Fundamental Modeling of Radiation Effects in AlGaN/GaN HEMTs

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Ionizing Radiation Sources

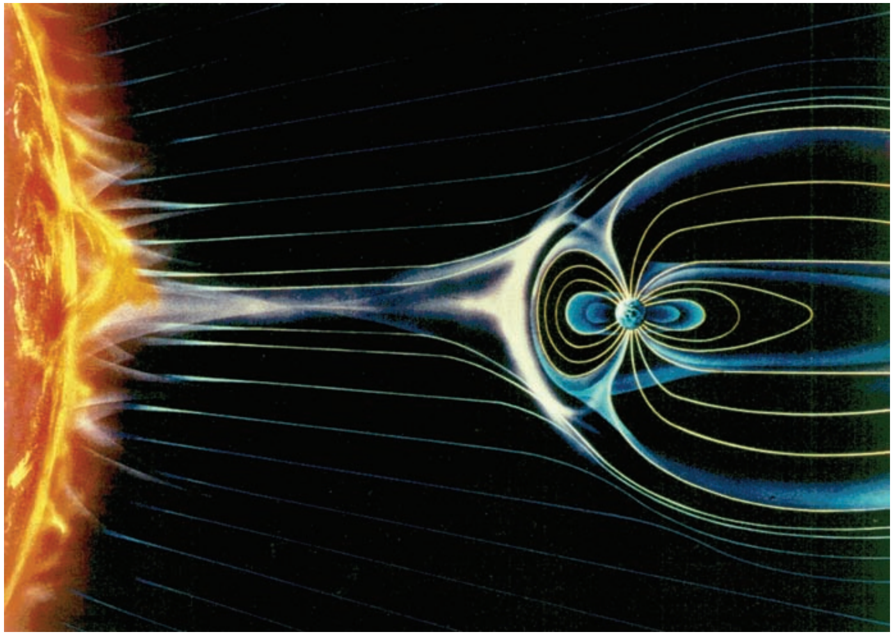
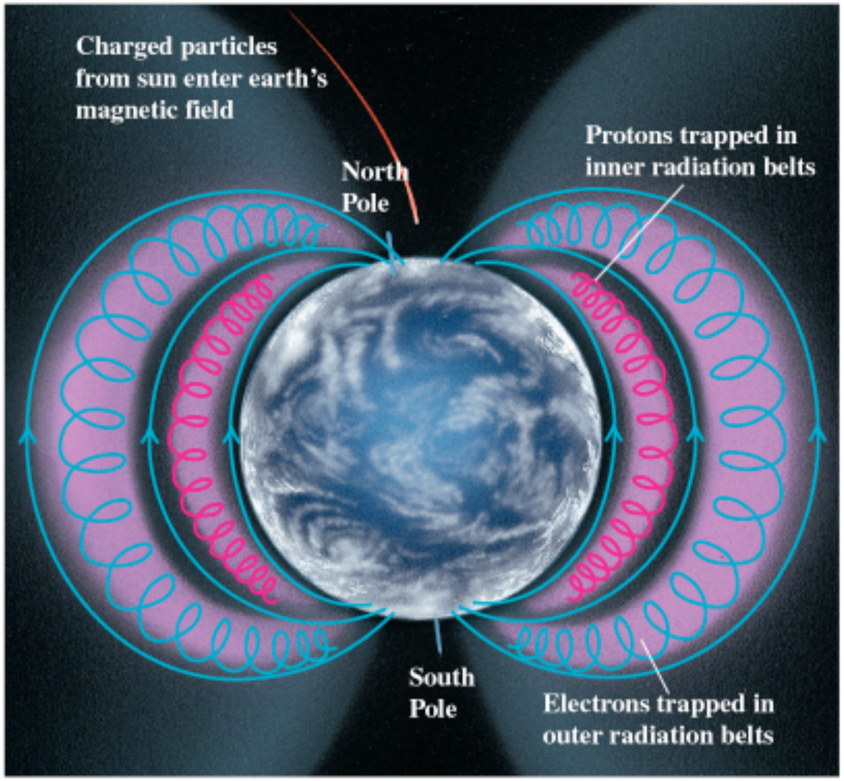


Image Credit: NASA.

1. Radiation from solar flares
   x-rays, gamma-rays, protons, electrons
2. Galactic cosmic radiation
   85% protons, 14% alpha particles, 1% heavy ions

Radiation in Low Earth Orbit

Van Allen belts



(a)

Inner belt - extends to 2.5 Earth radii

- protons up to 600 MeV and electrons up to several MeV

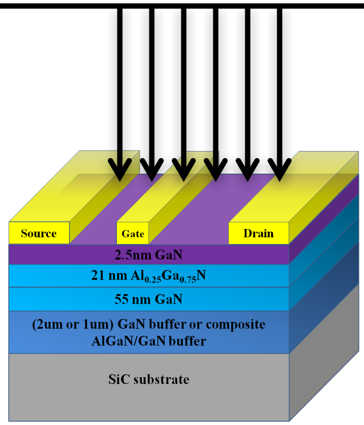
Outer belt - out to 10 Earth radii.

- electrons and protons (0.1 to 5 MeV)

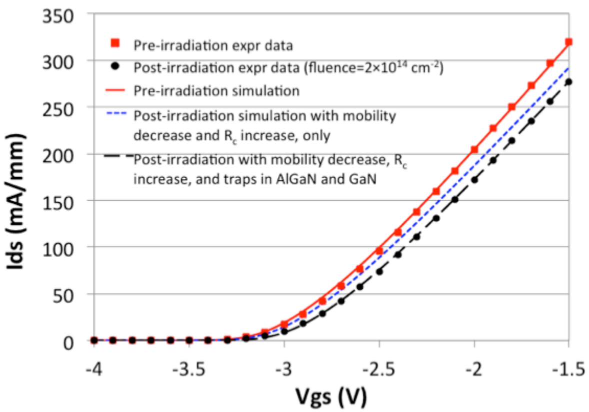
"Hacking the Van Allen Belts"
IEEE Spectrum, Feb, 2014

Overview

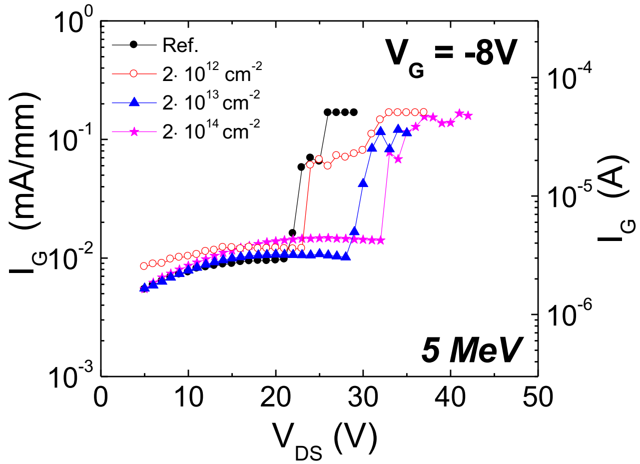
Radiation (total ionizing dose) effects on AlGaN/GaN HEMTs using FLOODS



