Pushing GaN Power Devices to the Limit – A Material and TCAD perspective

将GaN功率器件推向极限—材料和TCAD视角

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For IFWS2021

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Contents

Review of TCAD for lateral GaN: Including Quantum Physics in Semiconductor Equations

$$-\nabla\cdot\left(\frac{\epsilon_0\epsilon_{dc}}{q}\nabla V\right)=-n+p+N_D(1-f_D)-N_Af_A+\sum_j N_{tj}(\delta_j-f_{tj}),$$

Semiconductor eqn.

$$\nabla\cdot J_n-\sum_j R_n^{tj}-R_{sp}-R_{st}-R_{au}+G_{opt}(t)=\frac{\partial n}{\partial t}+N_D\frac{\partial f_D}{\partial t},$$

$$\nabla\cdot J_p+\sum_j R_p^{tj}+R_{sp}+R_{st}+R_{au}-G_{opt}(t)=-\frac{\partial p}{\partial t}+N_A\frac{\partial f_A}{\partial t}.$$

$$J_n=n\mu_n\nabla E_{fn}$$

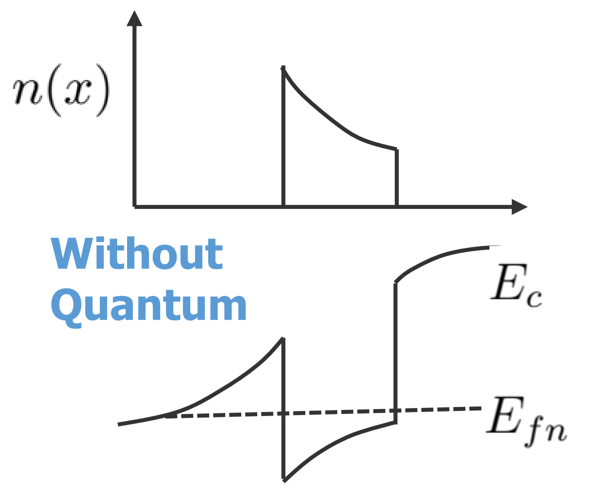
$$J_p=p\mu_p\nabla E_{fp}$$

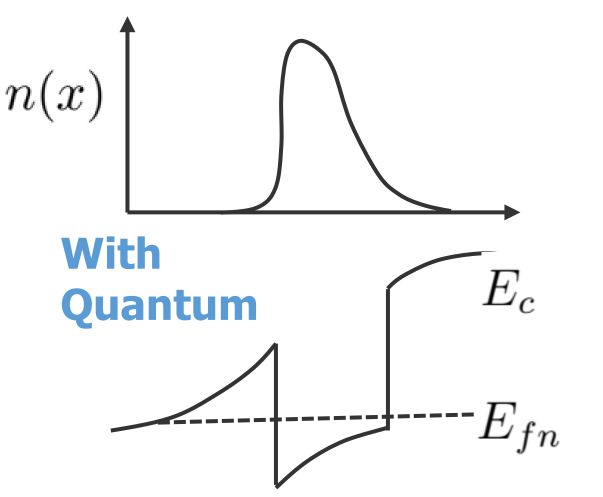
$$H(k)|\psi_i>=E_i(k)|\psi_i>$$

Quantum

$$n=\sum_j\rho_j^{x0}kTln\left[1+e^{(E_{fn}-E_j)/kT}\right]+unconfined\ electrons,$$

$$p=\sum_i\rho_i^{x0}kTln\left[1+e^{(E_i-E_{fp})/kT}\right]+unconfined\ holes,$$





Impact ionization

$$G=\alpha_nJ_n/q+\alpha_pJ_p/q$$

$$\alpha=\alpha_n^{\infty}e^{-\frac{F_{cn}}{F}}$$

factor $$\gamma=\frac{tanh\left(\frac{h\omega_{op}}{2kT_0}\right)}{tanh\left(\frac{h\omega_{op}}{2kT}\right)}$$

for both α_n^{∞} and F_{cn}

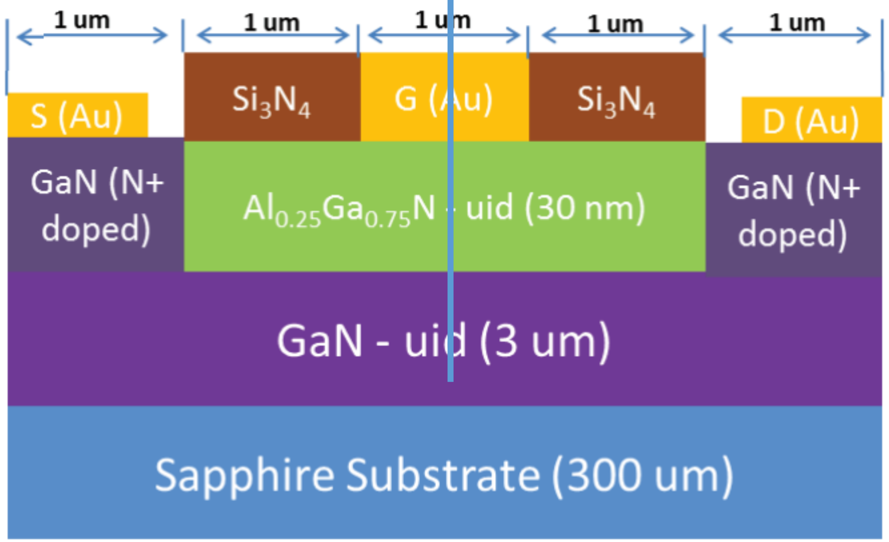
Early Struggle of Gate Control

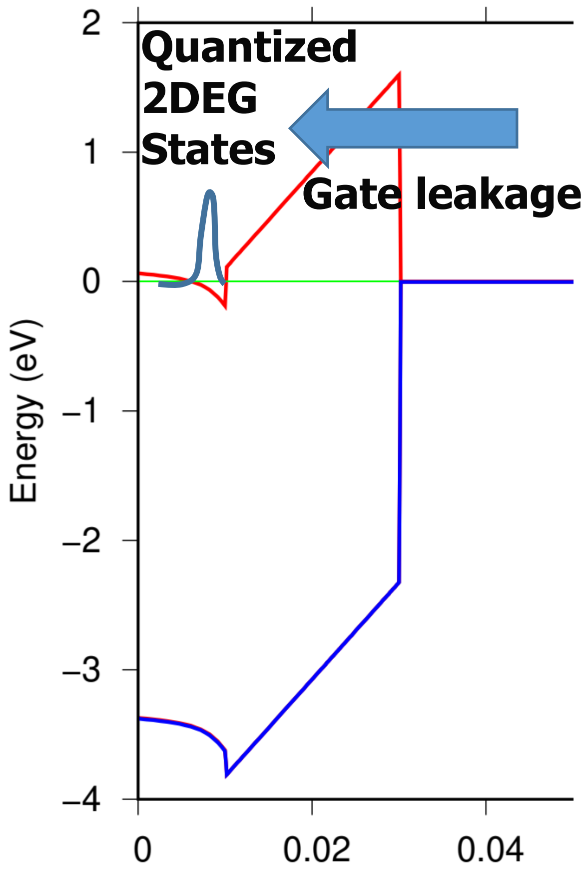
Gate control:

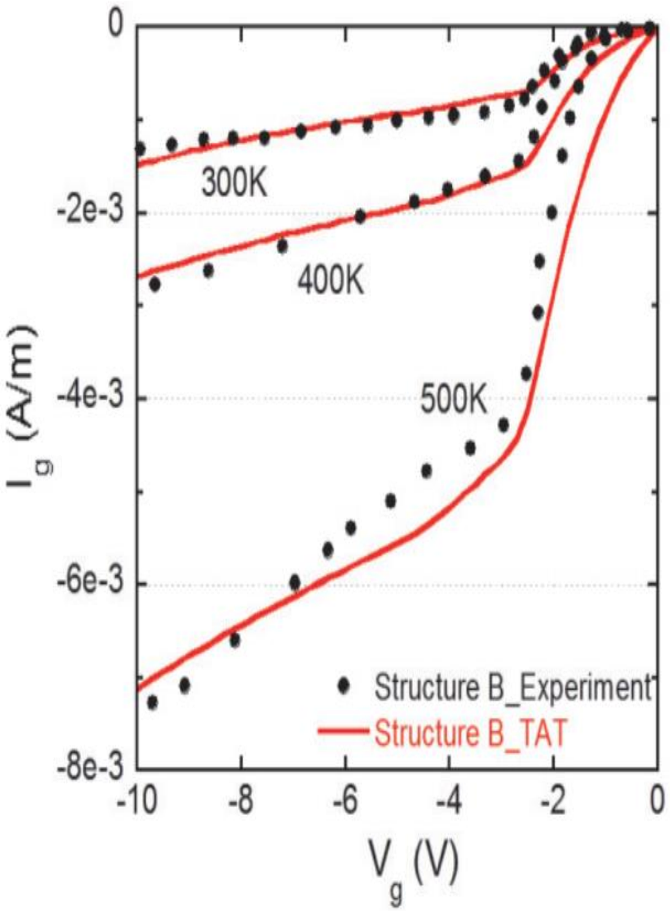
- **DMODE/EMODE**
- **P-GaN or MIS?**
- **Gate metal issues**
- **Gate leakage issues**

Latest technology in lateral GaN

Leakage study cut







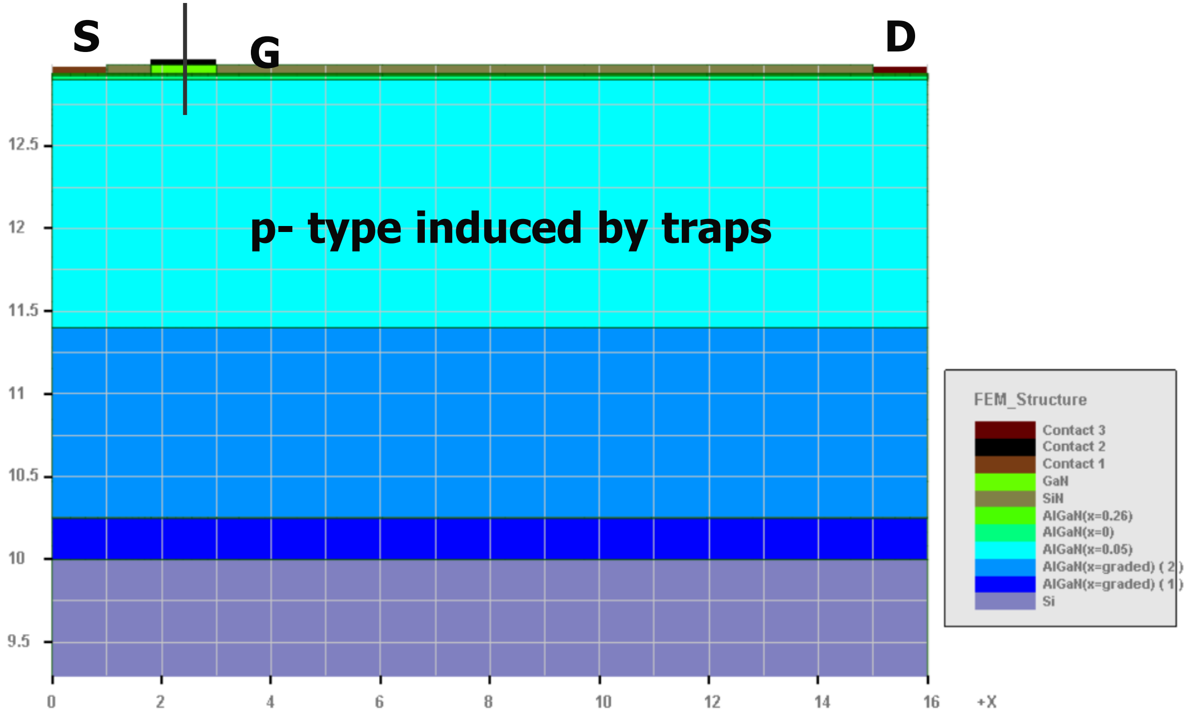
Modeling of the Reverse Gate Leakage Current of AlGaN/GaN HEMTs

2015 IEEE EDSSC

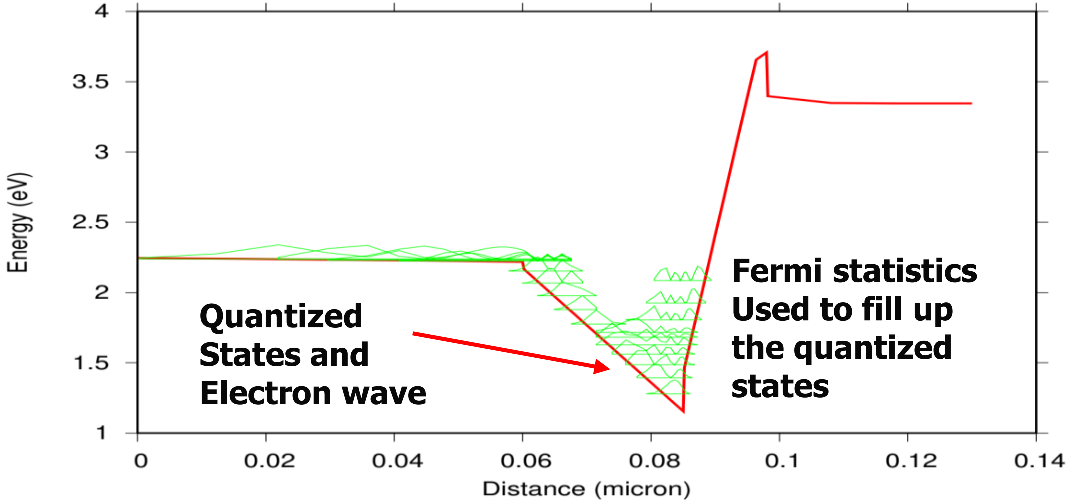
Recent technology: Typical p-GaN EMODE HEMT

