Simulation of Radiation Effects in AlGaN/GaN High Electron Mobility Transistors

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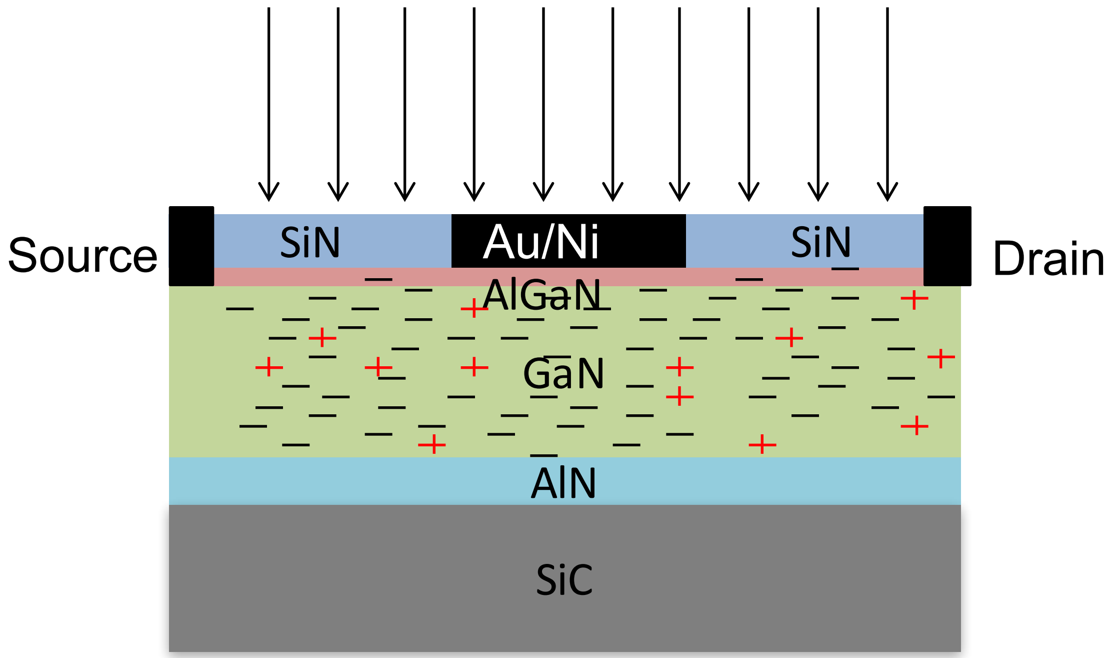
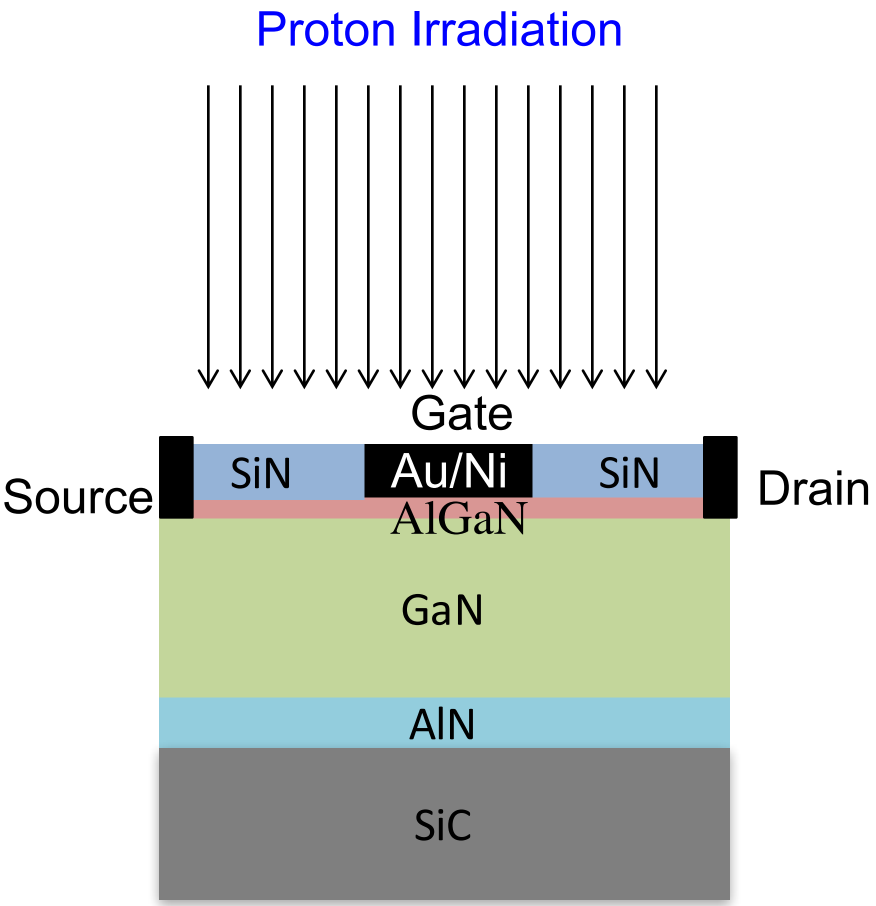
Why model / simulate?

- Predict device performance
- Optimize device performance
- Better understand underlying physical mechanisms



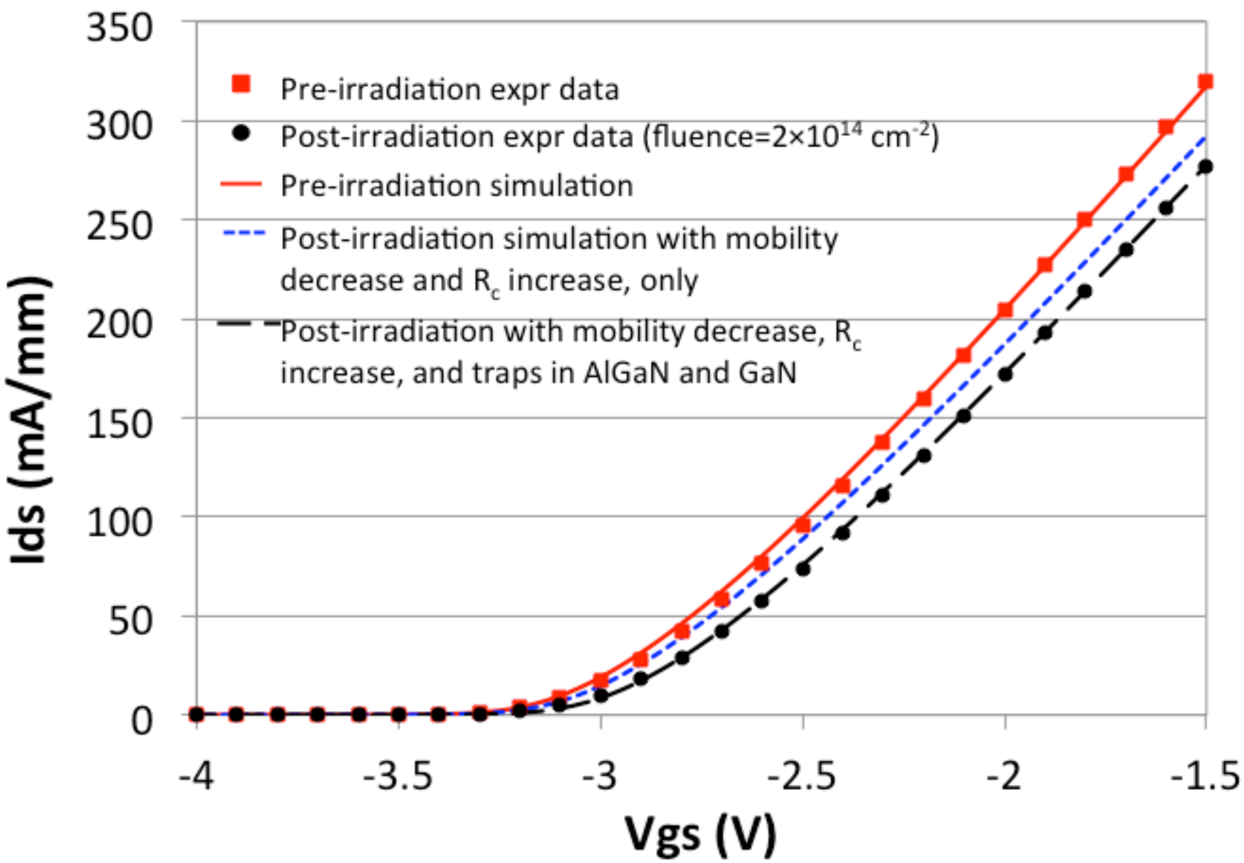
AlGaN/GaN HEMT DC Performance Degradation



