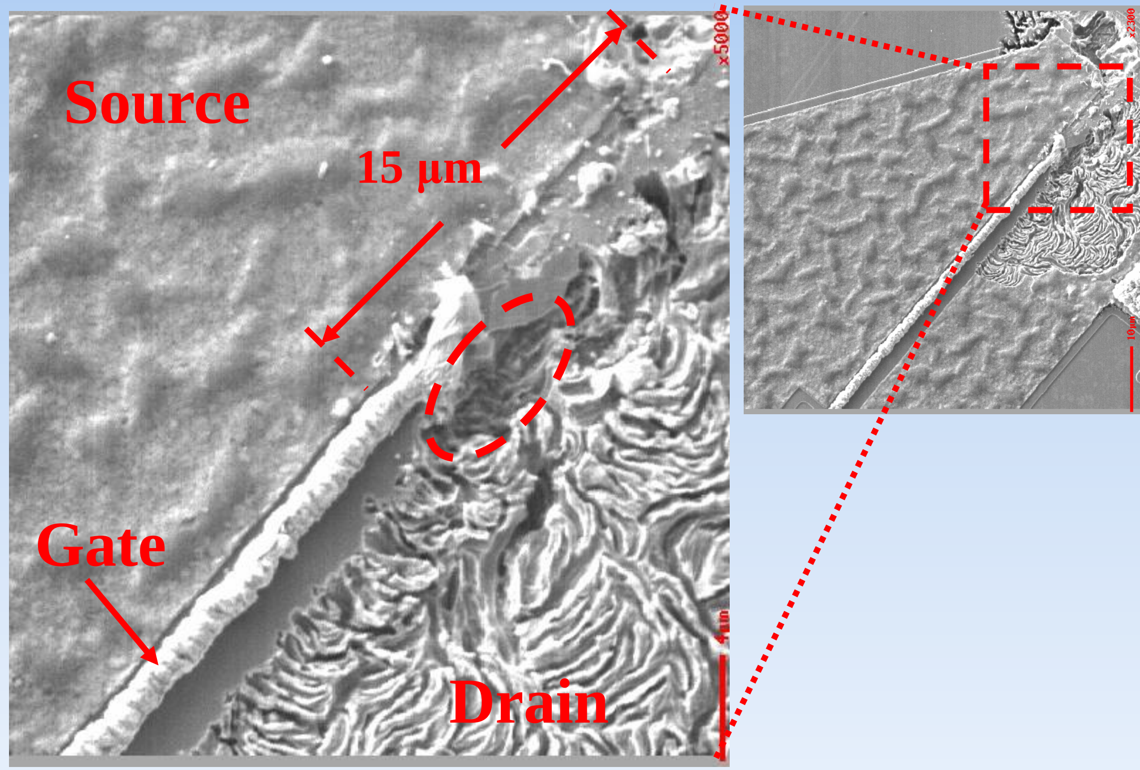
Correlation between AFM, KFPM & SEM

AFM *KPFM*



Before failure

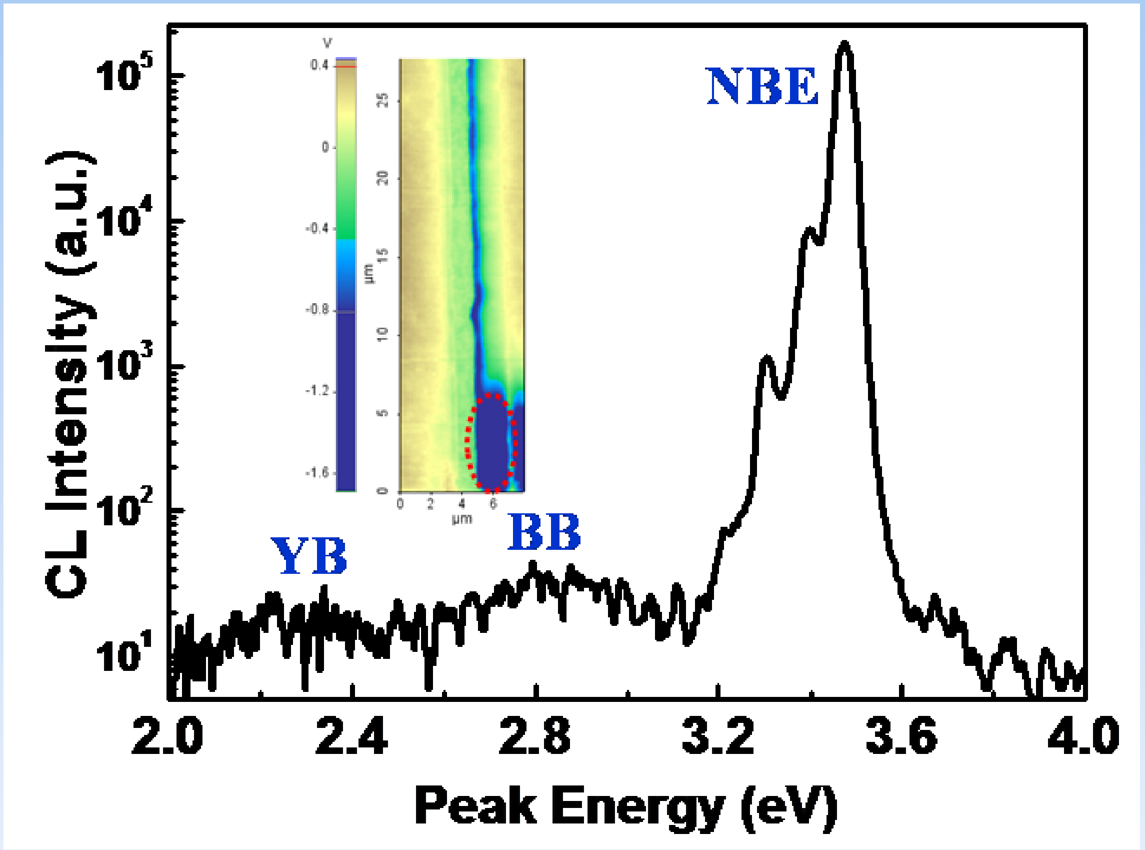
SEM



After failure

AFM, KPFM and SEM results reveal