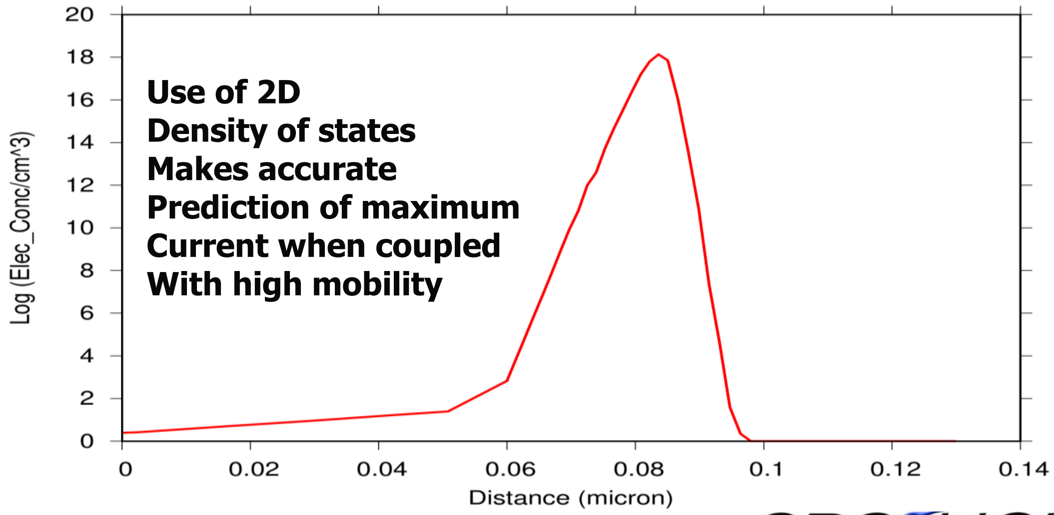
Vertical structure according to:
"Normally-off GaN Transistors for Power Applications,"
O. Hilt et. al. 2014 J. Phys.: Conf. Ser. 494 012001

Vertical cut

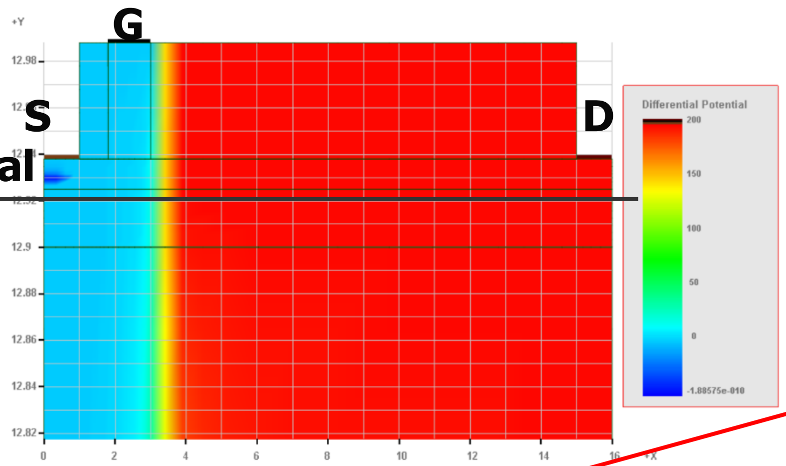


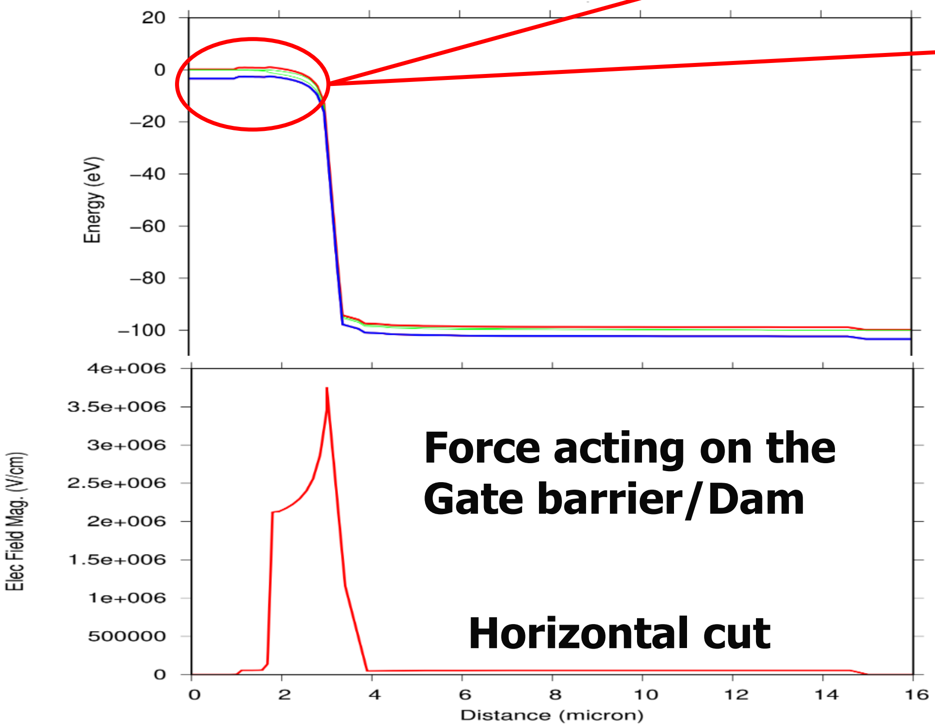
Vertical cut

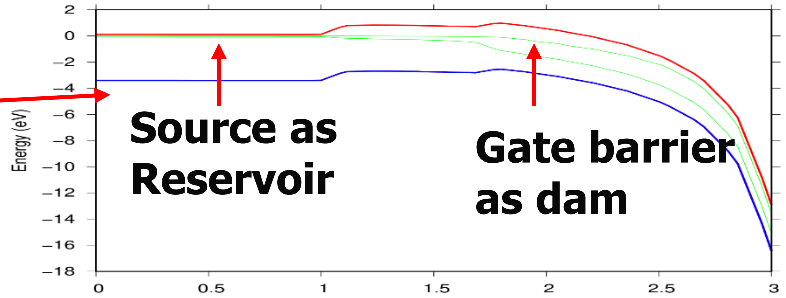


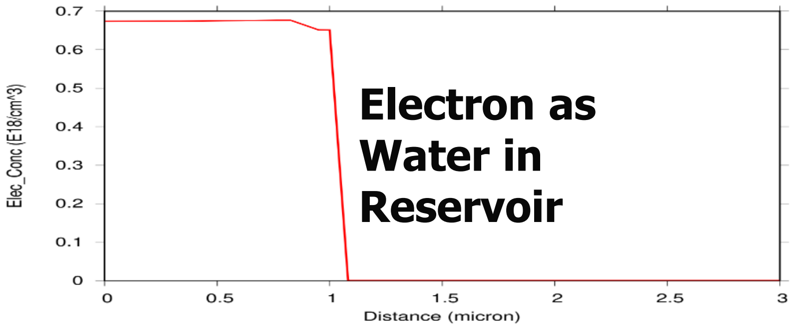


Cause of breakdown
(More of a gradual leakage)









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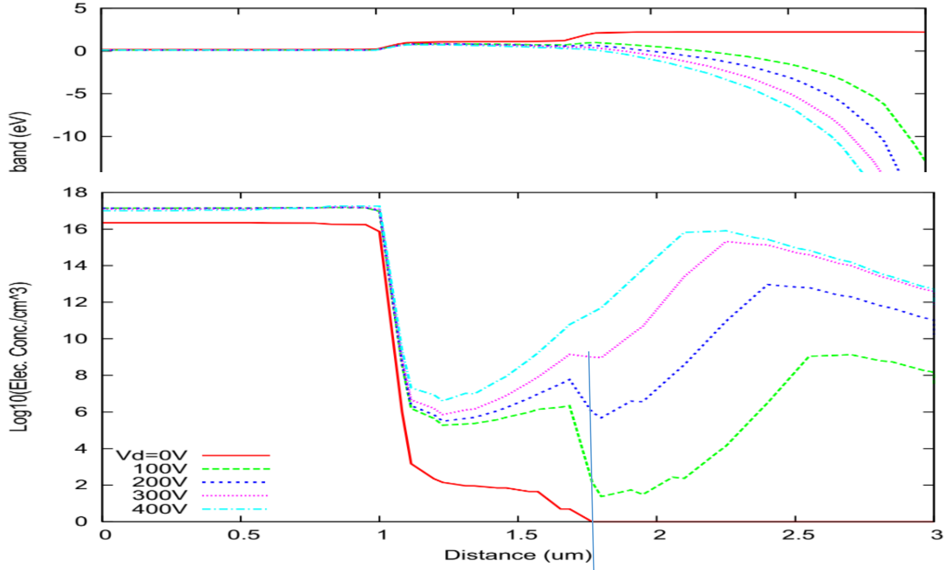
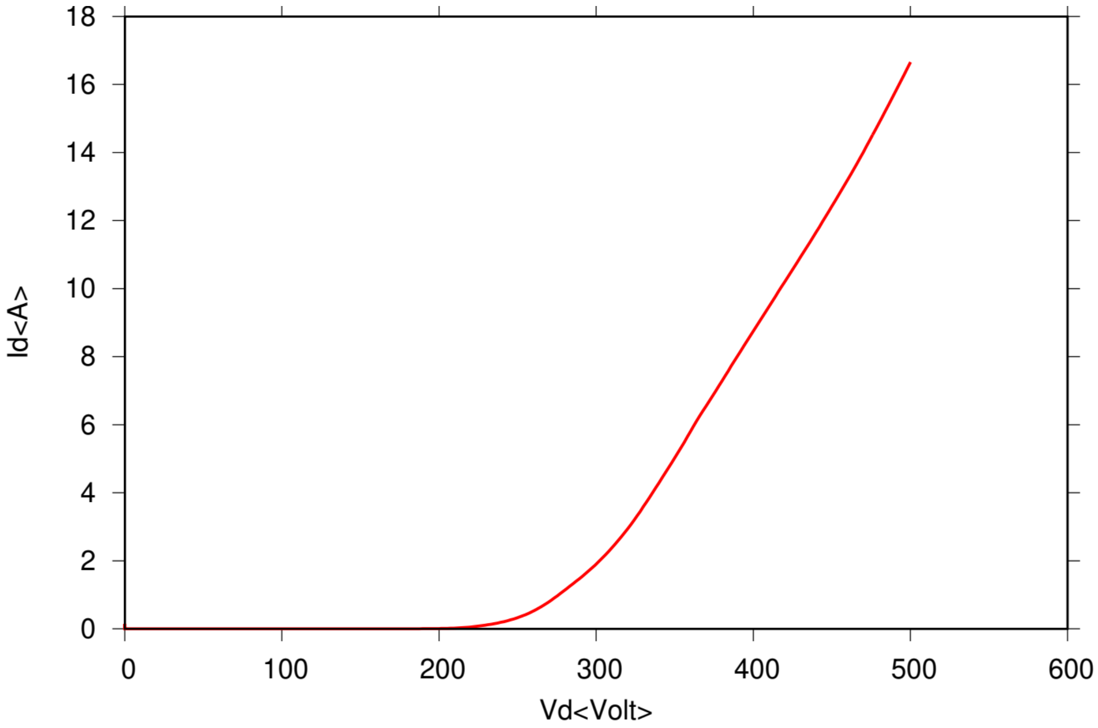
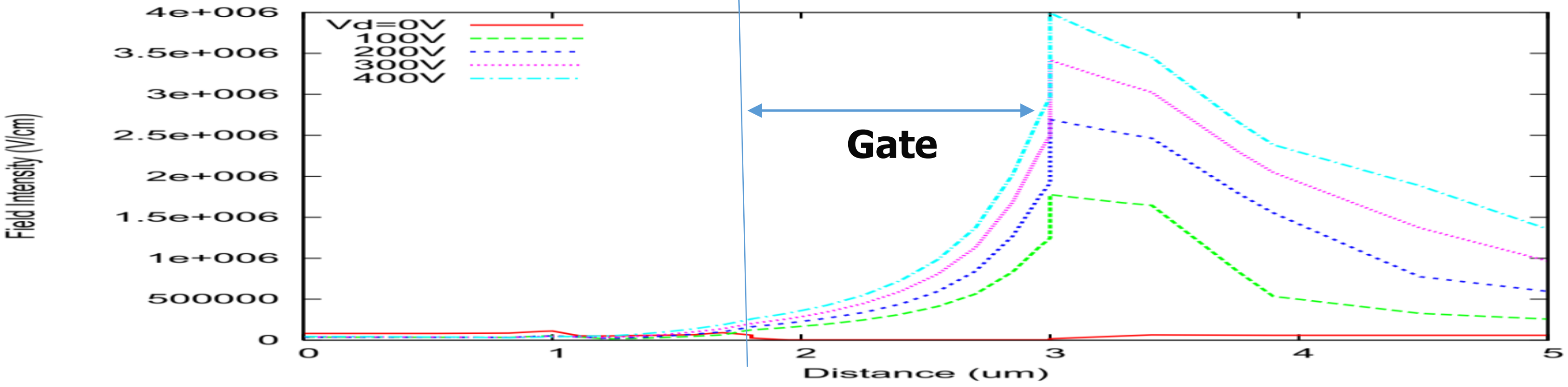
Cause of leakage







