Role of Electrochemical Reactions in the Degradation Mechanisms of AlGaN/GaN HEMTs

Feng Gao [1,2], Bin Lu [2], Carl V. Thompson [1],
Jesús del Alamo [2], Tomás Palacios [2]

1. Department of Materials Science and Engineering, Massachusetts Institute of Technology
2. Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology

This project is partially funded by the ONR DRIFT MURI program.

Introduction

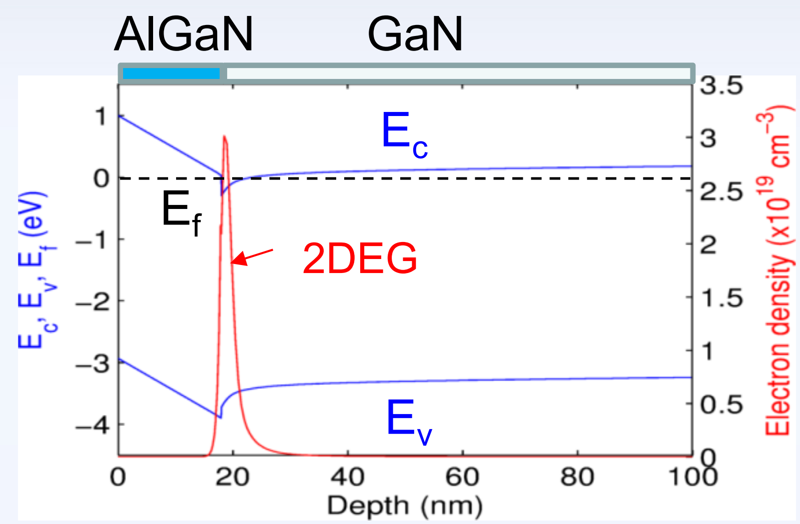
- **AlGaN/GaN HEMTs unique properties**

  Wide bandgap → $E_{critical}$ >3MV/cm

  Polarization → 2DEG density >10^{13}/cm^2

  High electron mobility: >1500 cm^2/V·s

  High electron peak velocity: 2.1×10^7cm/s



- **Excellent for High Power RF & Power Electronics Applications**

Wireless Base Station

Energy Conversion

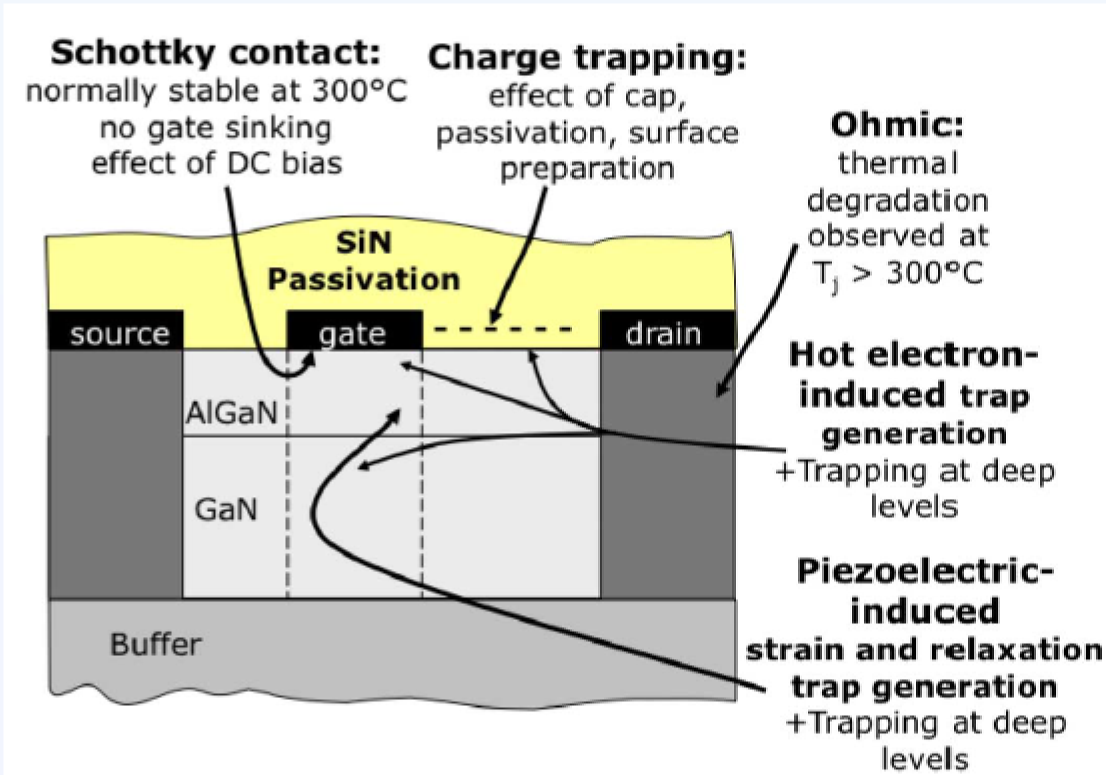
Automotive Electronics

fenggao@mit.edu

Motivation

— Reliability Bottleneck

- Device reliability is one of the greatest obstacles for AlGaN/GaN HEMTs: various degradation modes



[Meneghesso et. al., *IEEE Transactions on Device and Materials Reliability*, vol.8, no.2, p.332, 2008]

MTL microsystems technology laboratories

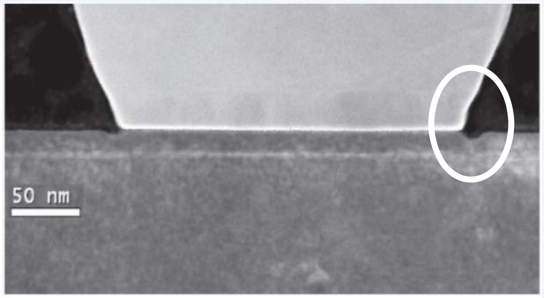
fenggao@mit.edu

Motivation

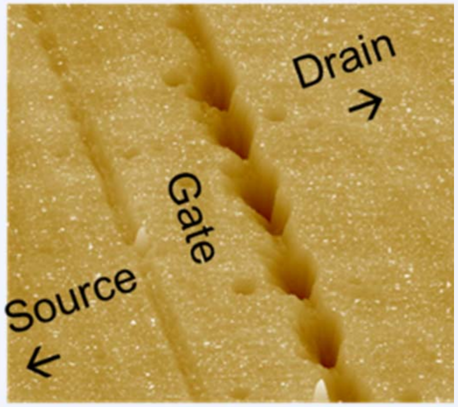
— Overview of Reliability Phenomena

- Permanent Degradation

Surface Pitting

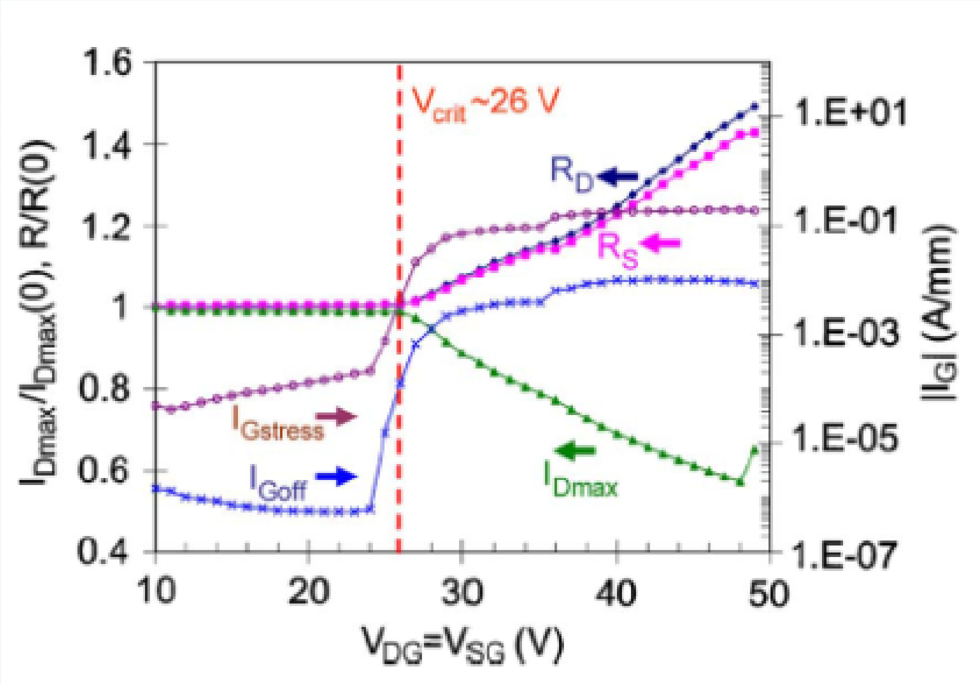


U. Chowdhury et al., *IEEE Electron Dev. Lett*, vol. 29, no.10, 2008.



P. Makaram et al., *Appl. Phys. Lett*., 96, 233509, 2010.

Electrical Degradation



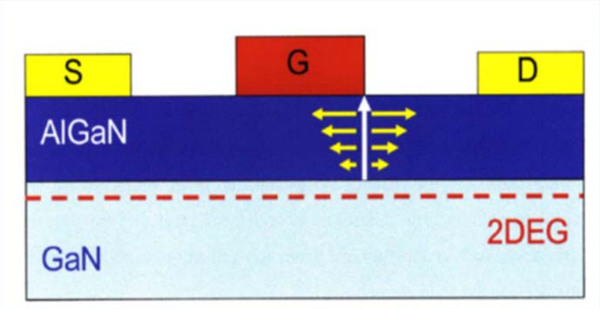
J. Joh et al., *IEEE Electron Dev. Lett*., vol. 29, no. 4, 2008.

fenggao@mit.edu

Motivation

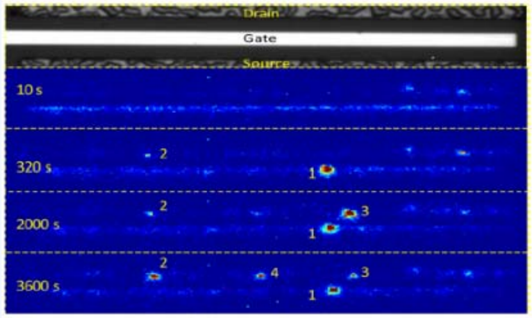
— Overview of Reliability Mechanisms

- Physical mechanism in permanent degradation
  - **Inverse Piezoelectric Effects**



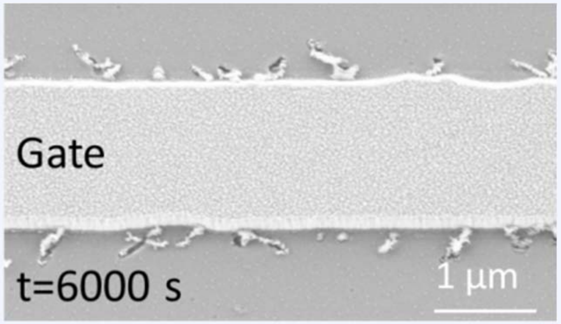
J. Joh et al., I*EDM 2007. IEEE International*, 2007, pp. 385–388.

