Simulating RF Performance of Proton Irradiated AlGaN/GaN High Electron Mobility Transistors (HEMT)s

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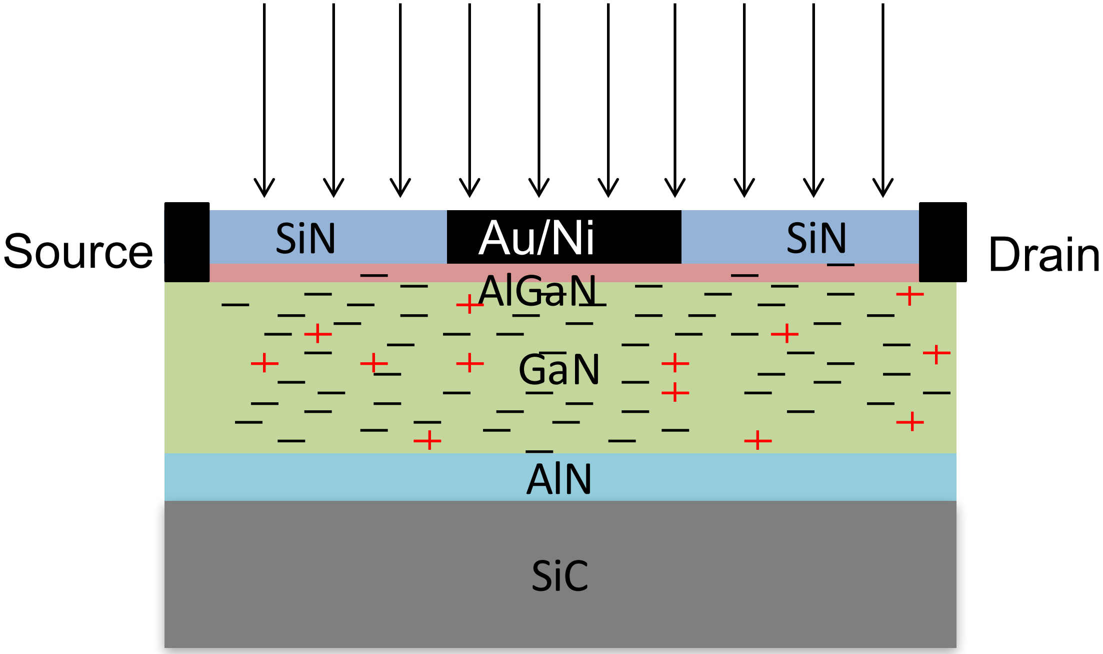
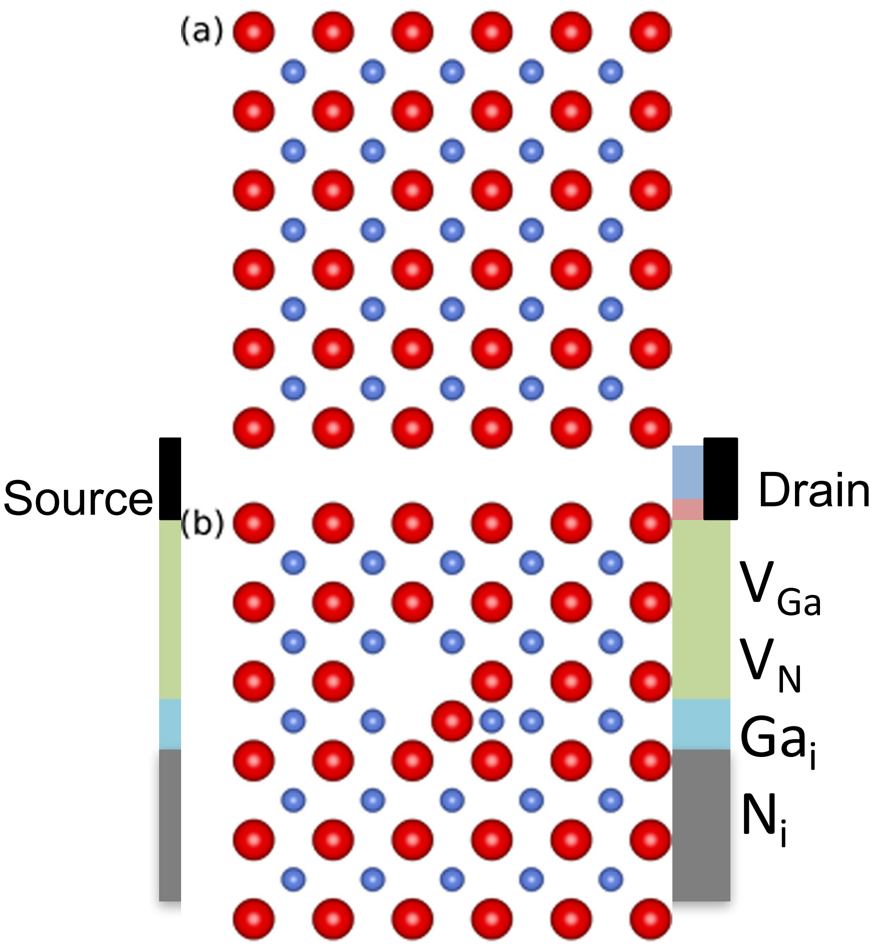
Why model / simulate?

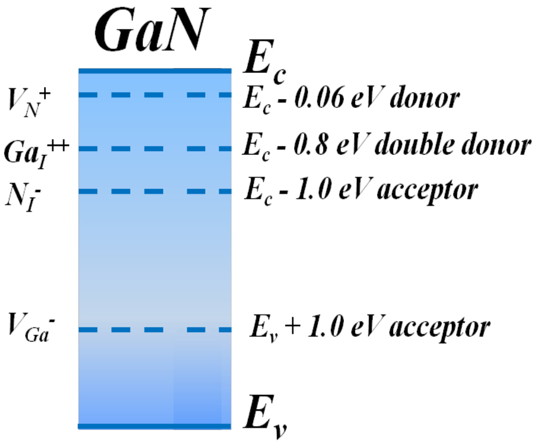
- Predict device performance
- Optimize device performance
- Better understand underlying physical mechanisms
  - Effect of radiation-induced traps



AlGaN/GaN HEMT Degradation by Point Defects



- Point defects create traps
- Ionized traps create:
  - Reduction in electron mobility (impurity scattering model)
  - Negative trapped charge
    - ↓ 2DEG density

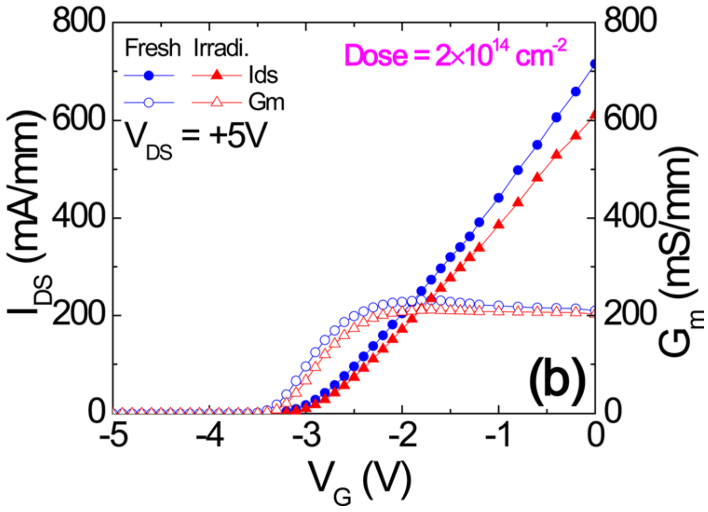


*Polyakov, et al. J. Mater. Chem. C, 2013, 1, 877–887.

Translation to Performance Degradation

DC Simulation

- Positive threshold voltage shift
- Reduction of drain current



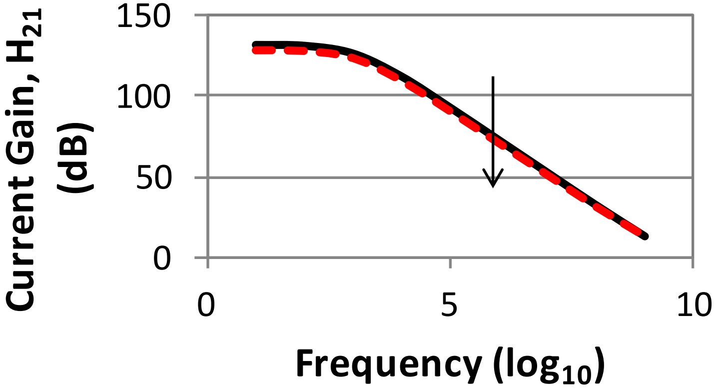
*Luo,, et al., J. Vac. Sci. Technol. B, Vol. 31, No. 4, 2013.