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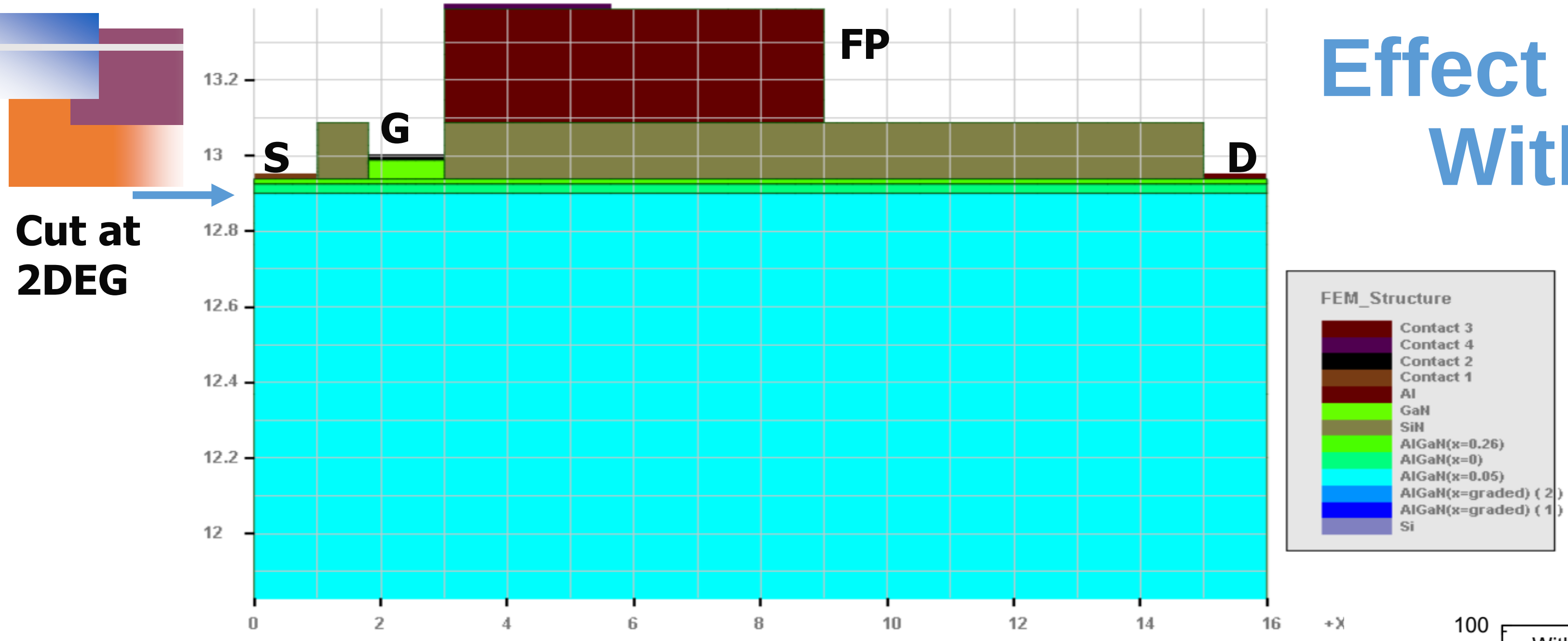
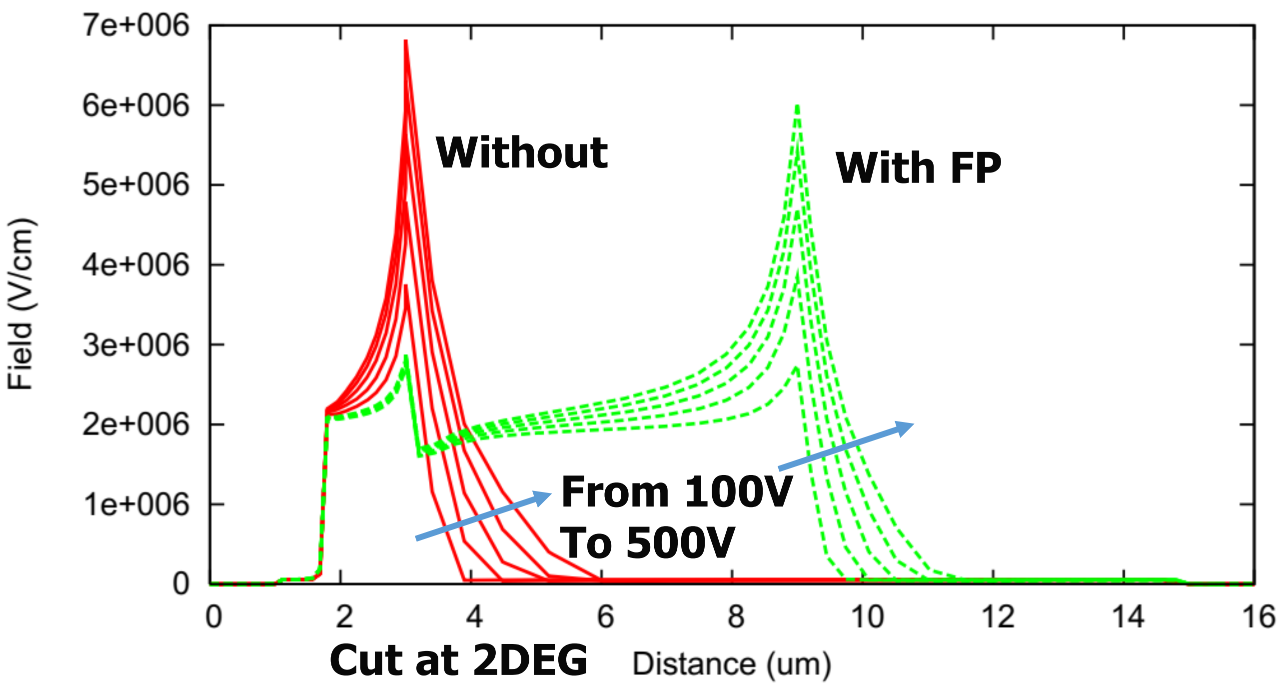
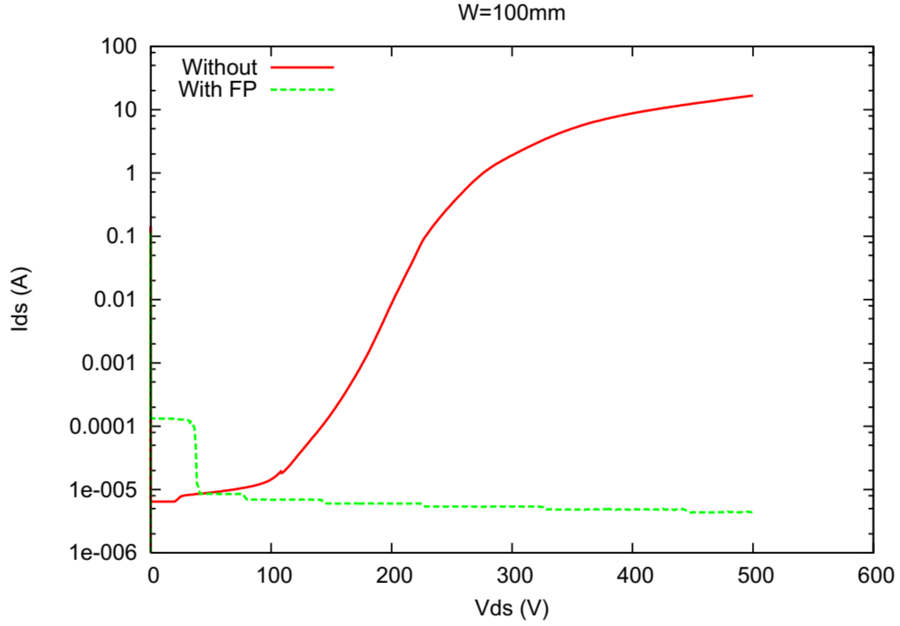
Effect of Field Plate (FP) Without avalanche



Design consideration:
The field plate should be far away from the gate to move the high field away





Contents

Some early works on impact ionization rate (IIR)

Extraction of impact ionization from IV curves

Impact ionization occurs in the localized region near the maximum electric field , and most of the generated holes are collected by the gate electrode:

$$I_{\text{hole}} = W \times \int\int \alpha_n(E) j_n \, dx \, dy \approx \alpha_n(E_{\max}) \times I_{ds} \times L.$$

$$\alpha_n = 5.6 \times 10^6 \exp(-2.4 \times 10^6 / E)$$

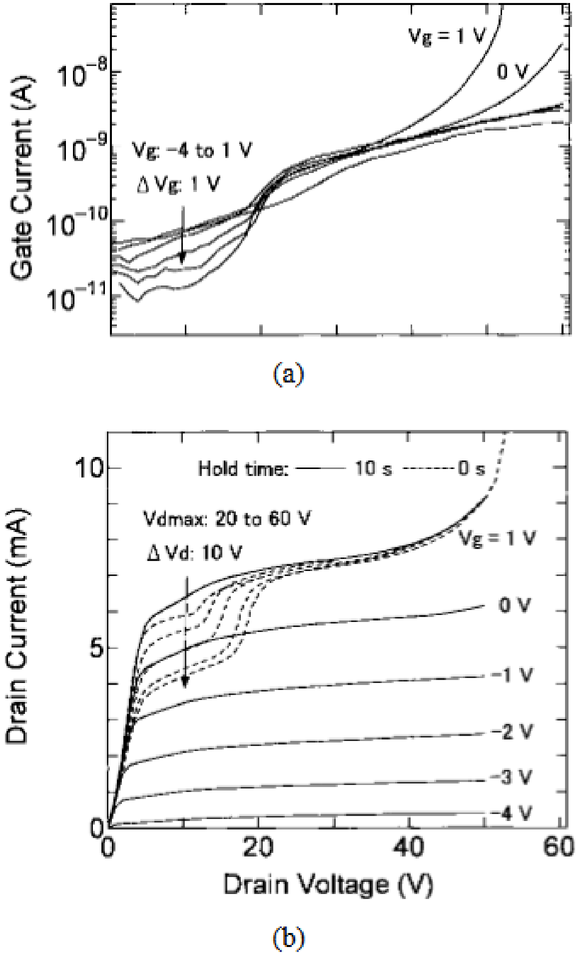


Fig. 1. DC characteristics of the AlGaN/GaN HJFET with a gate dimension of $0.9 \times 40\ \mu$m. (a) Gate current I_g versus drain voltage V_d. (b) Drain current I_d versus drain voltage. Drain currents are measured with (solid lines) and without (dashed lines) a time interval (10 s) between each gate voltage. When the drain currents are measured immediately after gate bias application, the currents are reduced in the low-drain voltage region.

