Threshold Voltage Hysteresis and Gate Leakage in AlGaN/GaN HEMTs

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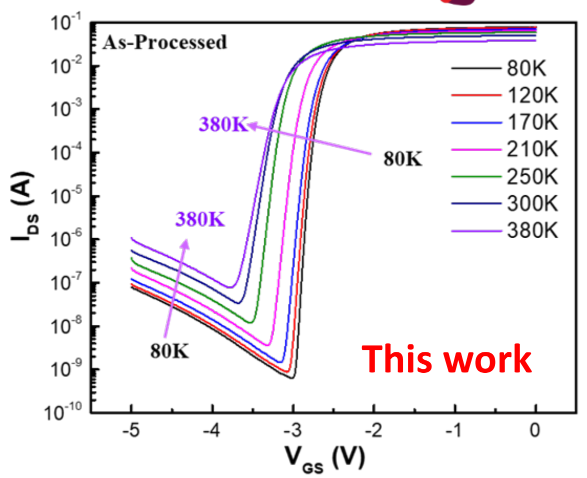
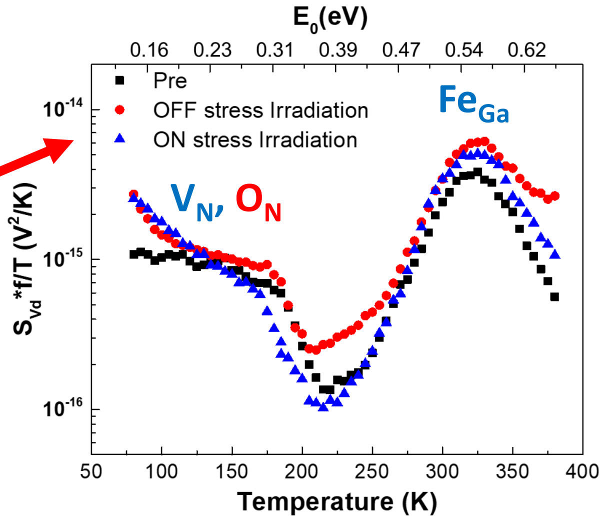
Motivation and Background

- GaN-based HEMTs increasingly important for space applications
  - Radiation and long-term stress are critical issues
  - Cryogenic applications envisioned
    - e.g., L. Nela, N. Perera, C. Erine, E. Matioli, "Performance of GaN power devices for cryogenic applications down to 4.2 K," *IEEE Trans. Power Electronics*, vol. 36, no. 7, pp. 7412-7416, Jul. 2021.

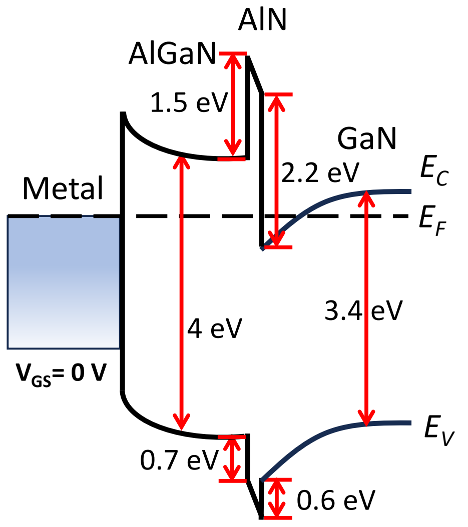


- Defects critical to radiation response of GaN-based HEMTs
  - Low-frequency noise measurements help identify defects
    - e.g., X. Li, P. F. Wang, X. Zhao, H. Qiu, M. Gorchichko, M. W. McCurdy, R. D. Schrimpf, E. X. Zhang, and D. M. Fleetwood, "Defect and impurity-center activation and passivation in irradiated AlGaN/GaN HEMTs," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 1, pp. 80-87, Jan. 2024.
    - Significant V_{TH} hysteresis and unusually large cryogenic leakage observed
      - Associated with O_N defects in AlGaN