Small Signal AC Simulation

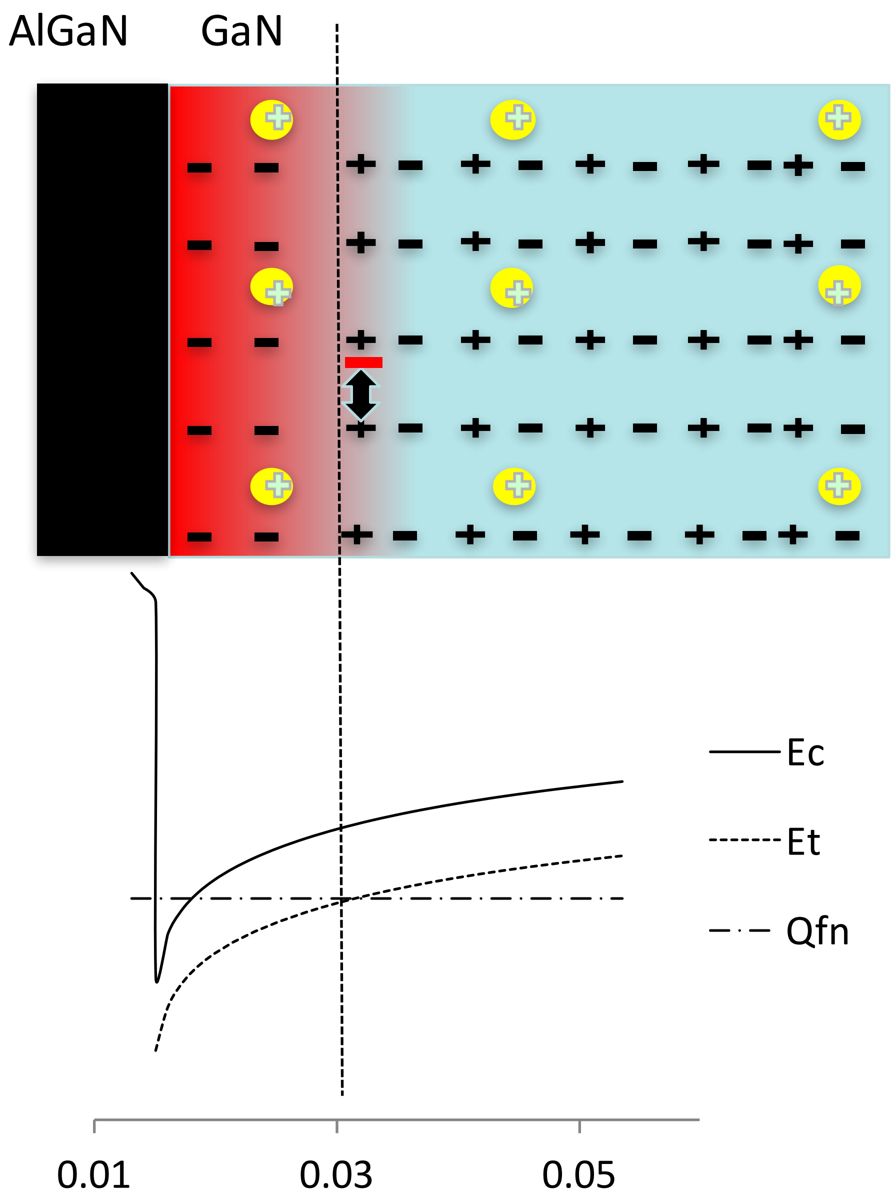
- Reduction of peak transconductance

AC Simulation - RF

- Reduction of Current Gain
- Reduction of Cutoff Frequency



Trapping Mechanism



- ● N-type Dopant
- − Acceptor defect
- + Donor defect
- 🟥 2DEG
- ↕ Capture and emission
- − Electron

Simulation Goals

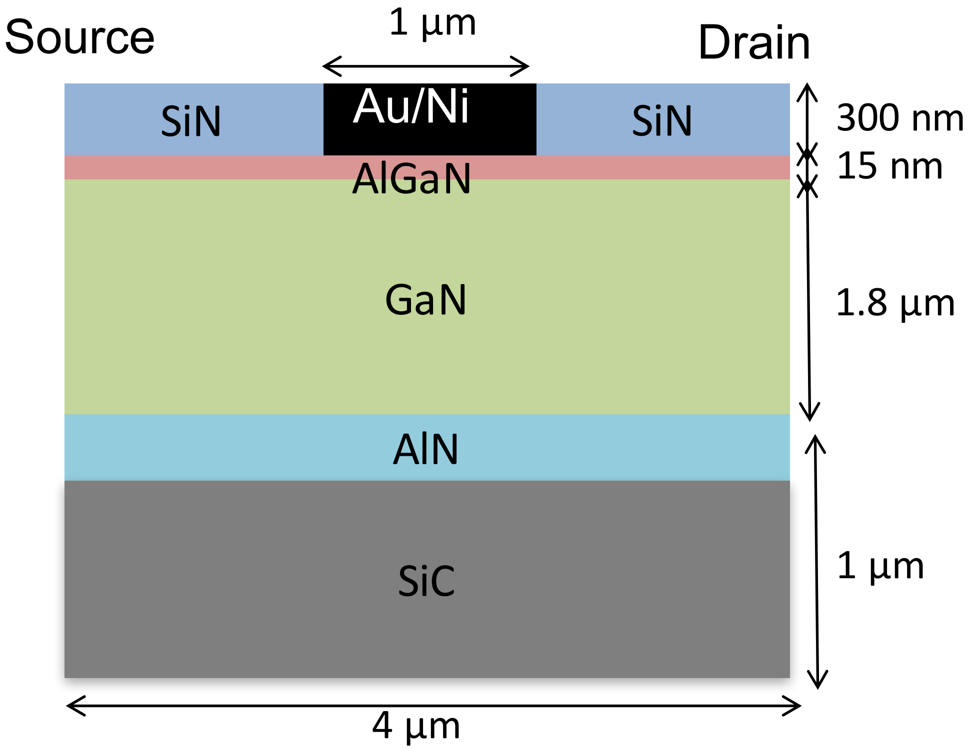
- Extent of DC performance has a dependence on donor compensation
- Q. What is the dependence of donor traps (static or dynamic) to RF performance degradation?

Talk Outline

1. Simulation methodology
2. What we learned from DC simulation studies
3. Small signal and RF simulation results: Effect of static and dynamic donor traps

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

Treatment of donor traps

Static

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

Treating traps close to Fermi-level as partially ionized.

Acceptor traps considerably below quasi Fermi-level, can also be modeled as completely ionized doping.

Dynamic

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla . J_n - K_f n N_D^+ + K_r (N_D - N_D^+)$$

$$\frac{\partial N_D^+}{\partial t} = -K_f n N_D^+ + K_r (N_D - N_D^+)$$

K_f - capture rate dependent on capture lifetime

K_r- emission rate dependent on trap energy level

$$\frac{K_f}{K_r} = \frac{2}{N_c} e^{E_T / kT}$$

$$\tau = 1 / K_f$$

Simulation Methodology

Small Signal AC analysis

Sinusoidal steady-state analysis (S3A) $n = n_{DC} + n_{SS} e^{j\omega t}$

For small-signal AC input, device response assumed to be linear around DC bias point.

$$J + jDX = B \xrightarrow{\text{for computation}} \begin{bmatrix} J & -D \\ D & J \end{bmatrix} \begin{bmatrix} X_R \\ X_I \end{bmatrix} = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