that device fails at the <u>lowest surface potential</u> area, where defect density is highest

Defect Spectroscopy of Low Potential Region



Within low potential region and at depth of 2DEG, DRCLS reveals formation of deep level defects

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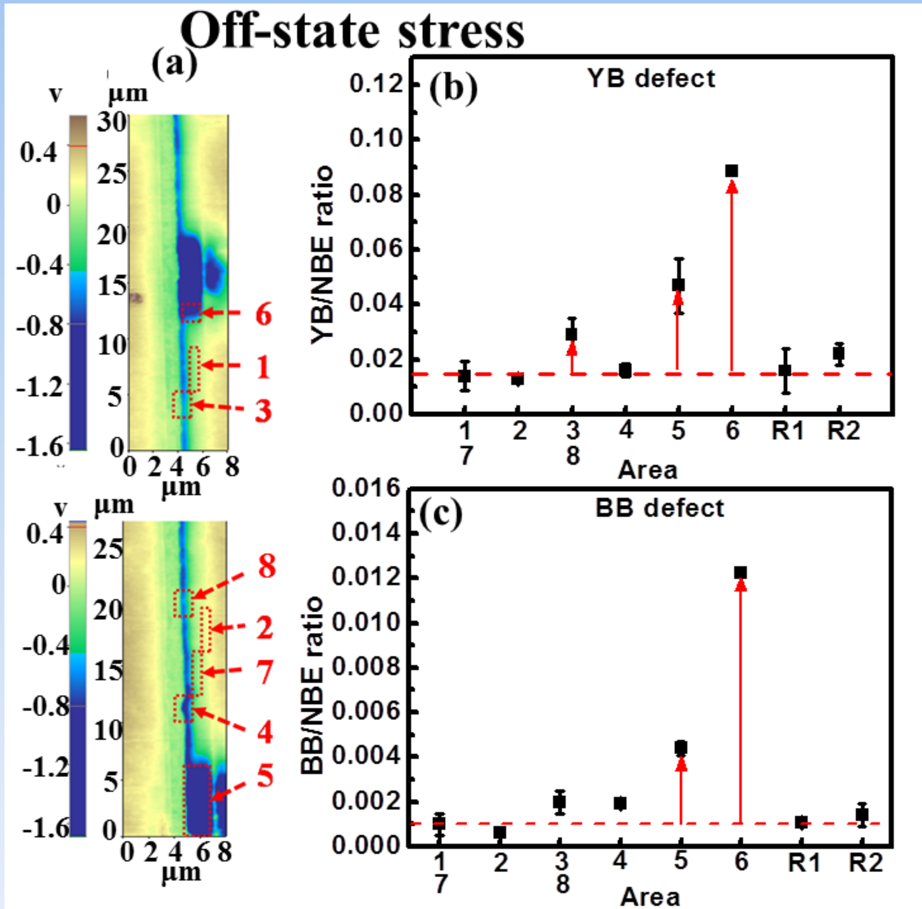
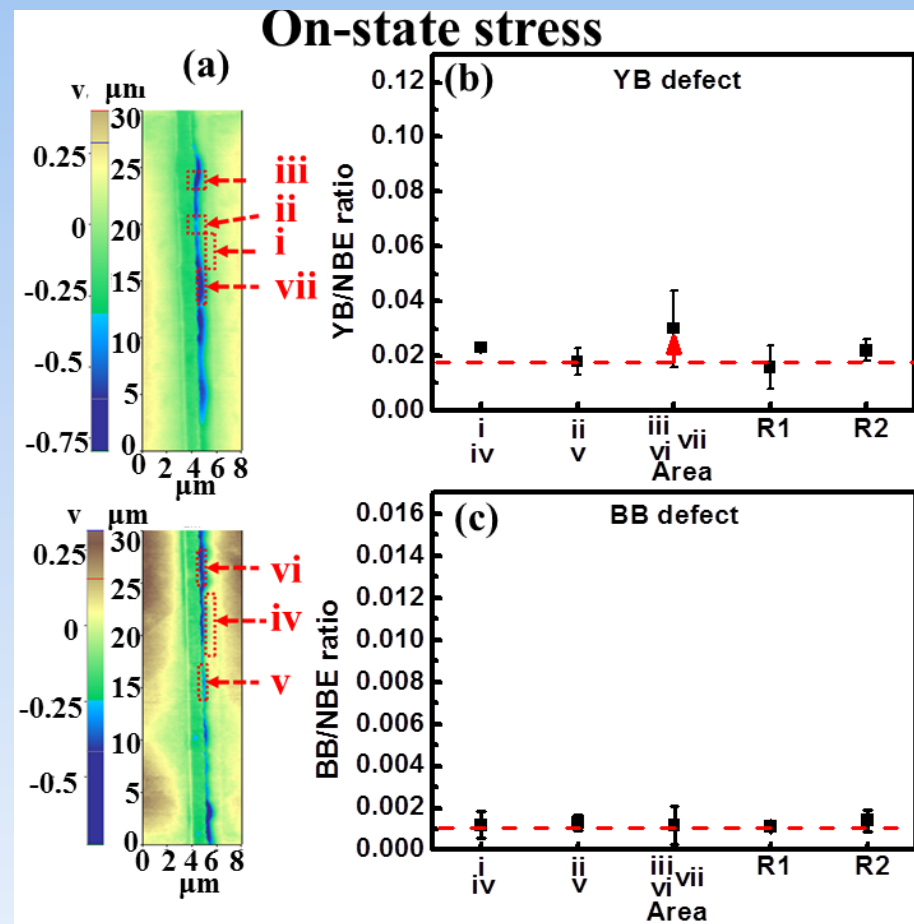
Defect Generation vs. Location