EEE ELECTRON DEVICE LETTERS, VOL. 20, NO. 12, DECEMBER 1999 p608

➔ **No clear indication of avalanche**

TCAD for lateral GaN: Including Quantum Physics in Semiconductor Equations

$$-\nabla\cdot\left(\frac{\epsilon_0\epsilon_{dc}}{q}\nabla V\right) = -n + p + N_D(1-f_D) - N_A f_A + \sum_j N_{tj}(\delta_j - f_{tj}),$$

Semiconductor eqn.

$$\nabla\cdot J_n - \sum_j R_n^{tj} - R_{sp} - R_{st} - R_{au} + G_{opt}(t) = \frac{\partial n}{\partial t} + N_D\frac{\partial f_D}{\partial t},$$

$$\nabla\cdot J_p + \sum_j R_p^{tj} + R_{sp} + R_{st} + R_{au} - G_{opt}(t) = -\frac{\partial p}{\partial t} + N_A\frac{\partial f_A}{\partial t}.$$

$$J_n = n\mu_n\nabla E_{fn}$$

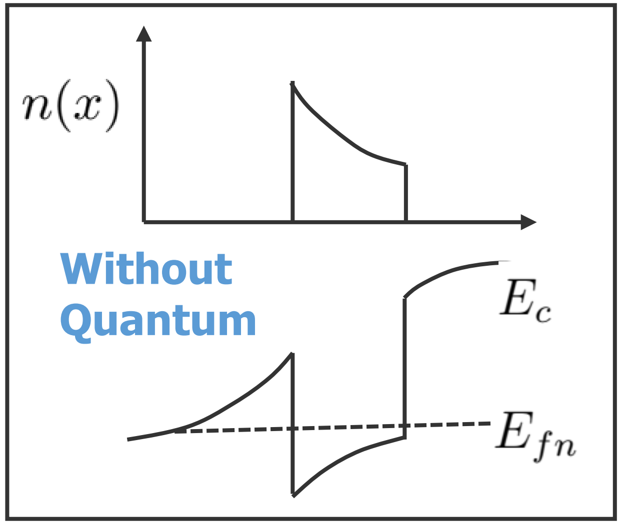
$$J_p = p\mu_p\nabla E_{fp}$$

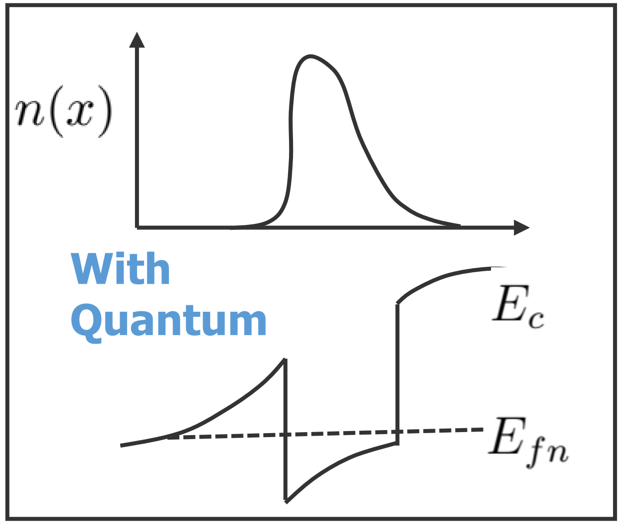
$$H(k)|\psi_i\rangle = E_i(k)|\psi_i\rangle$$

Quantum

$$n = \sum_j \rho_j^{x0} kT ln\left[1 + e^{(E_{fn}-E_j)/kT}\right] + unconfined\ electrons,$$

$$p = \sum_i \rho_i^{x0} kT ln\left[1 + e^{(E_i-E_{fp})/kT}\right] + unconfined\ holes,$$





Impact ionization

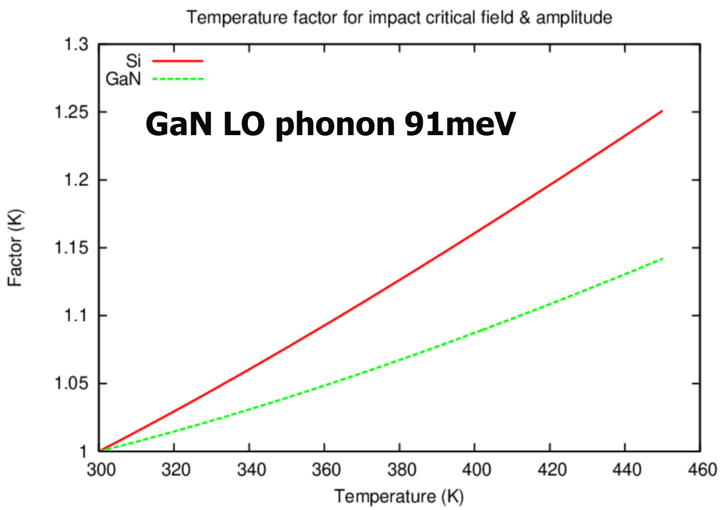
$$G = \alpha_n J_n/q + \alpha_p J_p/q$$

$$\alpha = \alpha_n^{\infty} e^{-\frac{F_{cn}}{F}}$$

factor $$\gamma = \frac{tanh\left(\frac{h\omega_{op}}{2kT_0}\right)}{tanh\left(\frac{h\omega_{op}}{2kT}\right)}$$

for both α_n^{∞} and F_{cn}

Temperature dependence of break down behavior as evidence of avalanche – GaN behaves just like any other semiconductor



Cent. Eur. J. Phys. • 10(2) • 2012 • 485-491
DOI: 10.2478/s11534-011-0100-x

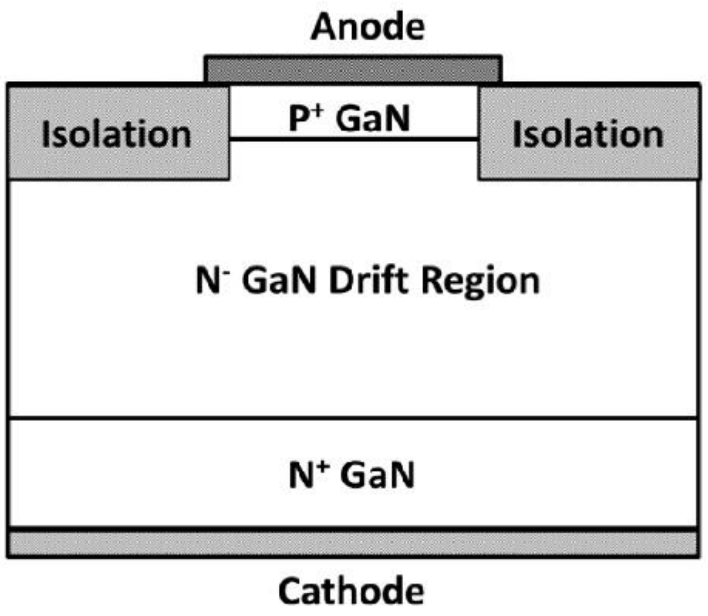


Fig. 1. Schematic cross-sectional view of the vertical GaN p-n diode on bulk GaN.

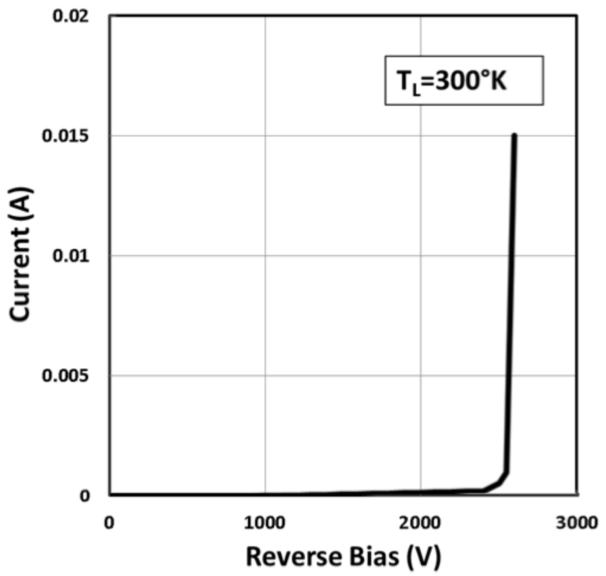


Fig. 3. Reverse characteristics of GaN p-n diode and avalanche breakdown.

DOI: 10.1109/TED.2013.2266664

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 60, NO. 10, OCTOBER 2013

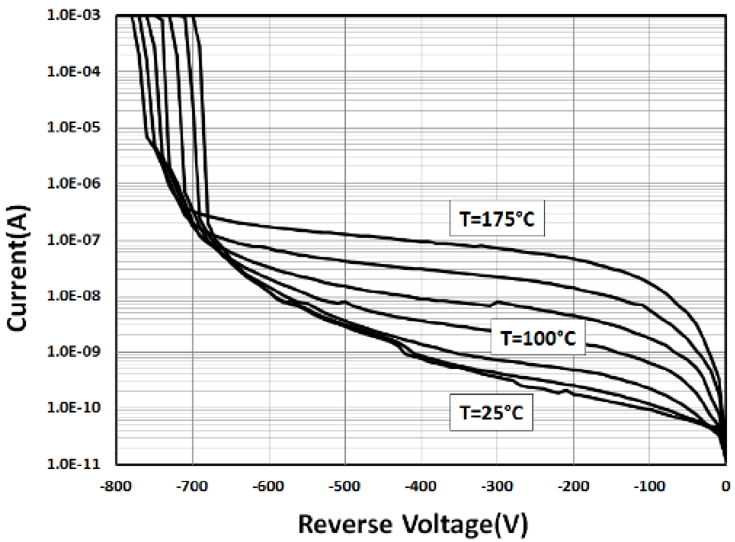
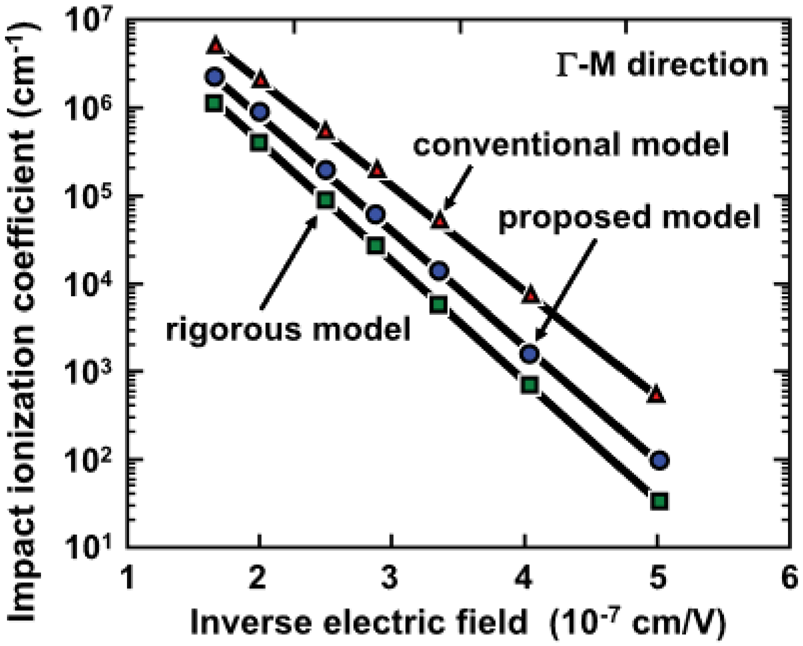


Fig. 4. Temperature dependence of the reverse I–V curves of the GaN diode.

Computing impact ionization rate

$$W_{\text{iir}}(n_1, \boldsymbol{k}_1) = \frac{2\pi}{\hbar}\frac{V^2}{(2\pi)^6}\sum_{n_{1'},n_2,n_{2'}}\int d^3\boldsymbol{k}_{1'}\int d^3\boldsymbol{k}_{2'} \times |M|^2\,\delta(E_1 + E_2 - E_{1'} - E_{2'}),$$



alpha_n=a+exp(-b/E)
a=2.31E8 (1/cm)
b=3.14E7 (V/cm)

➔ Theory looks much like optical transition computation!

Kodama et.al

J. Appl. Phys. **114**, 044509 (2013)

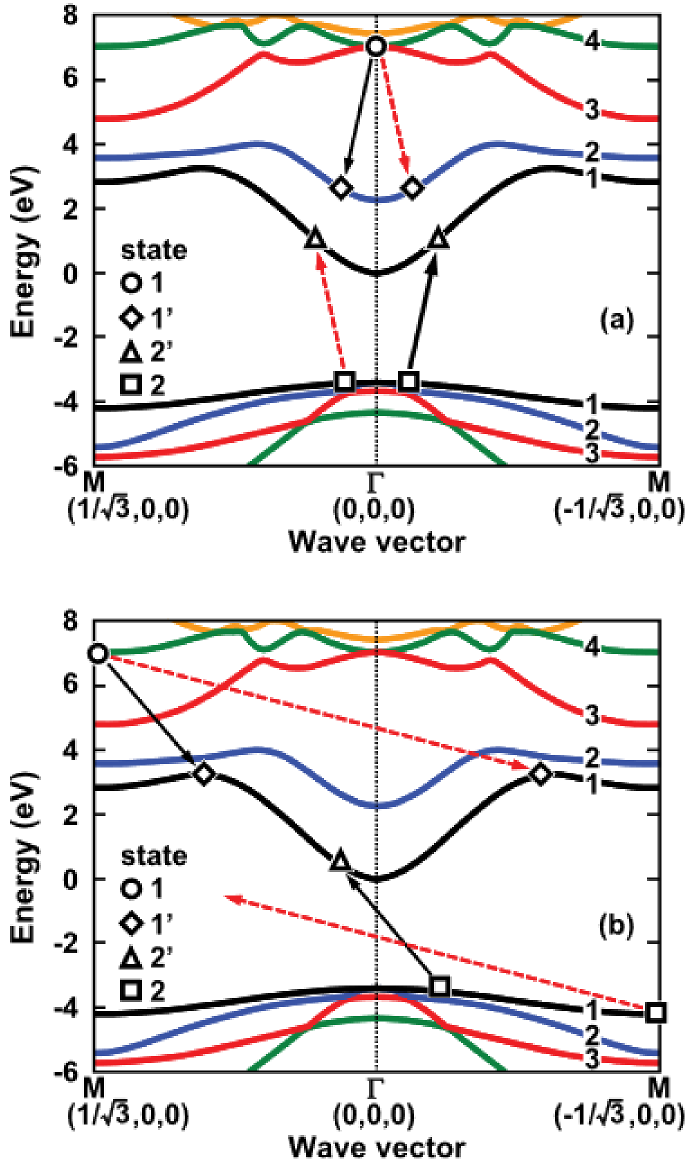


FIG. 4. Impact ionization processes for initial electrons located at (a) Γ and (b) M points. Circles correspond to electrons for state 1, squares for state 2, diamonds for state 1′, and triangles for state 2′. Arrows indicate direction of transition path.