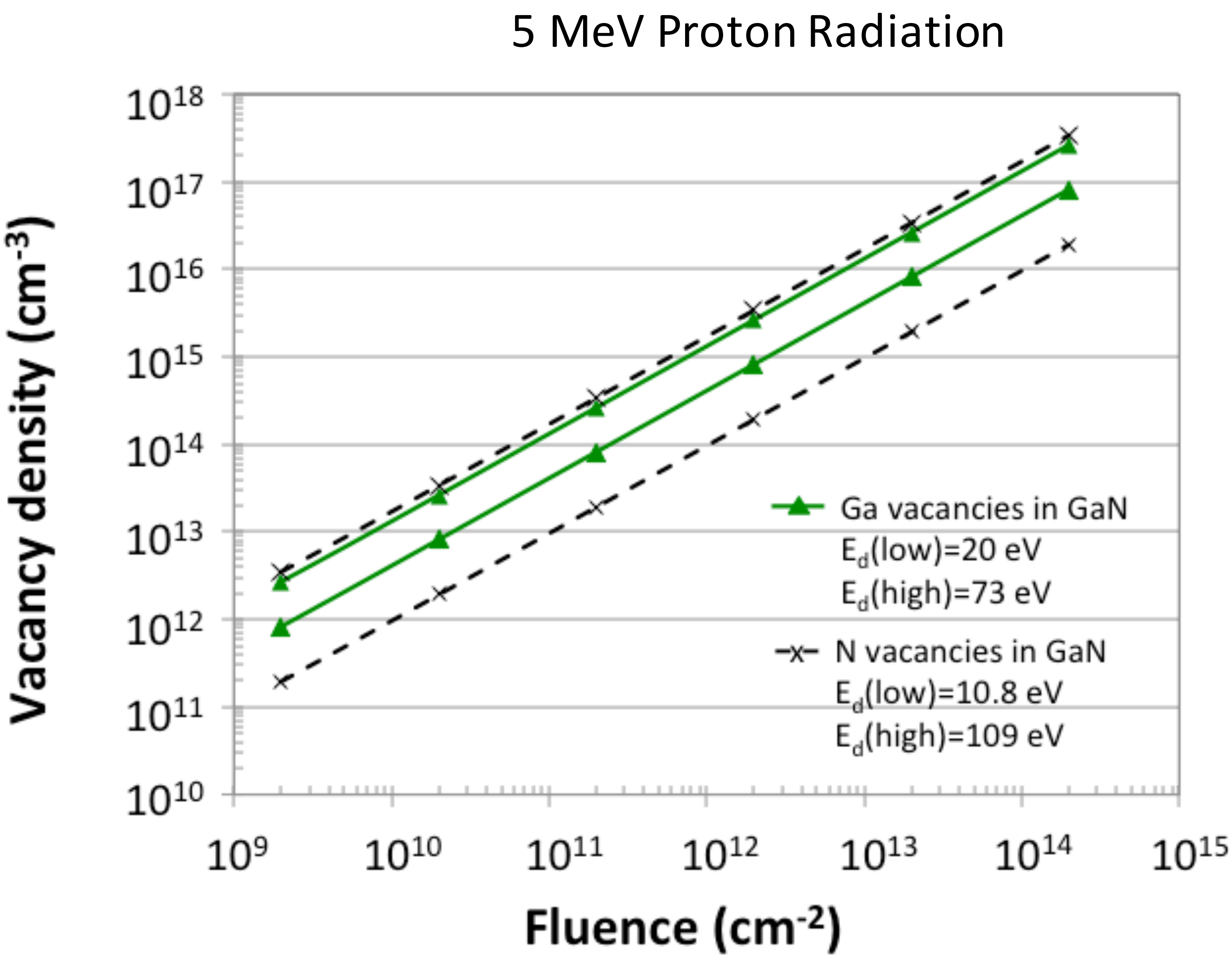
J: Jacobian at DC bias point
D: Diagonal matrix with frequency ω as diagonal elements
B: Small-signal boundary conditions at contacts
X_R, X_I : Real and Imaginary solution variables

Overview

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

1. Simulation methodology
2. What did we learn from DC simulation studies
3. Small signal and RF simulation results: Effect of dynamic donor traps

Radiation-induced Defect Estimation



TRIM (Transport of Ions in Matter) simulation results

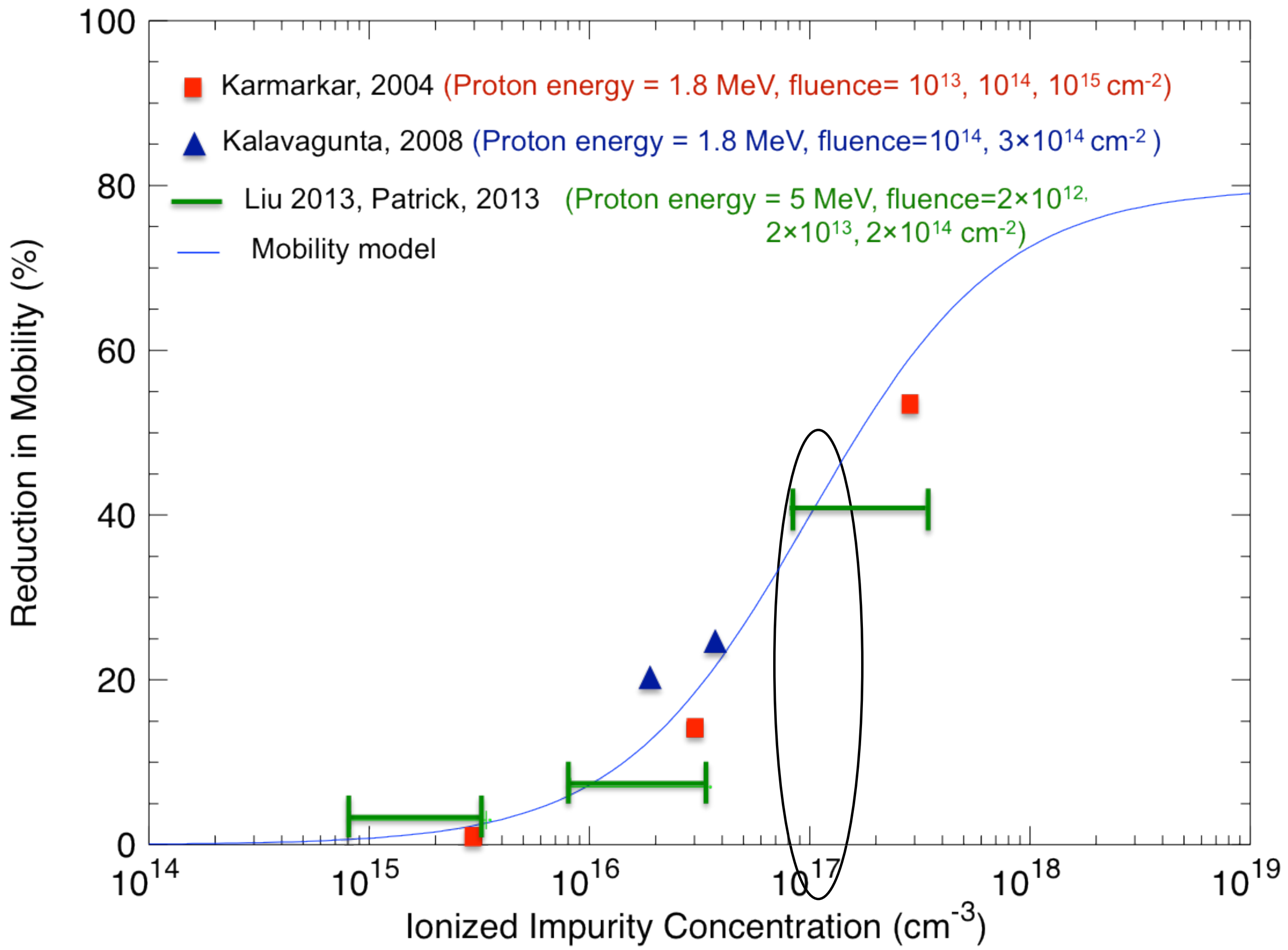
V_{GA} – acceptor-like traps (-)

V_N – donor-like traps (+)

Positive V_T shift needs acceptor-like traps

*Patrick. Et al., IEEE TRANS. NUCL. SCI., VOL. 60, NO. 6, 2013

Mobility Reduction: Ionized Impurity Scattering



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

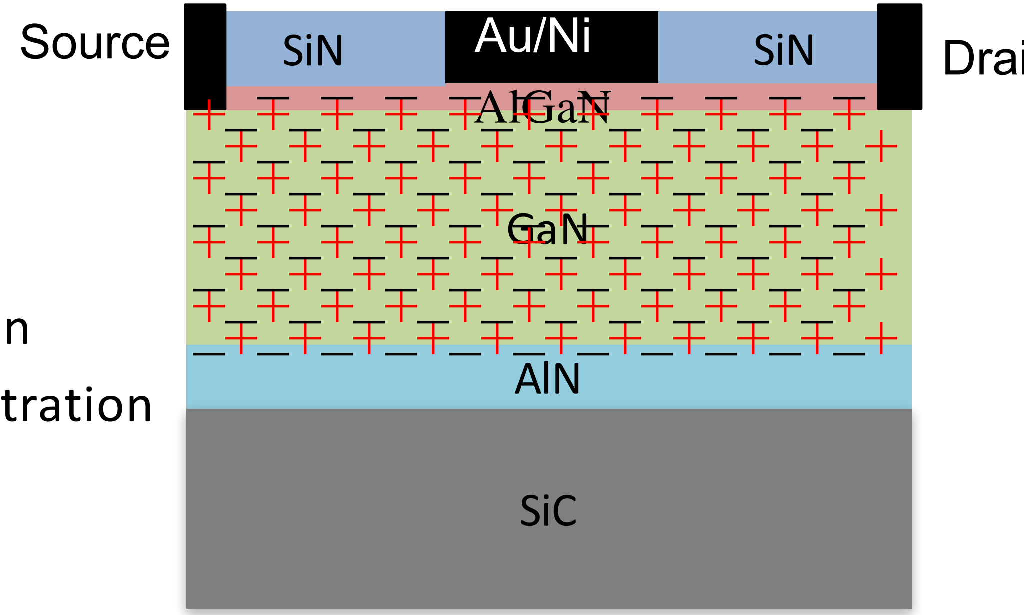
N – ionized dopant conc.