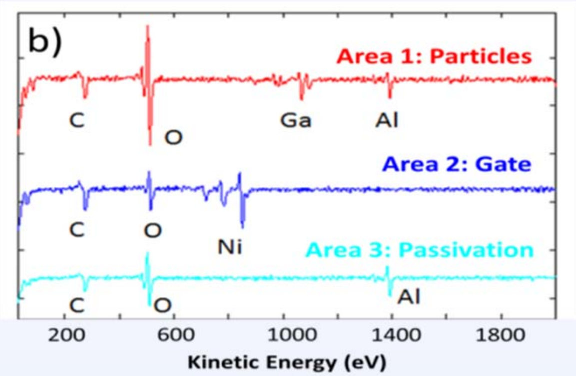
  - **Defect Percolation**



M. Meneghini et al., *Appl. Phys. Lett.*, vol. 100, no. 3, p. 033505, 2012.

  - **Mass-Transport**





F. Gao et al., *Appl. Phys. Lett.*, vol. 99, no. 22, pp. 223506, 2011.

fenggao@mit.edu

Goals of This Work

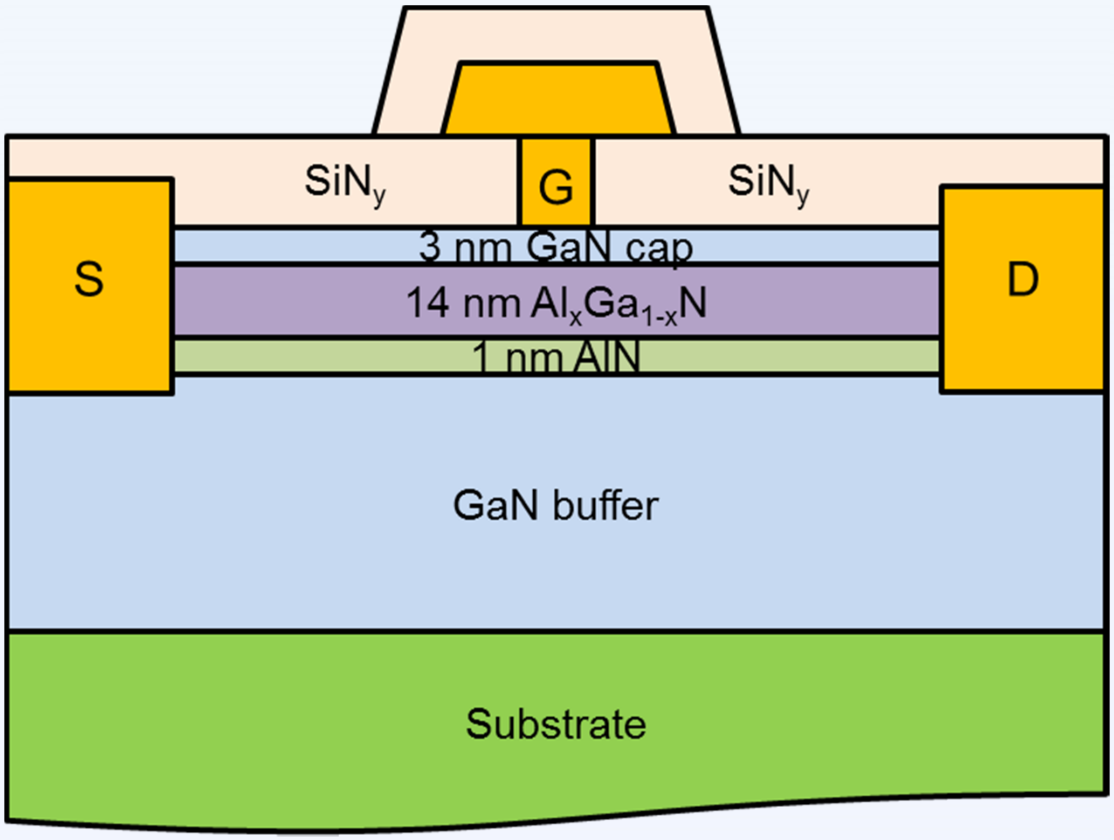
- Water-Assisted Electrochemical Mass Transport in Permanent Degradation

- Electrochemical Reaction Mechanism:
  - Holes generation
  - Water Diffusion

fenggao@mit.edu

AlGaN/GaN HEMTs Under Study

- Device provided by industrial collaborator



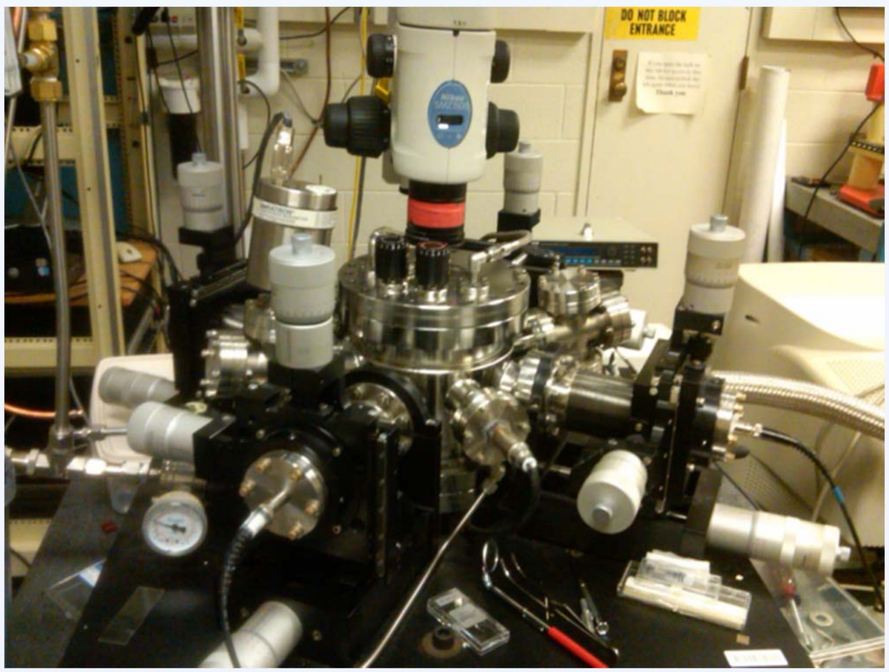
fenggao@mit.edu

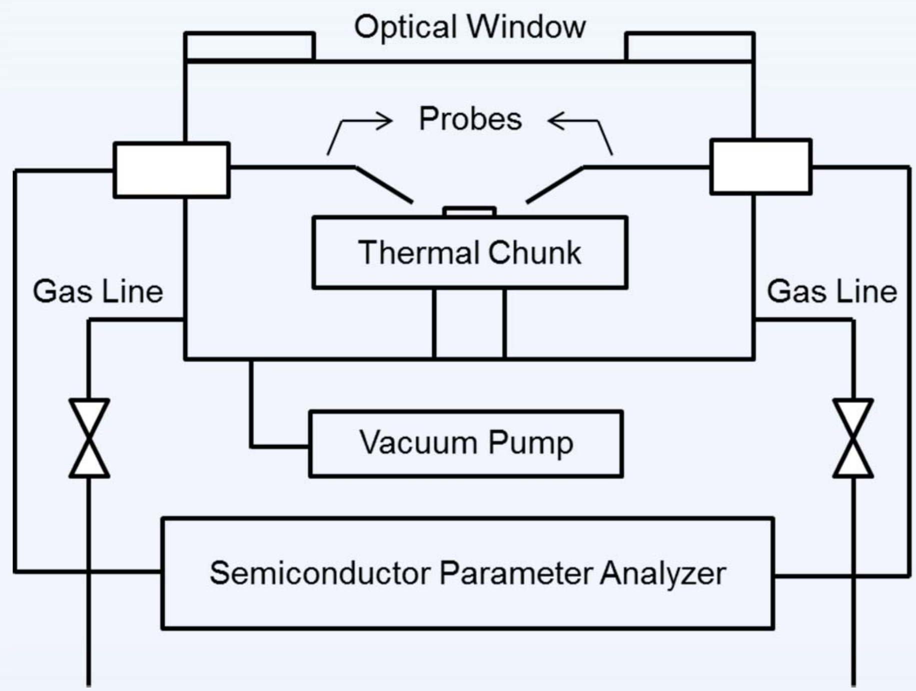
Experimental Setup

— High Vacuum and High Temperature Probe Station

Key features:

- Vacuum chamber of 1×10^{-7} Torr.
- Thermal chuck up to 600 °C.
- Four probes for electrical contact.
- Two gas lines that can supply the chamber with air, O_2, N_2, Ar, He and H_2.





MTL microsystems technology laboratories

Acknowledgement to Prof. Harry L. Tuller

fenggao@mit.edu

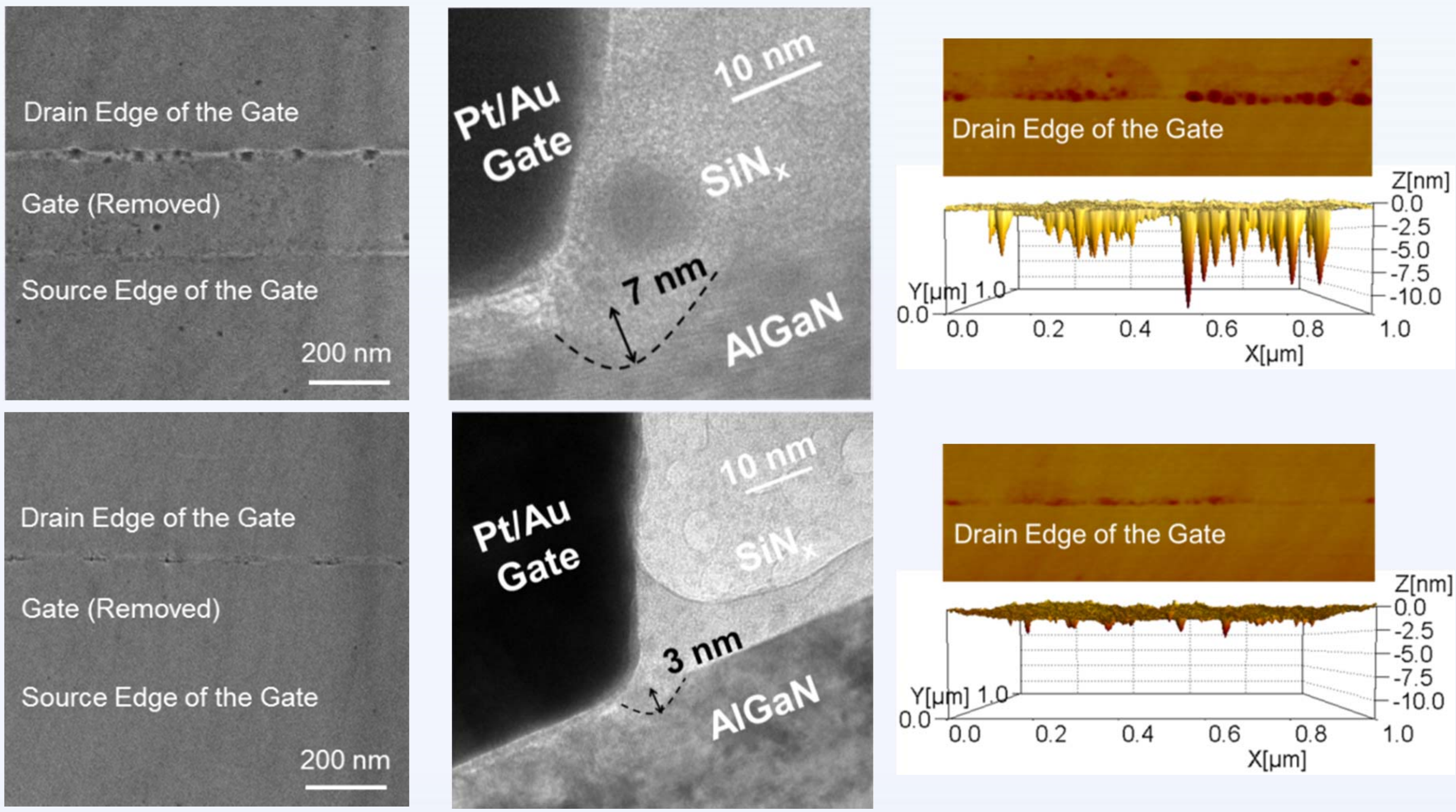
Impact of Atmosphere on Surface Pitting
— Ambient and Vacuum Control-Group

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

SEM Top View | TEM Cross Section | AFM Depth Profile

Stressed in ambient air

Stressed in vacuum of 1×10^{-7} Torr



Surface pitting caused by OFF-state electrical stress is significantly reduced in vacuum.