Areas of highest defect intensities and highest stress correlate

Lower defect creation for On-state stress

Largest defect increase at lowest potential region

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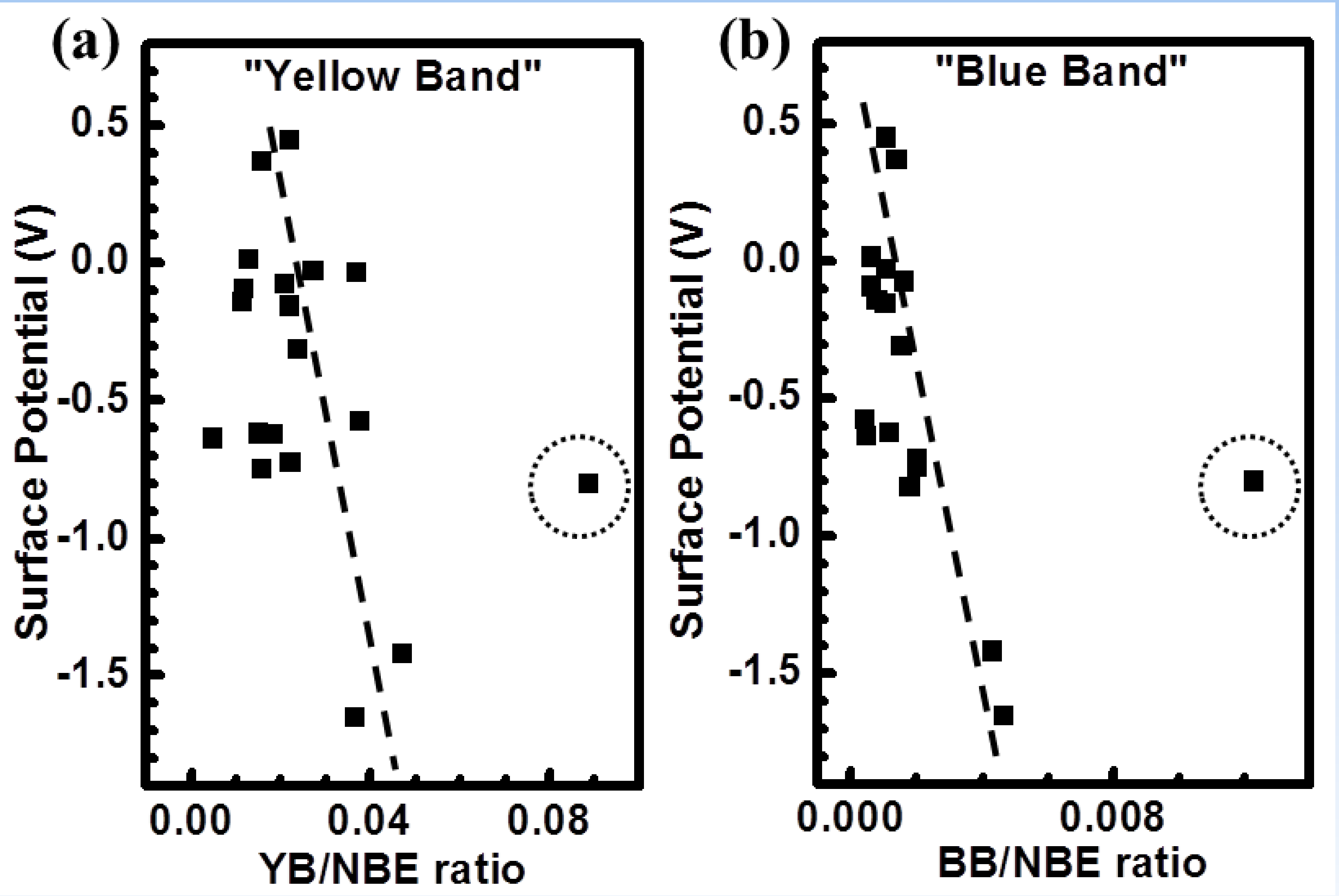
Defect Generation vs. Potential