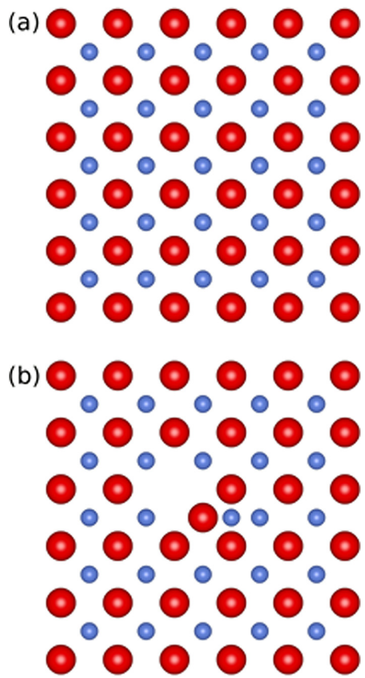
1. Modeling device degradation



2. Modeling reasons behind unexpected reliability enhancement from radiation

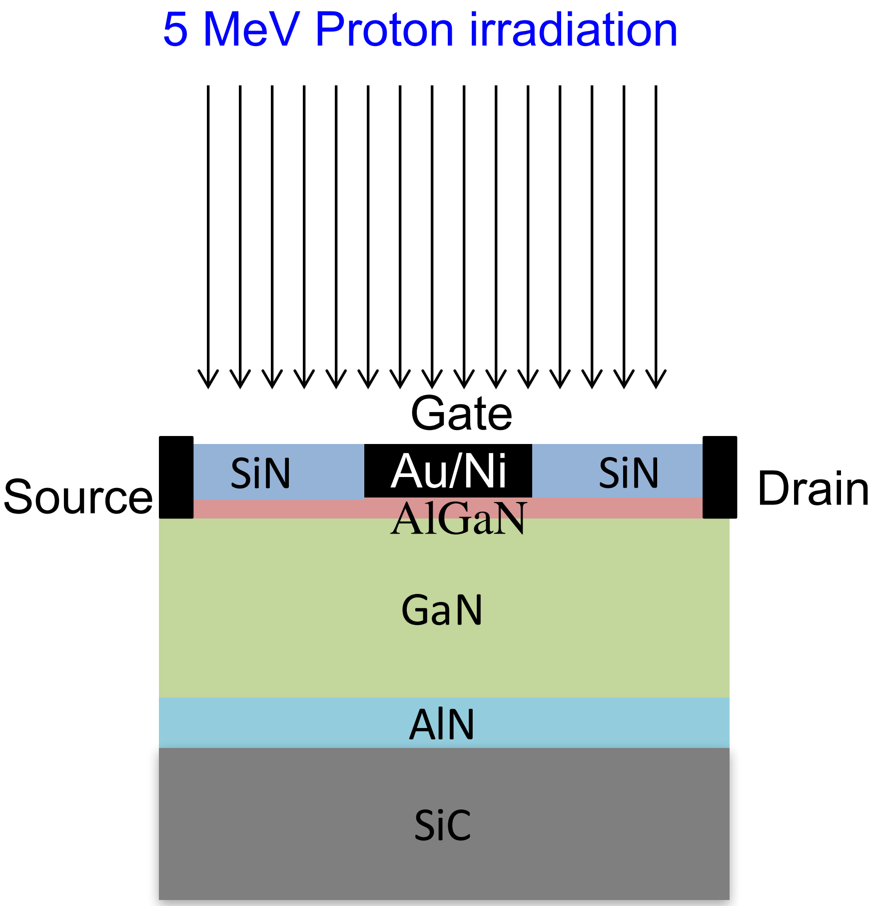


Radiation-Induced Damage



- Electron-hole pair generation
- Proton, electron, gamma-ray irradiation
  - Point defects
    - Frenkel pairs
      Ga vacancy (V_{Ga}), Ga interstitial (Ga_i)
      N vacancy (V_N), N interstitial (N_i)
    - Modification of existing defects
      - Dehydrogenation of defect complexes

AlGaN/GaN HEMT Performance Degradation



- Positive threshold voltage shift
- Reduction in mobility
- Reduction of drain current

GaN-based devices have at least 5 times more radiation tolerance than GaAs or Si devices

AlGaN/GaN HEMT Performance Degradation

Irradiation Dose (cm^{-2})	I_{DSS} (mA/mm)	Reduction of Sheet Carrier Concentration (%)	Reduction of Mobility (%)	Carrier Removal Rate (cm^{-1})
5×10^{9}	726	0	0	-
5×10^{10}	725	0	0	-
2×10^{12}	725	0	3	-
2×10^{13}	716	1	7	850
2×10^{14}	630	10	41	810

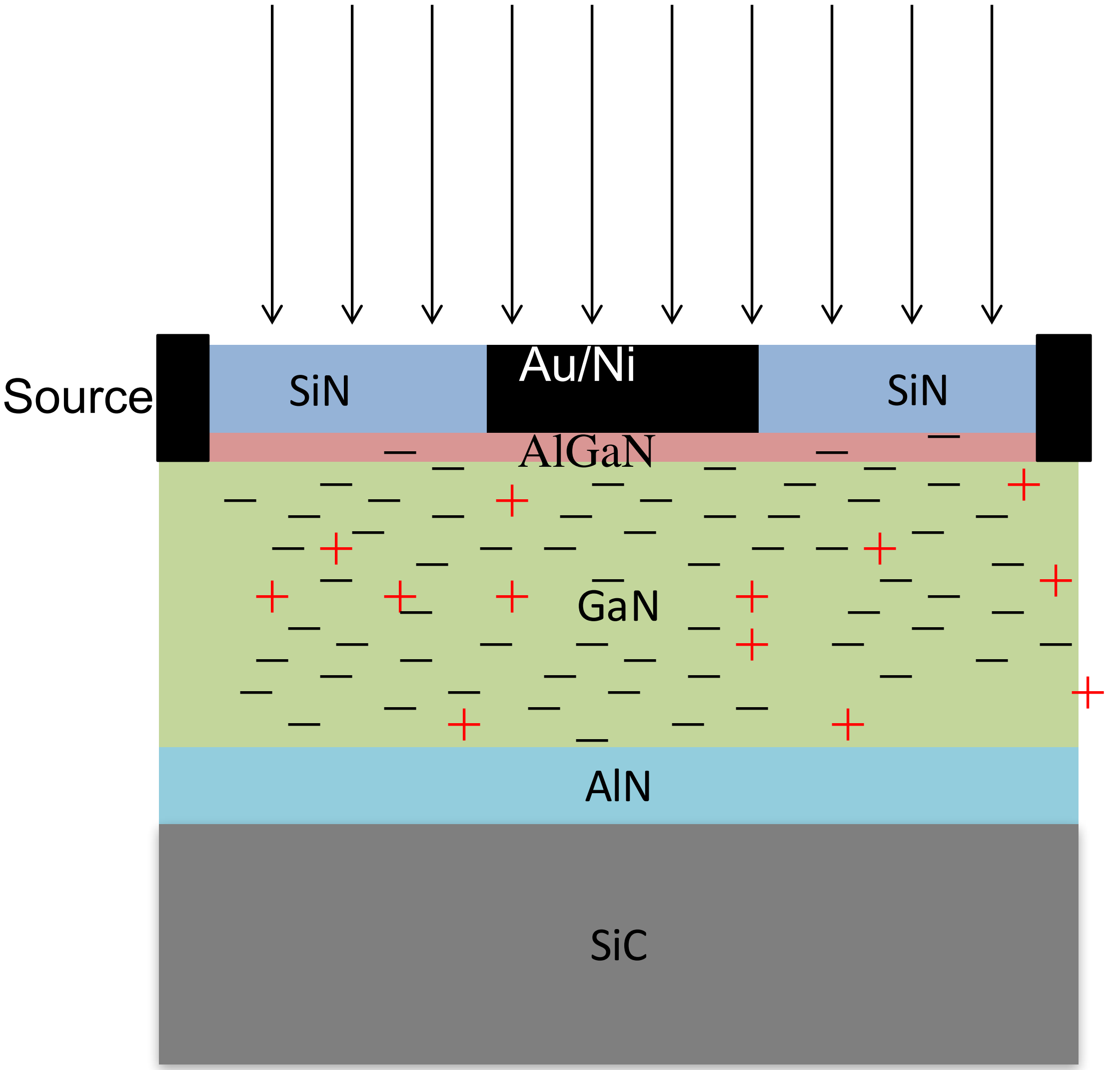
ΔV_{th} (mV)	Δg_m (%)	Reverse Gate Leakage at V_G = -5V and V_{DS} = 5V (μA/mm)
0	0	3.6
0	0	3.8
0	0	3.5
10	5	5.6
95	10	8.1

5 MeV Proton irradiation

Fluences below $2x10^{14}/cm^2$ have little effect on performance metrics

- radiation-induced defects in GaN buffer are on the same order of magnitude of as-grown defects

Displacement-Related Trap Creation



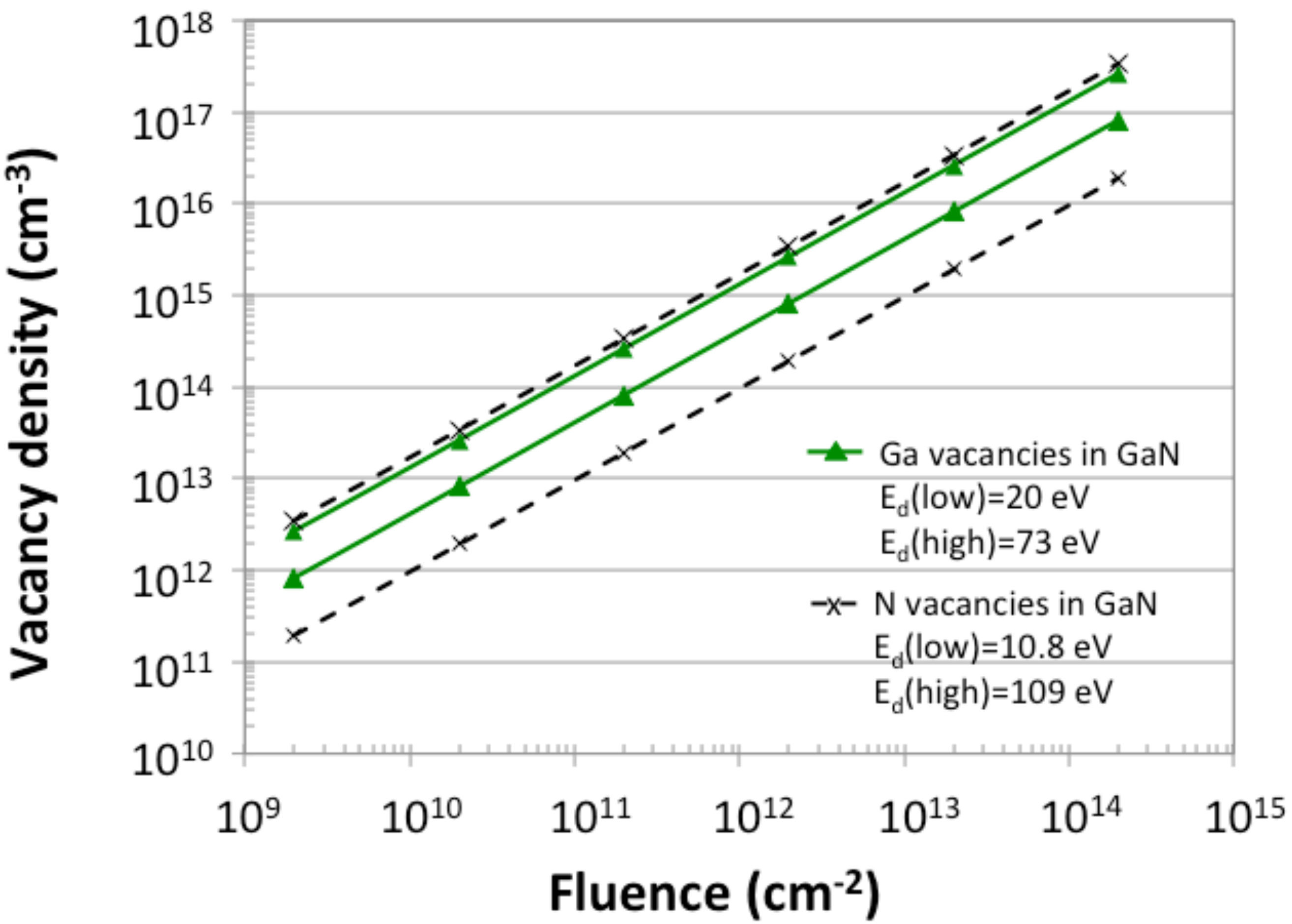
Device Equations

$$\nabla^2 \psi = -\frac{q}{\varepsilon}[p - n + Doping + Trap]$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n, \quad \frac{\partial p}{\partial t} = \frac{1}{q}\nabla \cdot J_p$$