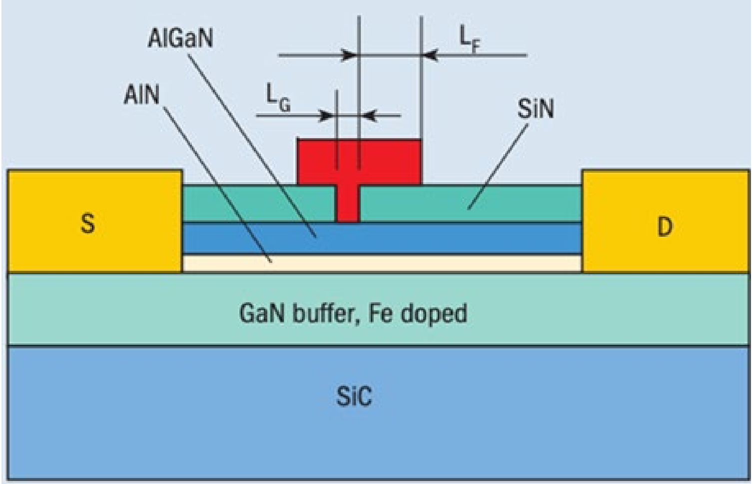
Outline and Experimental Details

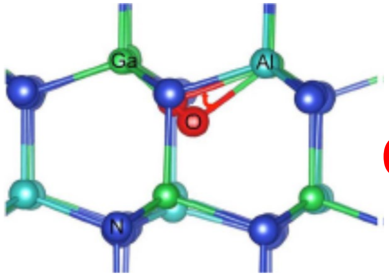
- Threshold-voltage V_{TH} hysteresis and enhanced gate leakage
  - Wolfspeed AlGaN/GaN HEMTs
  - 80 K to 380 K
- V_{TH} Hysteresis
  - Biased proton irradiation (ON, OFF)
  - O_N impurity centers in AlGaN
- Gate leakage vs. temperature and bias
  - Mott hopping: as-processed devices and OFF-bias irradiation
  - Enhanced leakage at cryogenic temperature and large negative bias after ON-bias irradiation or ON-bias stress (at 295 K)
    - ❑ O_N impurity centers in AlGaN facilitate trap-assisted tunneling
    - ❑ Radiation/stress induced O_N-H dehydrogenation key to process