Increasing defects densities correlate with decreasing potential

Surface Potential vs. Electrical Stress

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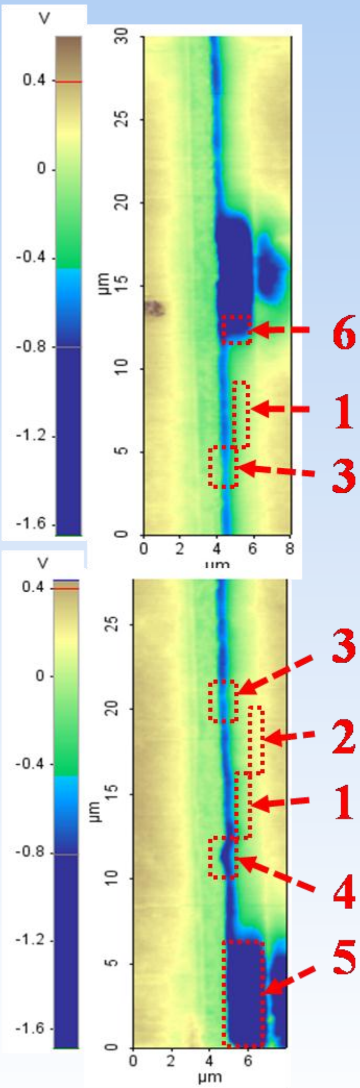
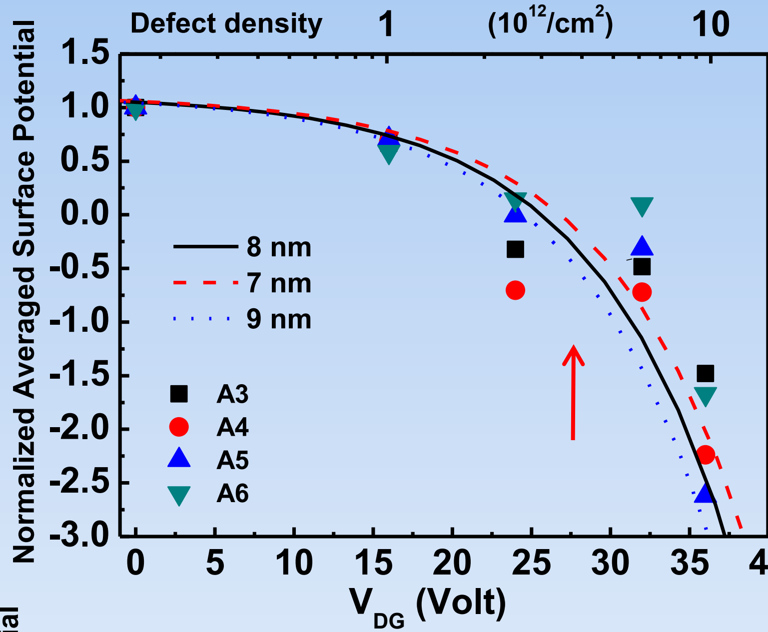
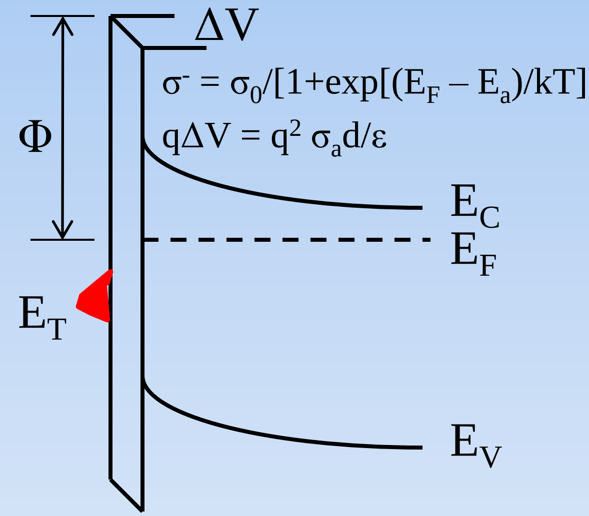
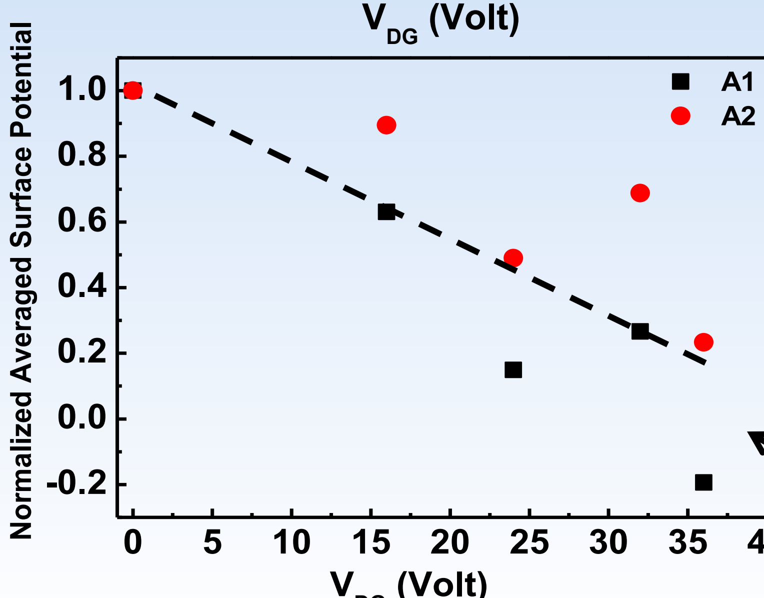
OFF-state









- E_F moves lower in gap as acceptor-like defects increase
- Drain-side surface potential decreases (Φ increases) with increasing V_{DG}
- Above V_{DG} threshold, faster decreases at low Φ patches
- Higher Φ patches decrease slower

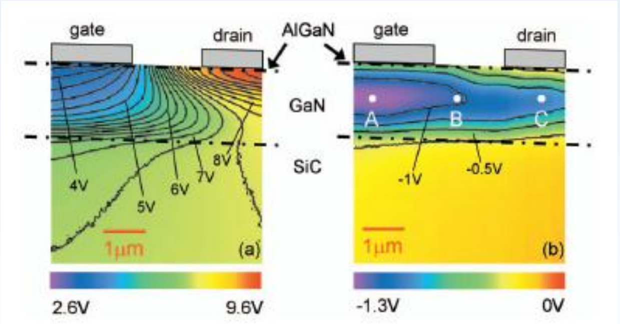
CLS Energy Comparison with Trap Spectroscopy

- **DLOS**: 3 traps observed: E_C-0.55 (dominant), 1.1, &1.7-1.9 eV

High DLOS 10^{12} cm^{-2} Trap Density: A. R. Arehart, A. C. Malonis, C. Poblenz, Y. Pei, J. S. Speck, U. K Mishra, S. A. Ringel, Phys. Stat. Sol. C **1-3** (2011) DOI 10.1002/pssc.201000955