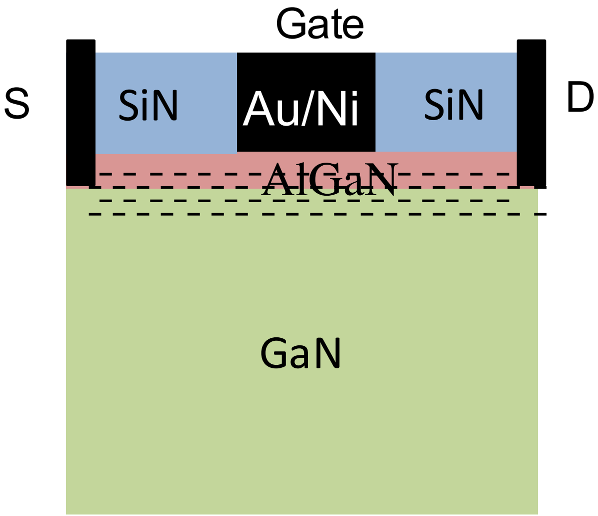
- Reduction in mobility
- Positive threshold voltage shift
- Reduction of drain current
- Reduction of transconductance

- Point defects create traps
- Ionized traps create:
  - Reductions in electron mobility
  - Negative trapped charge
    - ↓ 2DEG density

Problem: Understand Mechanisms

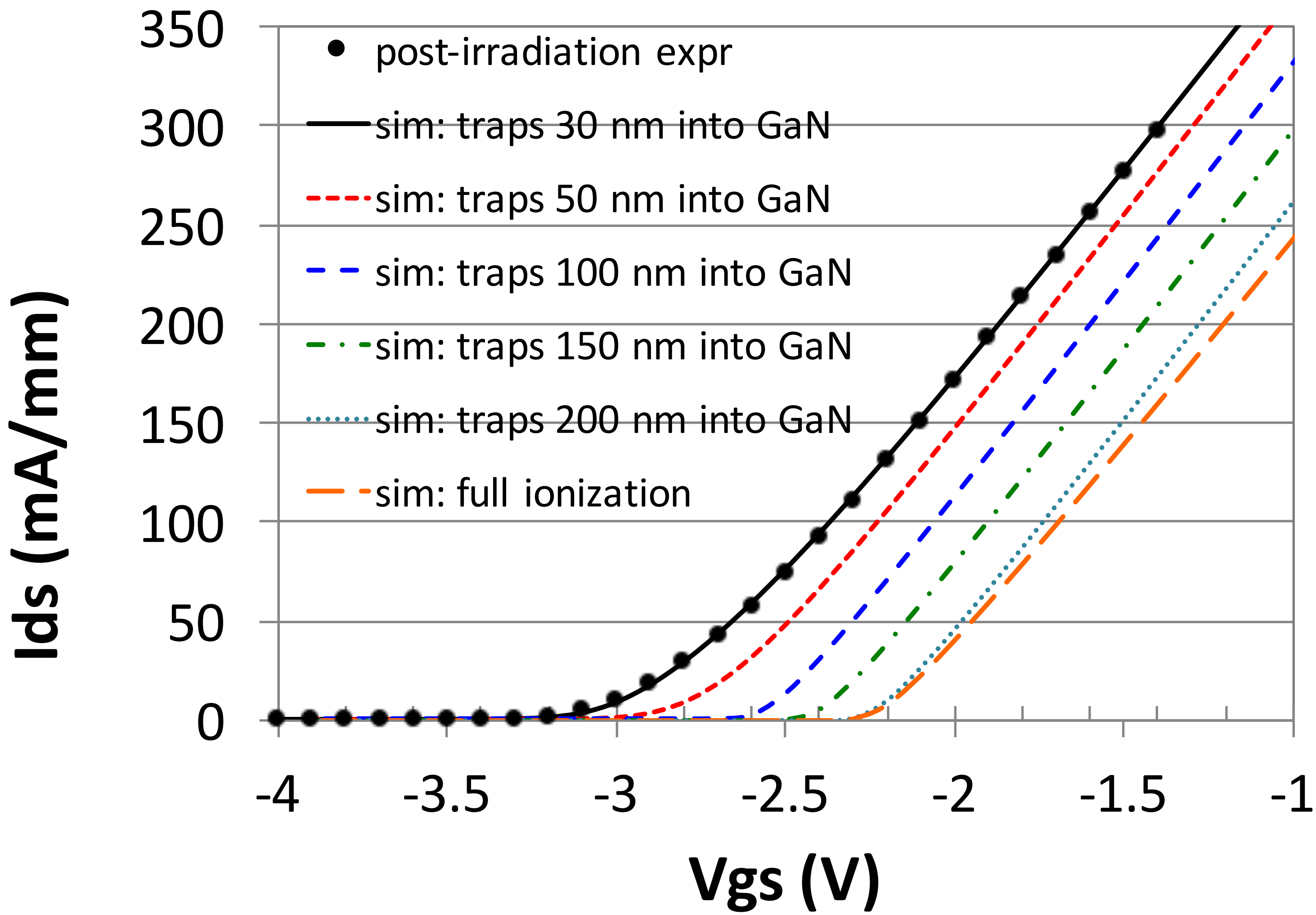


Neg trap conc:
1×10^{17} cm^{-3}
30 nm into GaN



E. Patrick, et al., *IEEE Trans. Nucl. Sci.*, v. 60., no. 6, pp. 4103-4108, 2013.

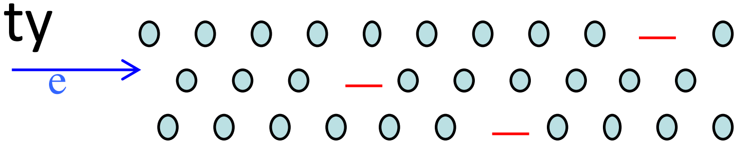
Partial Ionization and/or Compensation?



Overview

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

1. Test hypothesis of ionized impurity scattering as mobility reduction mechanism (TRIM)



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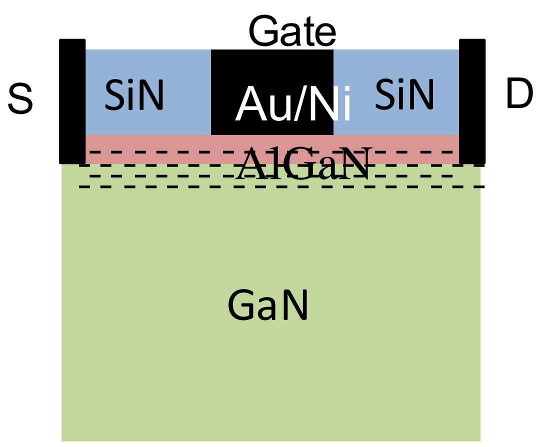
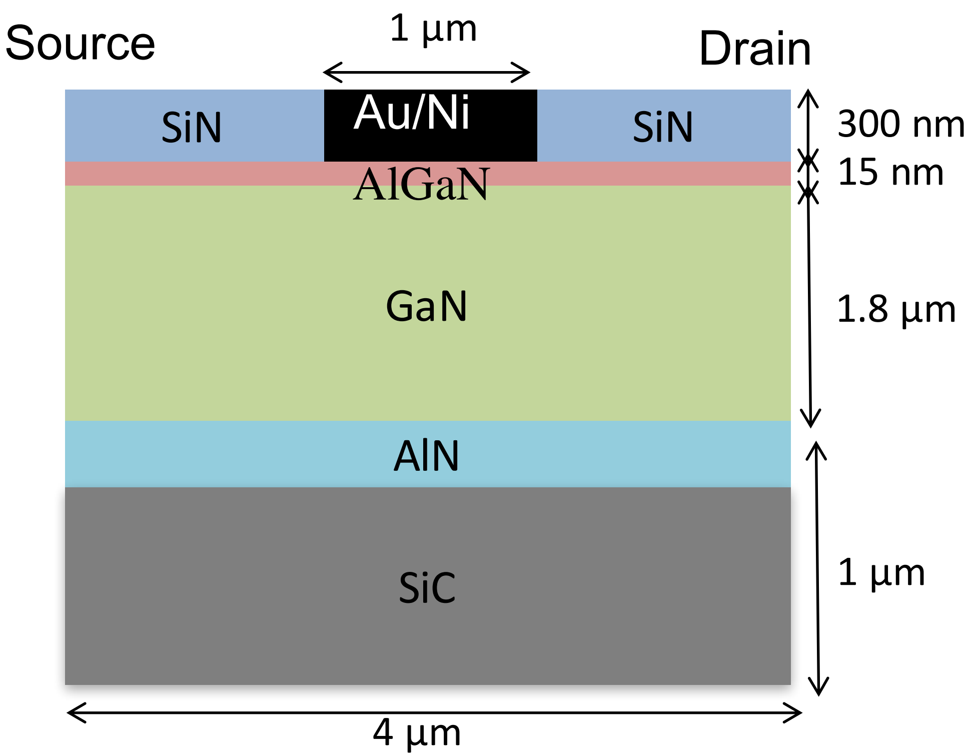


Simulation Methodology

TCAD Simulator: FLOODS

(Florida Object-Oriented Device Simulator)