F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

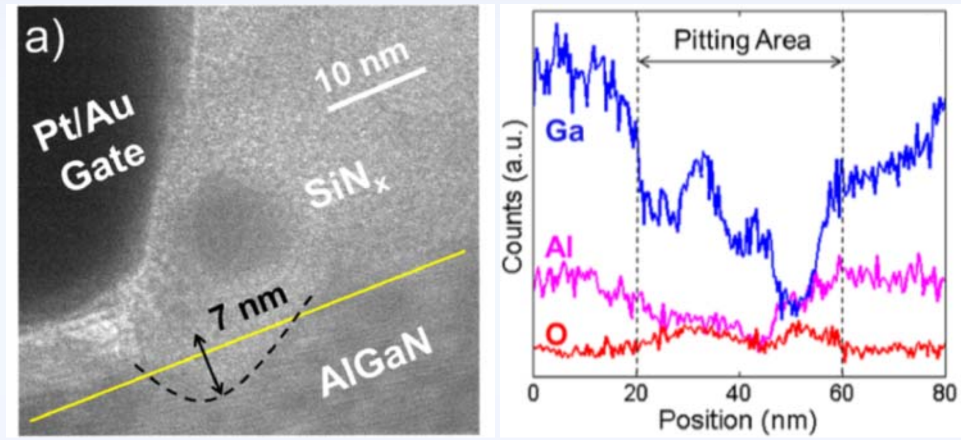
Role of Oxygen in Surface Pitting

— Ambient and Vacuum Control-Group

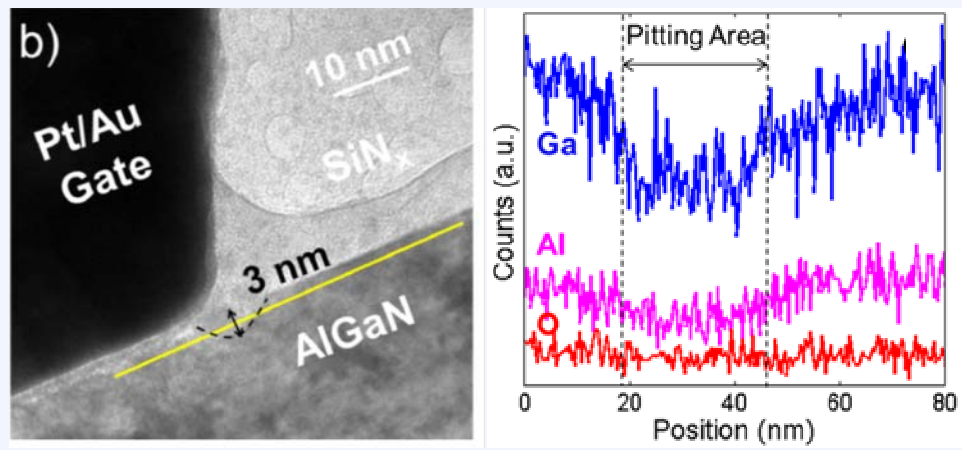
TEM

TEM EDX

Stressed in ambient air



Stressed in vacuum of 1×10^{-7} Torr



Higher concentration of oxygen (O) is found inside the surface pits for AlGaN/GaN HEMTs stressed in ambient air.

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

Influence of Ambient Air

Off-state stress

- Ambient air → more pits with deeper depther
- Ambient air → increase of oxygen in pitting area

Ambient air has N_2, O_2, H_2O, CO_2

What gas in the ambient air causes:

- *surface pitting?*
- *increasing of oxygen concentration in pitting area?*

microsystems technology laboratories

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

Impact of Moisture on Surface Pitting

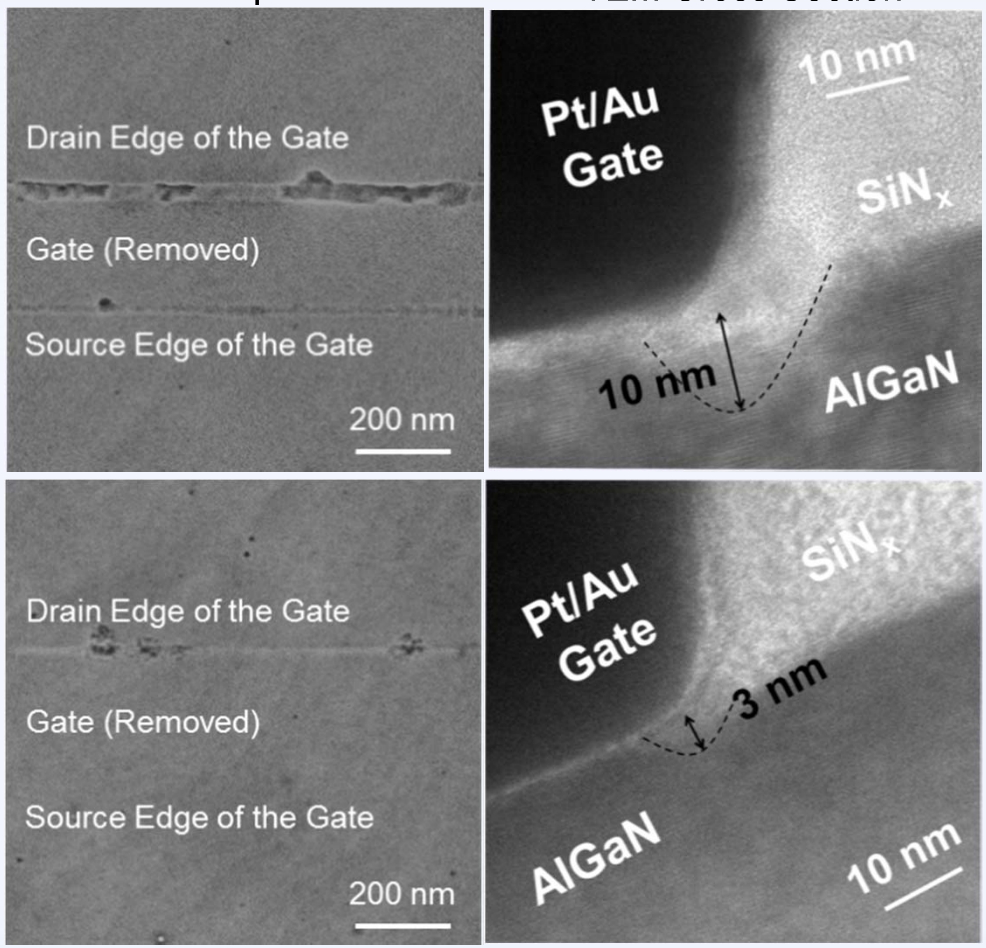
— Wet and Dry Control-Group

wet/dry Ar; wet/dry O_2 ; wet/dry N_2 ; wet/dry CO_2 ; wet/dry Air

SEM Top View | TEM Cross Section

Stressed in water-saturated gas (Ar)

Stressed in dry gas (Ar)



Water has a major impact on surface pitting & source of O in pitting area

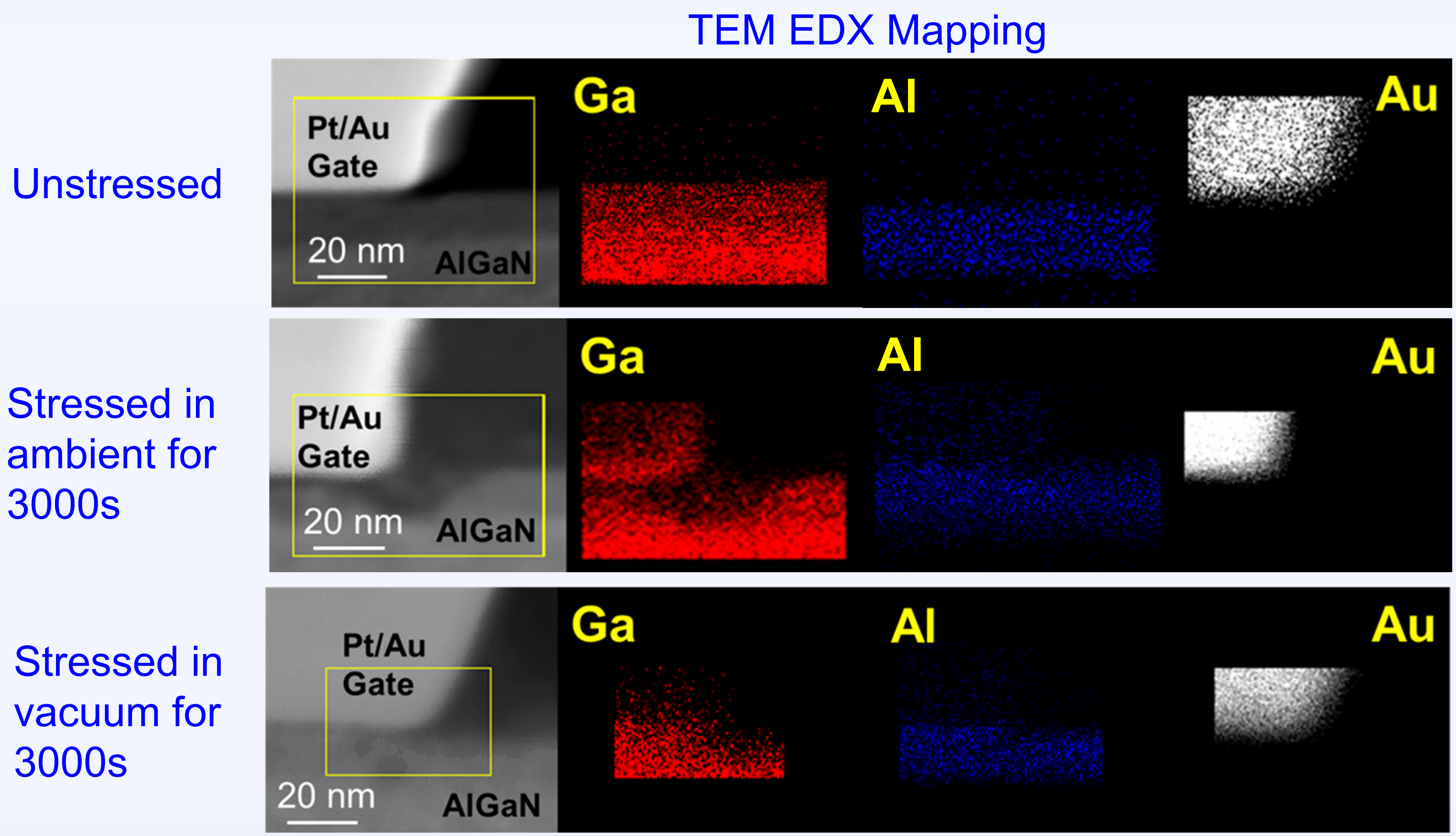
F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

Mass Transport

— Ga, Al migration

- **TEM EDX mapping: Ga and Al found in the gate region**



F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

Permanent Electrical Degradation

— By Off-State Stress

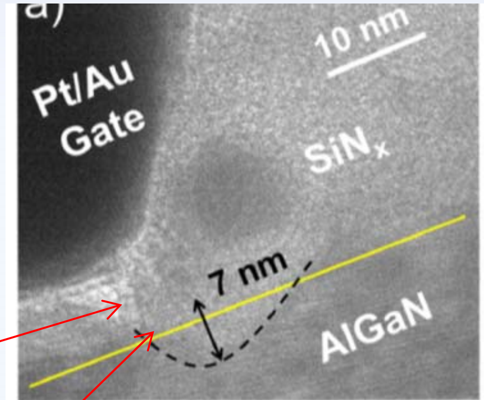
- Off-state stress: V_{gs} = -7V, V_{ds} = 43V, 3000s at RT in dark
- 1min UV illumination & 12hr at rest after Off-state to recover trapping transient
- I_{dss} and I_g measured at V_{gs} = 0, V_{ds} =5V