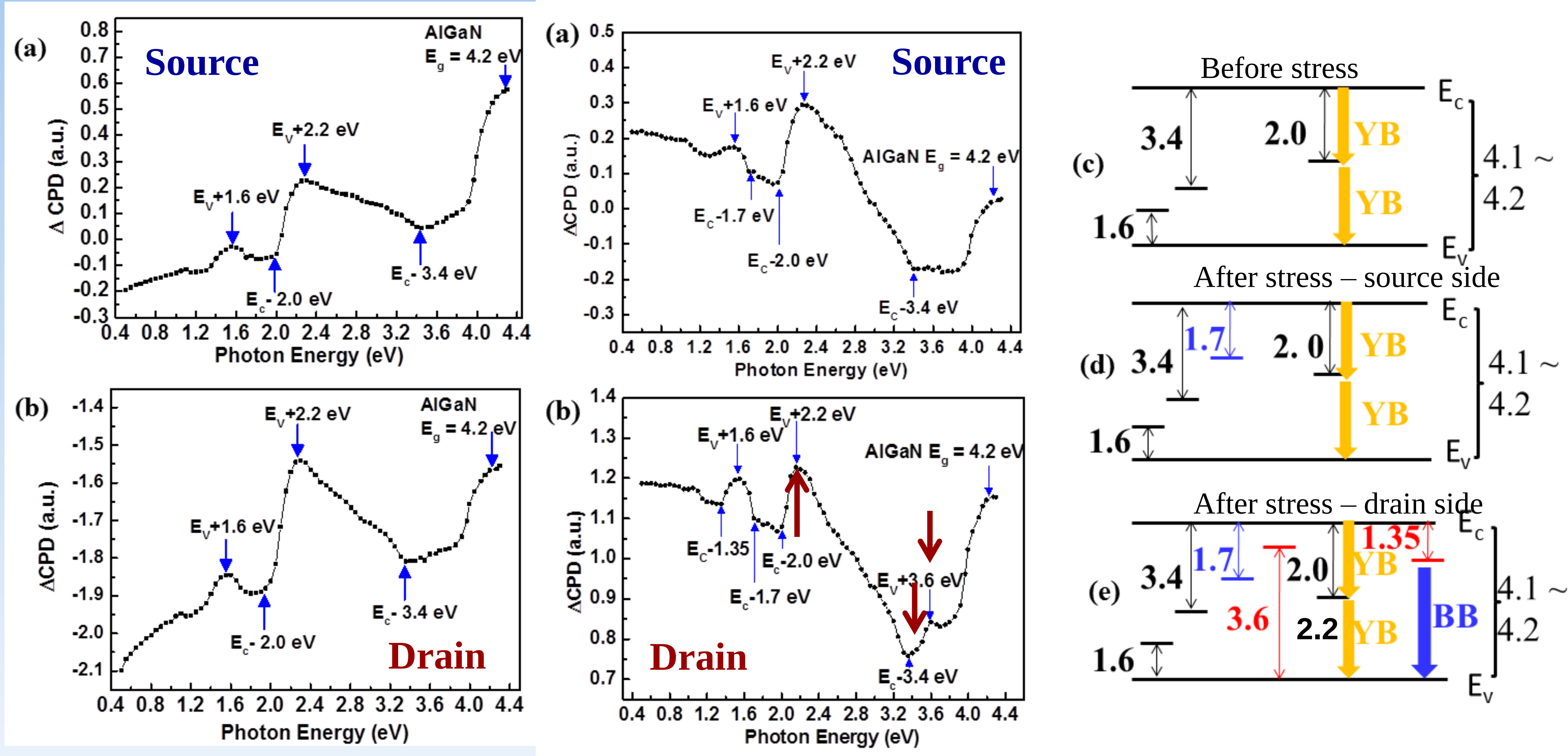
- **DRCLS:** 2.8 eV BB and 2.3 eV YB emissions: Traps that grow under DC stress – high 10^{12} cm^{-2} densities

KPFM E_a = 0.55 Activation Energy: S. Kamiya, M. Iwami, T. Tsuchiya, M. Kurouchi, J. Kikawa, T. Yamada, A. Wakejima, H. Miyamoto, A. Suzuki, A. Hinoki, T. Araki, and Y. Nanishi, Appl. Phys. Lett. **90**, 213511 (2007); M. Arakawa, S. Kishimoto, and T. Mizutani, Jpn. J. Appl. Phys. Part I **36**, 1826 (1997)