Device Equations

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

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

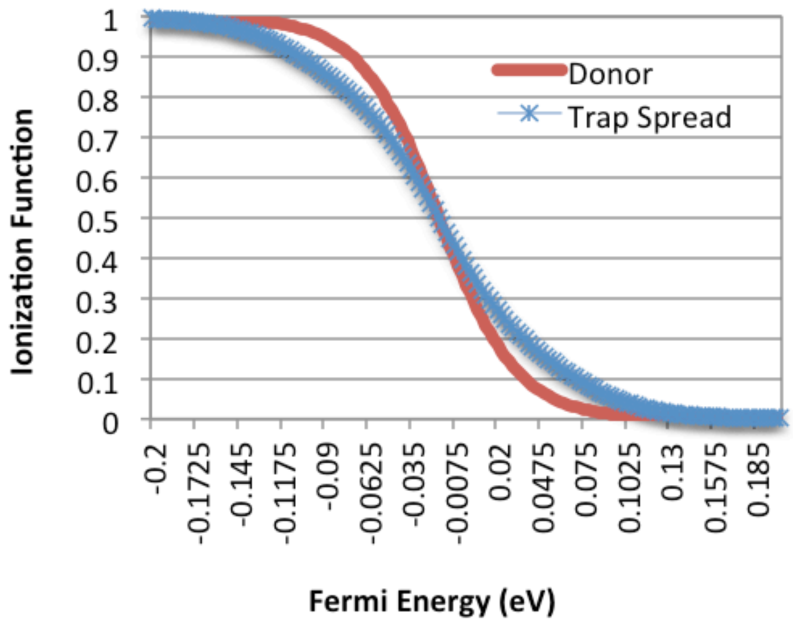
$$J_n = -q\mu_n n \nabla \phi_n, \quad J_p = q\mu_n p \nabla \phi_p$$

Simulation Methodology

Calculation of Partial Ionization

$$\frac{N_D^+}{N_D} = \frac{1}{1 + 2e^{\frac{E_F - E_T}{kT}}}$$

Prone to convergence issues



Trap Energy Level Spread

$$N(E) = \frac{N_D}{\nabla E\sqrt{2\pi}} e^{-\frac{(E-E_T)^2}{2\nabla E^2}}$$

$$\frac{N_D^+}{N_D} = \int \left(\frac{1}{1 + 2e^{\frac{E_F - E}{kT}}}\right)\left(\frac{1}{\nabla E\sqrt{2\pi}} e^{-\frac{(E-E_T)^2}{2\nabla E^2}}\right) dE$$

Numerically integrate using Gaussian-Hermite quadrature

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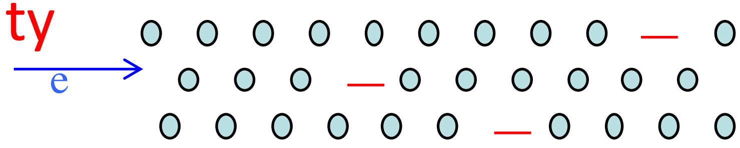

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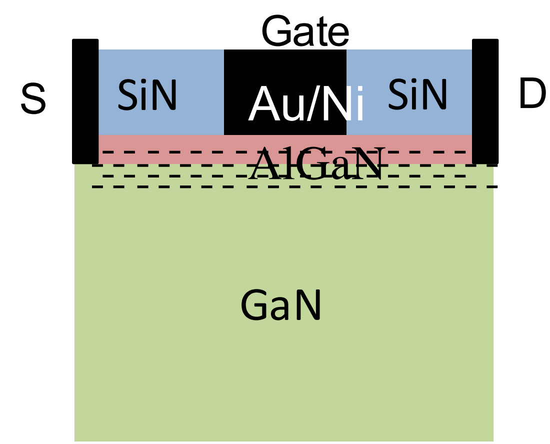
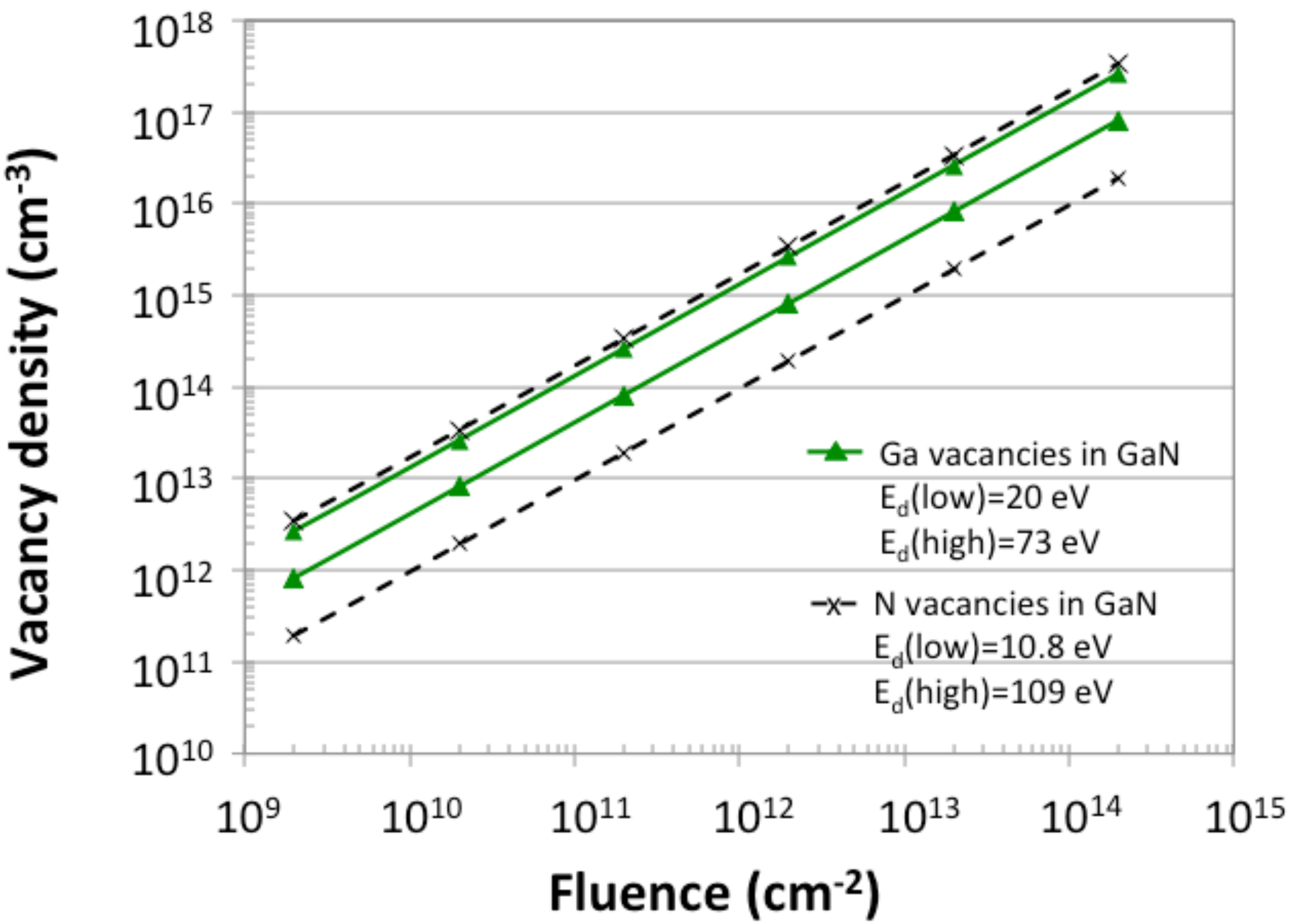