μ_{min}=295 cm2/Vs
μ_{max}=1406 cm2/Vs
$N_{ref} = 1\text{x}10^{17}$
α=0.66

*Farahmand et al., 2001

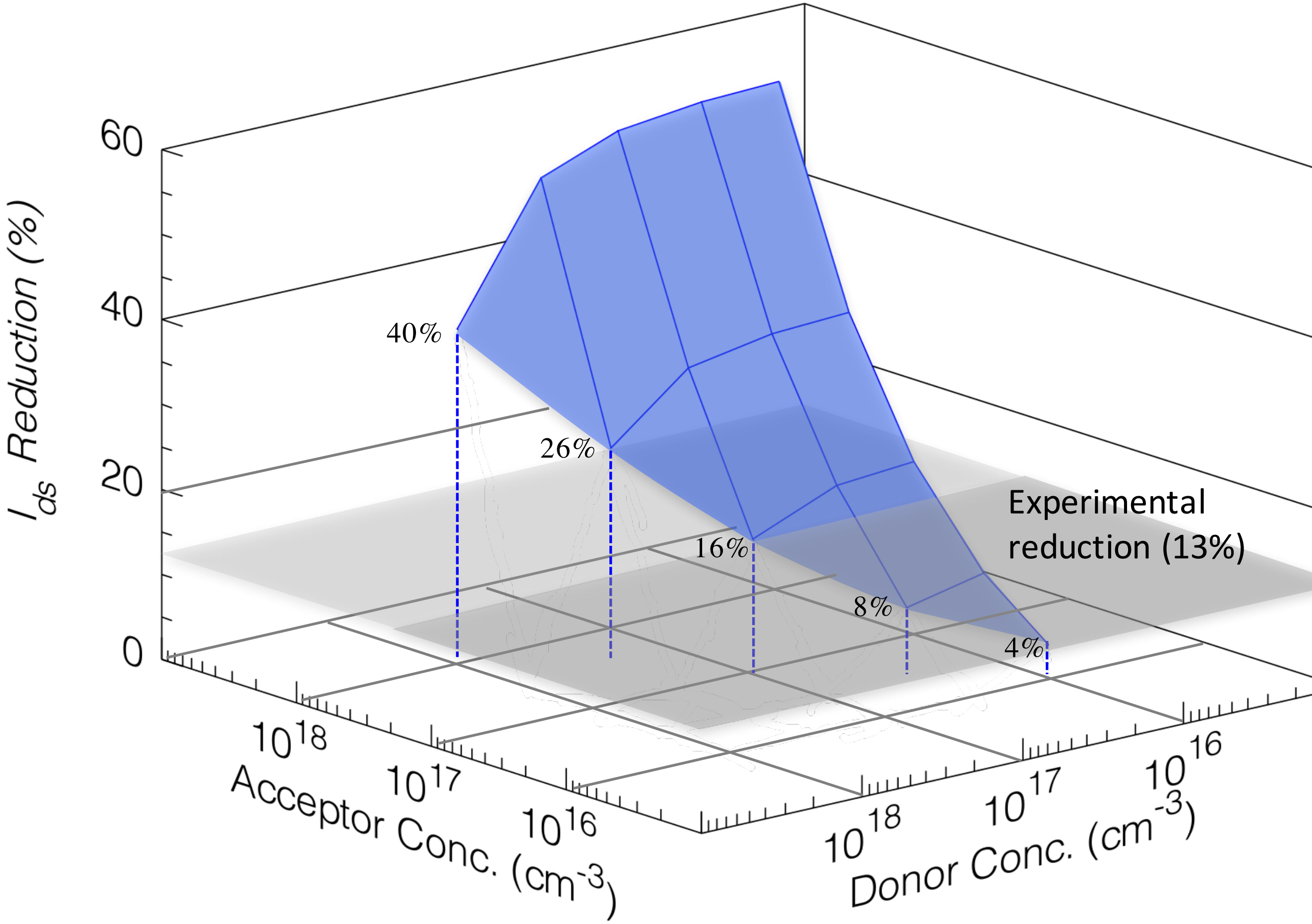
Test Effect of Donor Compensation

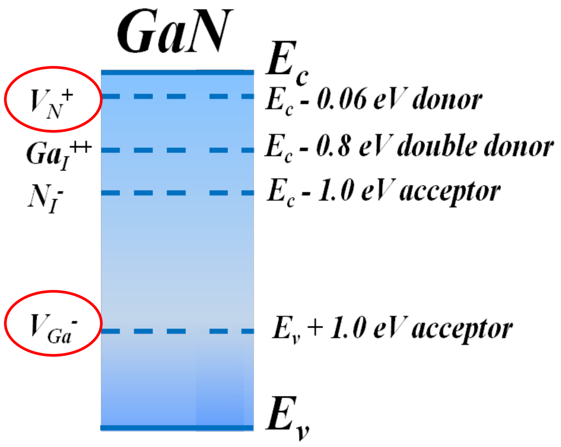
- Radiation case:
  - 5M eV Proton radiation, fluence= 2×10^{14} cm^{-2}
    - Ids reduction = 13%, Vt shift = 0.1 V (3%)
  - TRIM / Mobility model predict ~10^{17} cm^{-3} ionized acceptor traps near 2DEG



- Sensitivity Analysis
  - Donors
    - Vary trap concentration
    - Static acceptor concentration

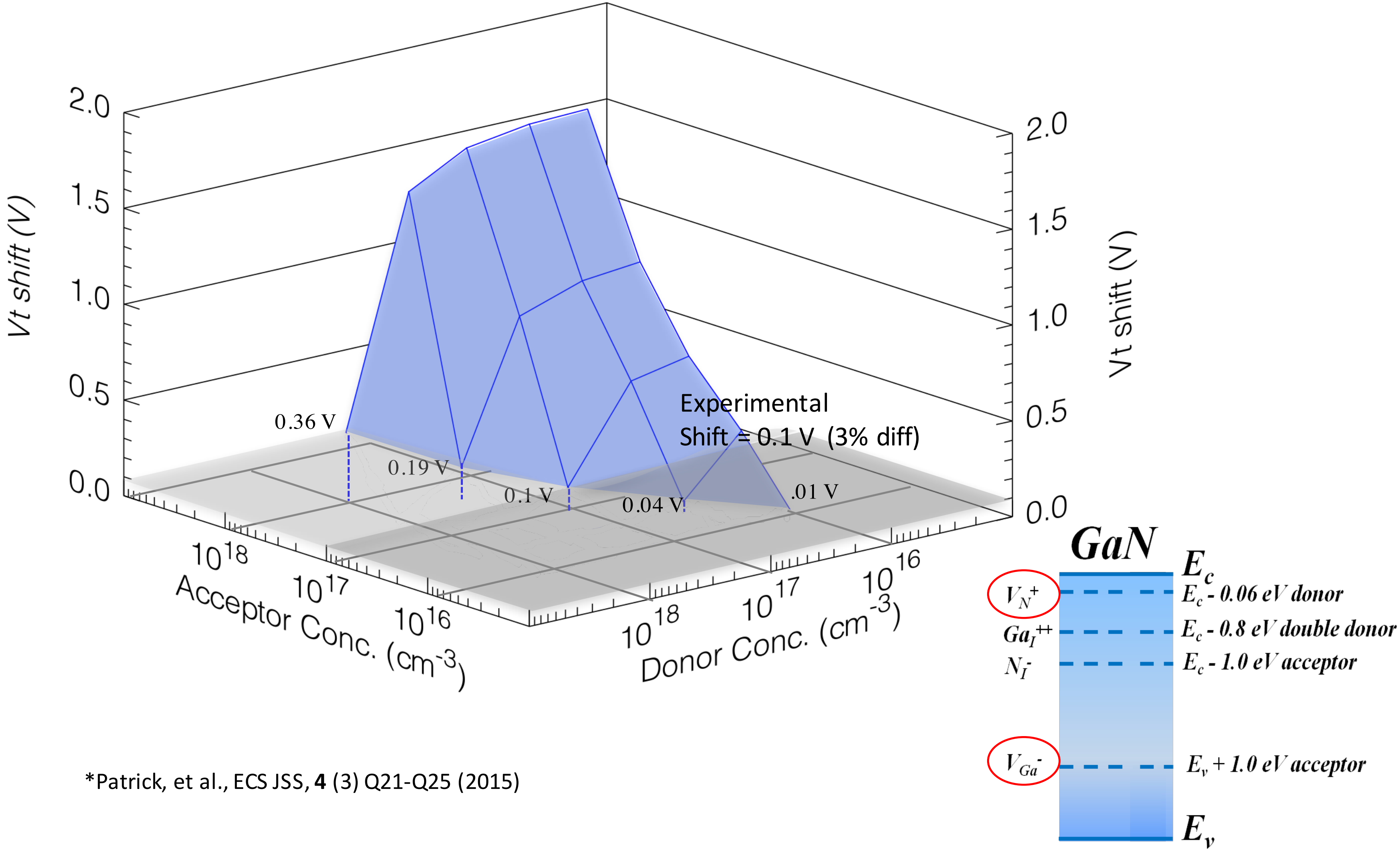
I_{ds} Reduction – Need for Donor Compensation