AlGaN/GaN HEMT Defect Location

Pre-stress **Post-stress**

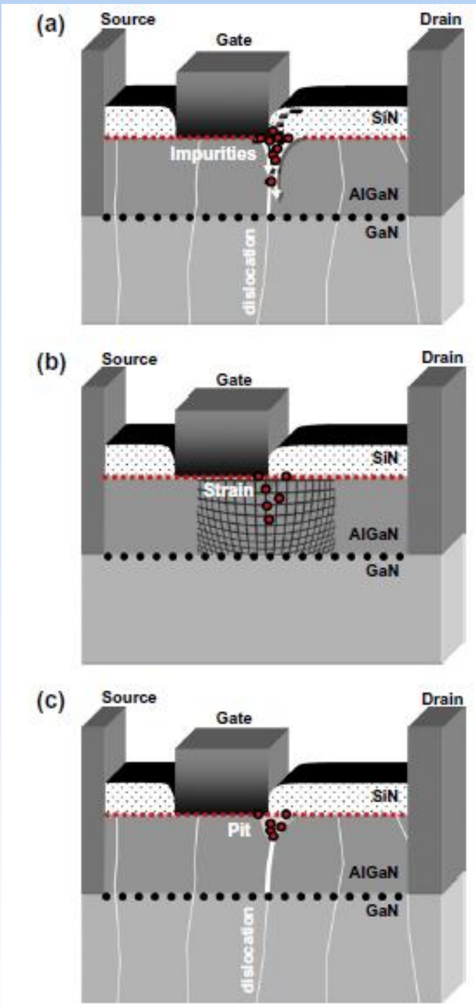


- **New 3.6 eV feature 0.5-0.6 eV below E_C → *BB defect within AlGaN***
- **Larger 2.2 eV threshold feature → higher YB defects with stress**
- **Higher Drain-side vs. Source-side changes: consistent with DRCLS**

AlGaN/GaN HEMT Physical Degradation Mechanisms

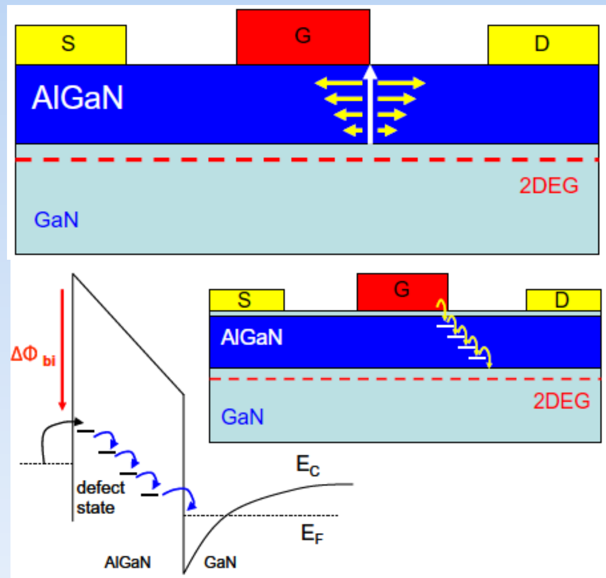
Strain- and Field-induced Impurity Diffusion

M. Kuball, et al., *Microelectron. Reliab*. **51**, 195 (2011)

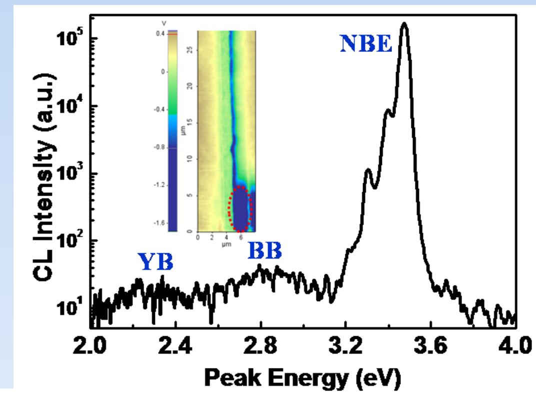


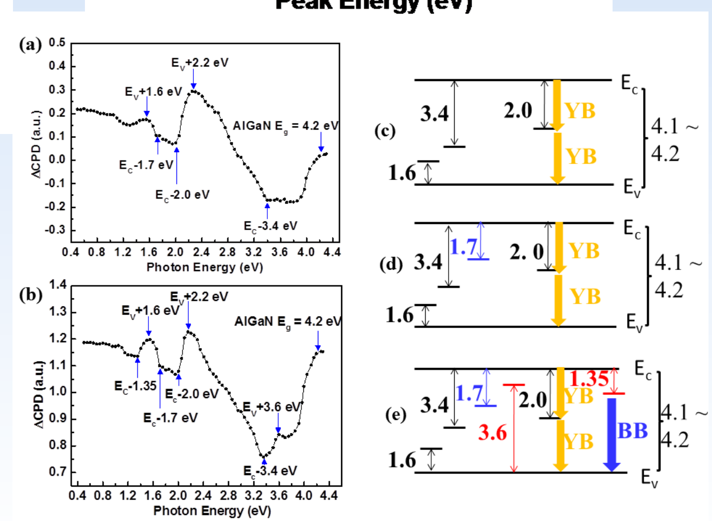
Inverse Piezoelectric Effect

del Alamo *et al*. Microelectron. Reliab., **49**, 1200 (2009)