$$J_n = -q\mu_n n \nabla \phi_n, \quad J_p = q\mu_n p \nabla \phi_p$$

Radiation-induced Defect Estimation



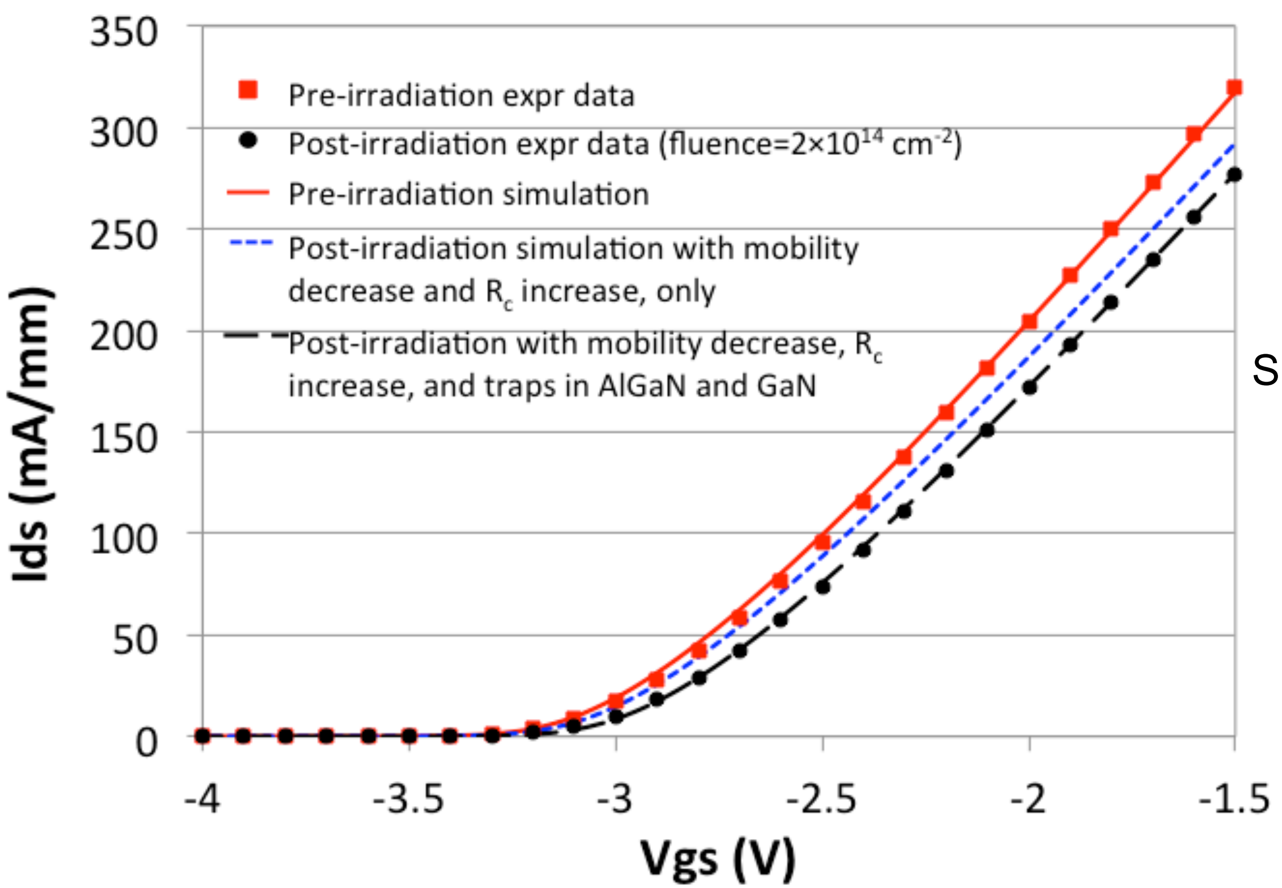
TRIM (Transport of Ions in Matter) simulation results

V_{GA} – acceptor-like traps (-)

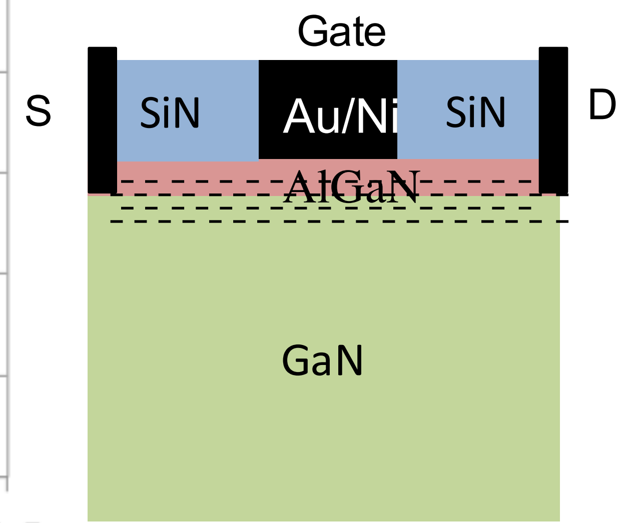
V_N – acceptor or donor-like traps (+)

Positive V_T shift needs acceptor-like traps

Modeling Threshold Voltage Shift



Neg trap conc:
1×10^{17} cm^{-3}
30 nm into GaN



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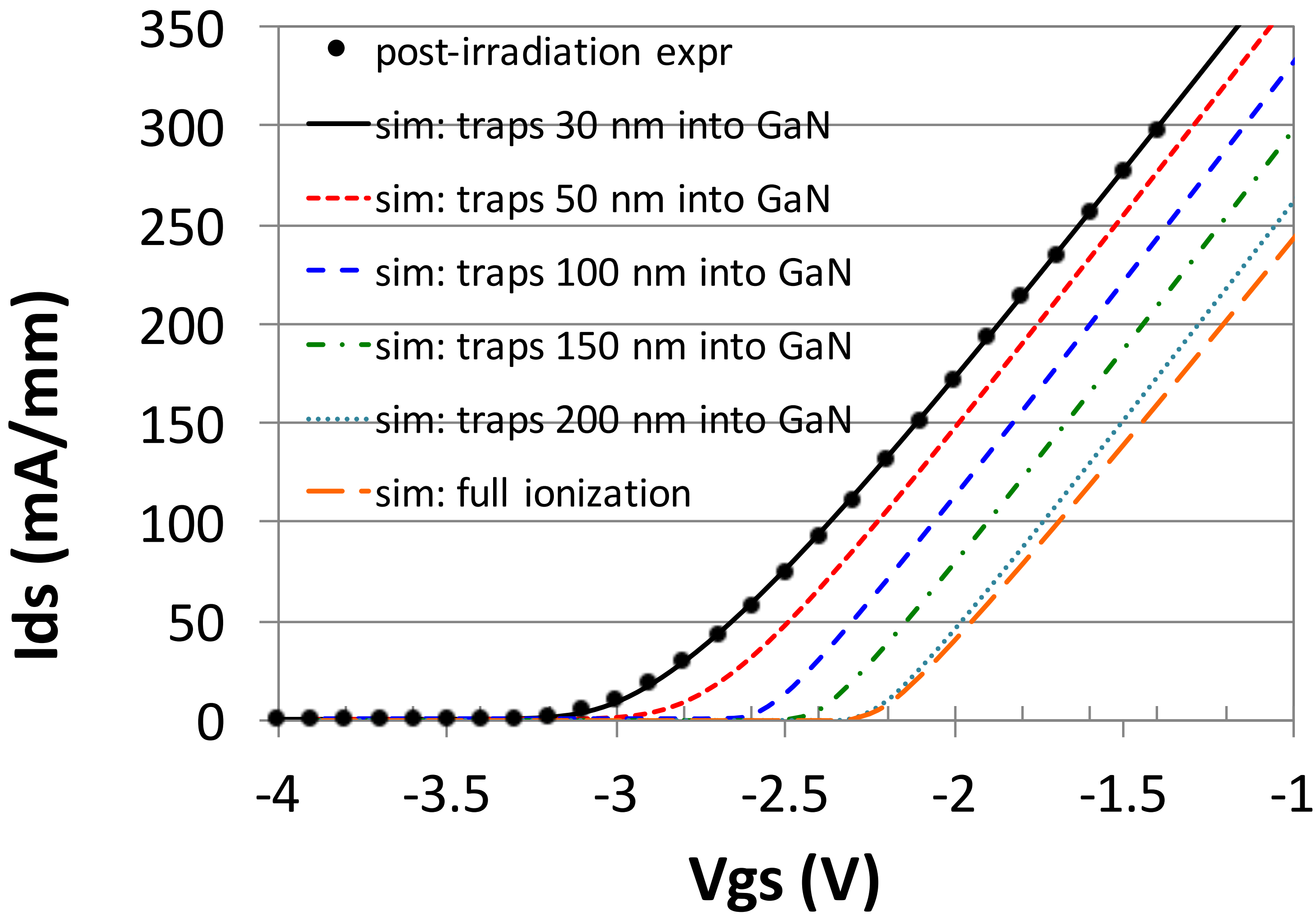
Role of Trap Ionization