*Patrick, et al., ECS JSS, **4** (3) Q21-Q25 (2015)

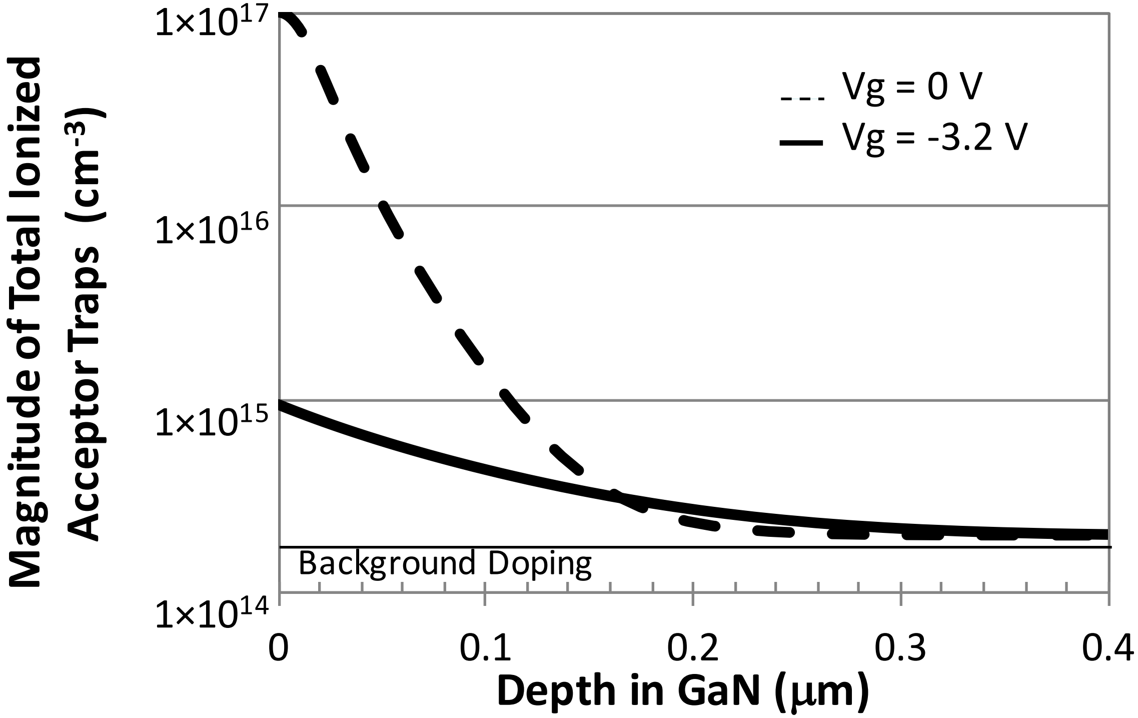
Vt Shift-Need for Donor Compensation

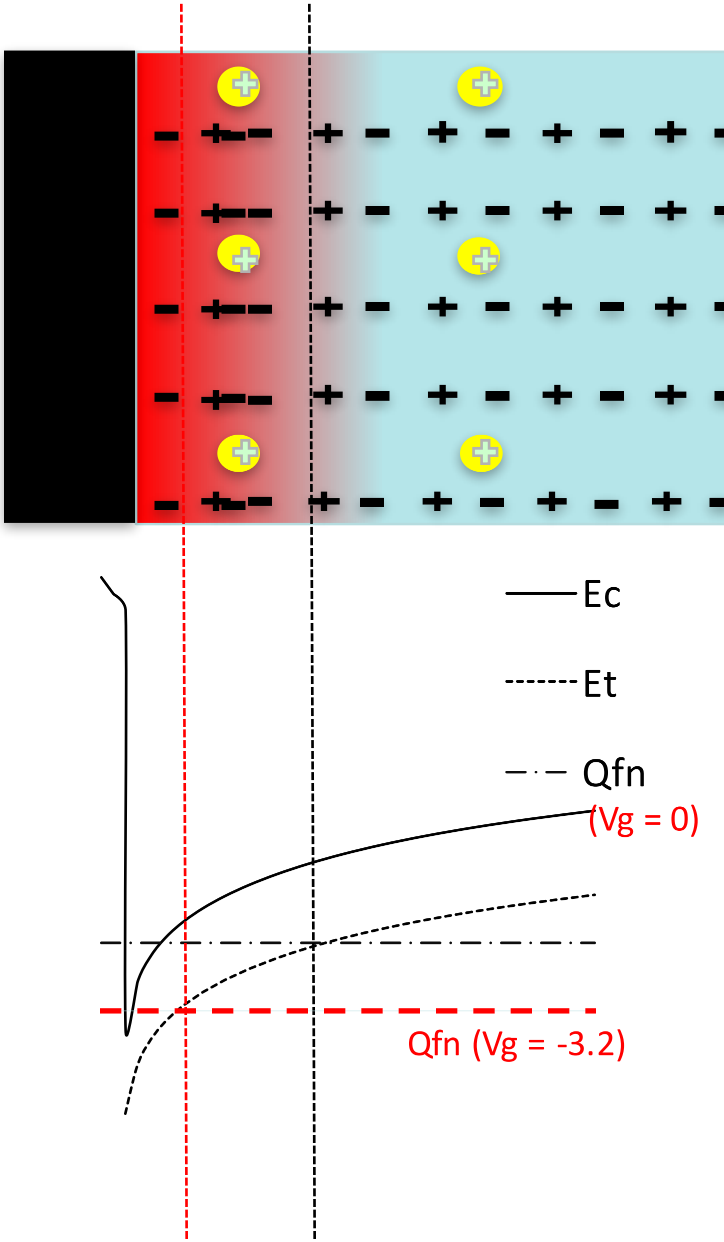


Experimental Shift = 0.1 V (3% diff)

*Patrick, et al., ECS JSS, **4** (3) Q21-Q25 (2015)