Threshold Voltage Hysteresis

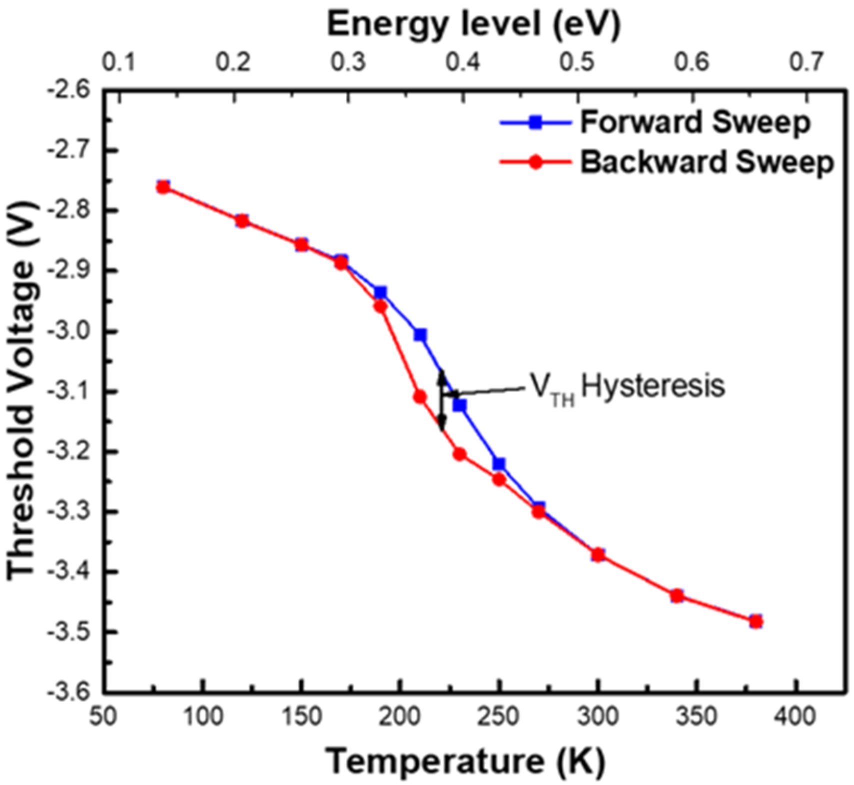
GaN HEMTs: 80 K – 380 K





O_N in AlGaN

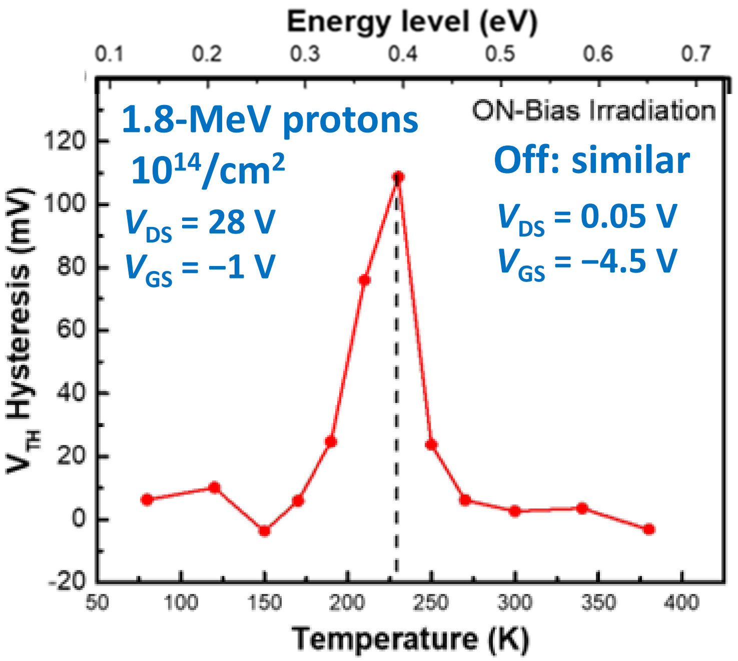
V_{TH} Hysteresis

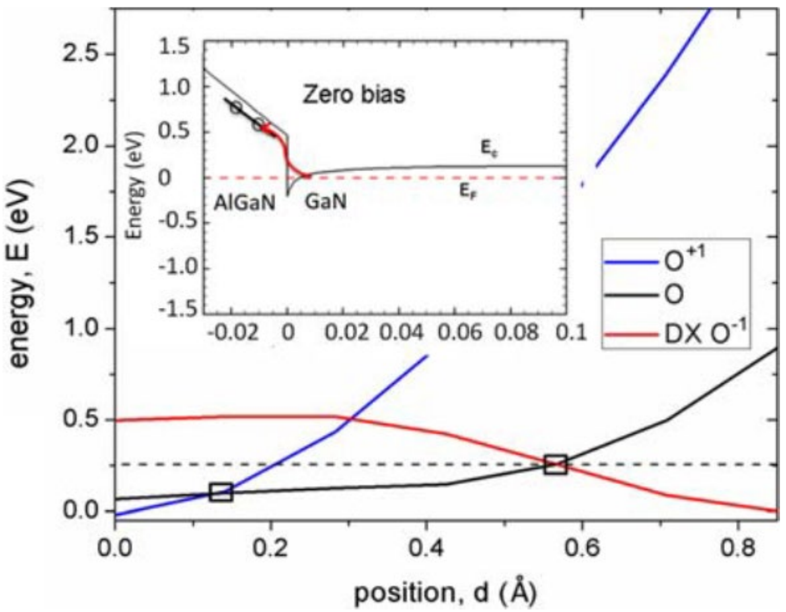


- Increase in V_{TH} with temperature: donor-like defects activated
- Hysteresis: defect reconfiguration with charge capture/emission
- Enhanced with OFF- or ON-Bias Irradiation

T. Roy *et al.*, *Appl. Phys. Lett.*, **99**, no. 20, 2011, Art. no. 203501
J. Chen *et al.*, *IEEE Trans. Nucl. Sci.*, **60**, no. 6, p. 4080, Dec. 2013

Mechanisms: V_{TH} Hysteresis





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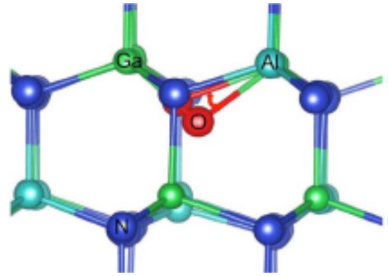
Energy Levels