Radiation-induced Defect Estimation



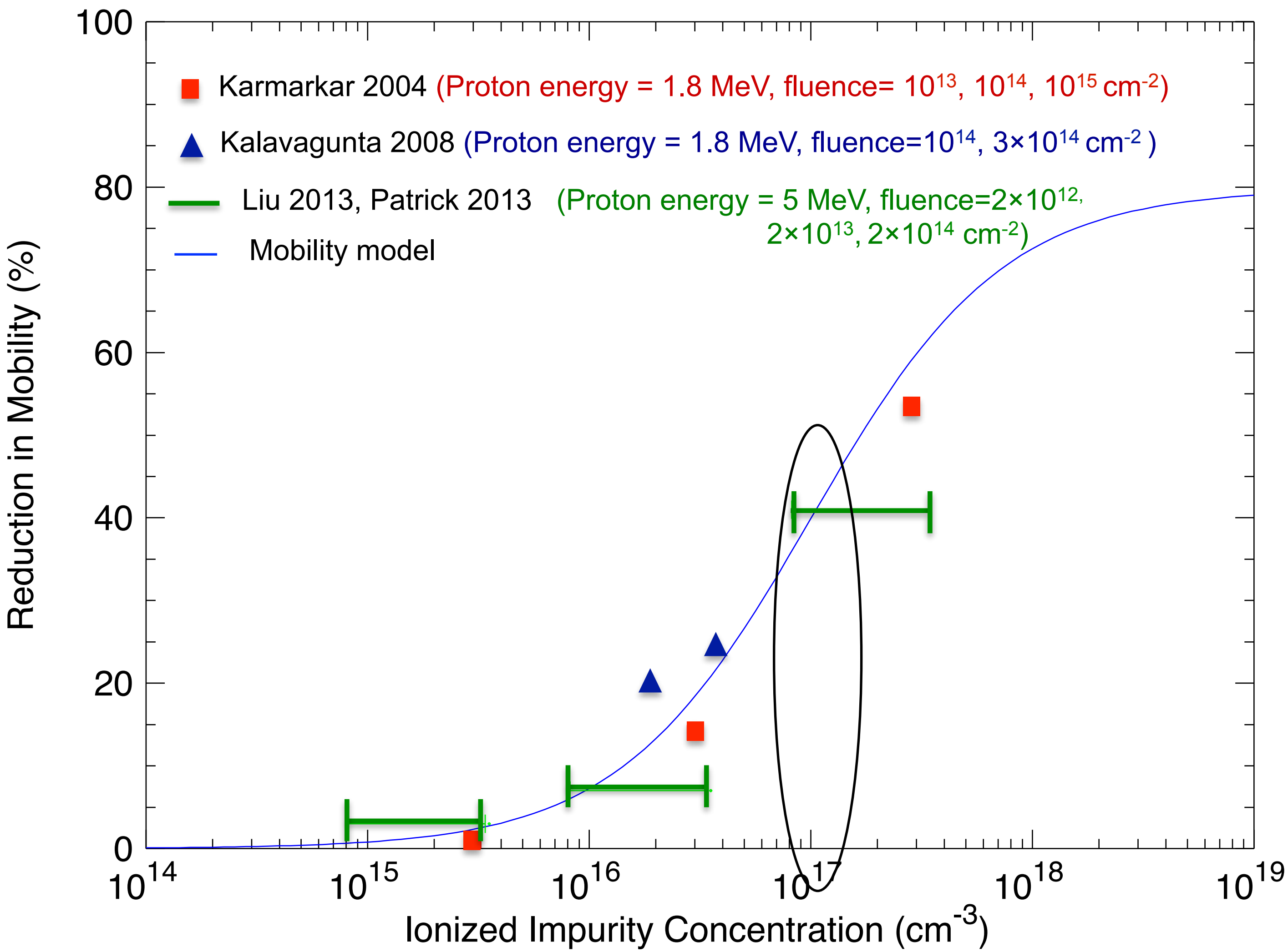
TRIM (Transport of Ions in Matter) simulation results

V_{GA} – acceptor-like traps (-)

V_N – donor-like traps (+)

Positive V_T shift needs acceptor-like traps

Ionized Impurity Scattering Hypothesis



$$\mu_0 = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N}{N_{ref}}\right)^{\alpha}}$$

N – ionized dopant conc.

μ_{min}=295 cm2/Vs
μ_{max}=1406 cm2/Vs
N_{ref} = 1x10^{17}
α=0.66

*Farahmand et al., 2001

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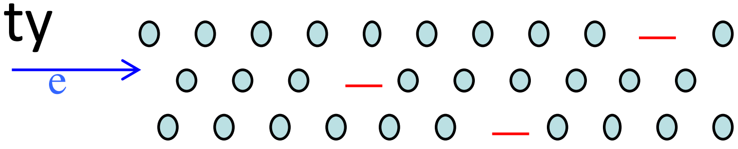

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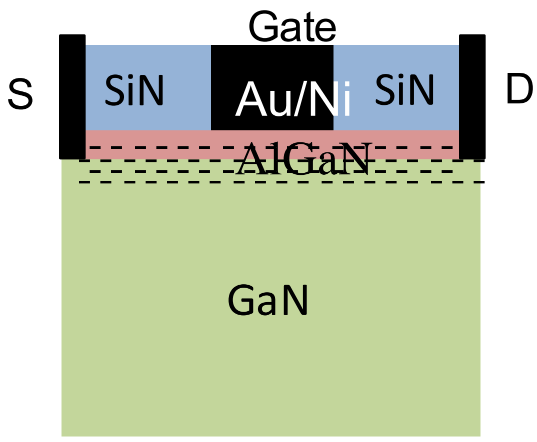
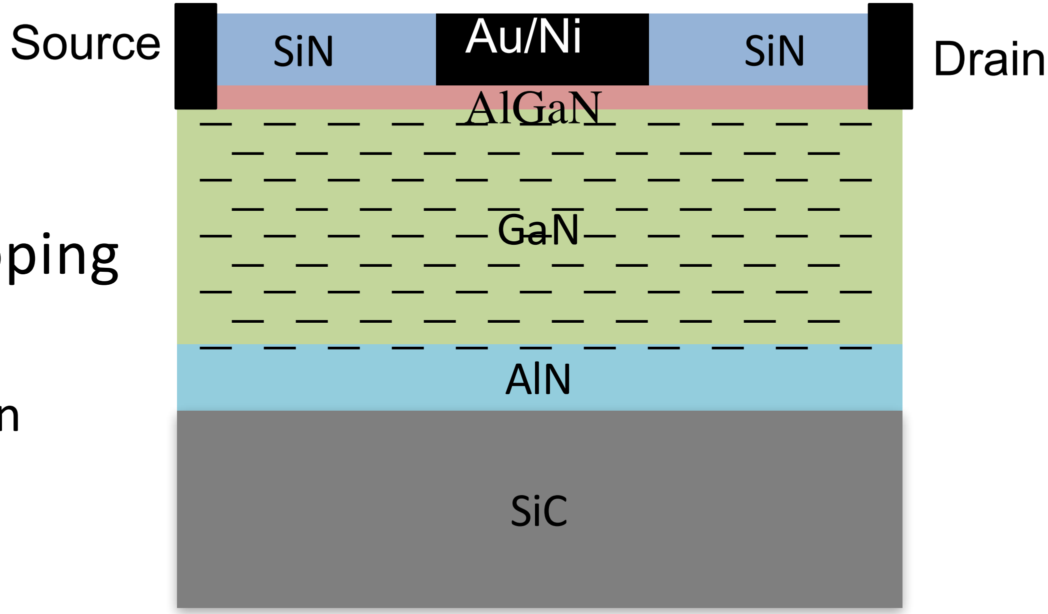


Test Acceptor Concentration and Ionization

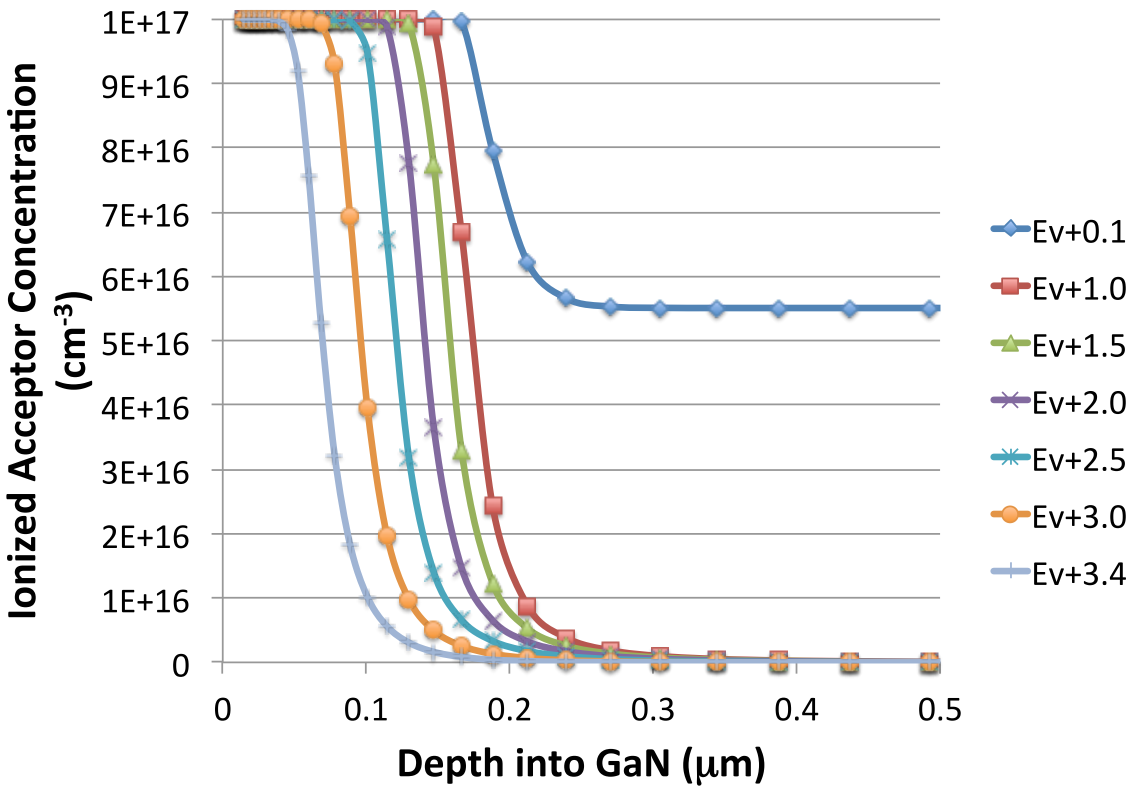
- Radiation case:
  - 5M eV Proton radiation, fluence= $2x10^{14}$ cm^{-2}
    - Ids reduction = 13%, Vt shift = 0.1 V (3%)
  - TRIM / Mobility model predict ~10^{17} cm^{-3} ionized acceptor traps near 2DEG