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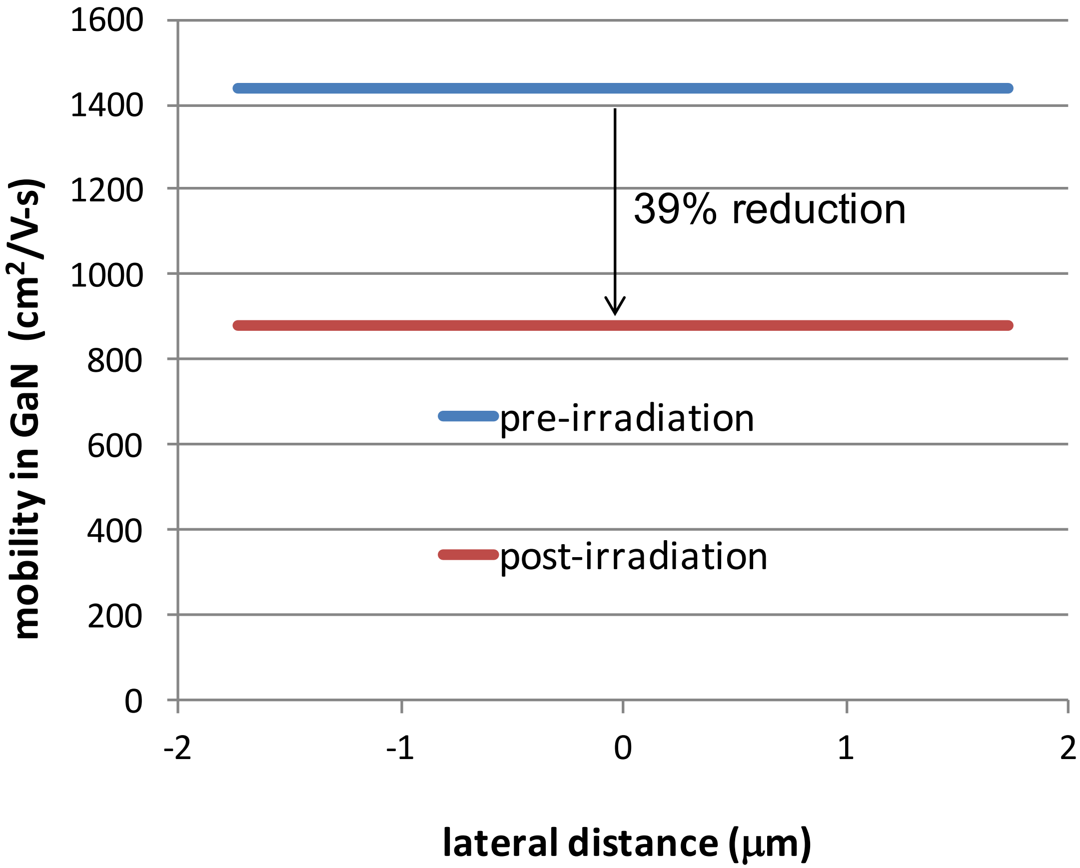
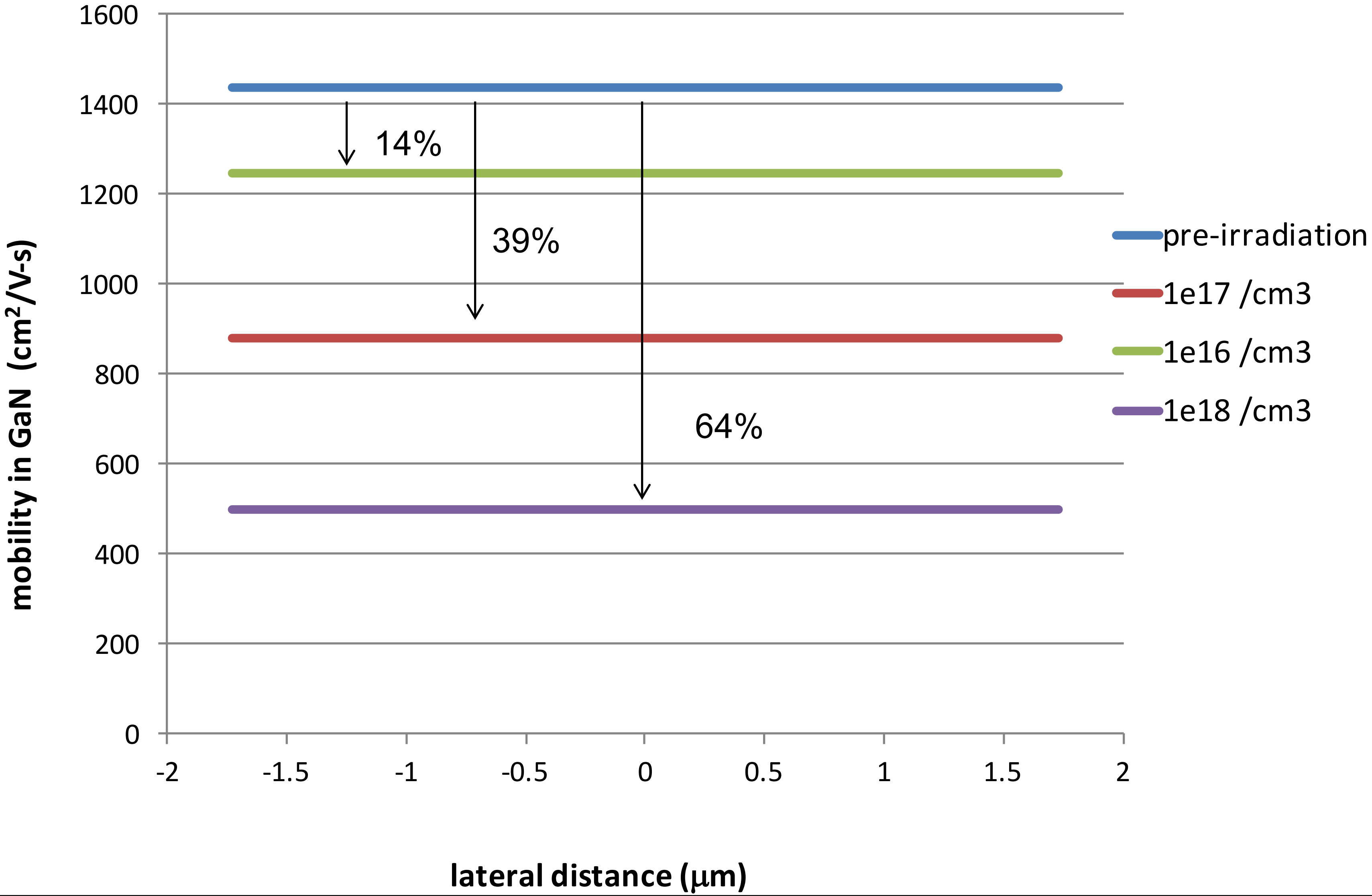
Modeling Mobility Reduction



$$\mu = \mu_{min}\left(\frac{T}{300}\right)^{\beta_1} + \frac{(\mu_{max} - \mu_{min})\left(\frac{T}{300}\right)^{\beta_2}}{1 + \left[\frac{Doping}{N_{ref}\left(\frac{T}{300}\right)^{\beta_3}}\right]}$$

Farahmand et. al., IEEE TED, 2001

Modeling Mobility Reduction



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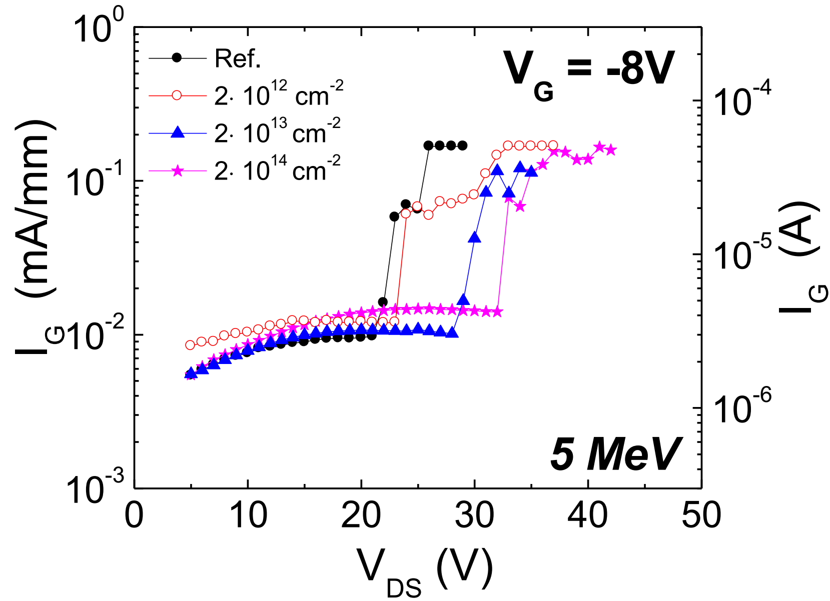
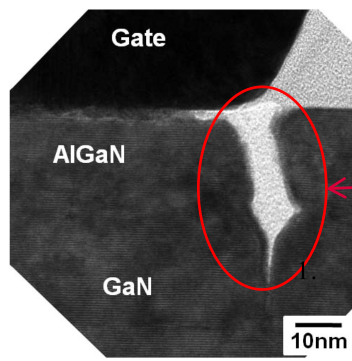
AlGaN/GaN HEMT Reliability Enhancement