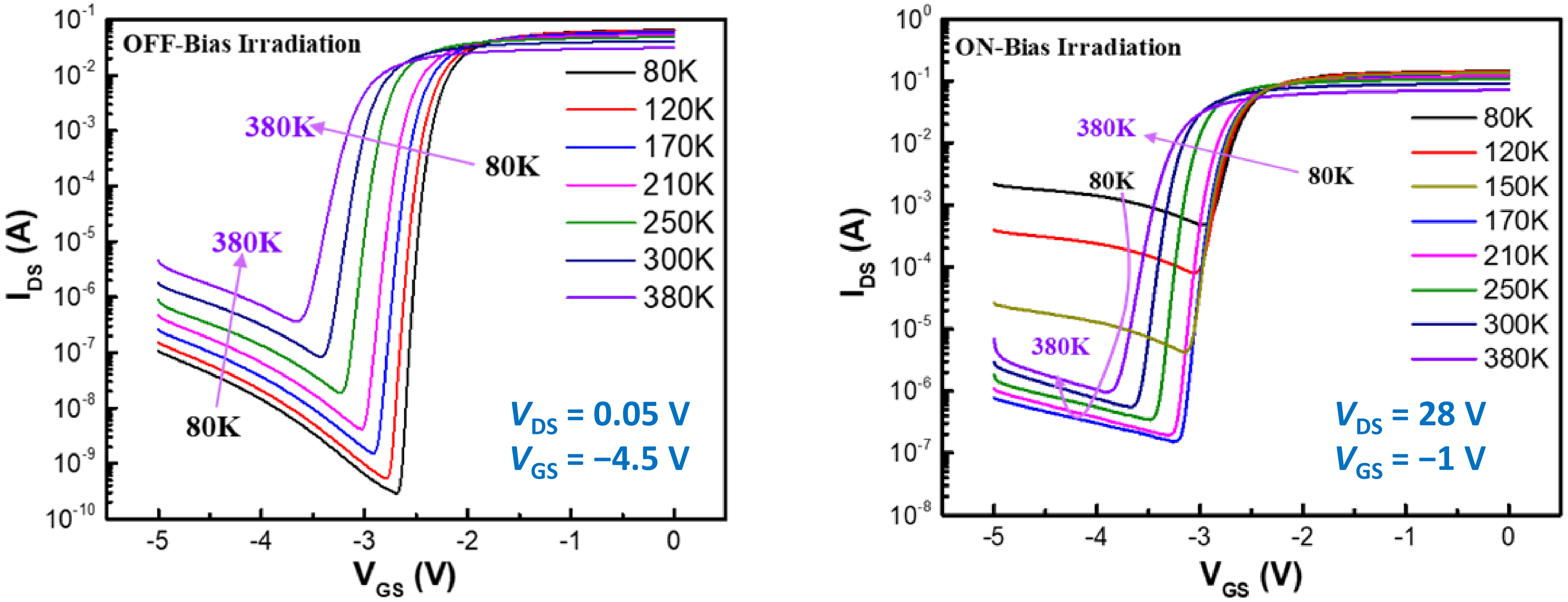
T (K)	E_o (eV)	Charge
< 225 K	< 0.4 eV	−1/0: O_N DX
≥ 225 K	≥ 0.4 eV	0/+1: O_N