Monte Carlo simulation results may vary widely.
➔ AlGaN is less likely to break down than GaN.

T.L.W. Ooi et al.: Eur. Phys. J. Appl. Phys. **92**, 10301 (2020) 3

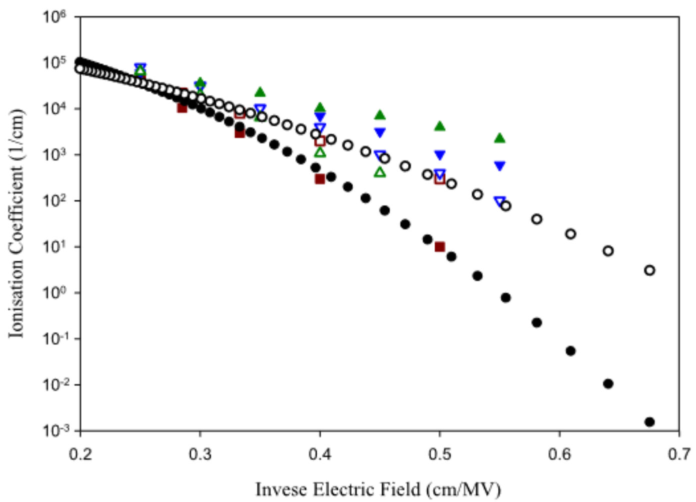


Fig. 1. Electron ionization coefficient, α (filled black circle) and hole ionization coefficient, β (empty black circle) of GaN from this work are compared with those by Bertazzi et al. [24] along T–M (α: filled green upright triangle, β: empty green upright triangle), Bertazzi et al. along T–A (α: filled blue down-pointing triangle, β: empty blue down-pointing triangle) and Oğuzman et al. [25] (α: filled red square, β: empty red square).

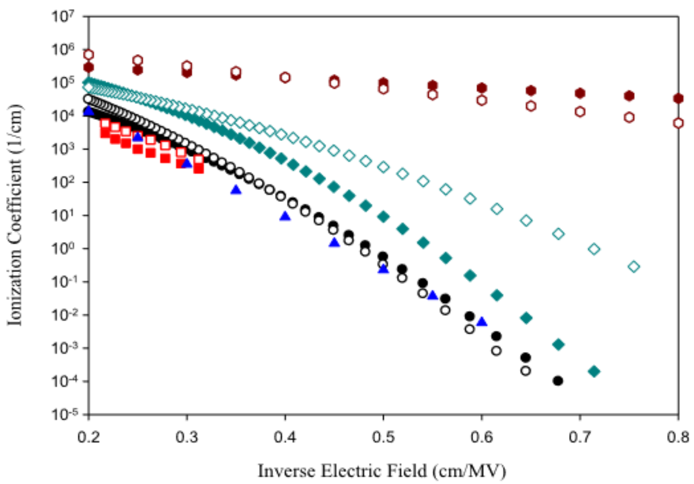


Fig. 2. Electron ionization coefficient, α (filled black circle) and hole ionization coefficient, β (empty black circle) of $Al_{0.45}Ga_{0.55}N$ from this work compared to Tut et al. [11] $Al_{0.4}Ga_{0.6}N$ (α: filled maroon hexagon, β: empty maroon hexagon), Bulutay [12] $Al_{0.4}Ga_{0.6}N$ (α: blue triangle), Bellotti et al. [13] $Al_{0.4}Ga_{0.6}N$ (α: filled red square, β: empty red square) and GaN of our work (α: filled teal diamond, β: empty teal diamond).

For GaN

$$\alpha = 7.32 \times 10^7 \exp\left[-\left(\frac{7.16 \times 10^8}{E}\right)^{1.90}\right] \mathrm{cm}^{-1}$$

$$\beta = 3.48 \times 10^7 \exp\left[-\left(\frac{6.56 \times 10^8}{E}\right)^{1.65}\right] \mathrm{cm}^{-1}$$

For Al(0.45)Ga(0.55)N

$$\alpha = 1.66 \times 10^7 \exp\left[-\left(\frac{8.51 \times 10^8}{E}\right)^{1.75}\right] \mathrm{cm}^{-1}$$

$$\beta = 8.01 \times 10^7 \exp\left[-\left(\frac{1.02 \times 10^9}{E}\right)^{1.65}\right] \mathrm{cm}^{-1}$$

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Measurement of avalanche multiplication utilizing Franz-Keldysh effect in GaN p-n junction diodes

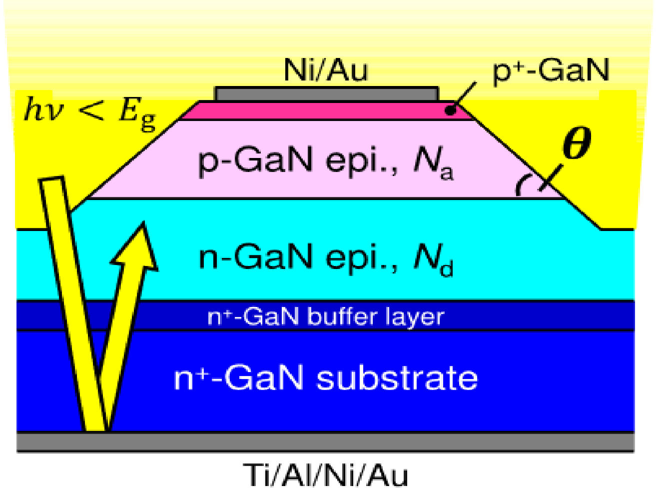
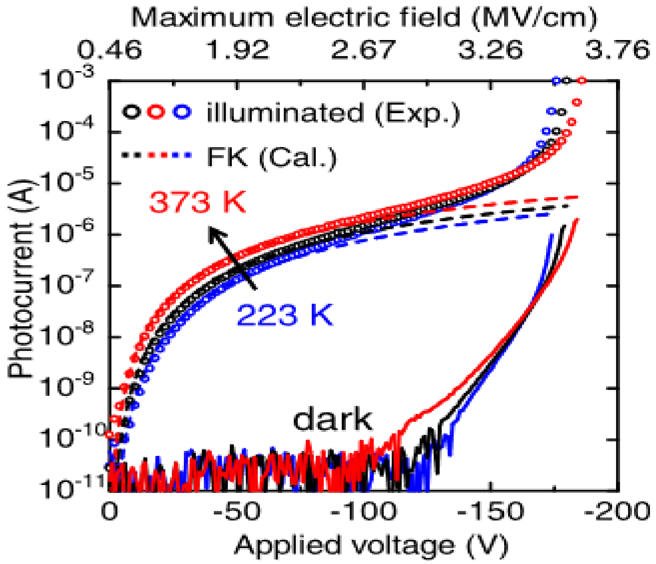


FIG. 1. Schematic cross section of a GaN PND with double-side-depleted shallow bevel termination. The sub-bandgap light was irradiated from the surface side.



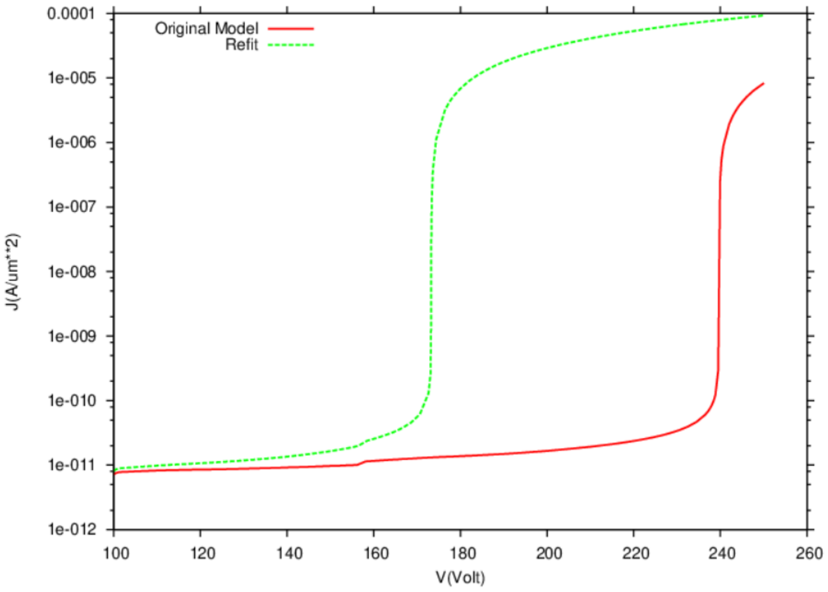
$$\alpha(E,T) = a(T)\cdot \exp\left[-\left(\frac{b(T)}{E}\right)\right]$$

$$a(T) = 1.30\times 10^{6}\cdot[1+1.5\times 10^{-3}\cdot(T-298)]\ \mathrm{cm}^{-1},$$

$$b(T) = 1.18\times 10^{7}\cdot[1+6.0\times 10^{-4}\cdot(T-298)]\ \mathrm{Vcm}^{-1}.$$

assume $\alpha_n = \alpha_p$ for simplicity

$$1-\frac{1}{M} = \int_{W_p}^{W_n}\alpha(E)dx.$$



➔ Optical method and electrical method (TCAD) have different results

To get BV, refit:
B=1.18E7 V/cm
➔ B=0.95E7 V/cm

Appl. Phys. Lett. 115, 142101 (2019);
https://doi.org/10.1063/1.5114844

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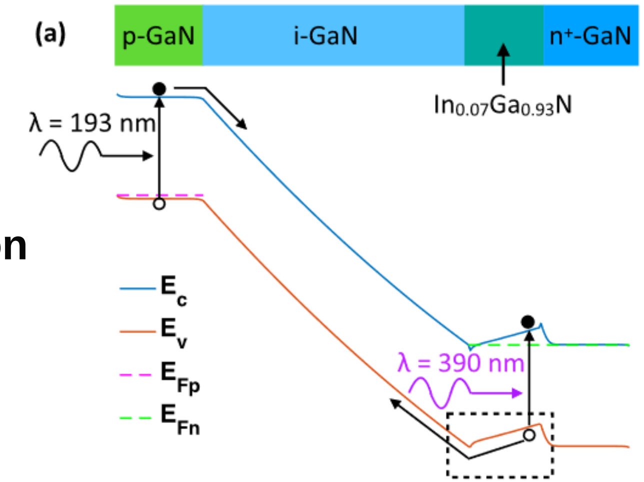
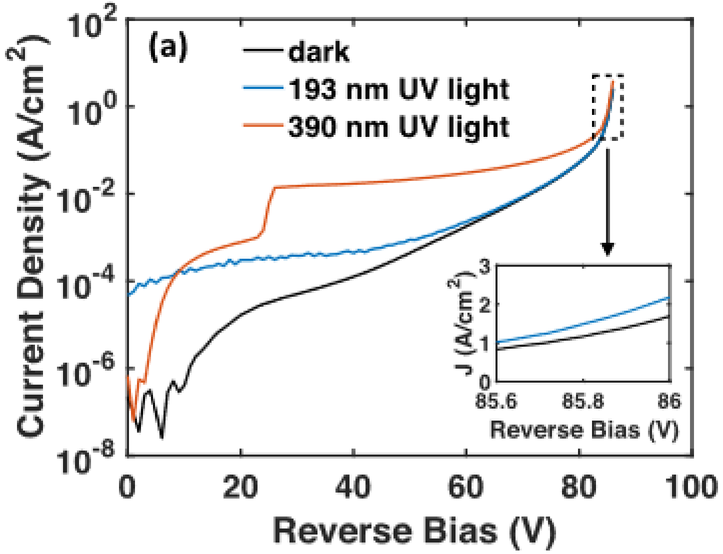
APPLIED PHYSICS LETTERS 112, 262103 (2018)