Irradiation Dose (cm^{-2})	Drain Breakdown Voltage V_{BR} (V)	Critical Voltage, V_{cri} (V)
Pristine	30	22
10^9	31	23
5×10^9	30	22
5×10^{10}	29	22
2×10^{12}	31	23
2×10^{13}	36	28
2×10^{14}	41	32

5 MeV Proton irradiation





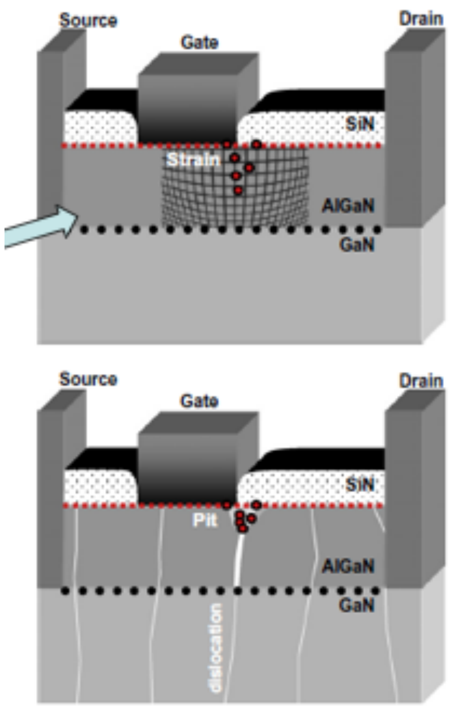
Pit-shaped defect

S. Y. Park et al., "Correlation between Physical Defects and Performance in AlGaN GaN," *Trans. Electrical and Electronic Materials*, vol. 11, no. 2 p.49-53, April 2010.

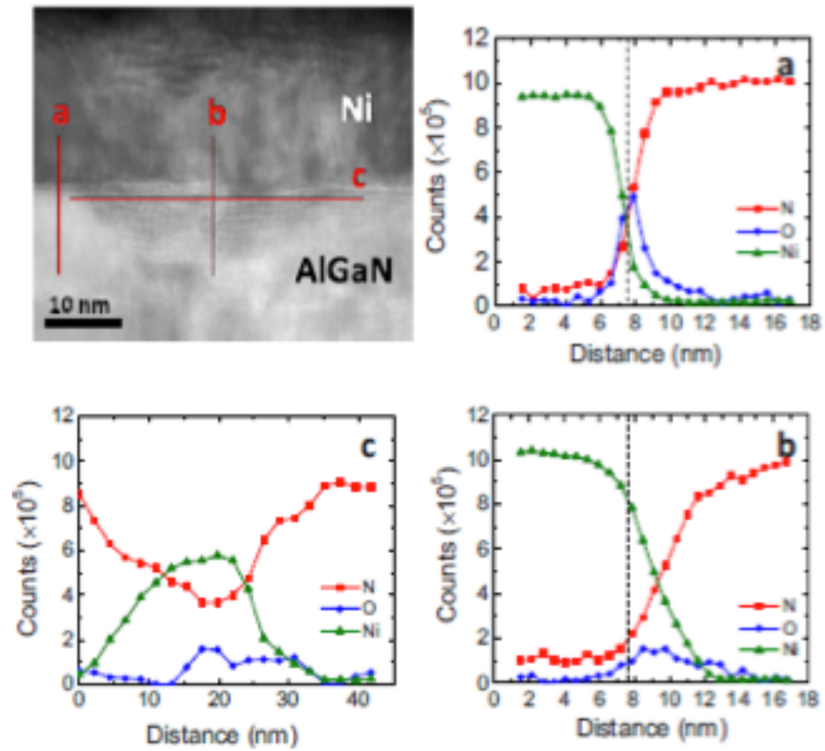
Gate-Diffusion Defect Formation

Pit-Shaped Defect Formation:

- Piezoelectric material ➔ high localized electric and strain fields (near gate / drain edge)
- Strain-enhanced gate metal diffusion



$$D' = D * exp\left(\frac{Q's}{kT}\right)$$

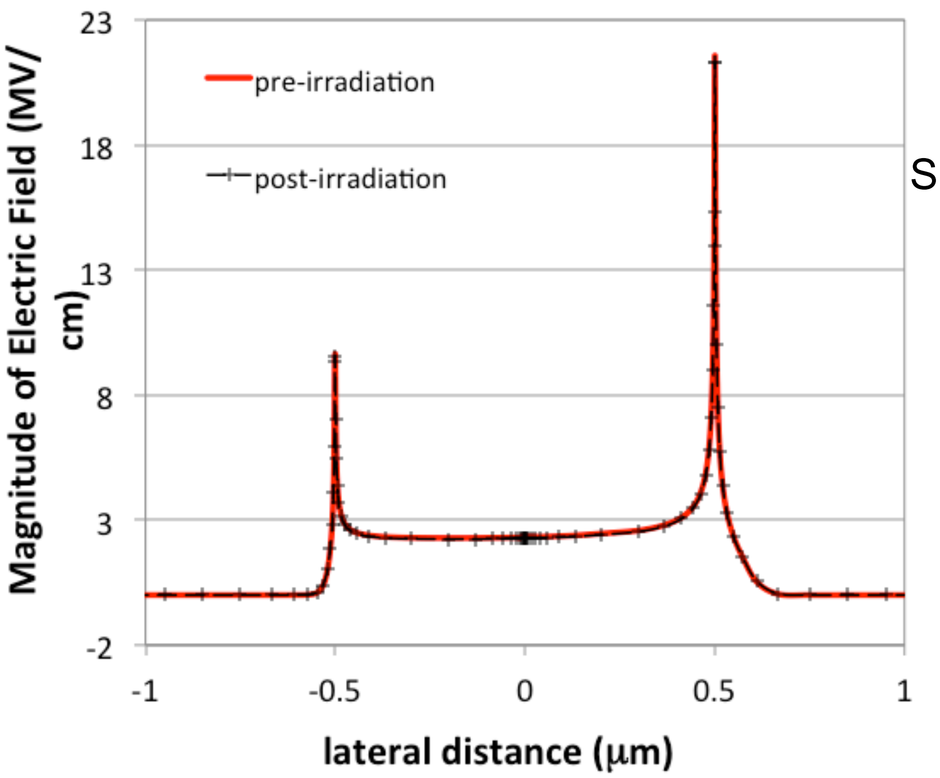


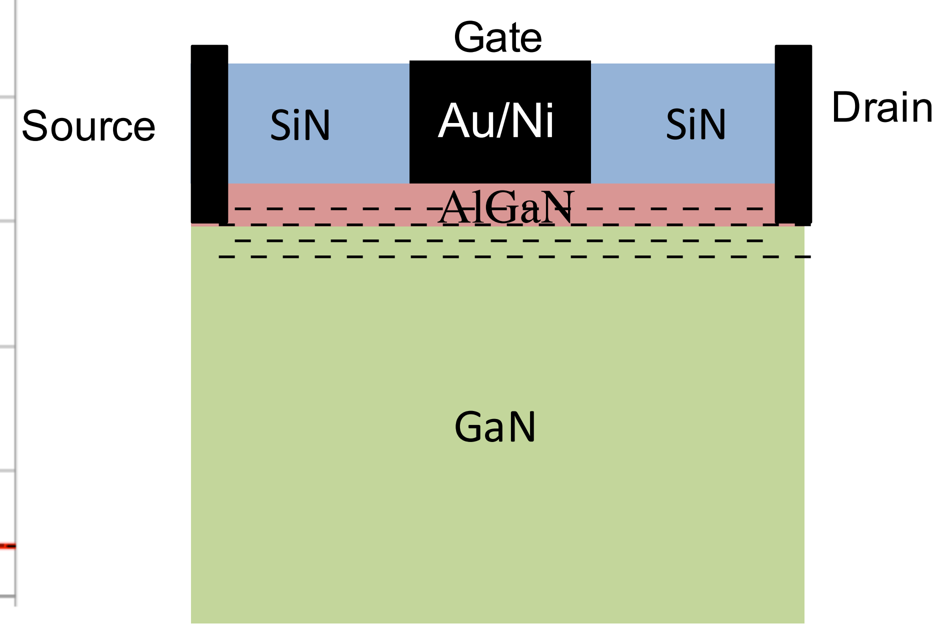
Kuball, M et al Microelectronics Reliability 51 2011 pp:195–200

Ren, F et al. JVST B 5 Microelectronics and Nanometer structures Apr 2011

Virtual Gate in GaN Buffer?