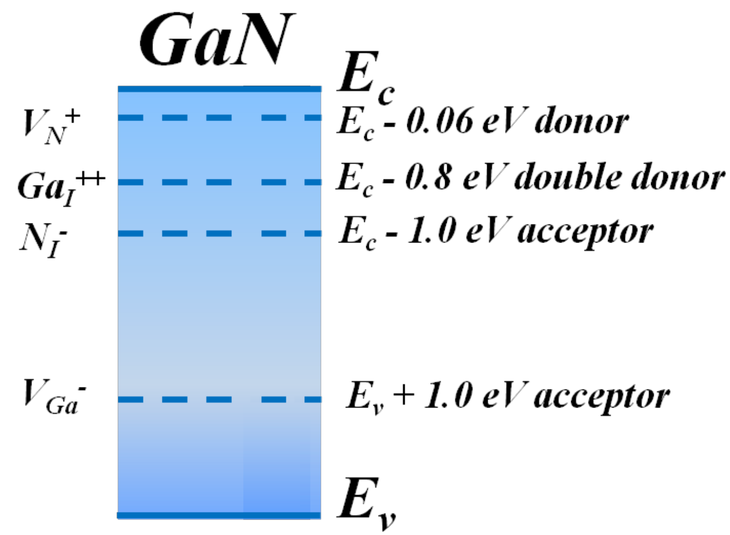


- Sensitivity Analysis
  - Uniform Acceptor Doping
    - Isolate layer
    - Vary trap concentration
    - Vary trap energy level

Acceptor Ionization

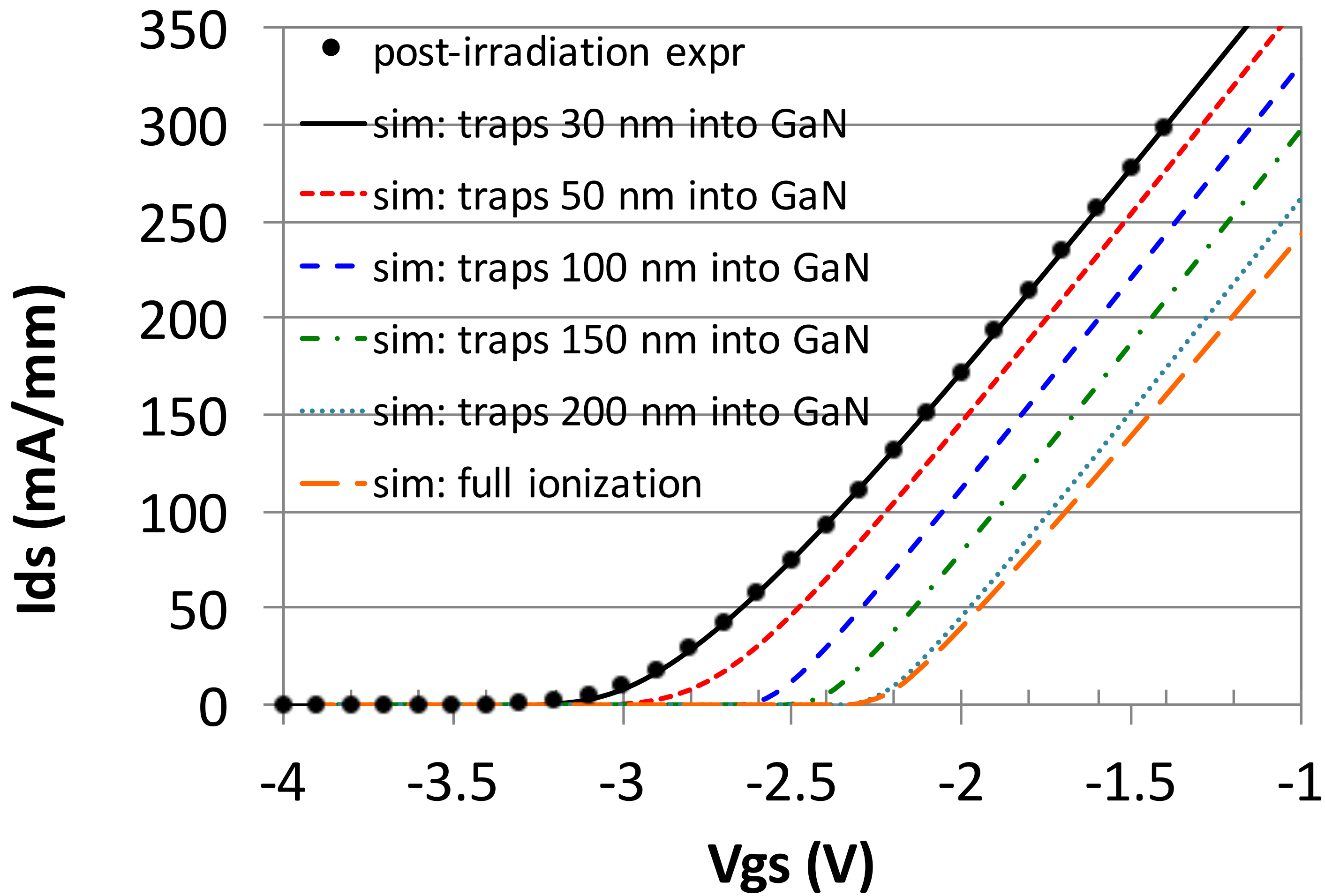
Bias conditions: V_{gs}= 0V, V_{ds} =1 V





*Polyakov, et al., J. Mater. Chem. C, 2013, 1, 877

V_{Ga} (E_V+1 eV) = fully ionized



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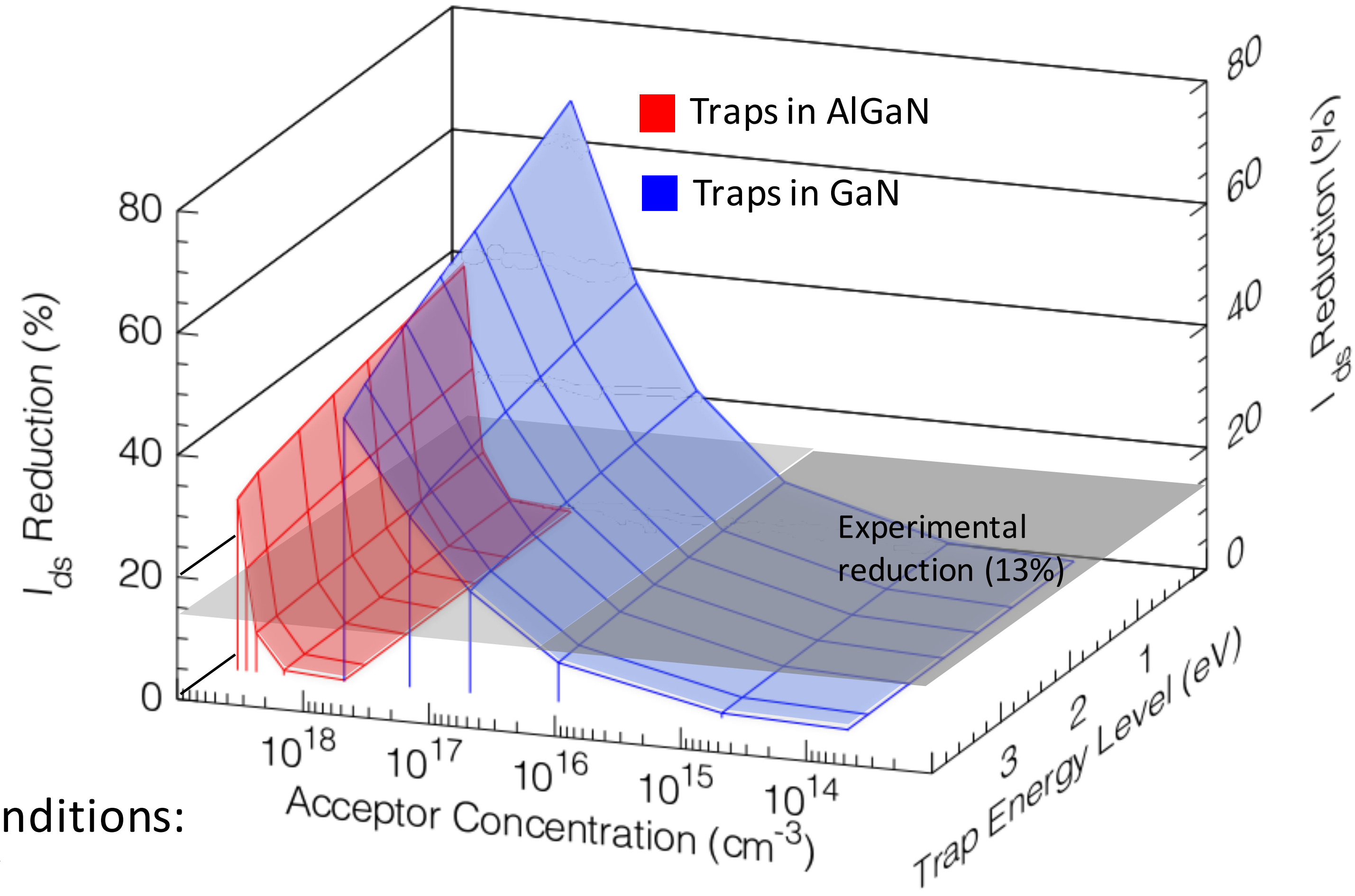
Simulation Results: Drain Current Reduction