O_N DX in AlGaN



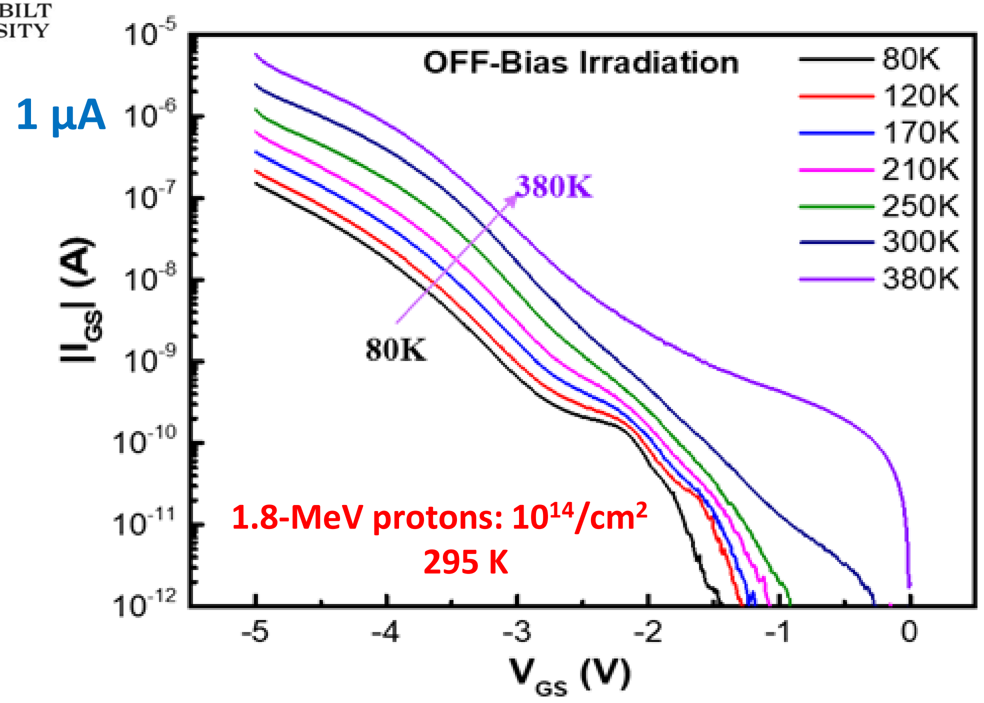
M. D. McCluskey, N. M. Johnson, C. G. Van de Walle, D. P. Bour, M. Kneissl, and W. Walukiewicz, "Metastability of oxygen donors in Al-GaN," *Phys. Rev. Lett*, vol. 80, no. 6, pp. 4008-4011, May 1998.

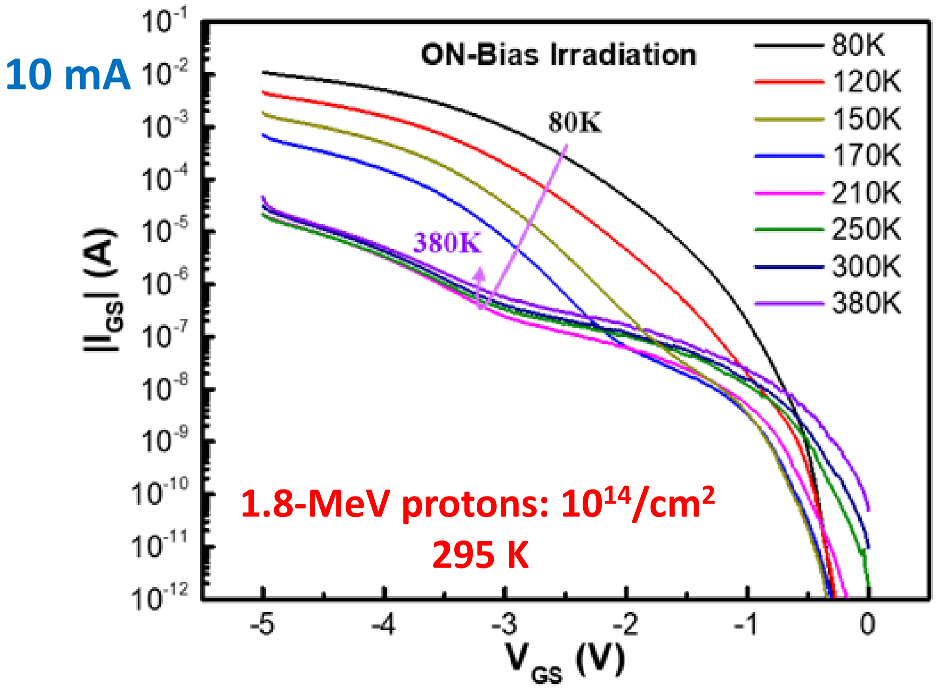
High Leakage Currents at 80 K: Irradiated Devices



- 1.8-MeV protons: $10^{14}/cm^2$
- OFF-bias: Leakage current increases with increasing *T*
  - Mott Hopping (detailed discussion in paper)
- ON-bias: Cryogenic leakage current increases with decreasing *T*