- **Hypothesis I: Acceptor-like traps in the GaN buffer = virtual gate**
- Floods Test: Peak electric field values (5 nm into AlGaN) show ~1% change for post-irradiation simulation (need 40% reduction to match experiments)





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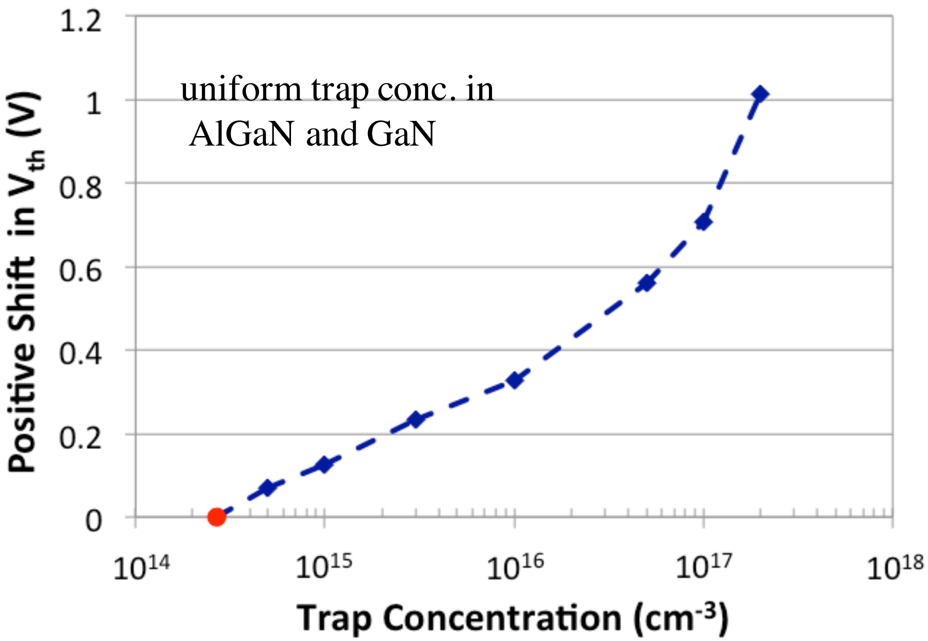
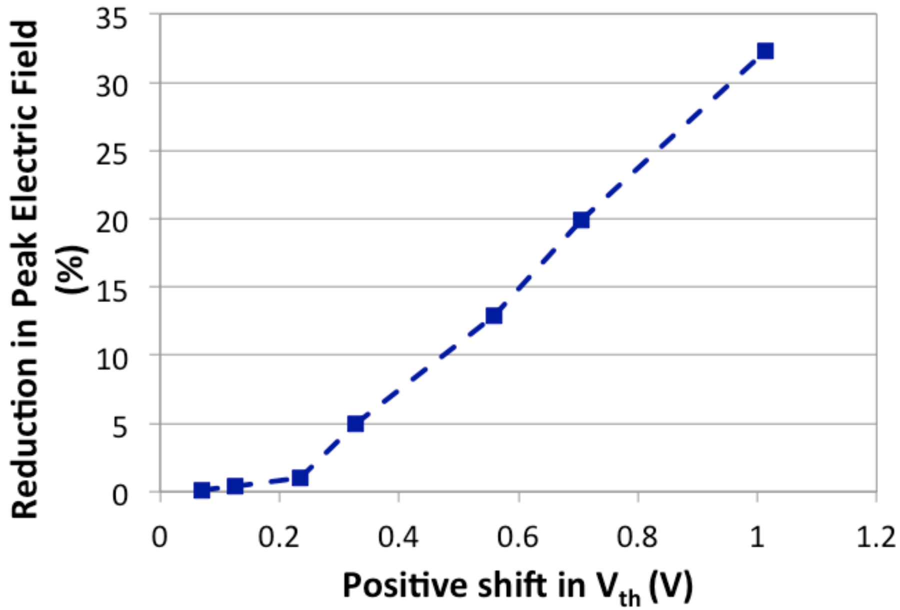
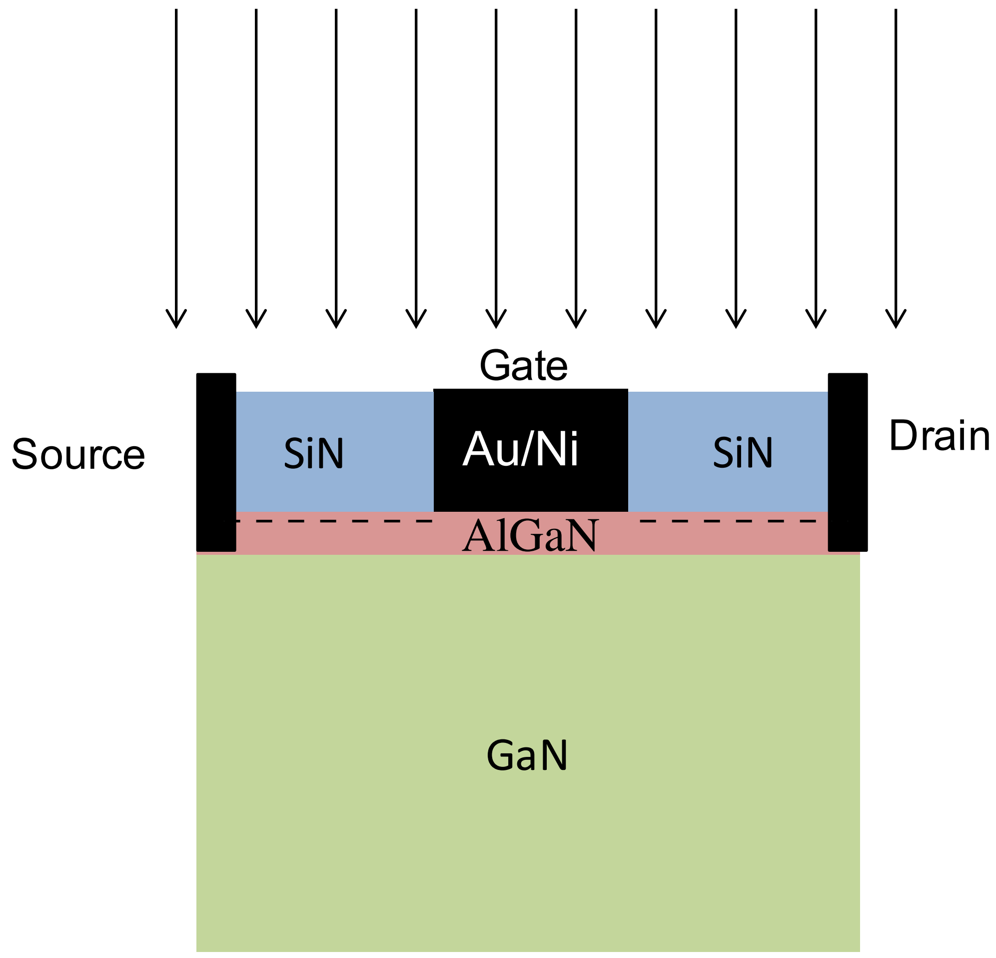




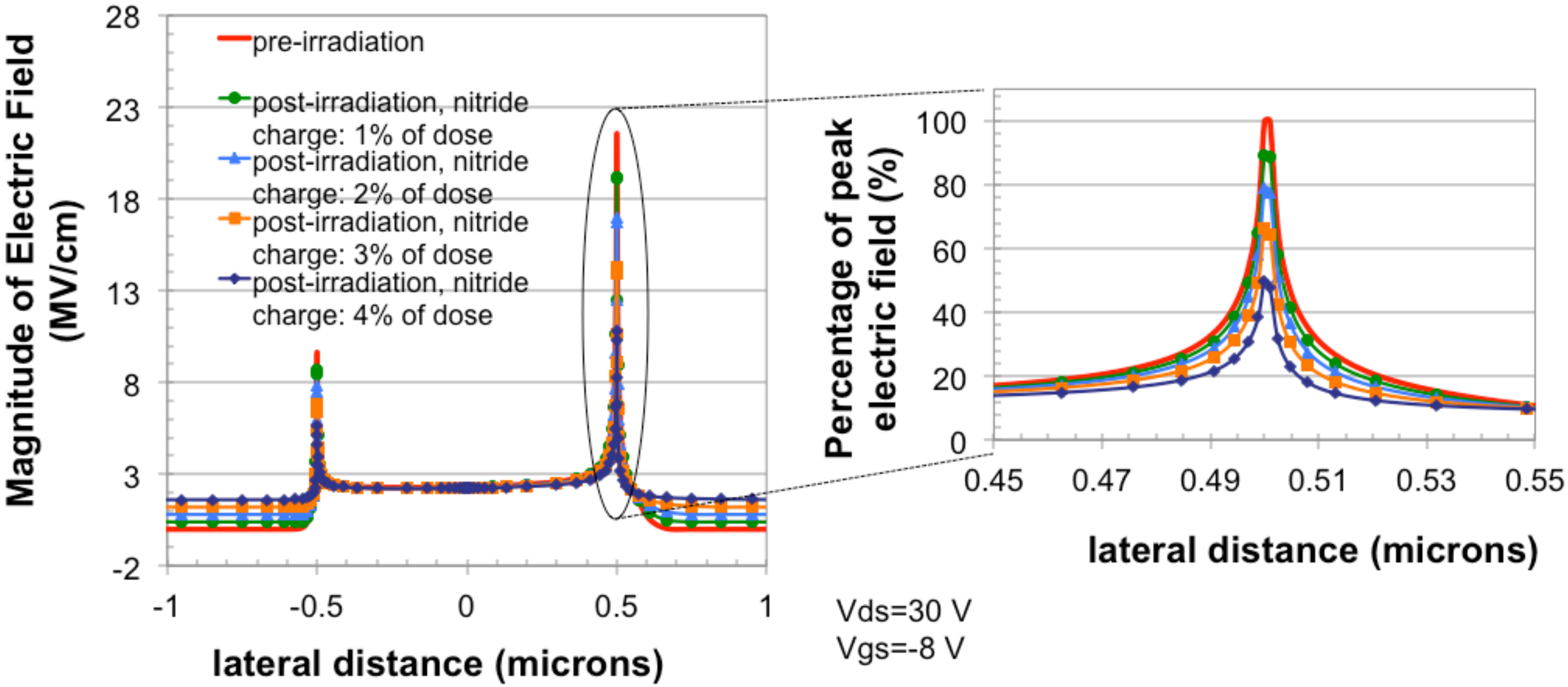
- **Hypothesis I is unlikely: Need a Vth shift ~1V for 30% e-field reduction**