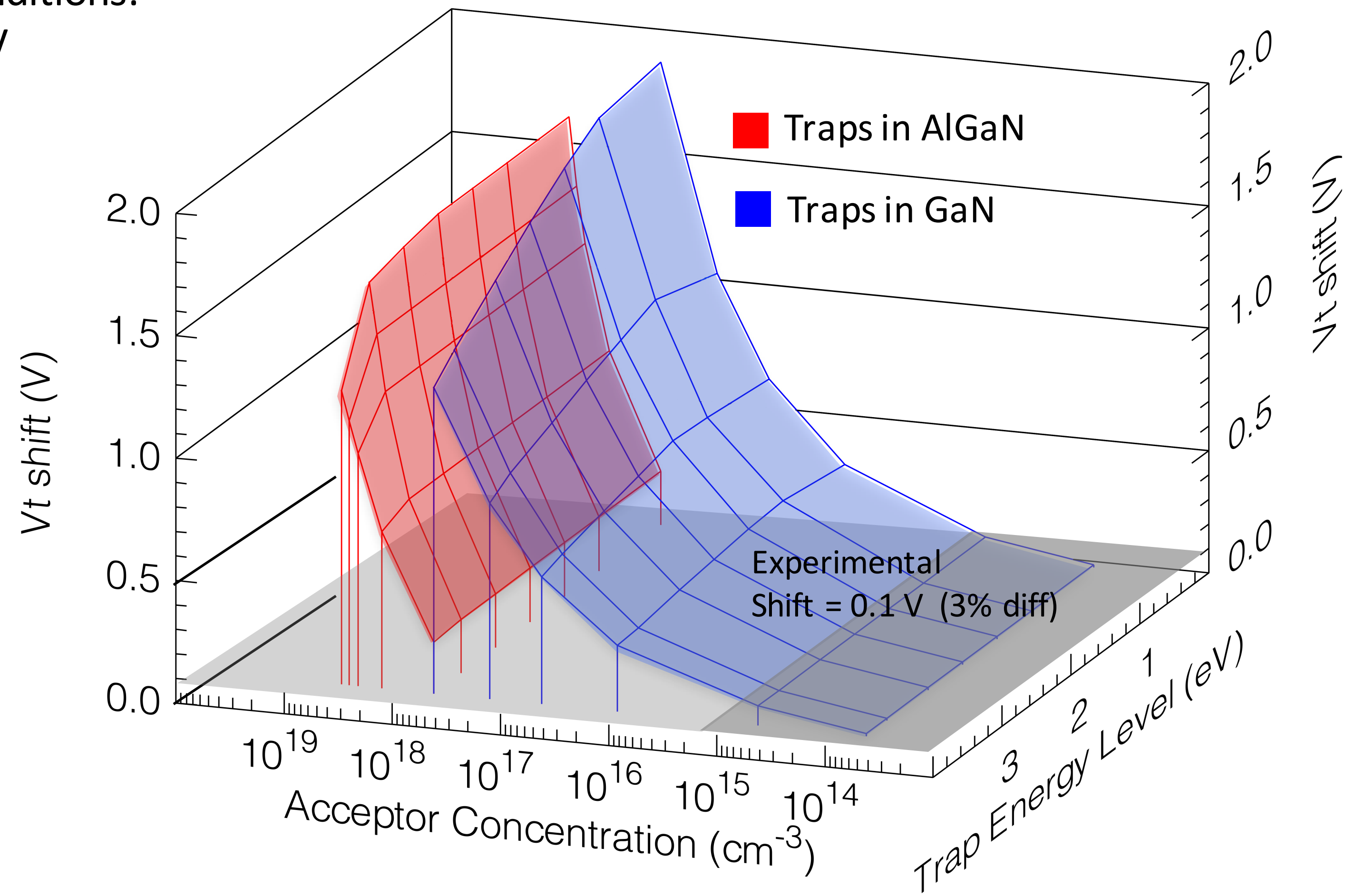
Bias conditions:

V_g= 0 V

V_{ds} = 1 V

Simulation Results: Threshold Voltage Shift

Bias conditions:
V_{ds} = 1 V



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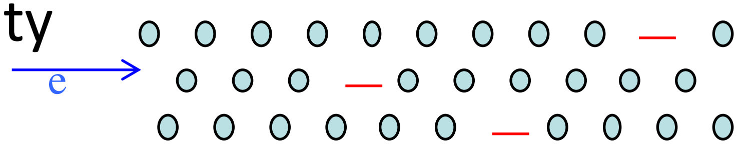

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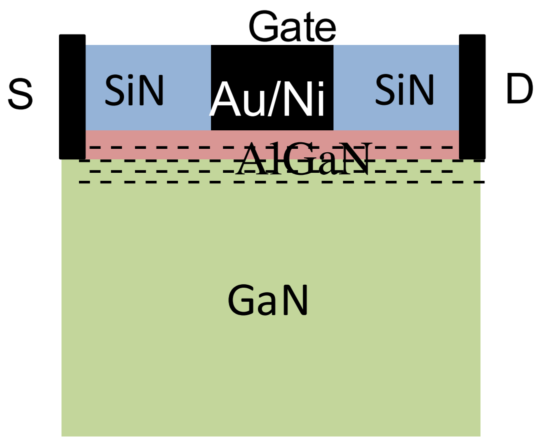

Test Effect of Donor Compensation

- Radiation case:
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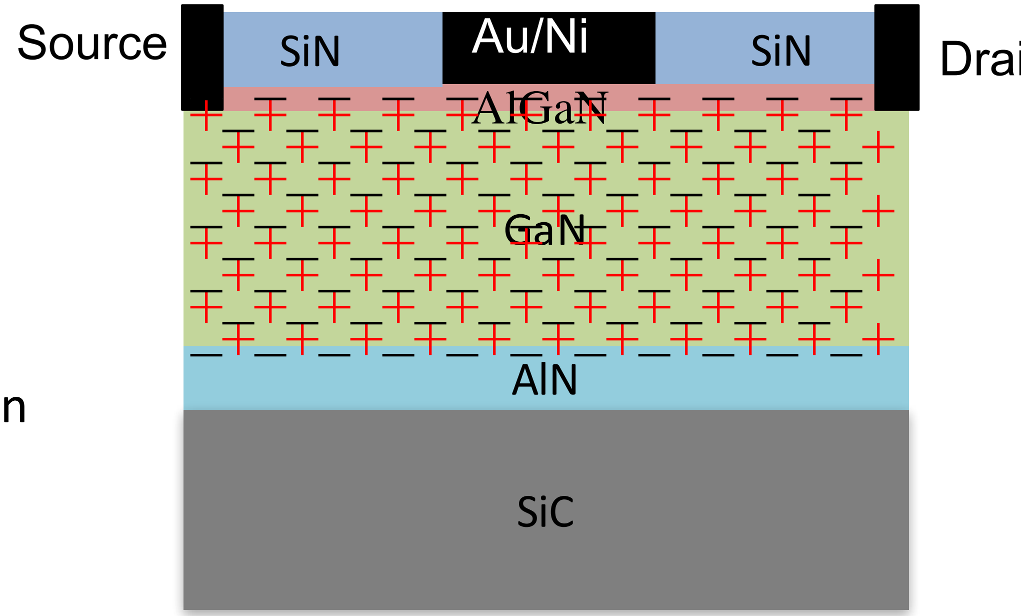
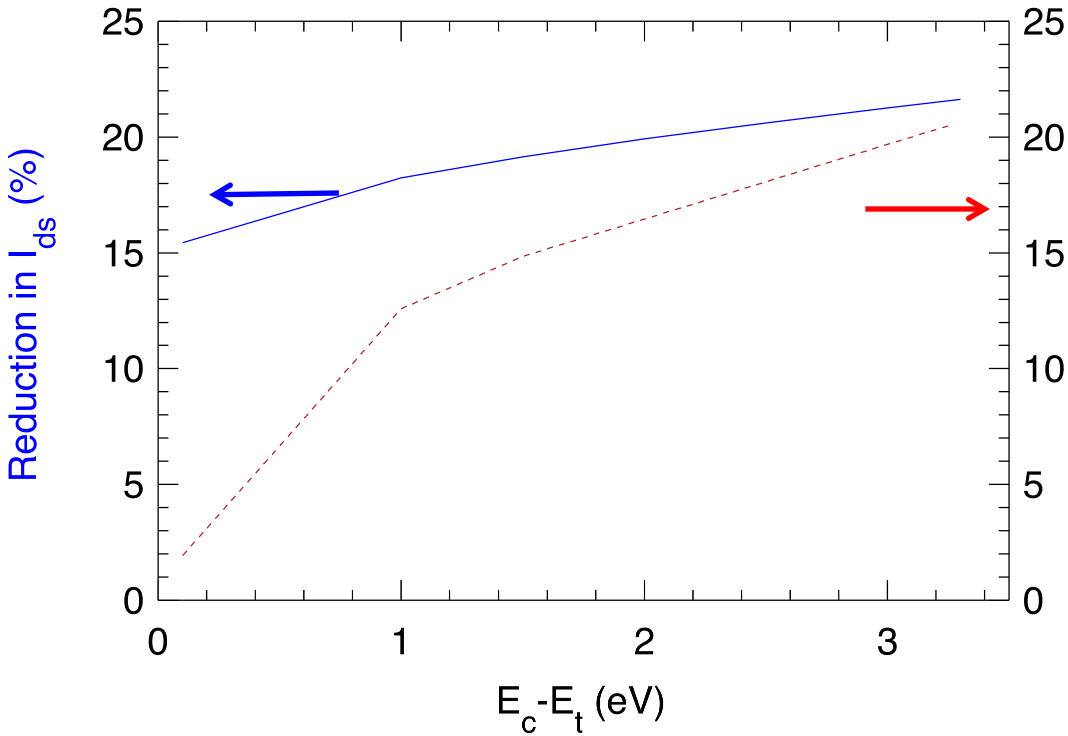
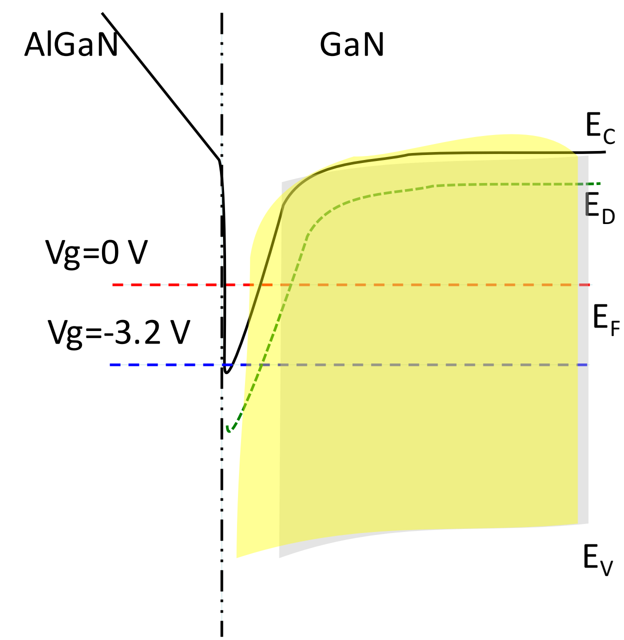
  - TRIM / Mobility model predict ~10^{17} cm^{-3} ionized acceptor traps near 2DEG