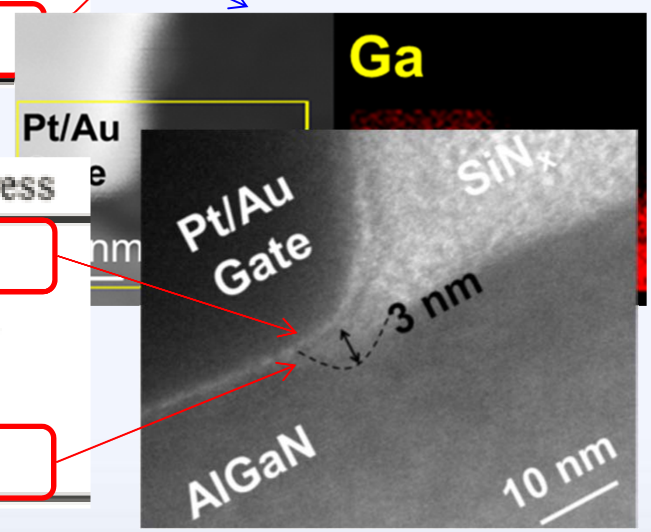
Stressed in ambient

	Before Stress	After Stress
I_{dss} (mA/mm)	766	728
I_g (mA/mm)	5.08×10^{-6}	1.40
V_T (V)	-2.98	-3.01
R_d (Ω·mm)	3.74	4.07

Stressed in vacuum

	Before Stress	After Stress
I_{dss} (mA/mm)	760	756
I_g (mA/mm)	9.88×10^{-6}	0.924
V_T (V)	-2.99	-2.99
R_d (Ω·mm)	3.76	3.90



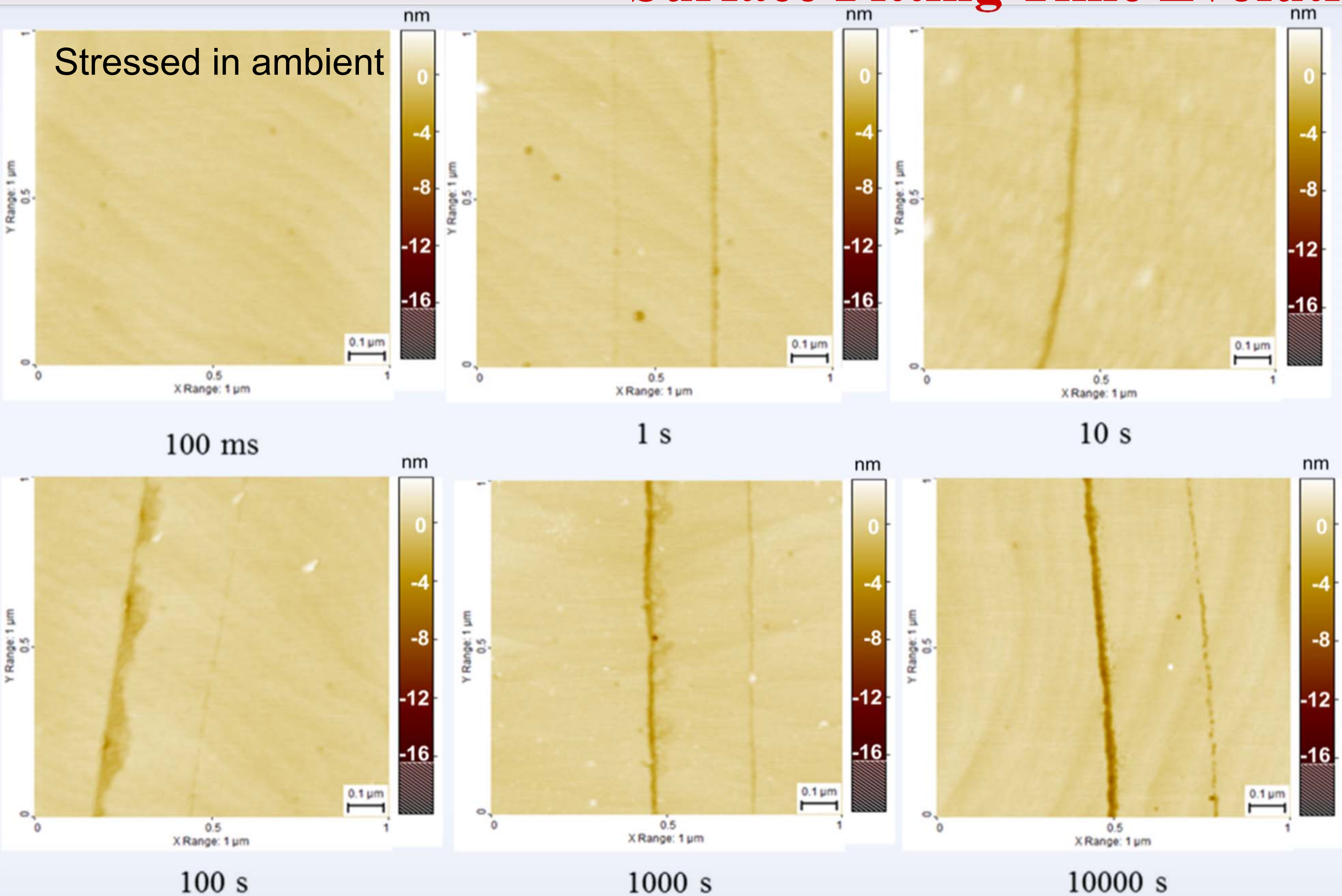


F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

Permanent Electrical Degradation

— Surface Pitting Time Evolution



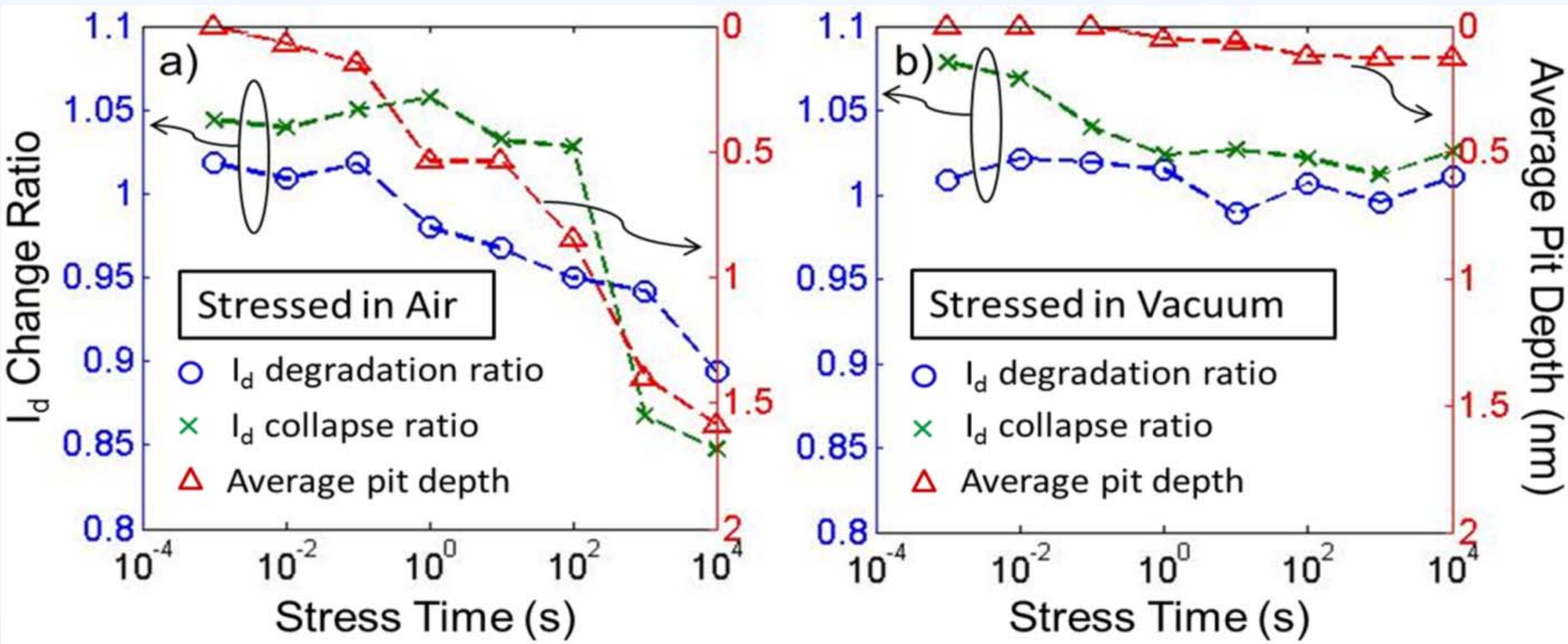
microsystems technology laboratories

fenggao@mit.edu

Permanent Electrical Degradation
— I_d Degradation Time Evolution

- Time Evolution of Drain Current Degradation:
  Id measured at V_{gs} = 0 and V_{ds} = 5 V

Drain current degradation evolves with the growth of the surface pits over stress time.



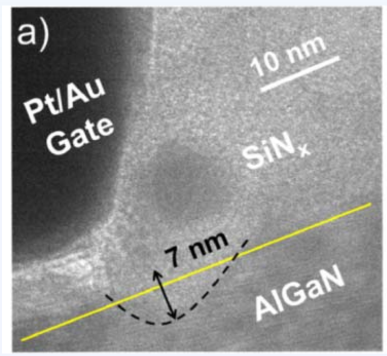
MTL microsystems technology laboratories

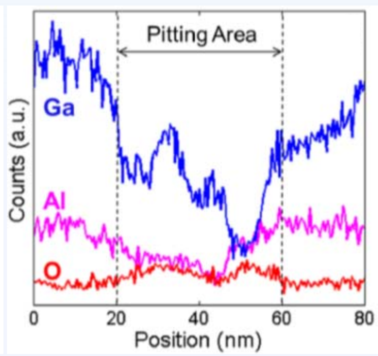
F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

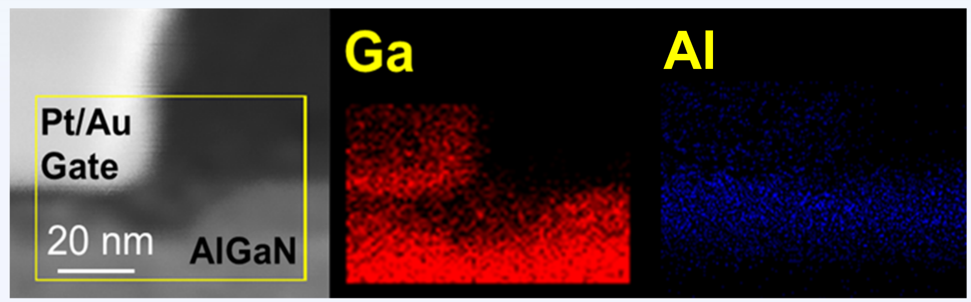
fenggao@mit.edu

Summary 1

- H_2O → surface pitting and source of oxygen in pitting area
- Ga, Al migration accompanies surface pitting
- Surface pitting & Ga, Al migration → permanent electrical degadation







What is the physical mechanism behind the impact of H_2O on the surface pitting ?

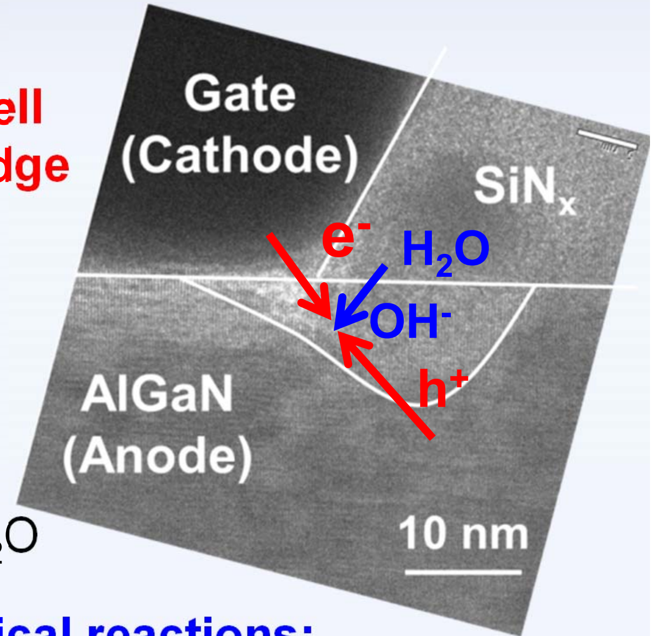
fenggao@mit.edu

Water-assisted Electrochemical Reactions
— Corrosion in AlGaN/GaN HEMTs

❖ **Reduction of water:**

$2H_2O + 2e^- = 2OH^- + H_2$

An electrochemical cell formed at the drain edge of the gate.