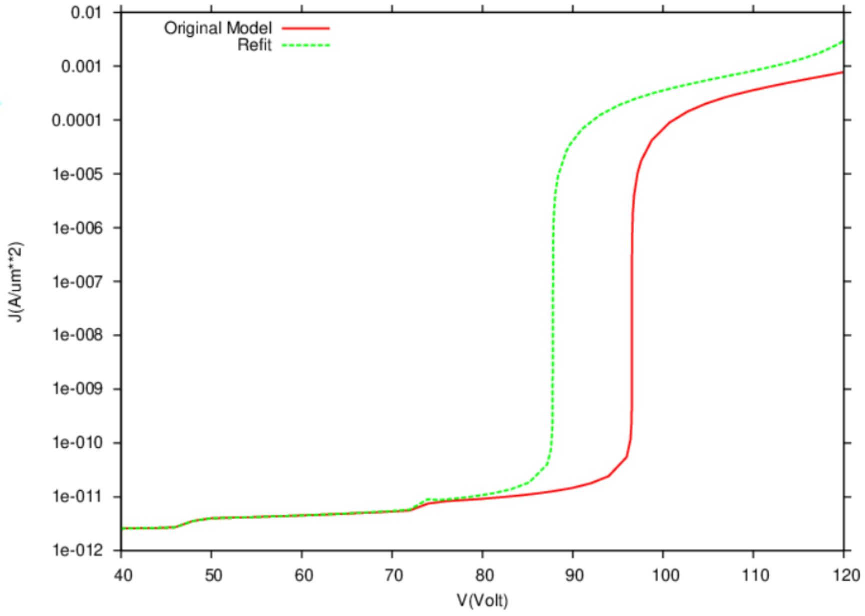
Experimental characterization of impact ionization coefficients for electrons and holes in GaN grown on bulk GaN substrates

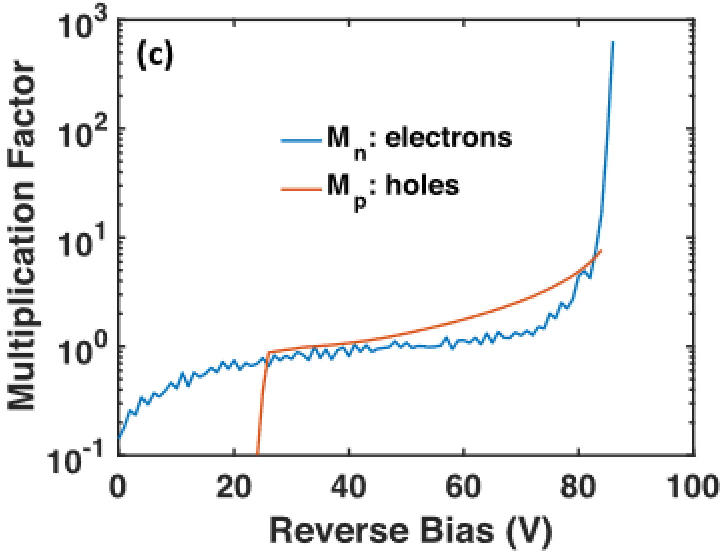
Lina Cao, et.al.





$$\alpha(E) = 4.48 \times 10^8 \exp\left(-3.39 \times 10^7/E\right),$$
$$\beta(E) = 7.13 \times 10^6 \exp\left(-1.46 \times 10^7/E\right).$$





Refit based on IV: a=3.39E7 revised to a=3.0E7 V/cm

➔Better agreement between optical and electrical extraction.

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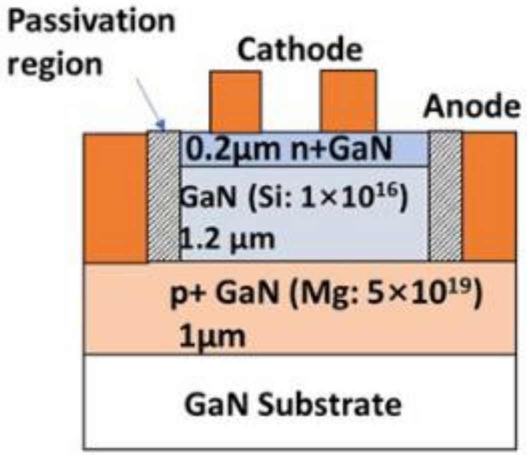
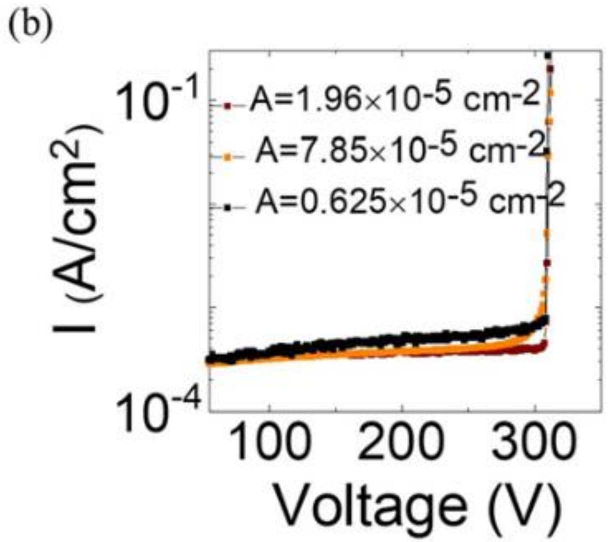
Experimental determination of impact ionization coefficients of electrons and holes in gallium nitride using homojunction structures

Ji, et.al. Appl. Phys. Lett. 115, 073503 (2019); doi: 10.1063/1.509924

Part 1/2

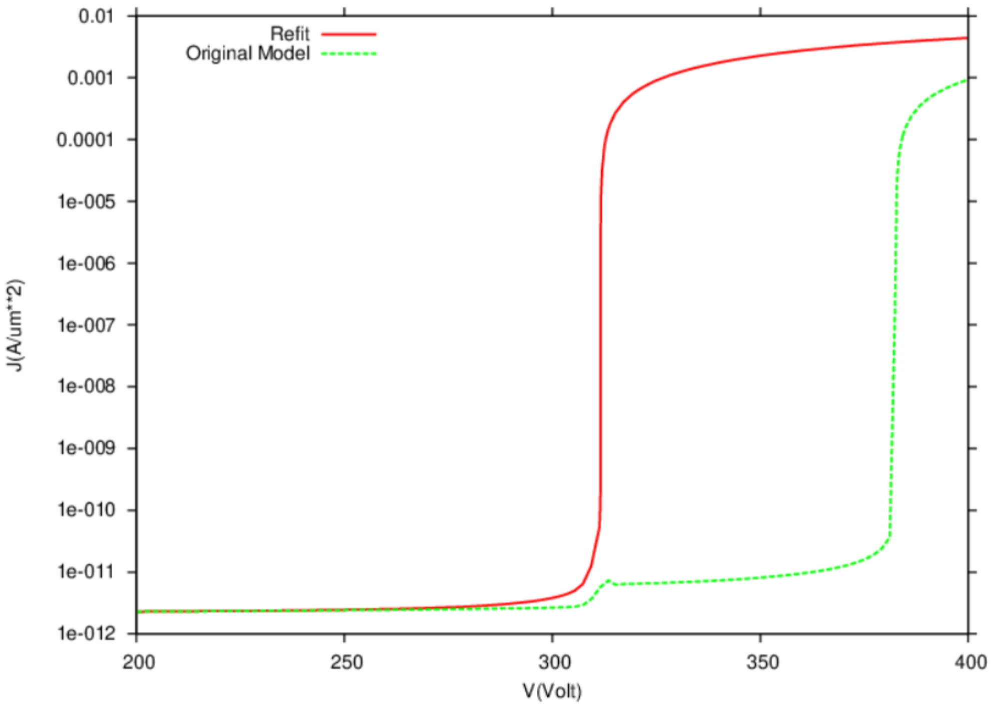




$$\alpha(E) = 2.11 \times 10^9 \, e^{-3.689\times10^7 \frac{1}{E}} \, \mathrm{cm}^{-1}.$$

$$\beta(E) = 4.39 \times 10^6 \, e^{-1.8\times10^7 \frac{1}{E}} \, \mathrm{cm}^{-1},$$

Use of optical generation to determine impact ionization rate



Alpha=a*exp(-b/E)
Coefficient b is refitted to get the correct BV:
b=3.689E7➔ b=2.8E7 V/cm

Substantial difference in optical/electrical extraction of IIR

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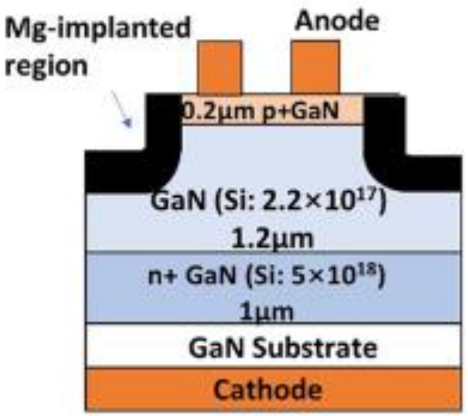
Experimental determination of impact ionization coefficients of electrons and holes in gallium nitride using homojunction structures

Ji, et.al. Appl. Phys. Lett. 115, 073503 (2019); doi: 10.1063/1.509924

Part 2/2

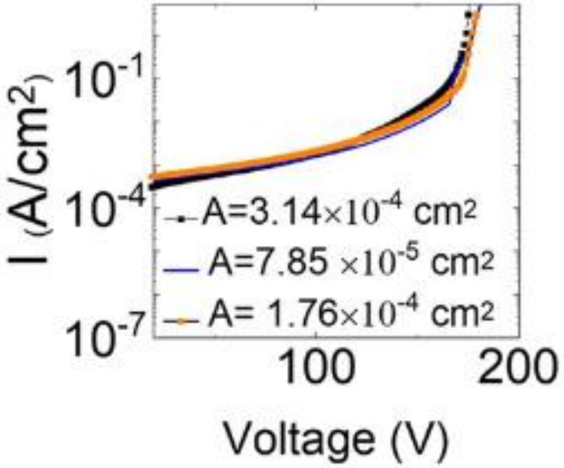


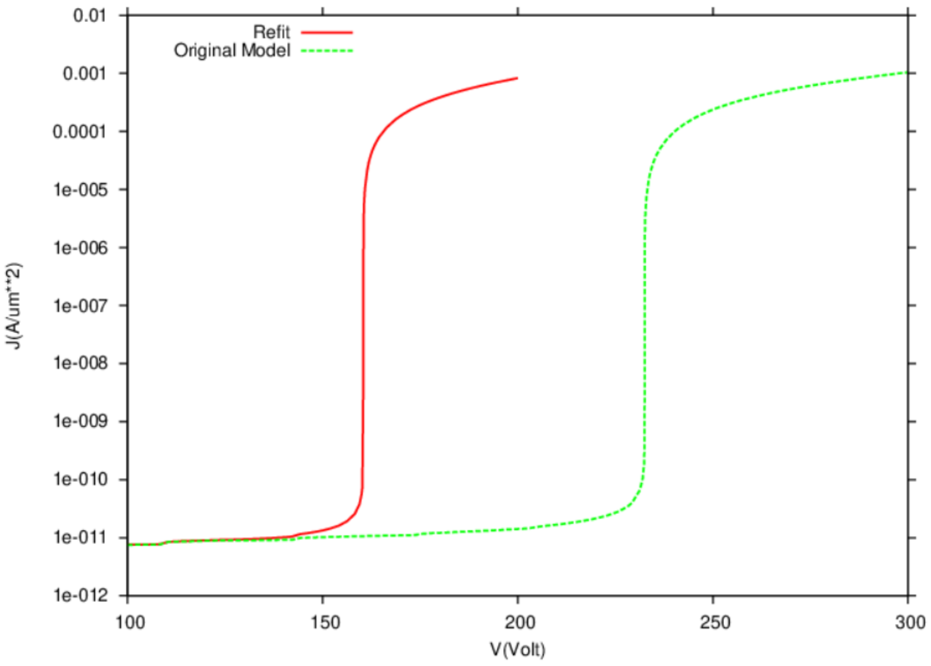
$$\alpha(E) = 2.11 \times 10^9\, e^{-3.689\times10^7\frac{1}{E}}\,\mathrm{cm}^{-1}.$$

$$\beta(E) = 4.39 \times 10^6\, e^{-1.8\times10^7\frac{1}{E}}\,\mathrm{cm}^{-1},$$

Use of optical generation to determine impact ionization rate

(d)





Alpha=a*exp(-b/E) Coefficient b is refitted to get the correct BV: b=3.689E7➔ b=2.8E7 V/cm

The difference persisted in another experimental structure from the same paper. Issues with optical experiment or extraction method?