Gate Leakage Currents at 80 K: Irradiated Devices





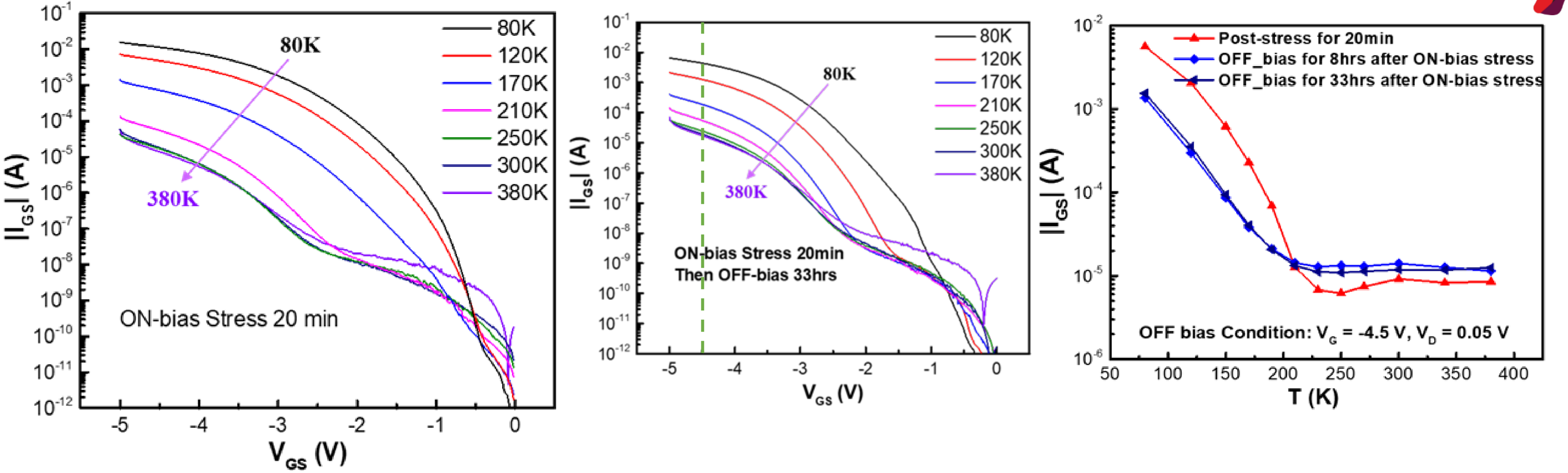
Gate Leakage @ −4.5 V

T (K)	$|I_{GS}|$:OFF	$|I_{GS}|$:ON
80 K	0.06 μA	8 mA
380 K	2 μA	10 μA

> 10^5× increase!

- How stable?
- What about bias only?

Gate Leakage After ON-Bias Stress



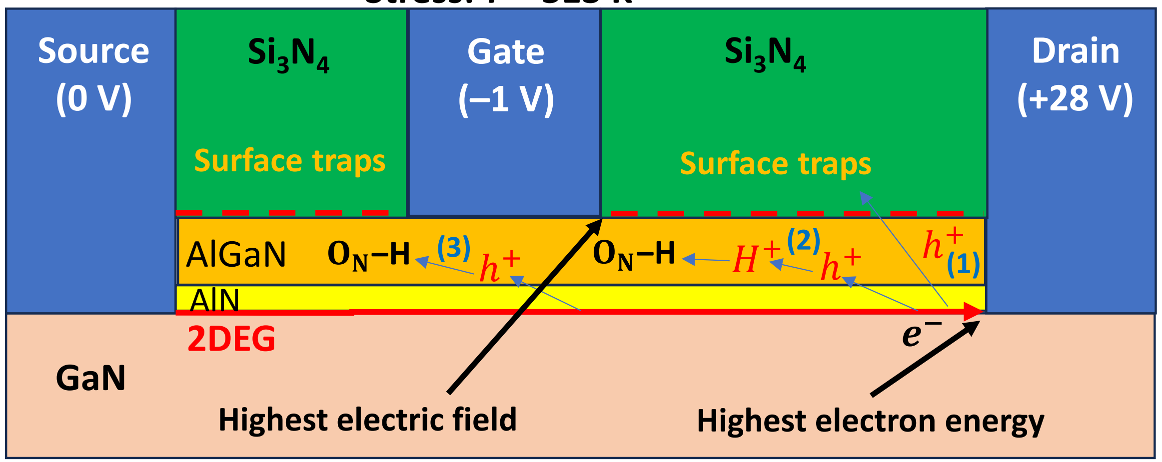
- **Stable leakage!**
- **Strongly bias dependent**
- **Maximized at low *T***
- **What causes this?**