❖ **Anodic oxidation of AlGaN:**

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

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

❖ **Complete Reduction-oxidation (redox) electrochemical reactions:**

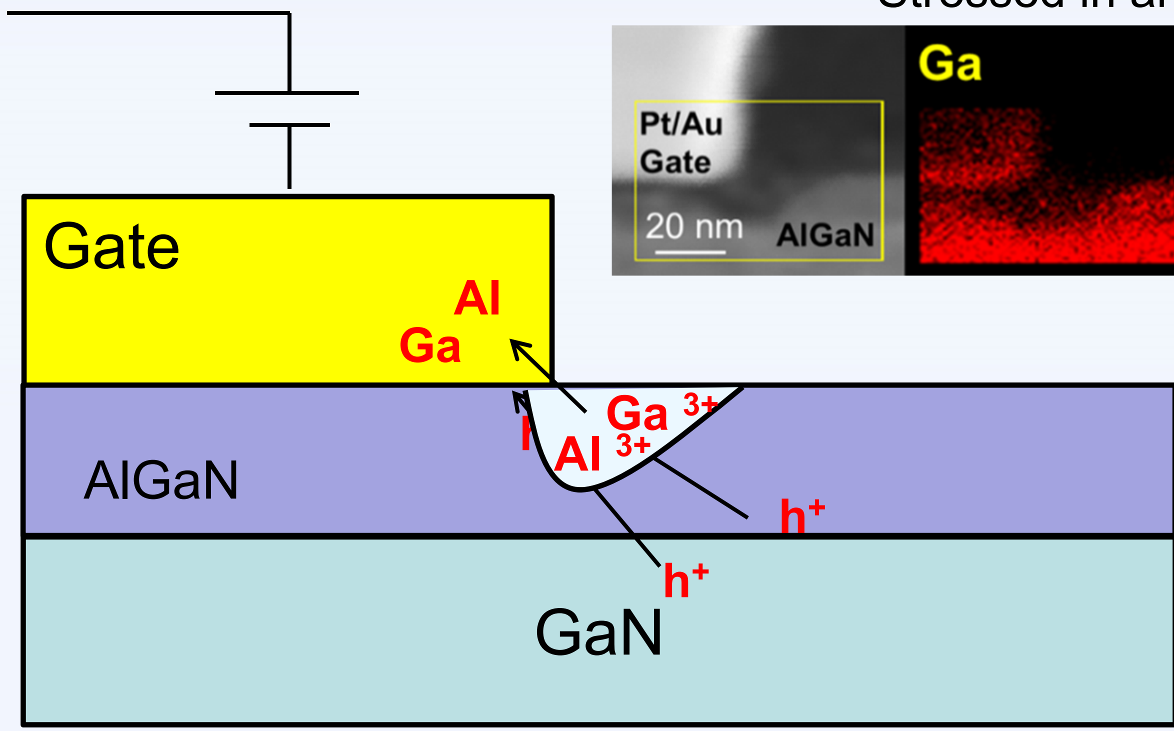
$$2Al_xGa_{1-x}N + 3H_2O = xAl_2O_3 + (1-x)Ga_2O_3 + N_2 + H_2$$

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

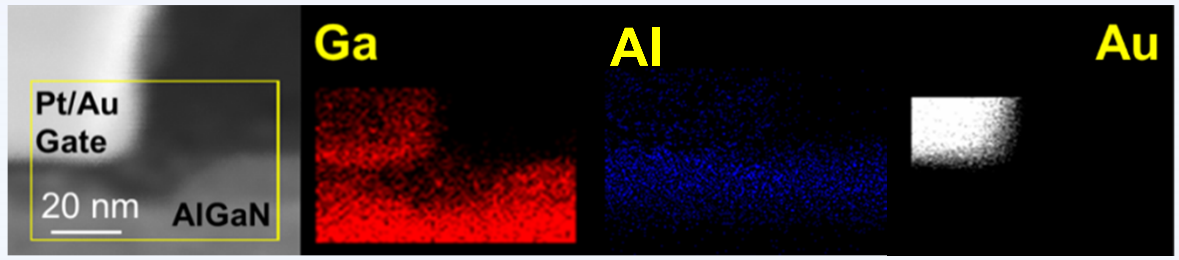
fenggao@mit.edu

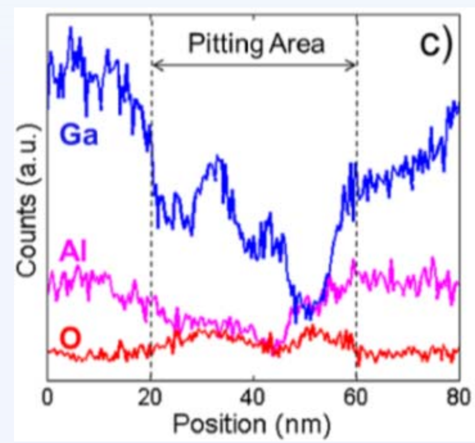
Water-assisted Electrochemical Reactions

— Ga, Al out diffusion



Stressed in ambient for 3000s





❖ **Two necessary conditions:**

1. Holes are generated and accumulated at the AlGaN surface.
2. Ambient water diffuse through the SiN_x passivation and reach the AlGaN surface.

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

Source of Holes

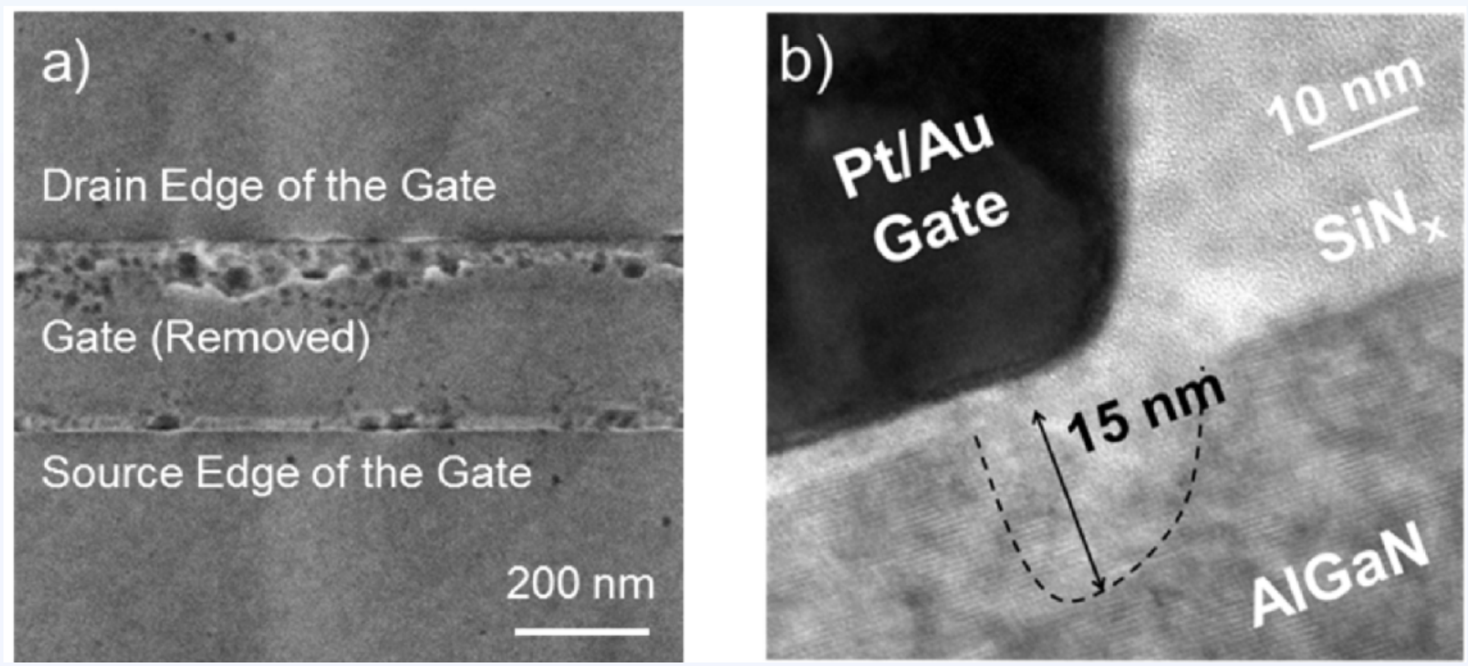
— Photo-Generated Holes

- Stressed under 254-nm UV illumination in ambient air at V_{ds} = 43 V V_{gs} = -7 V for 3000s at RT

Increasing surface pitting

SEM Top View

TEM Cross Section



microsystems technology laboratories

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

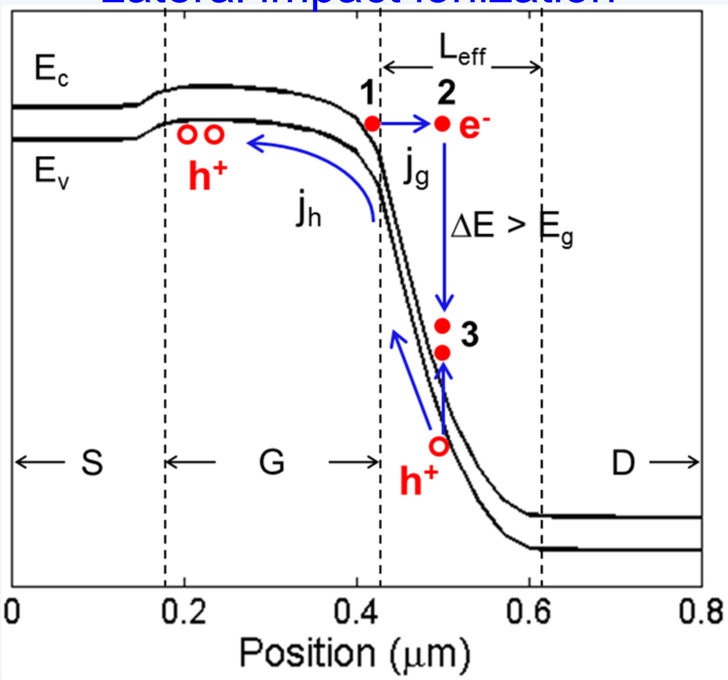
Source of Holes

— Impact Ionization vs Inter-band Tunneling

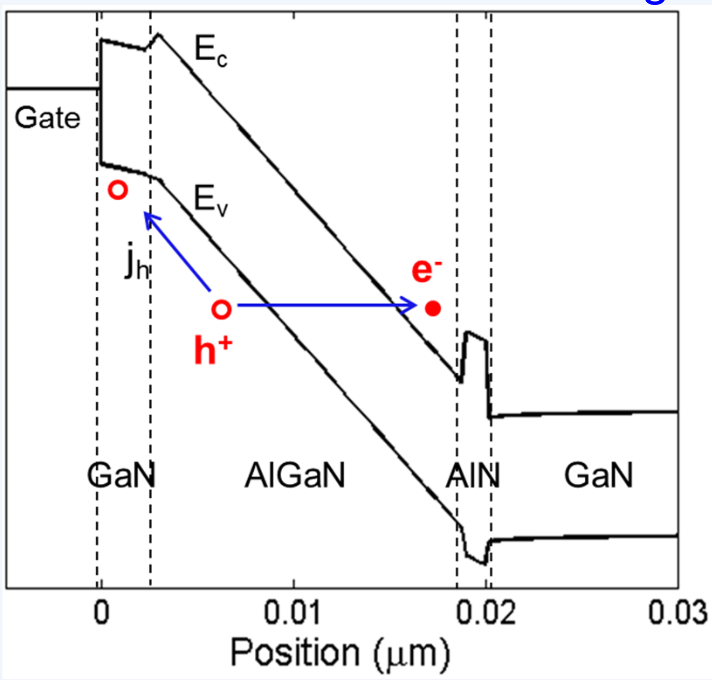
$$j_h \propto \exp(-\frac{E_i}{E_{\max}}) \times j_g$$