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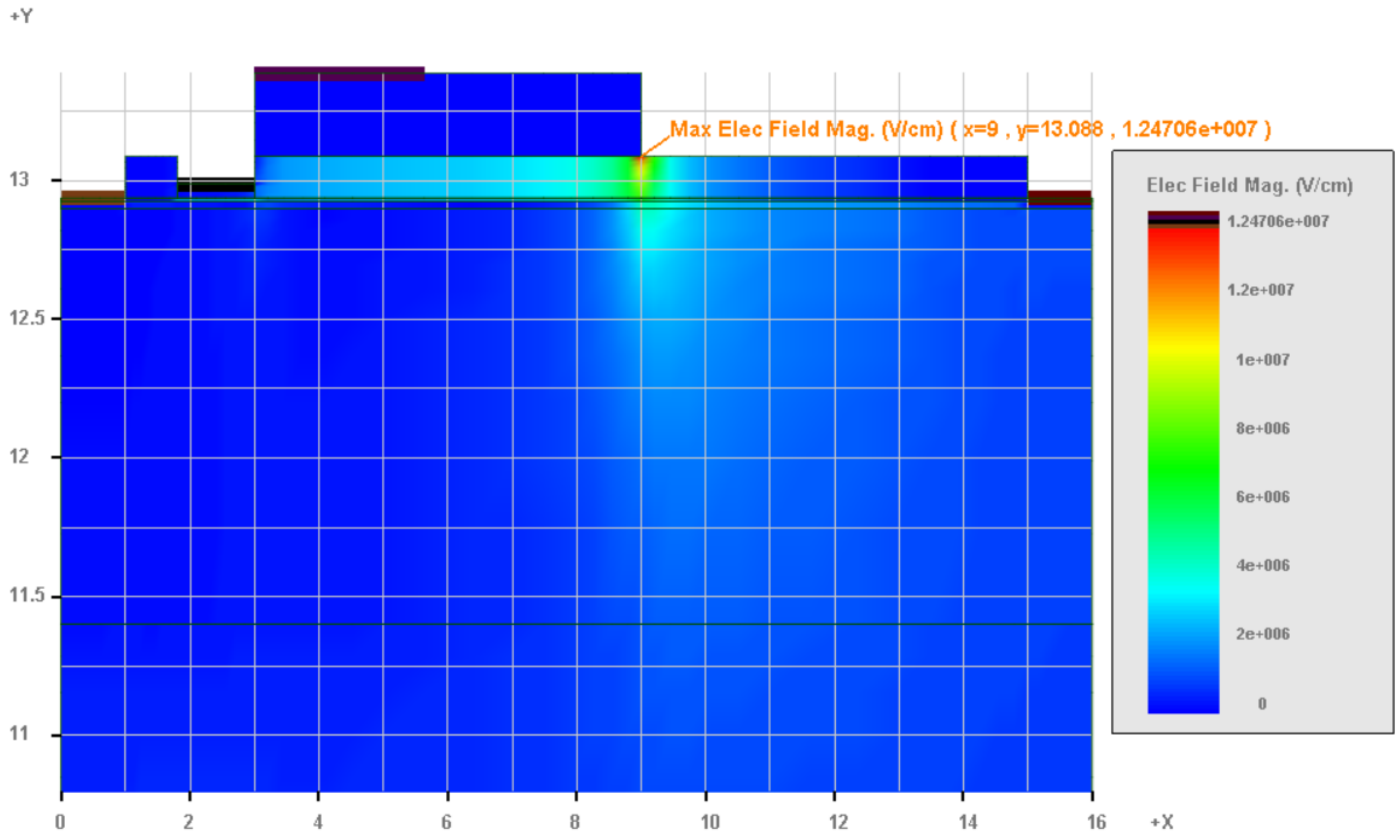
Contents

- Importance of field plates for lateral GaN
- Avalanche effect in GaN
- Avalanche in lateral GaNFET and FP design
- Summary

➔ **Electrical field range to consider ~ 1E7 V/m**
➔ **Highest field point shall be right below FP edge**



Vd=800V

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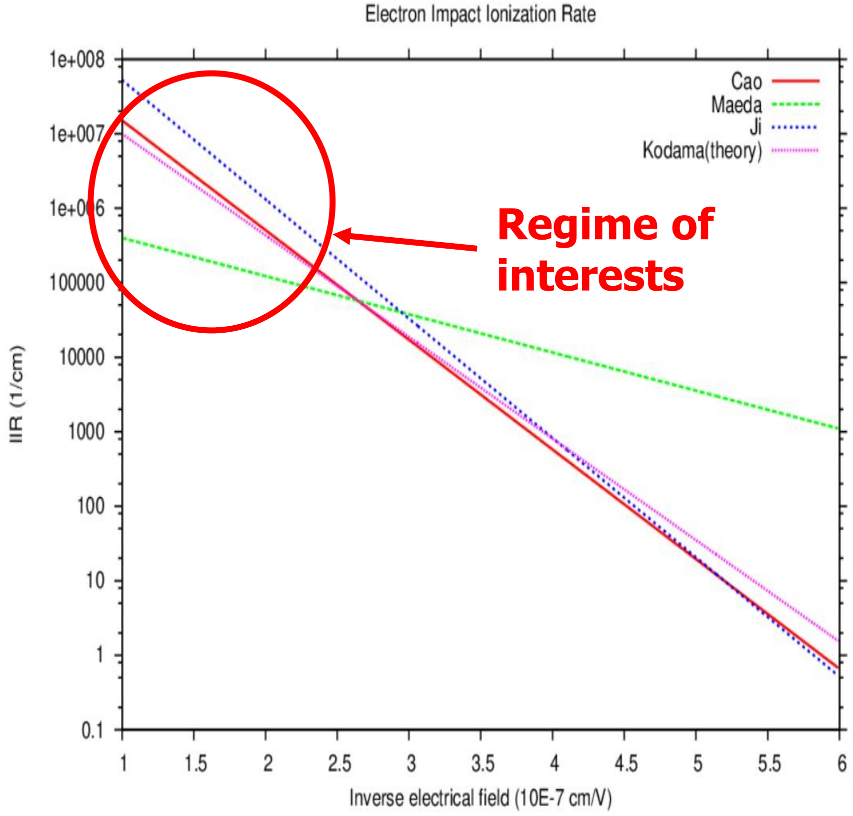
Recent experimental impact ionization coefficients
alpha=a*exp(-b/F)

Ref	Electron (a ,1/cm)	Electron (b,V/cm)	Hole (a,1/cm)	Hole (b,V/cm)
Cao et. Al [1]	4.48E8	3.39E7 (refit 3.0E7)	7.13E6	1.46E7
Maeda et. Al [2]	1.30E6	1.18E7 (refit 0.95E7)	1.30E6	1.18E7 (refit 0.95E7)
Ji et. Al [3]	2.11E9	3.689E7 (refit 2.8E7)	4.39E6	1.8E7



➔Rogorous theory agrees well with one of the experimental works.

[1] APPLIED PHYSICS LETTERS 112, 262103 (2018)

[2] Appl. Phys. Lett. 115, 142101 (2019); https://doi.org/10.1063/1.5114844

[3] Ji, et.al. Appl. Phys. Lett. 115, 073503 (2019); doi: 10.1063/1.509924

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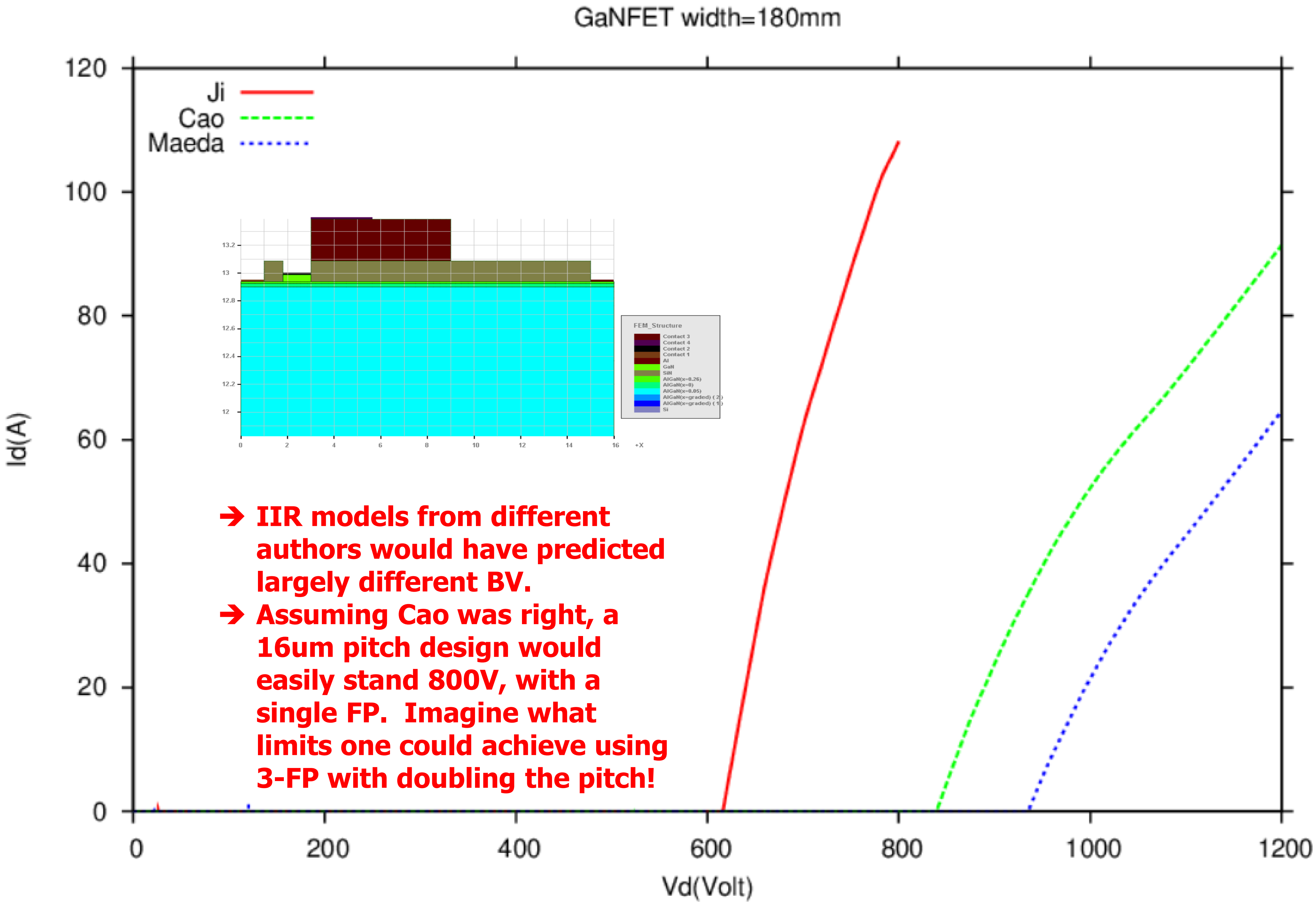

→ **IIR models from different authors would have predicted largely different BV.**

→ **Assuming Cao was right, a 16um pitch design would easily stand 800V, with a single FP. Imagine what limits one could achieve using 3-FP with doubling the pitch!**

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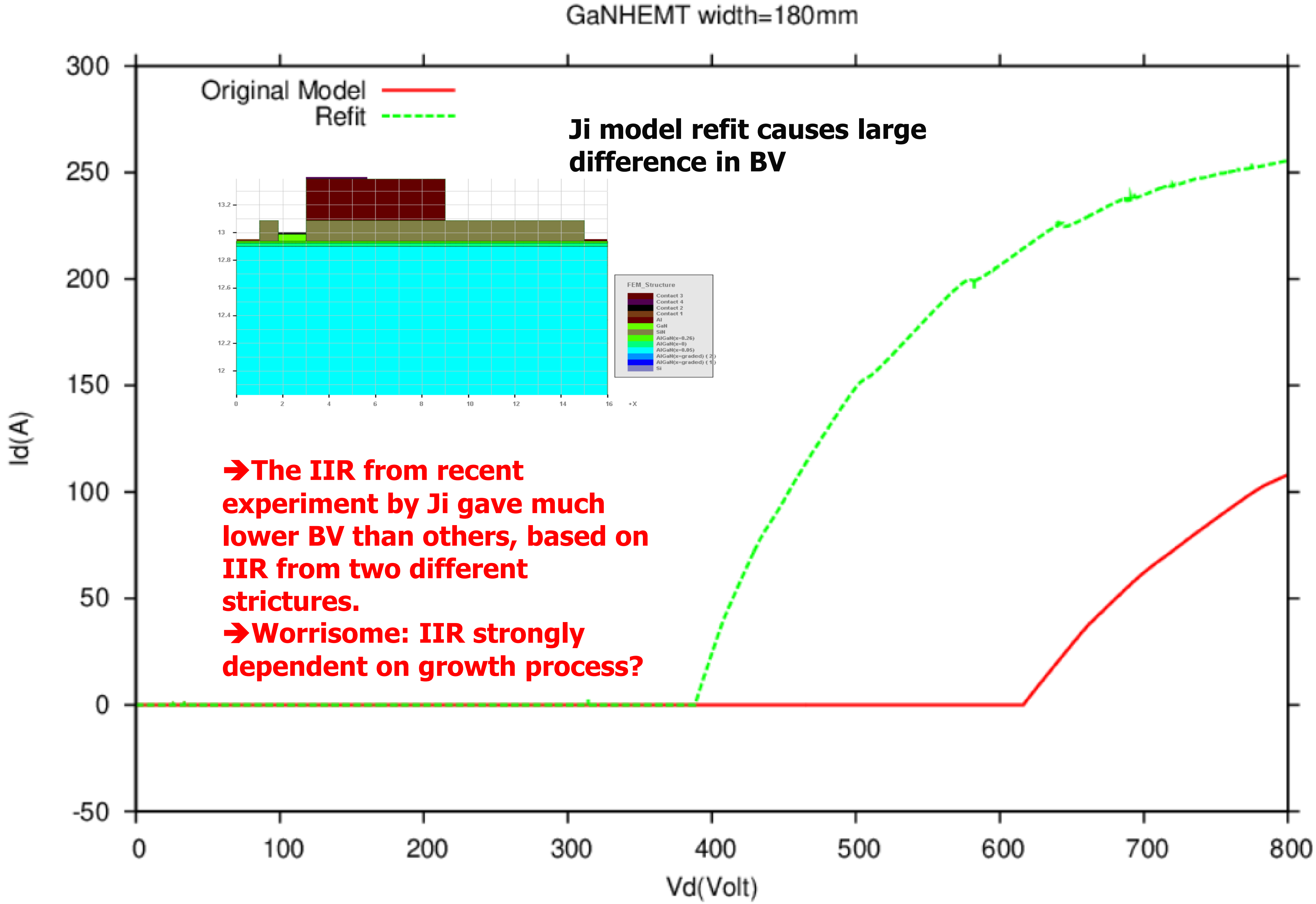