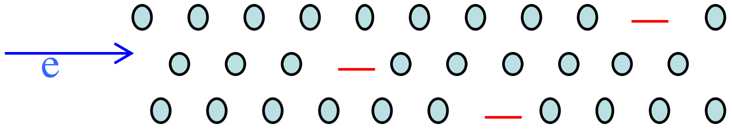
Negative Space Charge Confinement



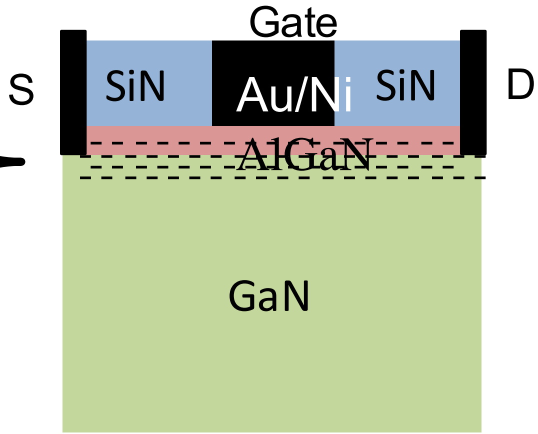


Conclusions From DC Simulation

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



Overview

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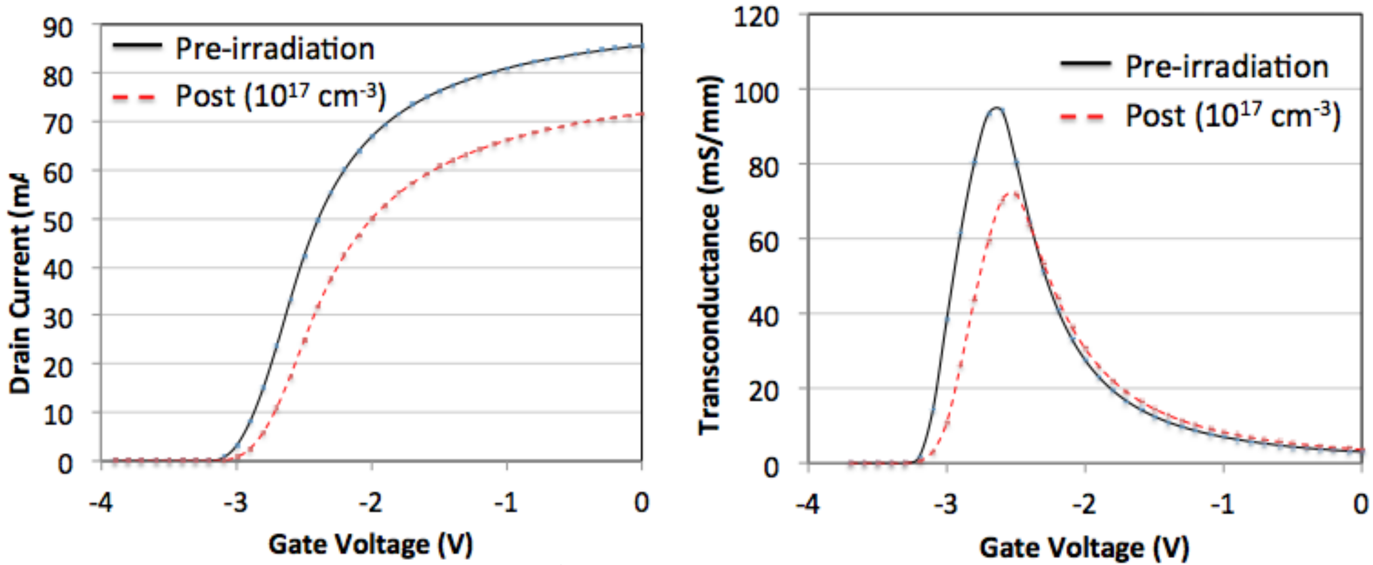
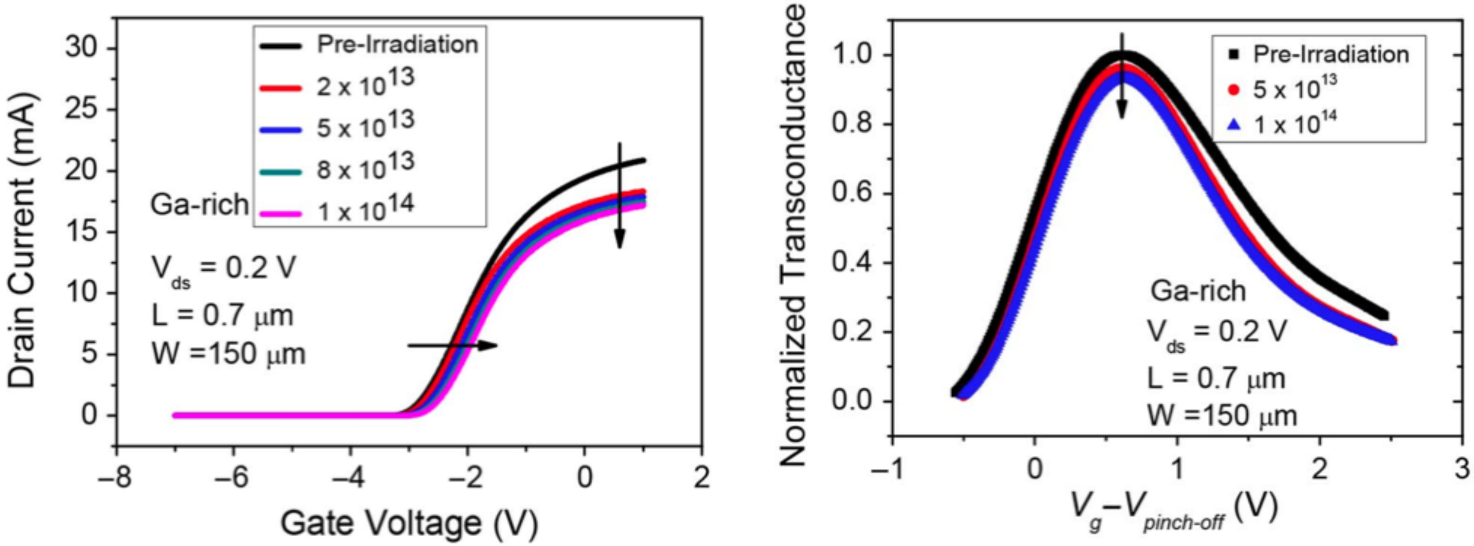
AC Simulation Results