$$j_h \propto E_{\max}^2 \times \exp(-\frac{E_t}{E_{\max}})$$

Lateral impact ionization



Vertical inter-band tunneling



Keldysh, Soviet Phys. JETP, vol. 33, no.4, p763, 1958

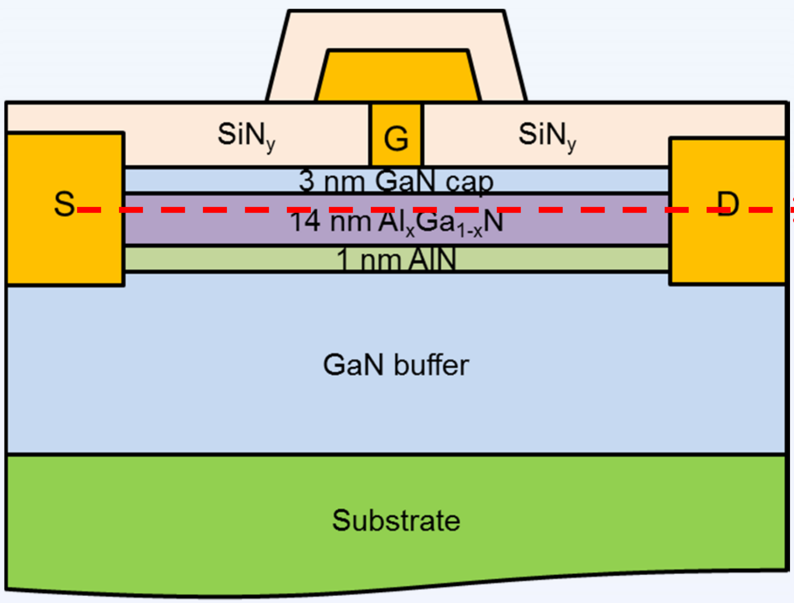
F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

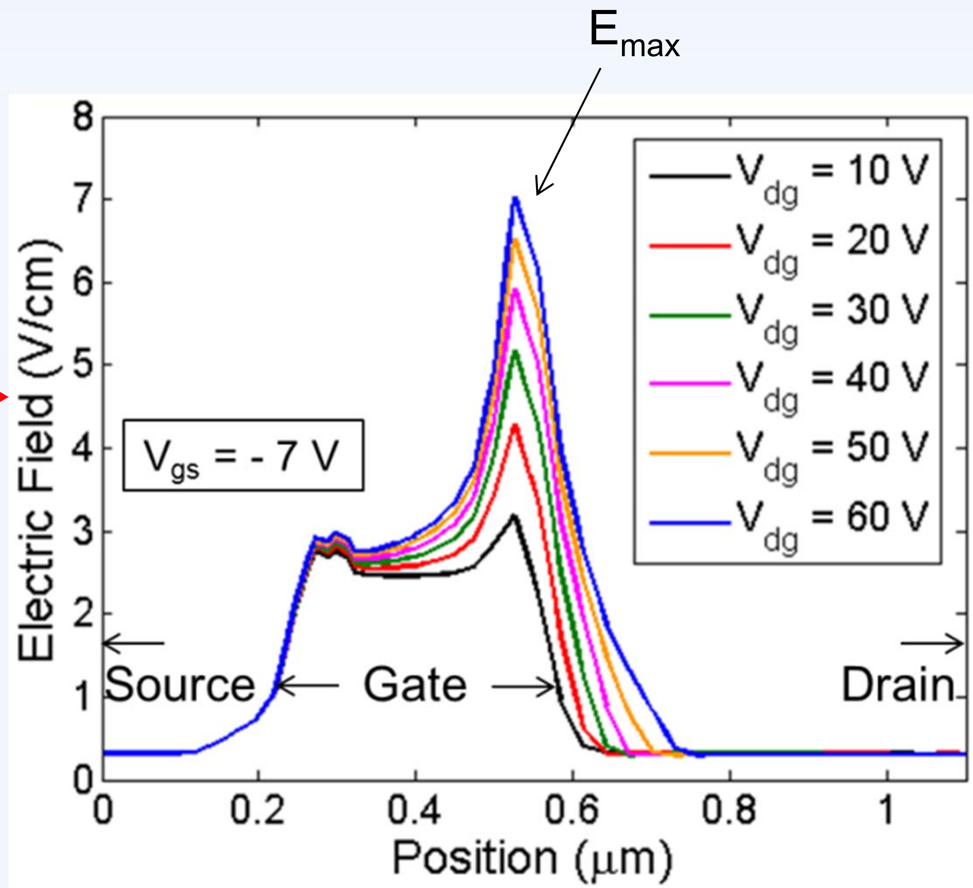
fenggao@mit.edu

Source of Holes

— Quantitative Analysis: E-field

- **Silvaco simulation of Electric Field in AlGaN Layer**





F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

Source of Holes

— Quantitative Analysis: j_h

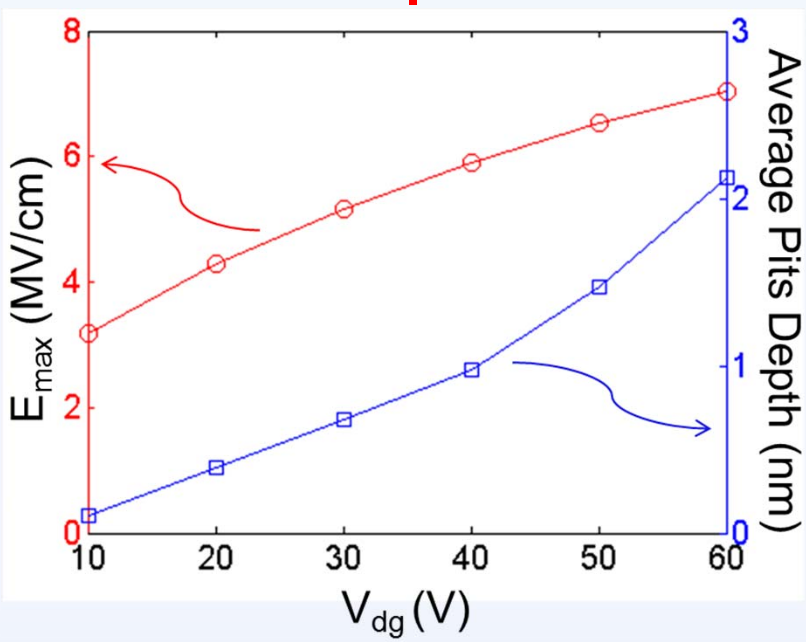
- **Relationship of Surface Pits and Holes**

$$2Al_x Ga_{1-x}N + 6h^+ = 2xAl^{3+} + 2(1-x)Ga^{3+} + N_2$$

$$j_h \propto \frac{3d\rho N_A q}{Mt} \propto d$$

Average pits depth measured by AFM

+



J_h *vs* E_{max}

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu

Source of Holes

— Surface Pitting and Holes

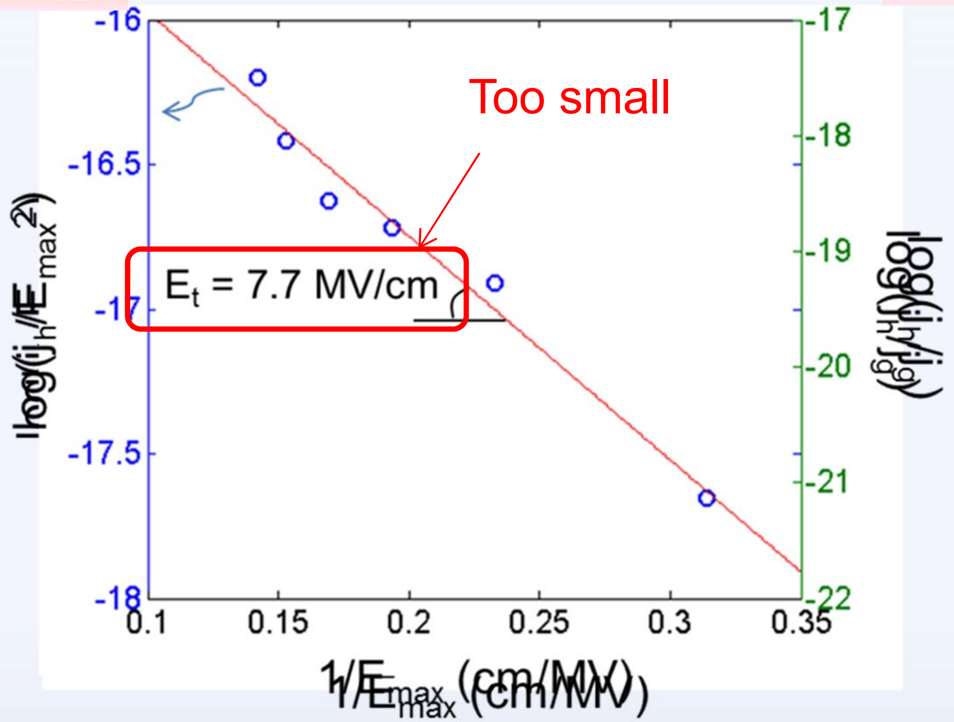
- Data match with inter-band tunneling equation
- Data do not match with impact ionization equation