- Sensitivity Analysis
  - Donors
    - Vary trap energy level
    - Vary trap concentration

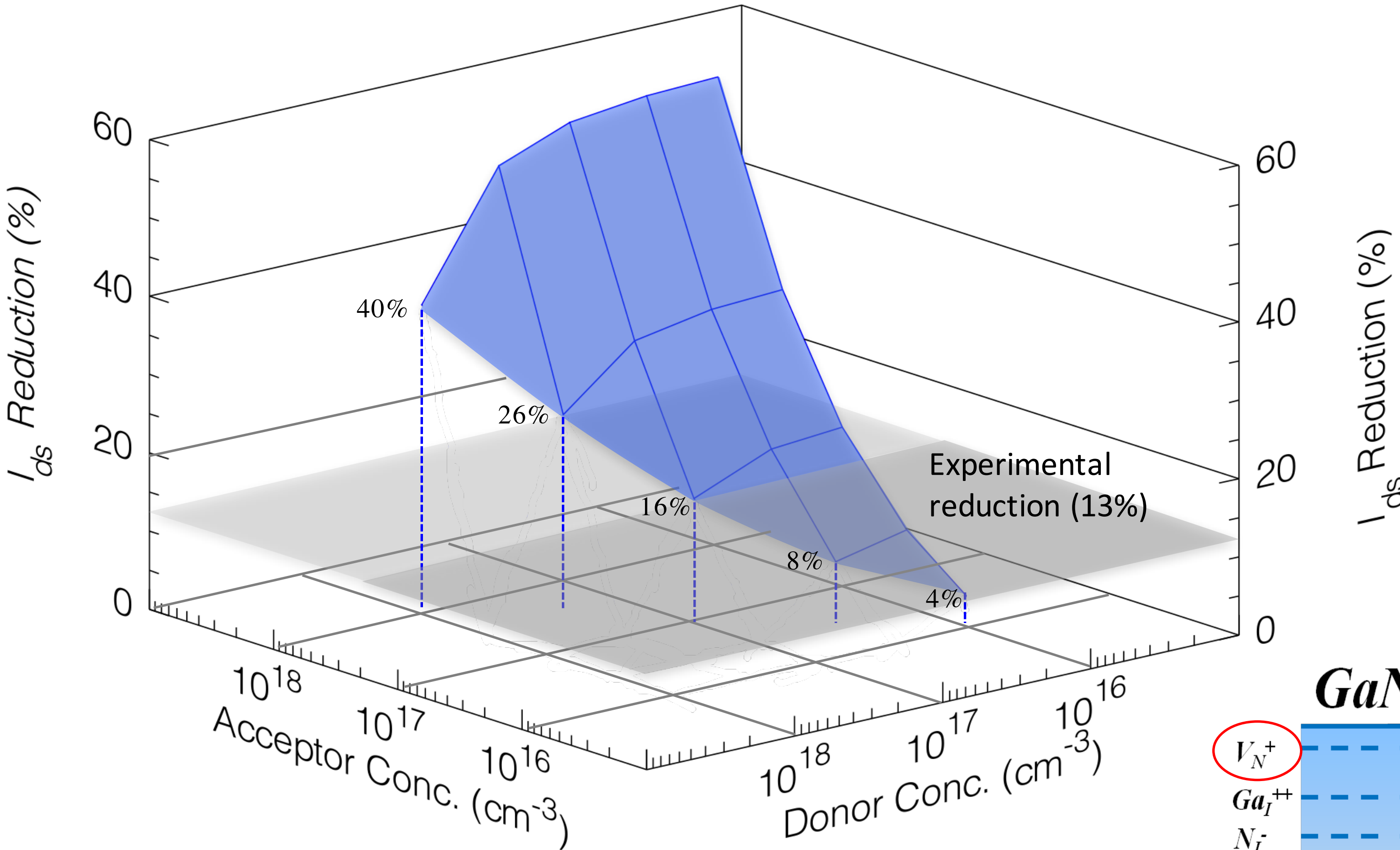
Effect of Donor Compensation

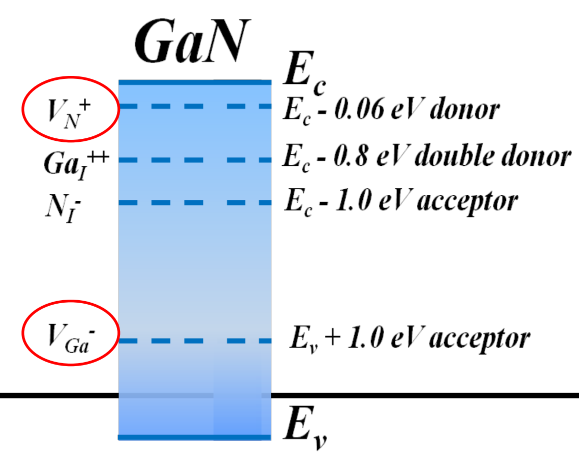




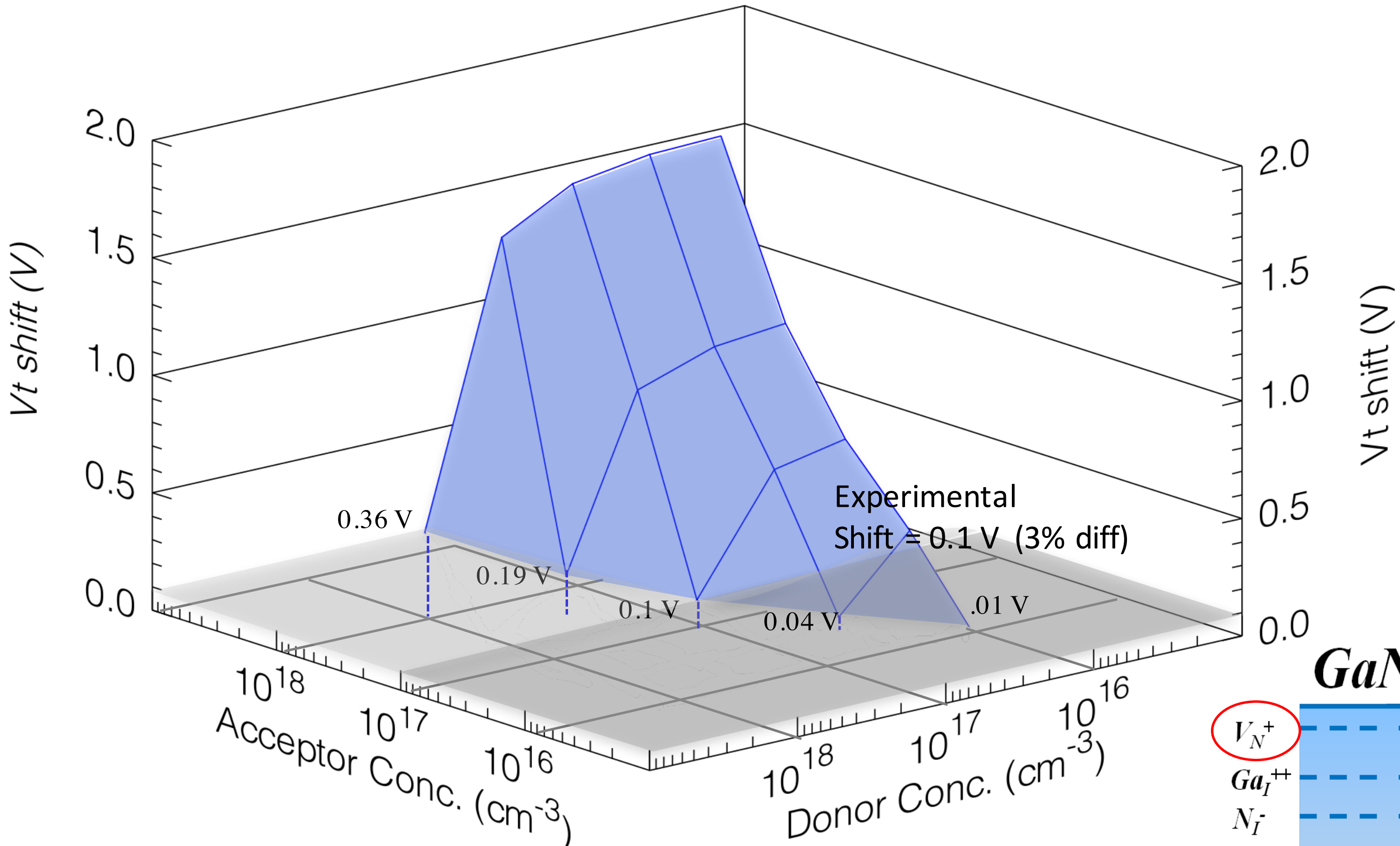
- $10^{17}/cm^3$ uniform acceptor doping throughout GaN
- $N_D = 10^{17}/cm^3$ donor compensation in GaN using partial ionization

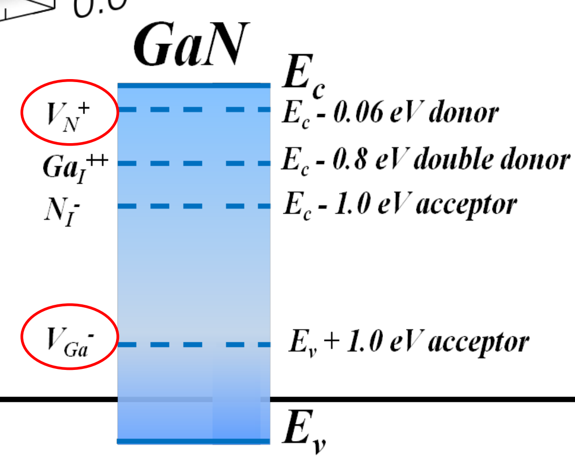
I_{ds} Reduction – Simulation Matches Experimental



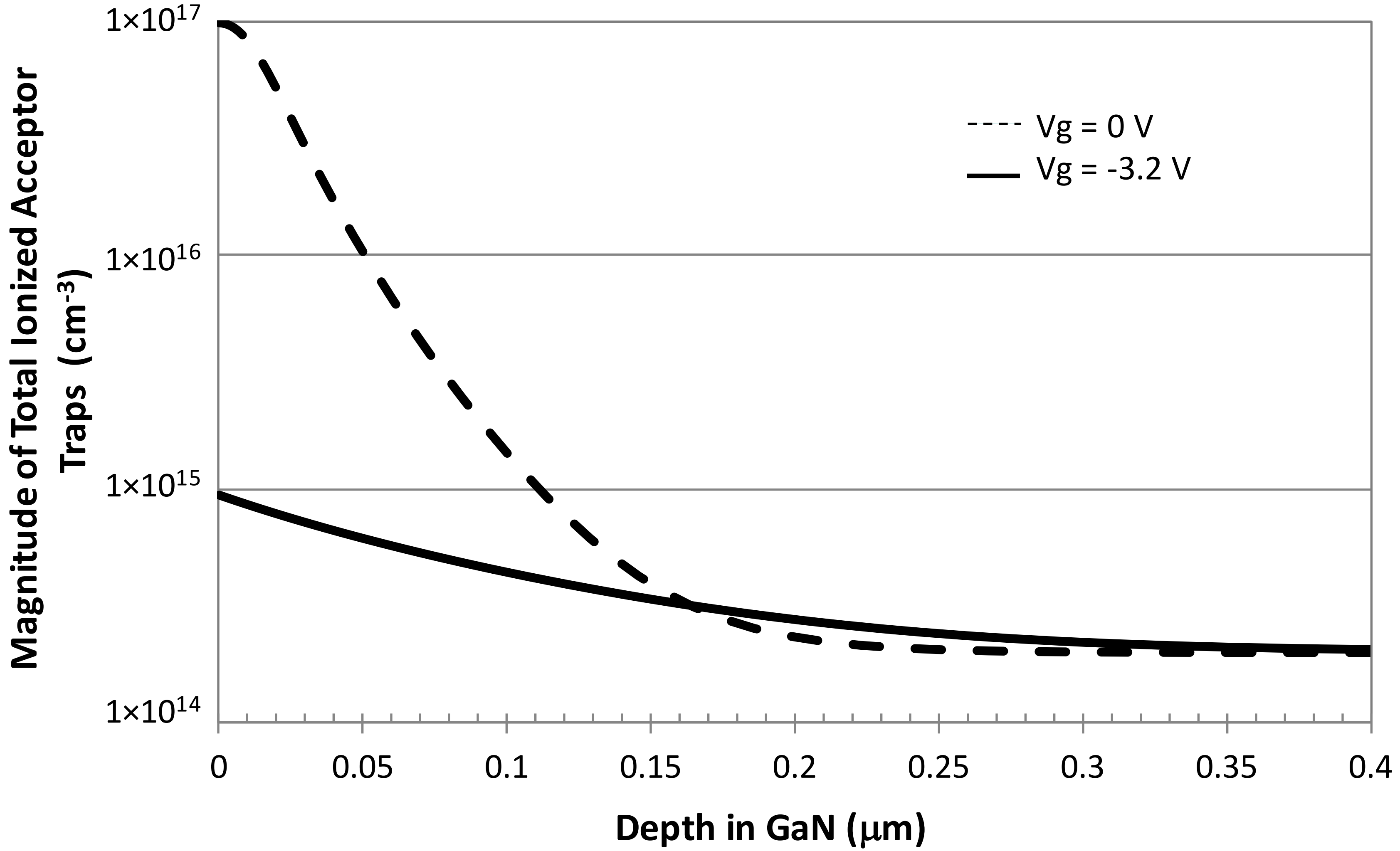


Vt Shift- Simulation Matches Experimental





Negative Space Charge Confinement