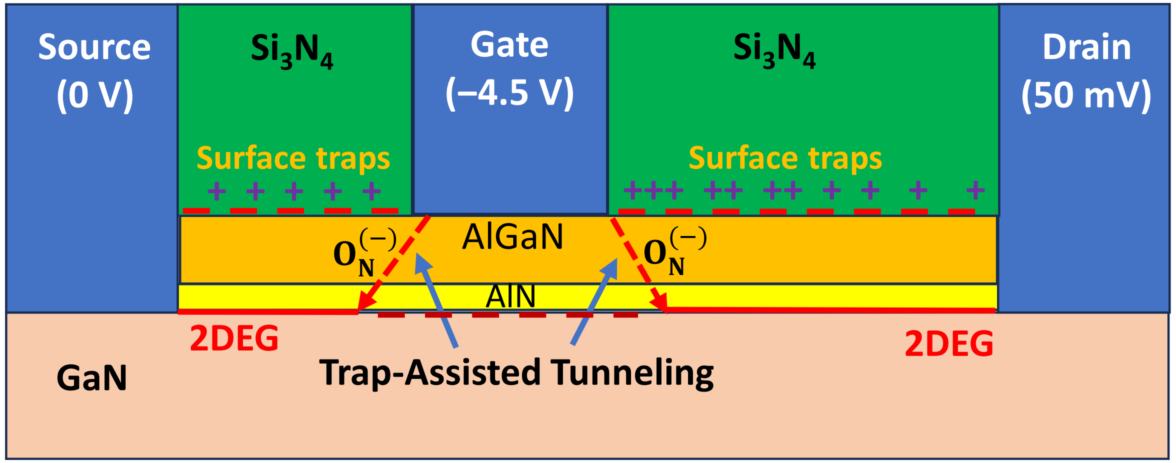
$|I_{GS}|$@ −4.5 V

T (K)	ON-Stress	$|I_{GS}|$:ON
80 K	10 mA	8 mA
380 K	20 µA	10 µA

Similar!

Gate Leakage Current in Stressed Devices at 80 K





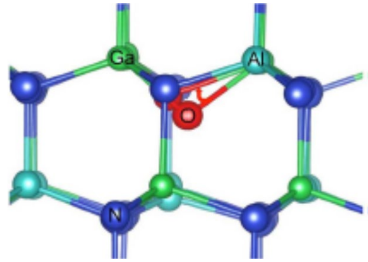
- H^+, h^+ generated: ON-bias irradiation/stress
- React with O_N-H to enhance O_N concentration

- Lower-T: O_N^- DX electron level allows tunneling
  - Reconfiguration suppressed
- Higher-T: No available electron level on O_N, O_N^+

Energy Levels

T (K)	E_o (eV)	Charge
< 225 K	< 0.4 eV	−1/0: O_N DX
≥ 225 K	≥ 0.4 eV	0/+1: O_N

O_N in AlGaN



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Summary and Conclusions

- V_{TH} hysteresis in AlGaN/GaN HEMTs at ~150-250 K
  - Reconfiguration of O_N in AlGaN
  - Negatively charged at lower T; positively charged at higher T
- Full temperature range: gate leakage current increases with *increasing* temperature as processed or proton-irradiated devices at OFF-bias
  - Mott hopping in AlGaN (model fits provided in paper)
- Cryogenic temperatures: Gate leakage increases with *decreasing* temperature for devices irradiated or stressed at ON-bias
  - Trap assisted tunneling of electrons in AlGaN
  - Enabled by dehydrogenation of O_N–H impurity centers
  - Significant concern for cryogenic space and terrestrial applications

Under review for *IEEE Transactions on Nuclear Science*

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