Inter-band tunneling

$$\log(j_h / E_{\max}^2) \propto -\frac{E_t}{E_{\max}}$$

Impact ionization

$$\log(j_h / j_g) \propto -\frac{E_i}{E_{\max}}$$



F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

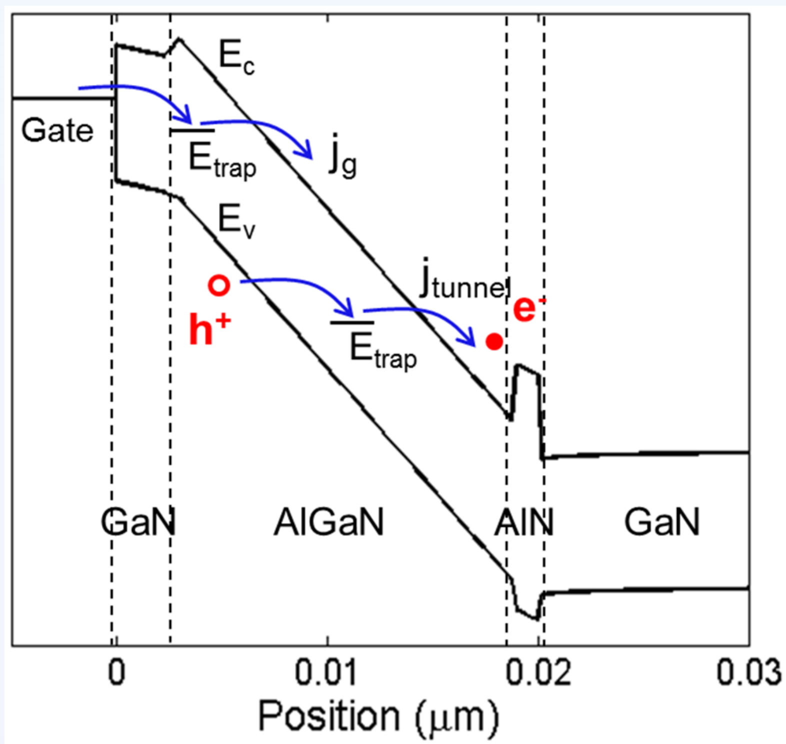
fenggao@mit.edu

Source of Holes

— Trap-assited inter-band Tunneling

- Traps assist inter-band tunneling causing a lower E_t

Traps assist inter-band tunneling



MTL microsystems technology laboratories

F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

Trap Assisted Inter-Band Tunneling

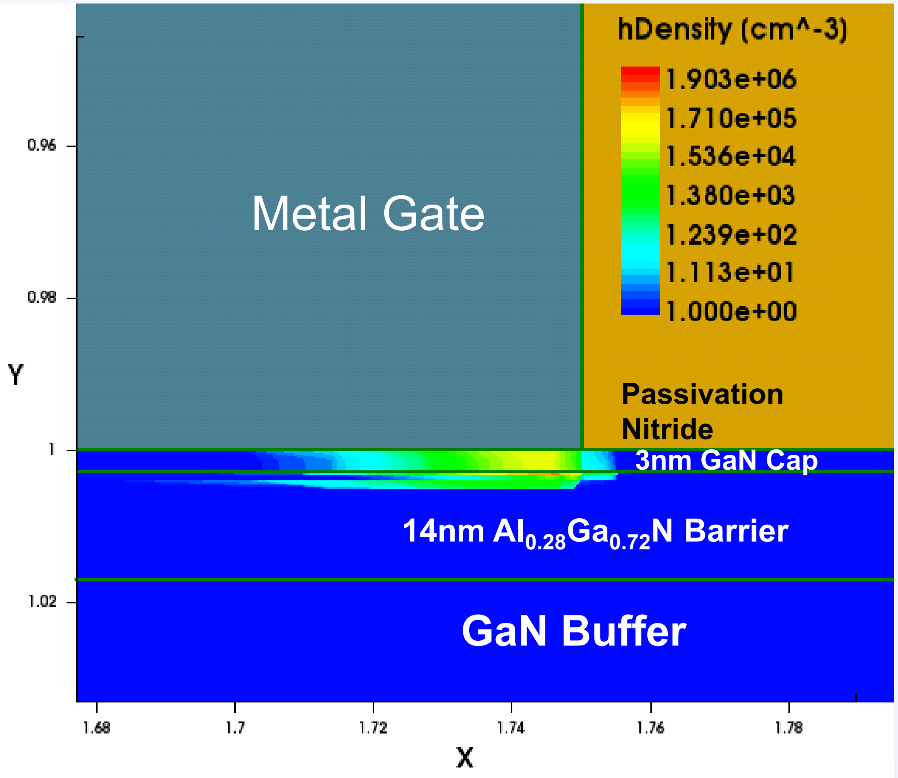
— TCAD Simulations

- **TCAD simulation of trap-assisted inter-band tunneling**

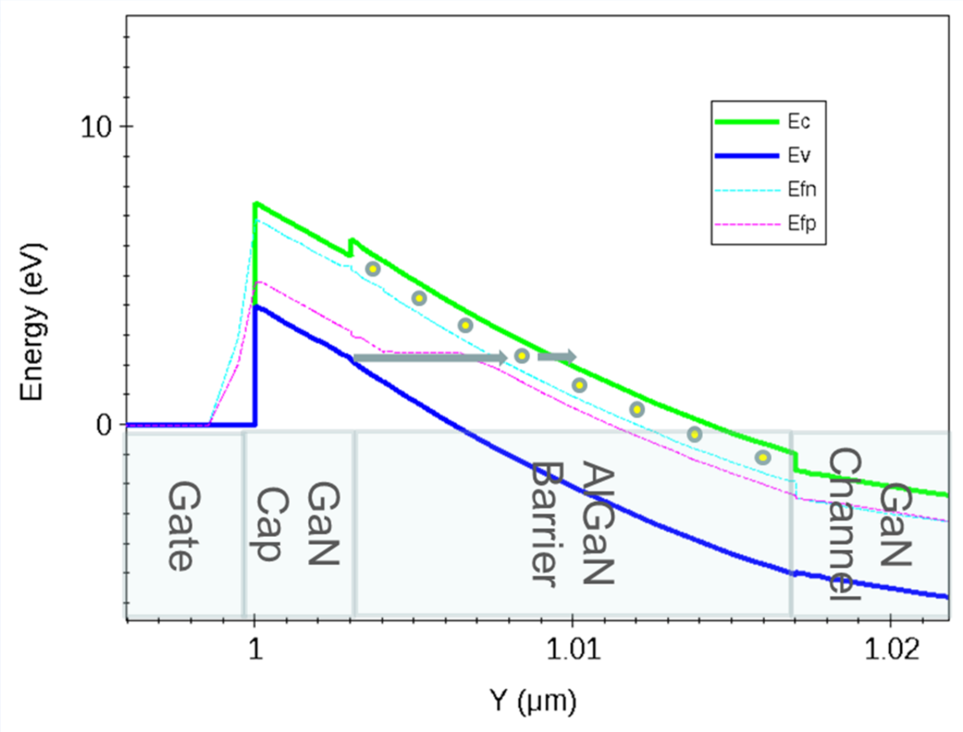
  Donor trap states w. $E_c - E_t$ = 0.45eV, $N_t = 5\times10^{18}$ /cm^3

  V_{ds} = 43 V, V_{gs} = -7 V

Hole Concentration



Vertical Cut at Gate-Drain Edge



SYNOPSYS® Accelerating Innovation

MTL microsystems technology laboratories

Acknowledgement to our collaborators: Hiu-Yung (Hugh) Wong, Ph.D et al at Synopsys, Inc.

fenggao@mit.edu

Last Question: Diffusion of Water

— Water Vapor Transmission Rate

Water Vapor Transmission Rate (WVTR) of PECVD SiN

$2Al_x Ga_{1-x}N + 3H_2O$
$= xAl_2O_3 + (1-x)Ga_2O_3 + N_2 + H_2$

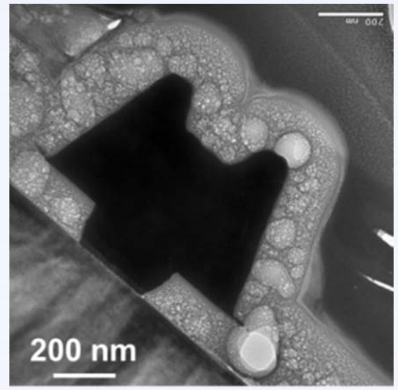
$$WVTR \approx \frac{3}{2}\frac{d\rho M_{H_2O}}{Mt}$$

$\approx 0.05\text{-}0.1\ g/m^2/day$

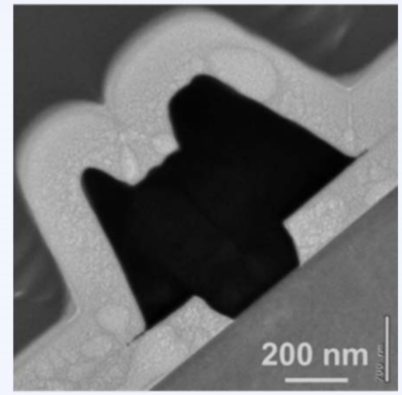
Estimated WVTR is consistent with the reported value for PECVD SiN (0.01-0.1 $g/m^2/day$) in literature [1-2].

[1] A.S. da Silva Sobrinho, et al. J. Vac. Sci. Technol. A, vol. 16, no. 6, pp. 3190-3198, 1998.
[2] D.S. Wuu, et al. Surf. Coat. Technol., vol. 198, no.1-3, pp. 114-117, 2004.

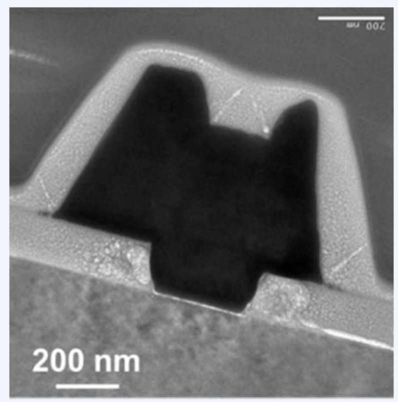
Degradation of SiN Passivation



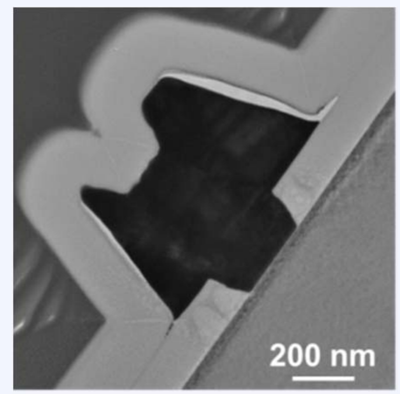
Stressed in wet air



Stressed in dry air



Stressed in ambient air



Stressed in vacuum

Defects are created in SiN during off-state stress to accelerate water diffusion.

F. Gao et al., *IEEE Trans. Electron Devices*, vol. 61, no.2, 2014

fenggao@mit.edu

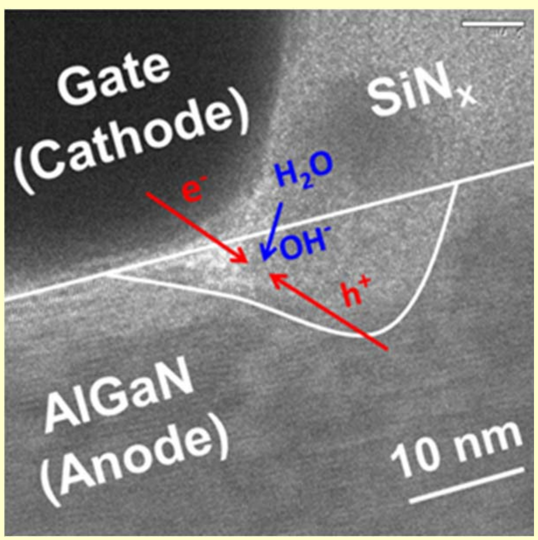
Conclusion

Mechanisms of Permanent Degradation

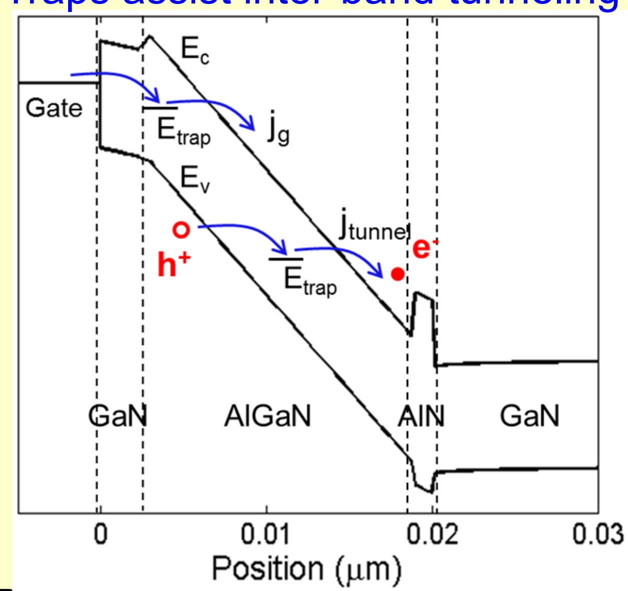
A Water-assisted Field-induced Electrochemical Process

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

- Cause surface pitting & Ga, Al migration
- Cause permanent I_d drop



Traps assist inter-band tunneling



fenggao@mit.edu

Thank You!

God made the bulk;
surfaces were invented by the devil.

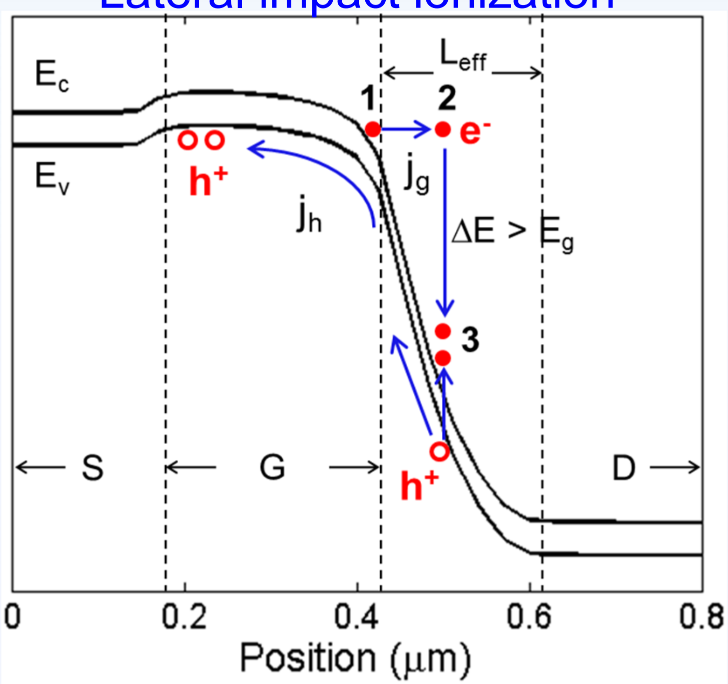
— Wolfgang Pauli

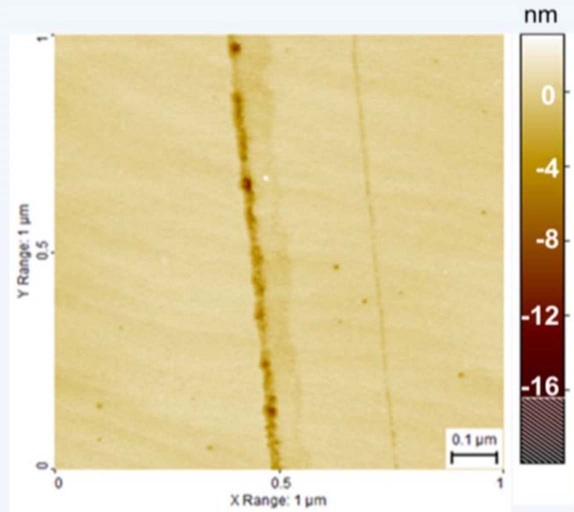
fenggao@mit.edu

Is There Impact Ionization ?