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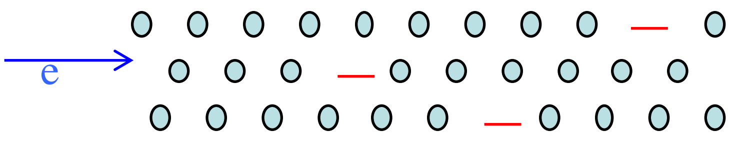
Conclusions

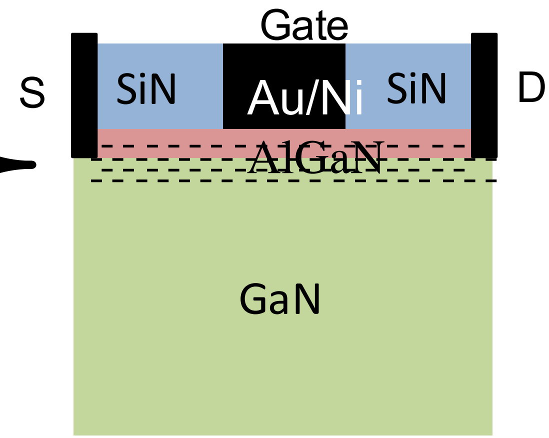
1. Hypothesis of ionized impurity scattering as mobility reduction mechanism is confirmed



2. Performance is much less sensitive to traps in AlGaN

3. Acceptor traps at E_v+1 eV are effectively ionized throughout GaN

4. Confinement of negative trapped charge near 2DEG is due to compensation of Acceptor traps by Donor ➔ determines amount of DC performance degradation



Future Work

- Identify donor trap lifetimes
- Simulate RF performance degradation due to radiation