Virtual Gate at SiN/AlGaN Interface



Virtual Gate at SiN/AlGaN Interface

- **Hypothesis II: Acceptor-like traps in the SiN/AlGaN interface = virtual gate**



- **Peak electric field values (5 nm into AlGaN) show 10 to 50% change for various sheet charge densities (4% = $8{\times}10^{12}$ /cm-2)**

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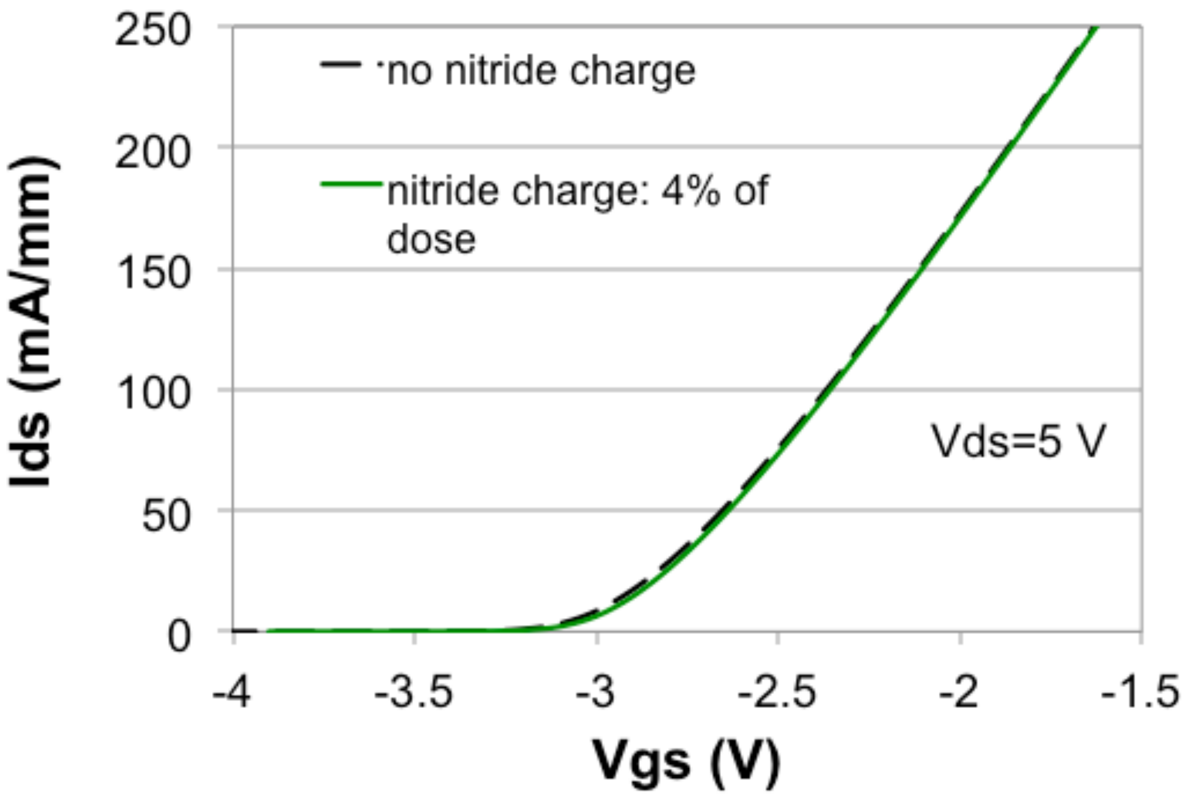
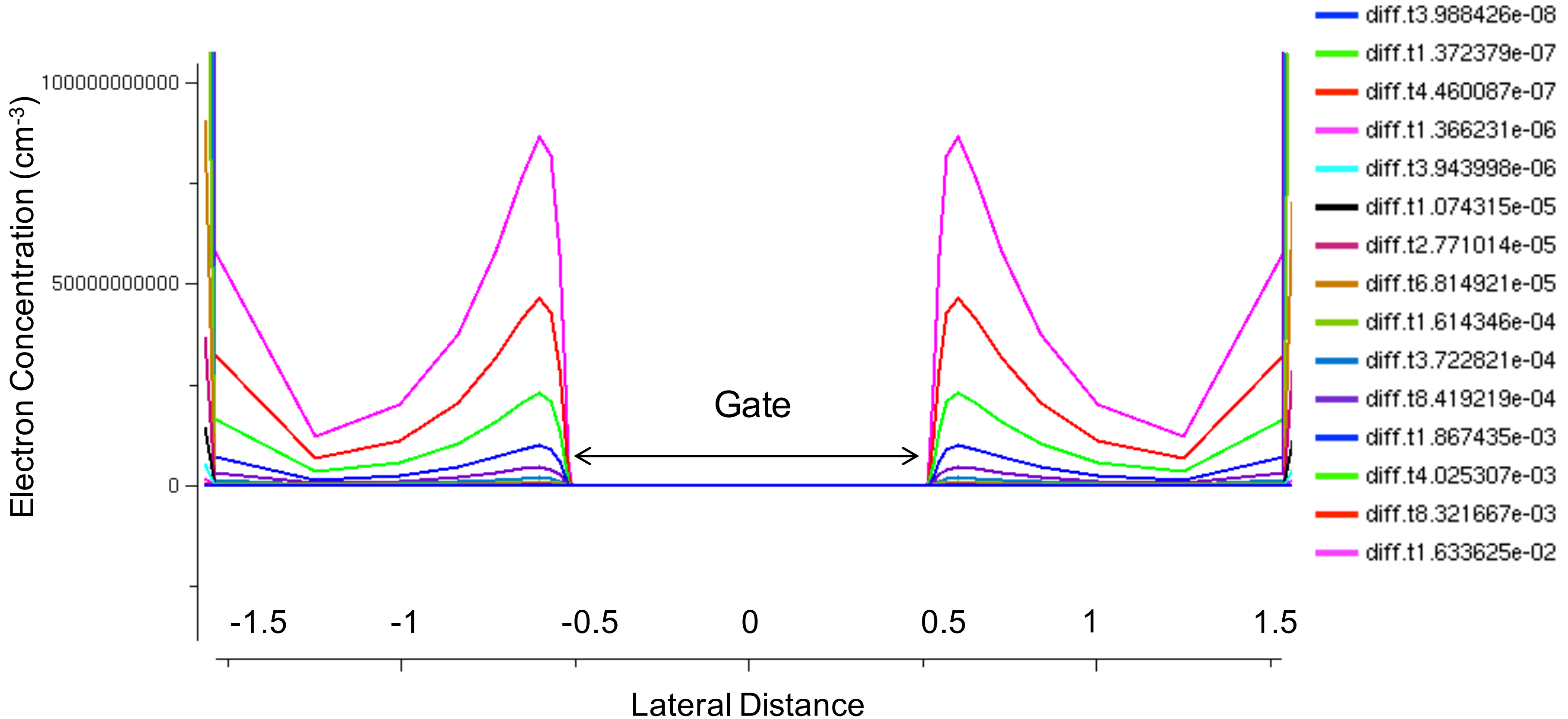
Virtual Gate at SiN/AlGaN Interface



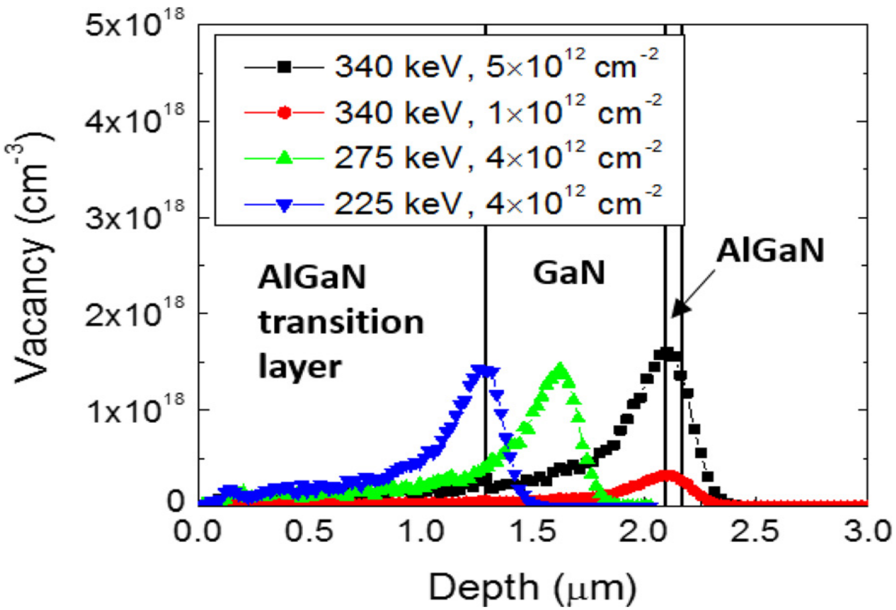
- **The Id-Vg curves do not change much with the nitride charging.**
- **Hypothesis II is plausible.**

Nature of SiN/AlGaN Charging?