Fluence
$=2 \times 10^{14}$ cm^{-2}
Vds = 0.5 V

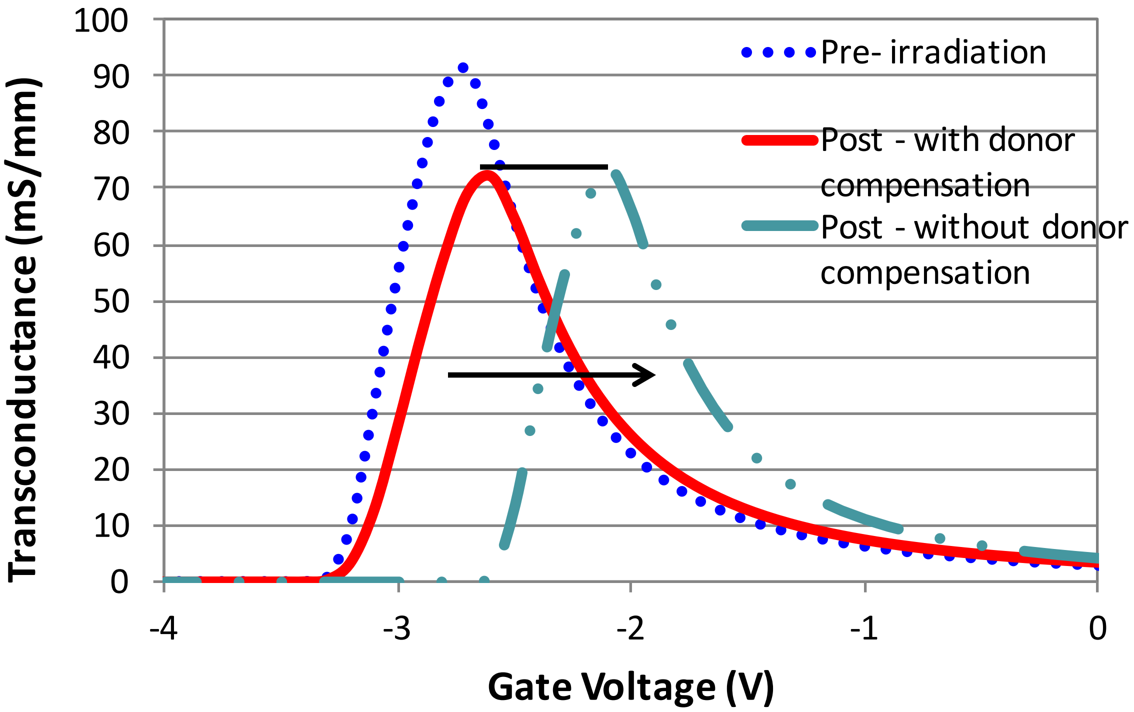


*FLOODS simulation results



*Chen et. al. IEEE Trans. Nucl. Sci., vol 60, no. 6, 2014

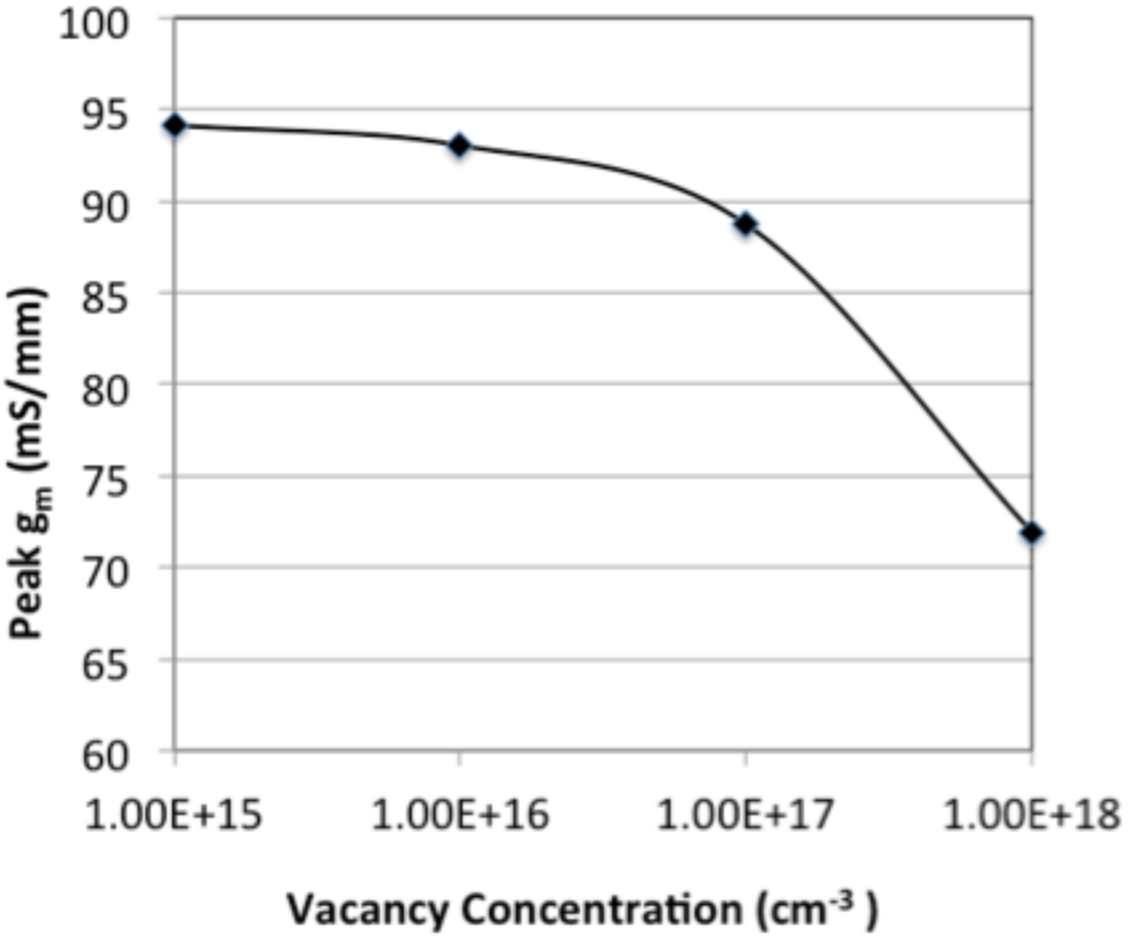
Role of Donor Compensation on g_m



V_{ds}= 0.5 V
f_{AC} = 100 Hz

- Peak g_m stays the same, curve is shifted because V_t shifts
    - as expected, mobility in channel is not affected by donor compensation

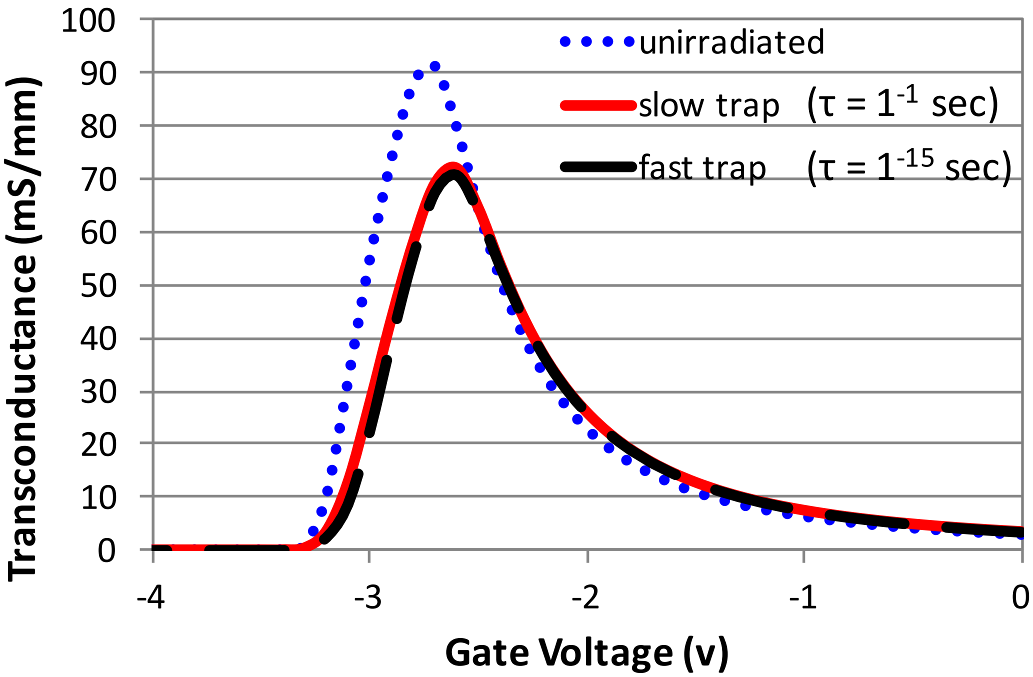
g_m Dependence on Acceptor Trap Concentration