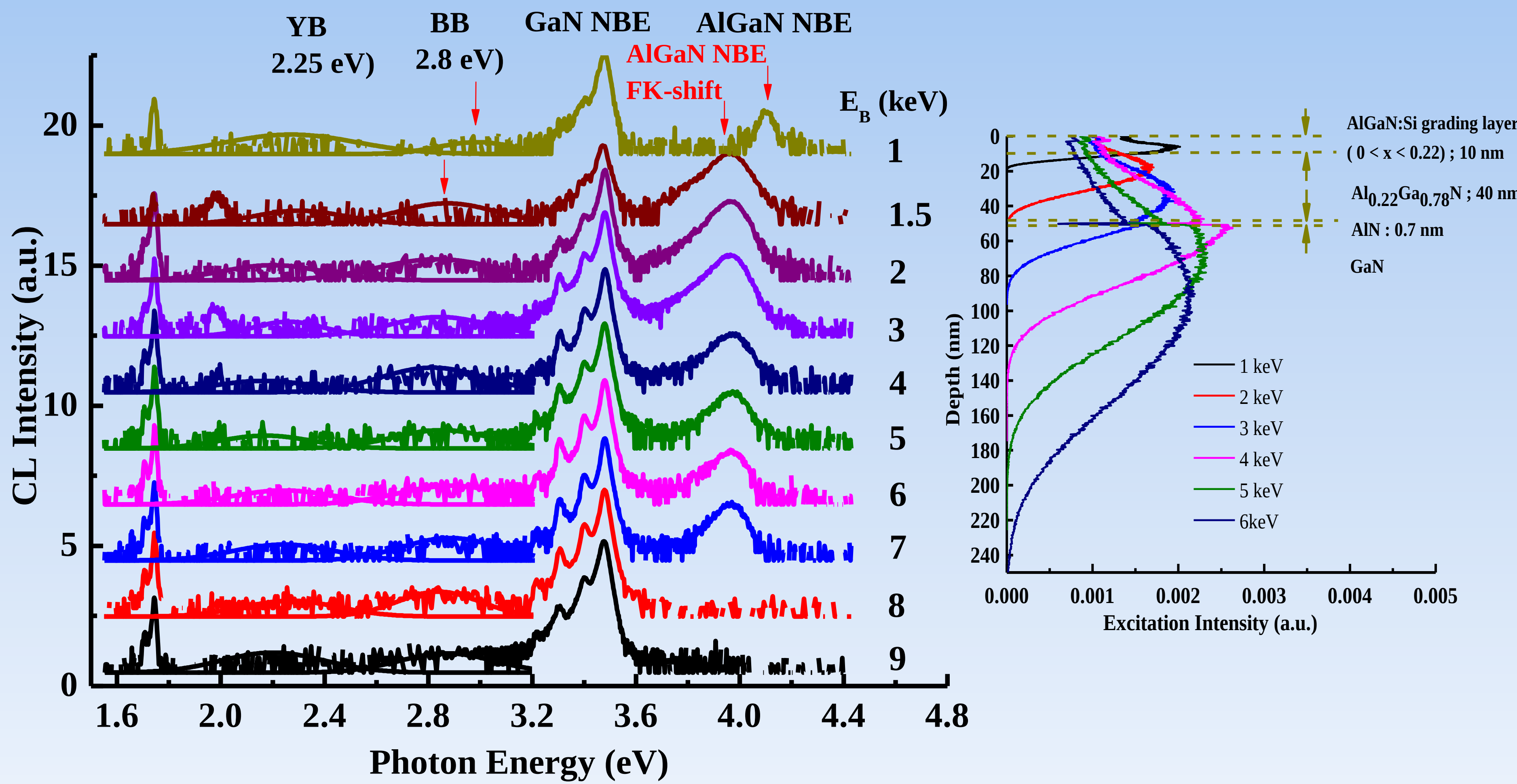
Electronically-Active Defect Formation





Multiple possible mechanisms that all create electronically-active defects

AlGaN/GaN HEMT Defect Location



- **BB peak shifts with AlGaN → <u>BB defect in AlGaN</u>**
- **Shifted AlGaN NBE and BB features appear only when excitation reaches 40 nm $Al_{0.22}Ga_{0.78}N$ layer → Additional piezoelectric strain field**

Conclusions

- **DRCLS measures electric field-induced stress and current-induced heating on a nanoscale *during* OFF-state and ON-state operation**
- **KPFM maps reveal expanding low potential patches where defects form and device failure will occur**
- **Separation of field- vs. current-induced degradation demonstrates their relative impact on AlGaN/GaN reliability**
- **Nanoscale patch potential and defect evolution inside AlGaN vs. V_{DG} threshold effect at drain-side gate foot support inverse piezoelectric degradation model**