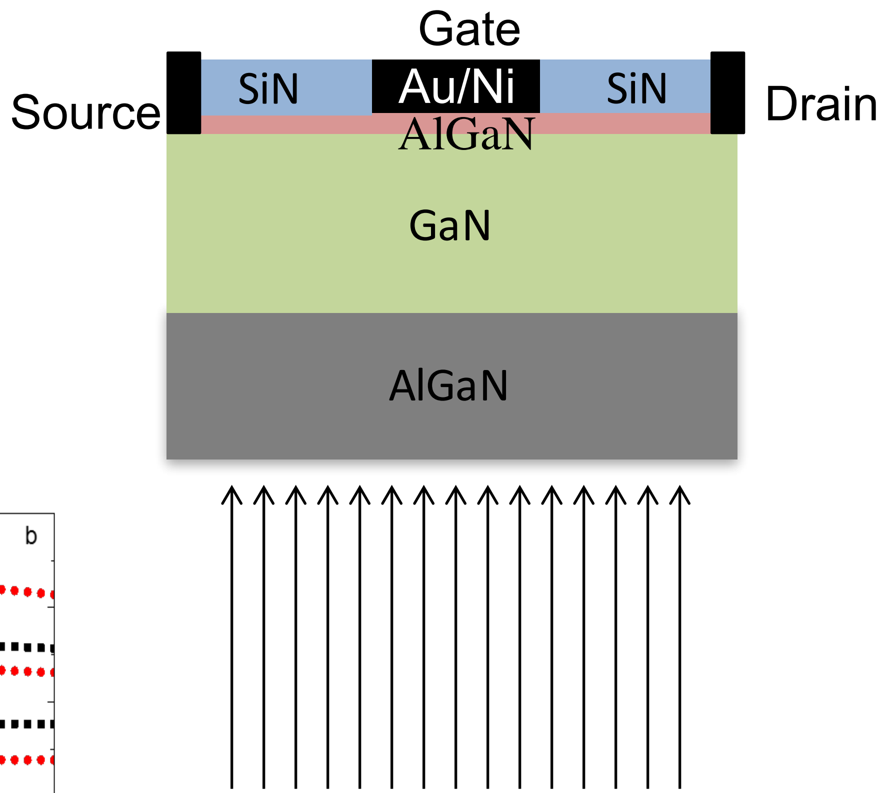
- Electron/hole pair generation
  - 2×10^{16} (pairs/cm^3-s) calculated by TRIM

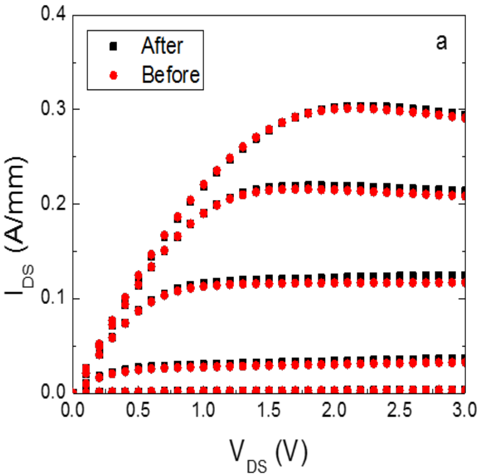


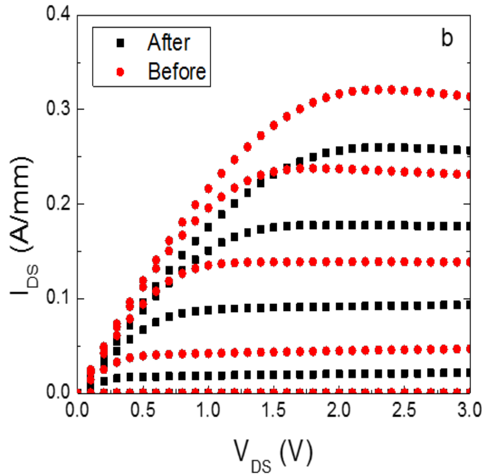
Nature of Nitride/AlGaN Charging?



Backside Irradiation Experiment

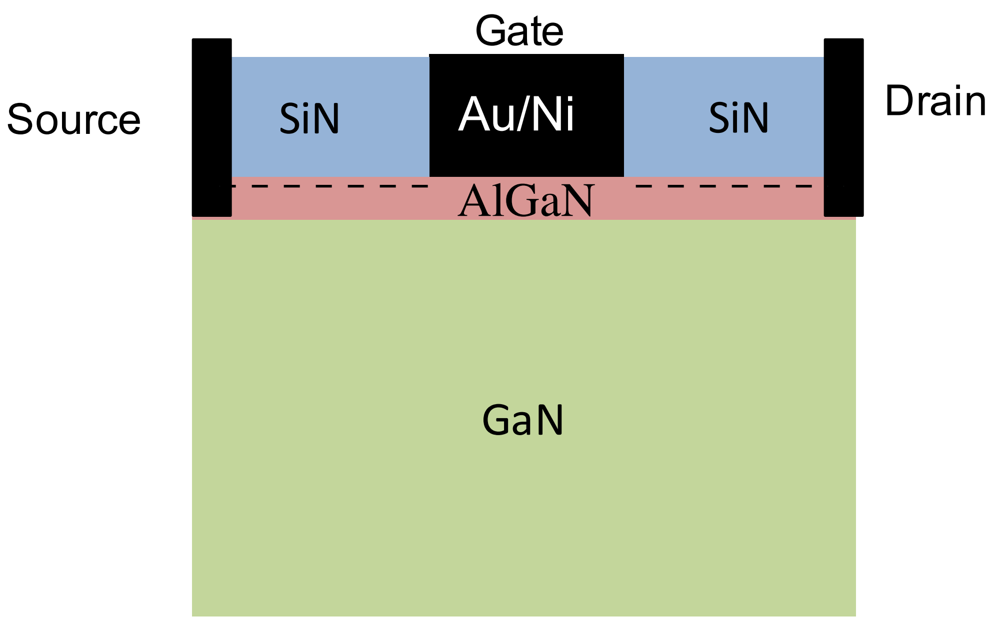






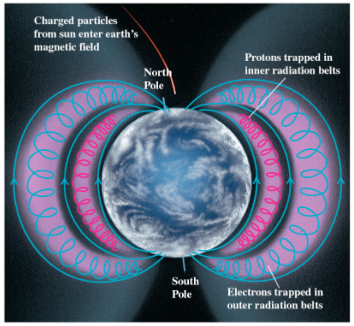
Nature of Nitride/AlGaN Charging?

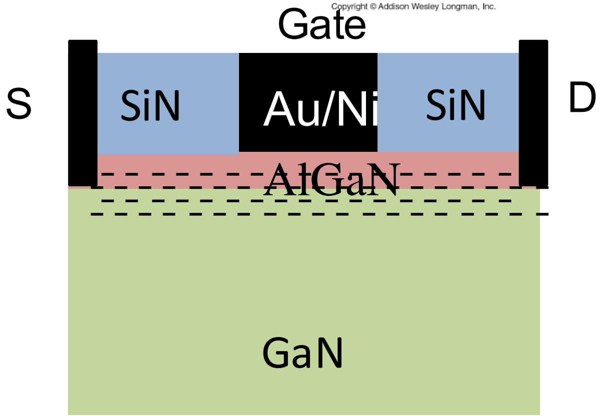
- Mobile defect-related trap states that agglomerate at Nitride/AlGaN interface
  - Maybe assisted by electron cloud

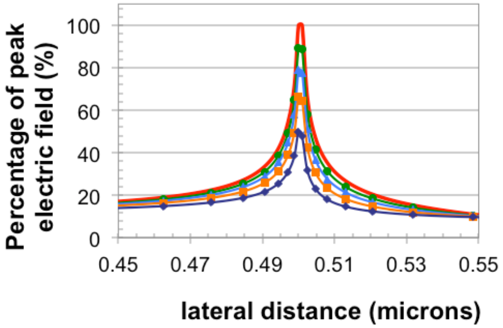


Summary

- GaN-based devices are robust to irradiation
- DC device degradation can be modeled by negative trapped charge near 2DEG
- Enhanced reliability can be modeled by negative trapped charge at SiN/AlGaN interface
  - Reduces peak electric field
  - Mechanism unclear







Funding source: DTRA, AFRL