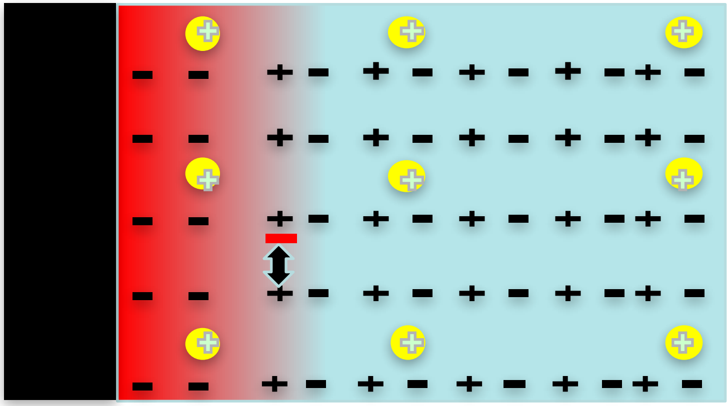


V_{ds}= 0.5 V

f = 100 Hz

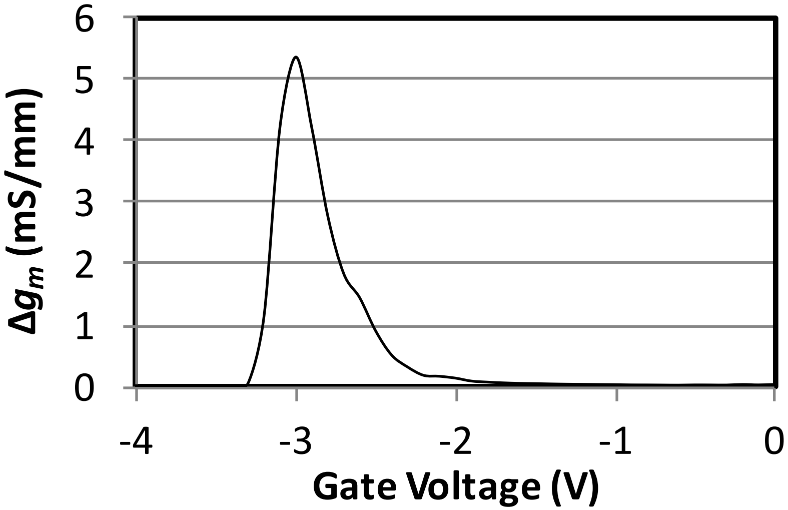
Role of Donor Trap Dynamics on G_m





V_{ds}= 0.5 V

f_{AC} = 100 Hz

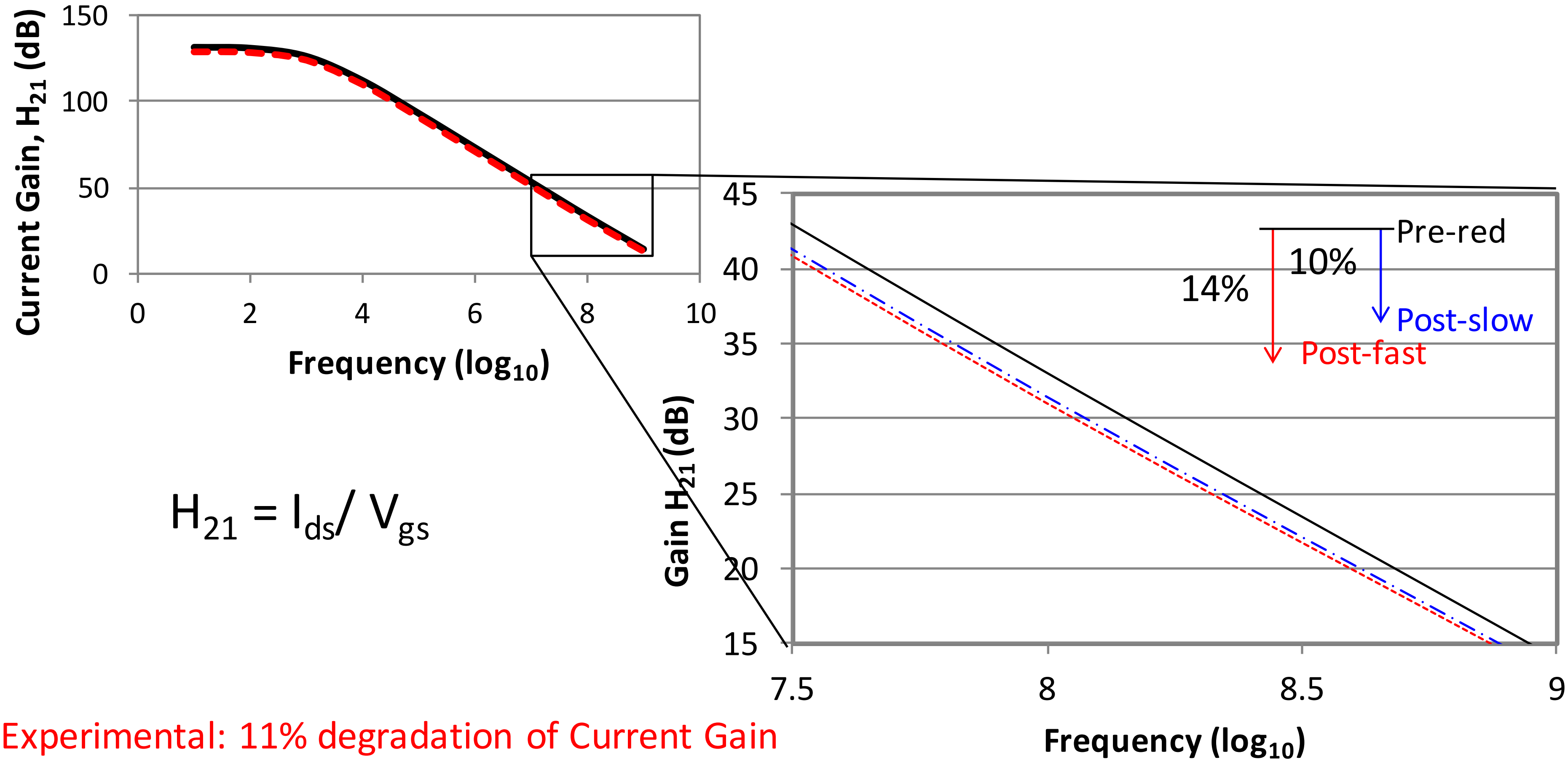


Current Gain v. Frequency

V_{ds}= 5 V

V_{gs} = peak g_m voltage

- Pre-irradiation
- Slow defects (τ = 1^{-1} sec)
- Fast defects (τ = 1^{-15} sec)

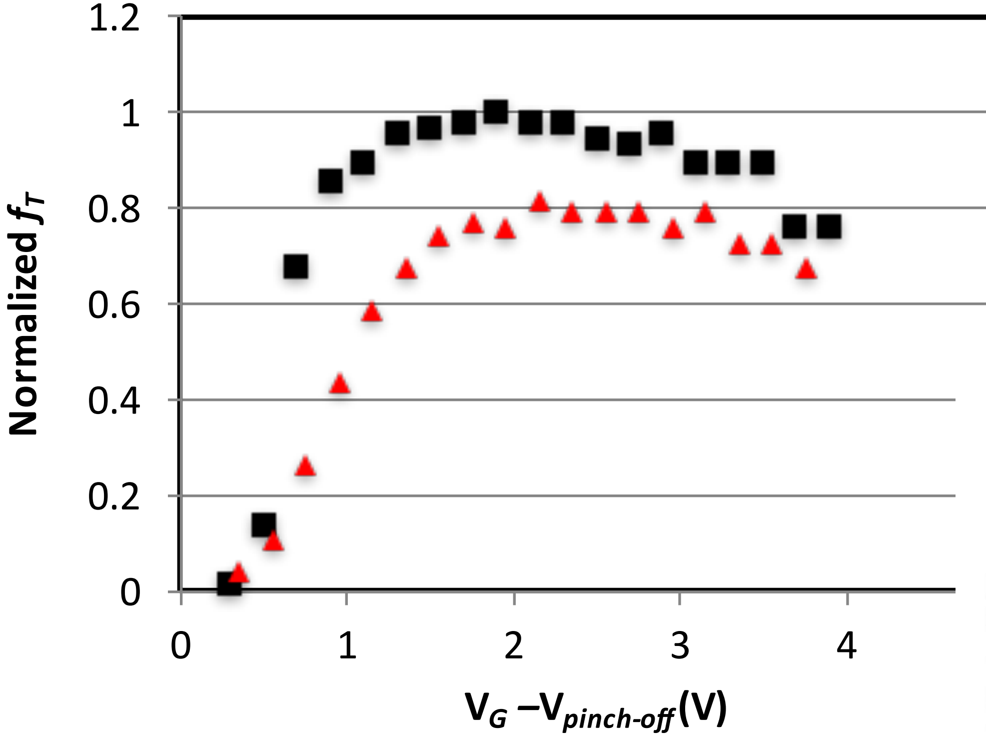


$$H_{21} = I_{ds}/ V_{gs}$$

Experimental: 11% degradation of Current Gain

*Chen et. al. IEEE Trans. Nucl. Sci., vol 60, no. 6, 2014

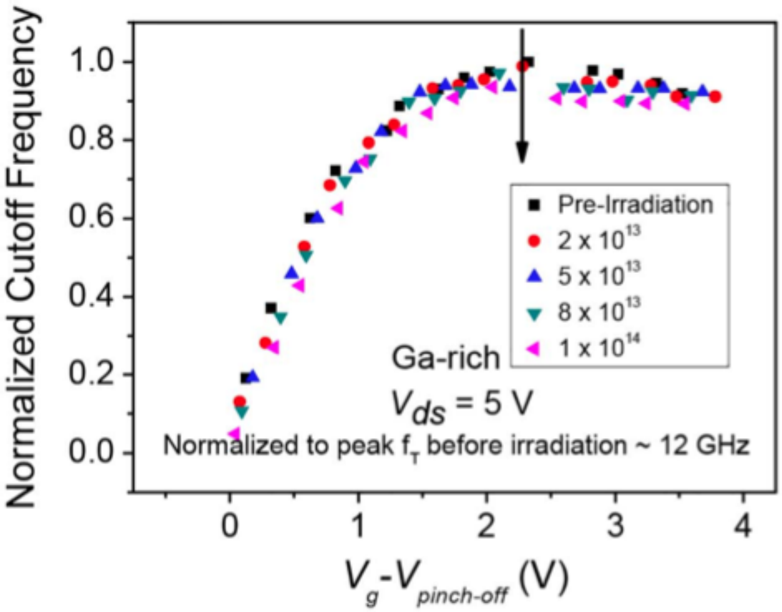
Degradation in Cutoff Frequency, f_T



■ Pre-irradiation

▲ Post (2×10^{14} cm^{-2} fluence)
-Fast traps

Average decrease in f_T = 24%



Average decrease in f_T = 8%

*Chen et. al. IEEE Trans. Nucl. Sci., vol 60, no. 6, 2014

Conclusions

- Incorporated small signal and RF simulation capability in FLOODS
- Looked at the role of donor traps in the GaN buffer in AC simulations
  - Donor traps do not greatly effect peak g_m
    - Dominant effect is from static acceptor traps
  - Dynamic donor traps also do not greatly affect RF metrics
  - RF Experimental results are well captured by including static acceptors
- Future work: Explore the role of surface traps in AC simulations and transient Gate-lag simulations