- Holes are swept to the source-edge of the gate

Lateral impact ionization





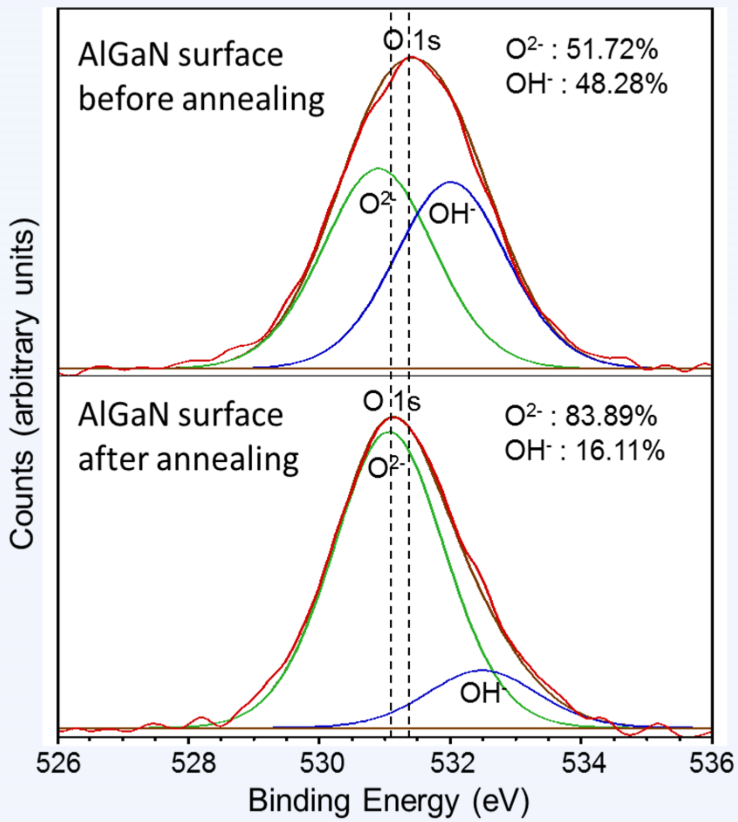
V_{gs} = -7 V, V_{ds} = 43 V

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

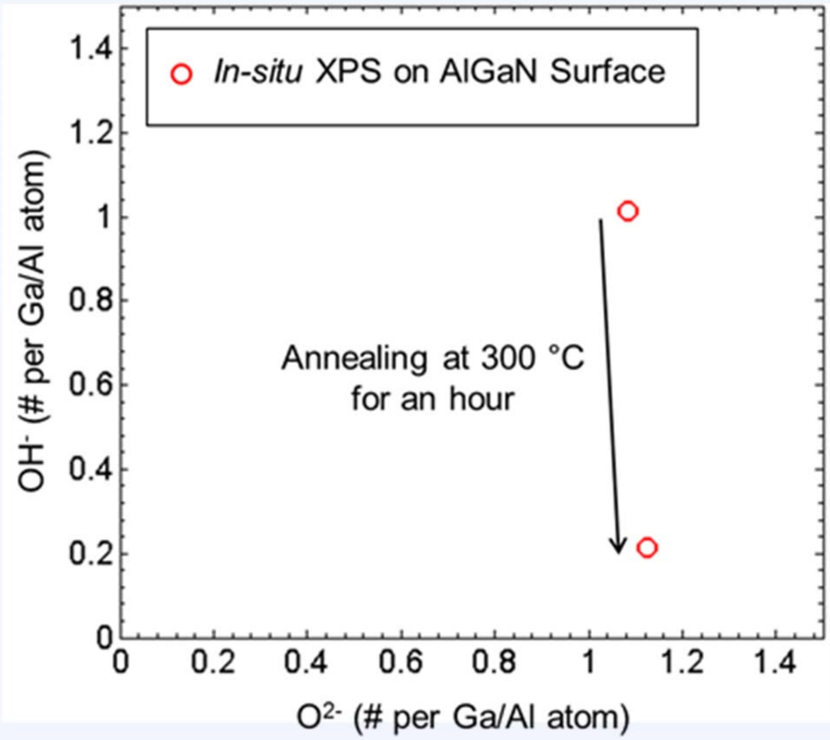
fenggao@mit.edu

Why is there still pits in devices stressed in vacuum ?

Water desorption requires vacuum annealing with T > 200 °C



In-situ XPS Analysis

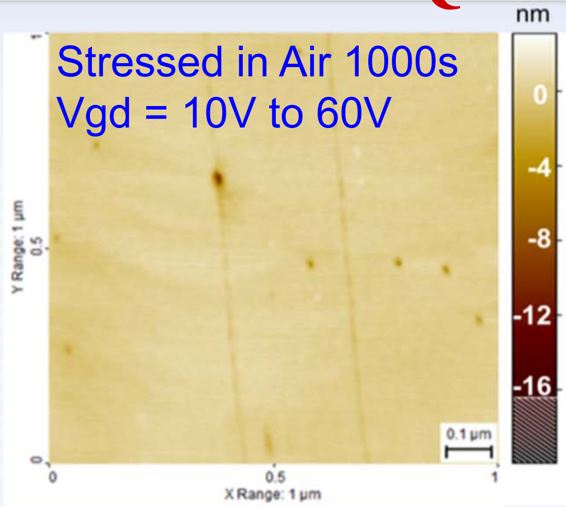


fenggao@mit.edu

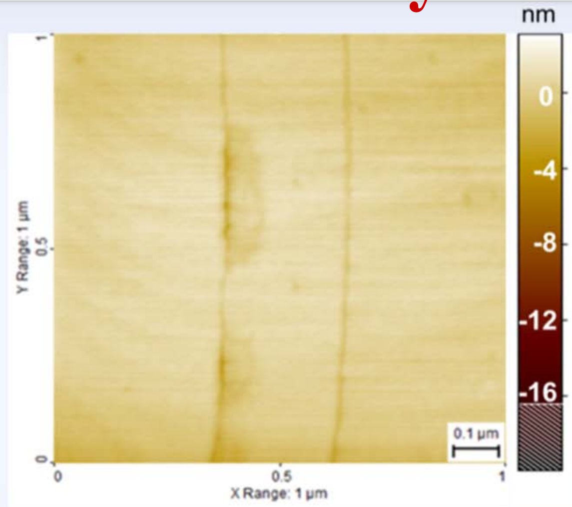
microsystems technology laboratories

Source of Holes

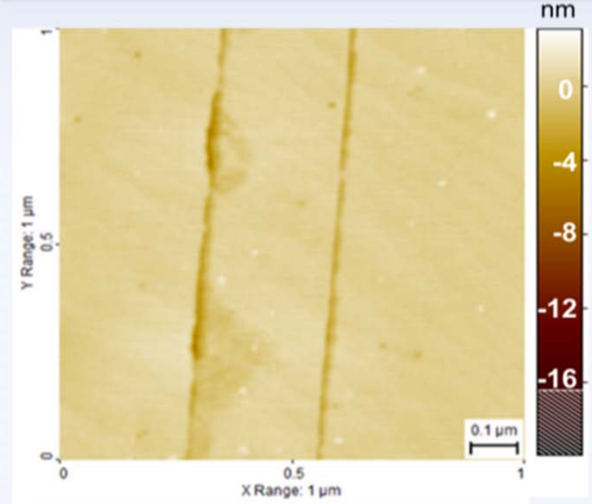
— Quantitative Analysis:Pits Formation vs V_{ds}



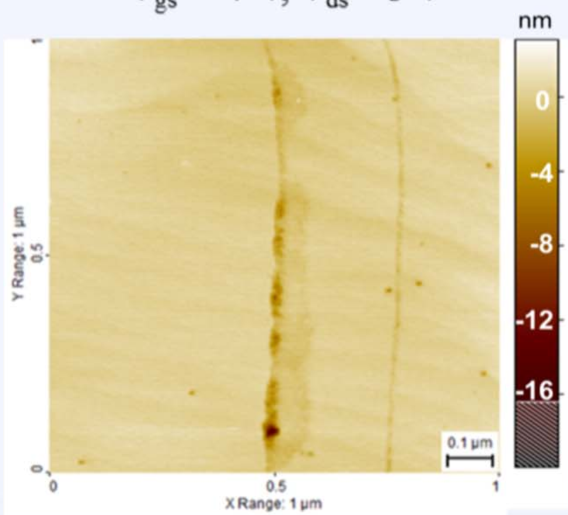
V_{gs} = -7 V, V_{ds} = 3 V



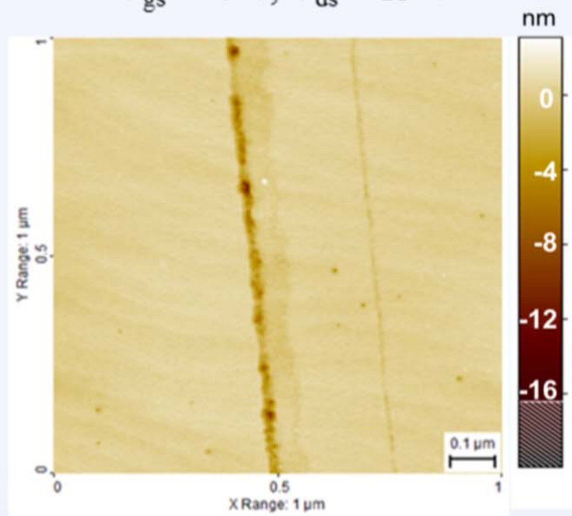
V_{gs} = -7 V, V_{ds} = 13 V



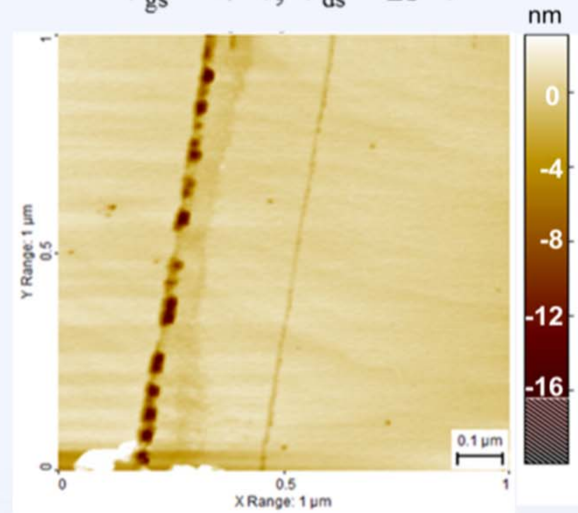
V_{gs} = -7 V, V_{ds} = 23 V



V_{gs} = -7 V, V_{ds} = 33 V



V_{gs} = -7 V, V_{ds} = 43 V



V_{gs} = -7 V, V_{ds} = 53 V

F. Gao et al., *IEEE Trans. Electron Devices,* vol. 61, no.2, 2014

fenggao@mit.edu