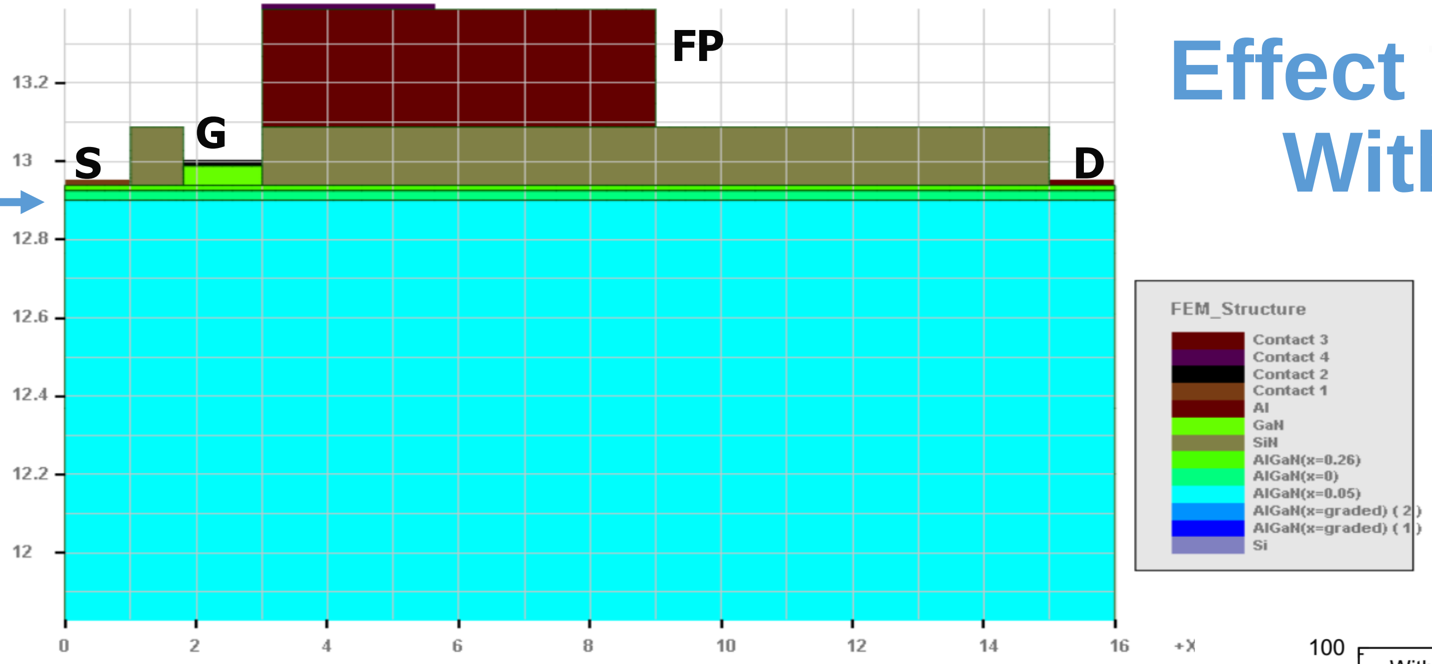
Ji model refit causes large difference in BV

➔The IIR from recent experiment by Ji gave much lower BV than others, based on IIR from two different strictures.

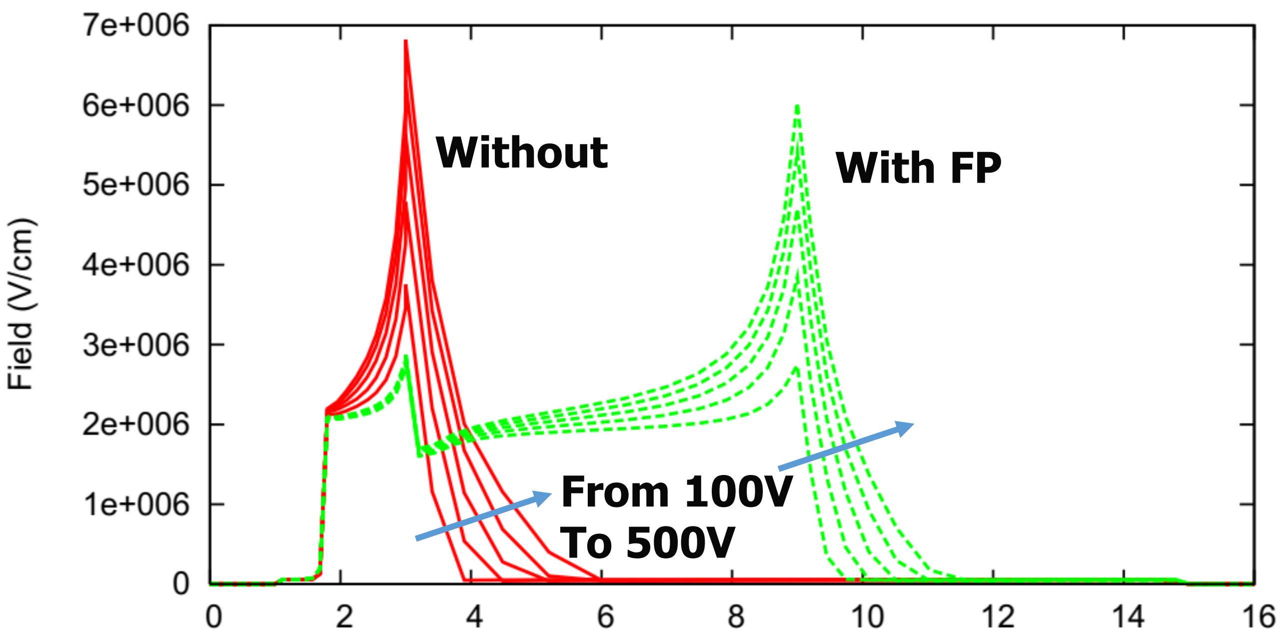
➔Worrisome: IIR strongly dependent on growth process?

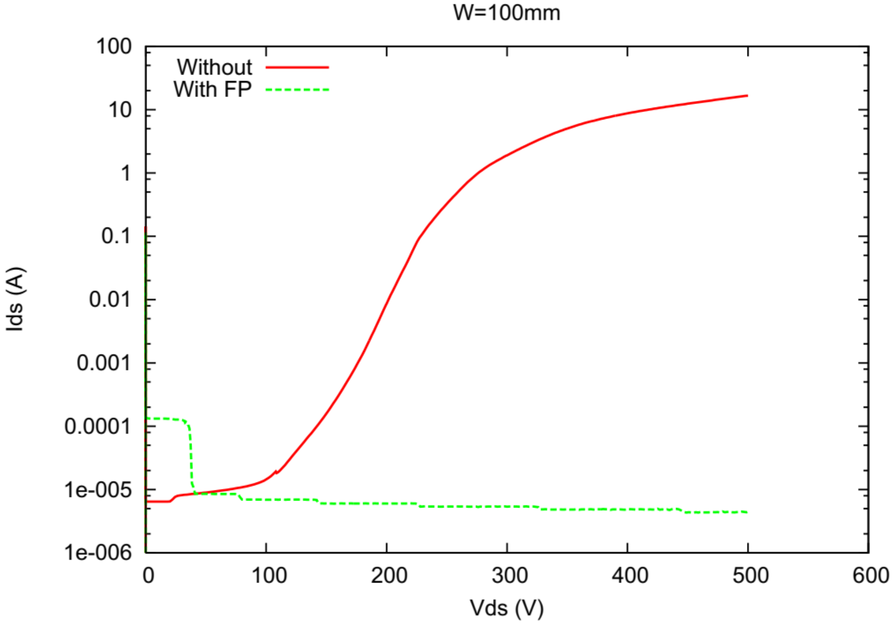
Effect of Field Plate (FP) Without avalanche

Cut at 2DEG



→FP edge better be away from the gate





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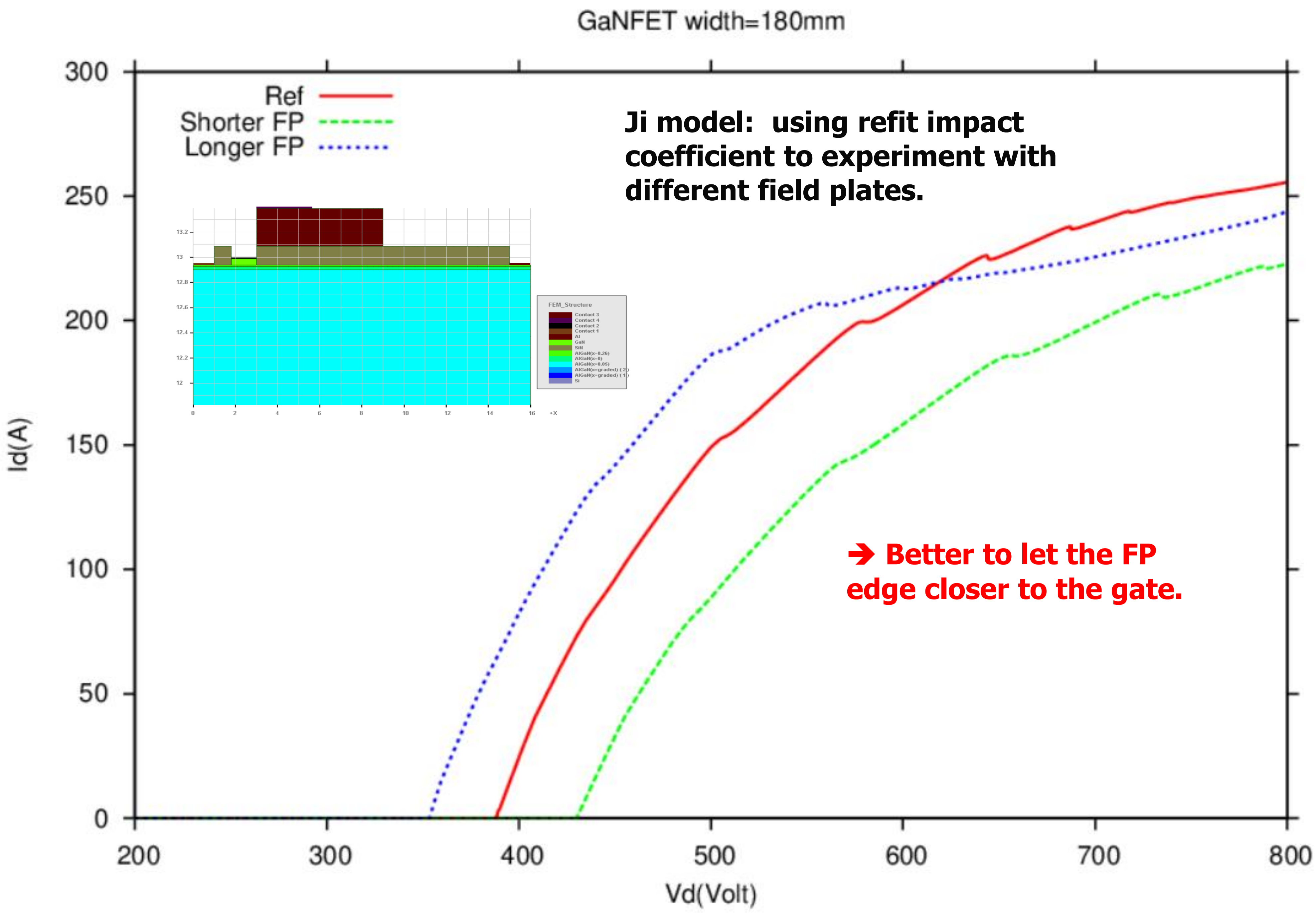

GaNFET width=180mm
Ref
Shorter FP
Longer FP
Ji model: using refit impact coefficient to experiment with different field plates.
➔ Better to let the FP edge closer to the gate.
Id(A)
Vd(Volt)
0
50
100
150
200
250
300
200
300
400
500
600
700
800

Summary

- For commercially available lateral GaNFET at 650V or 1200V, avalanche may play a role.
- More study is needed to explain the large difference in experimental IIR from different labs and from different extraction methods.
- Crosslight-TCAD is a suitable tool for avalanche simulation and GaNPower has a handle on 1200V GaN design.

Thanks for your attention!

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