# Sub-100 nm GaN HEMTs for W-band power amplifier applications and beyond

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# Research Experience in the US

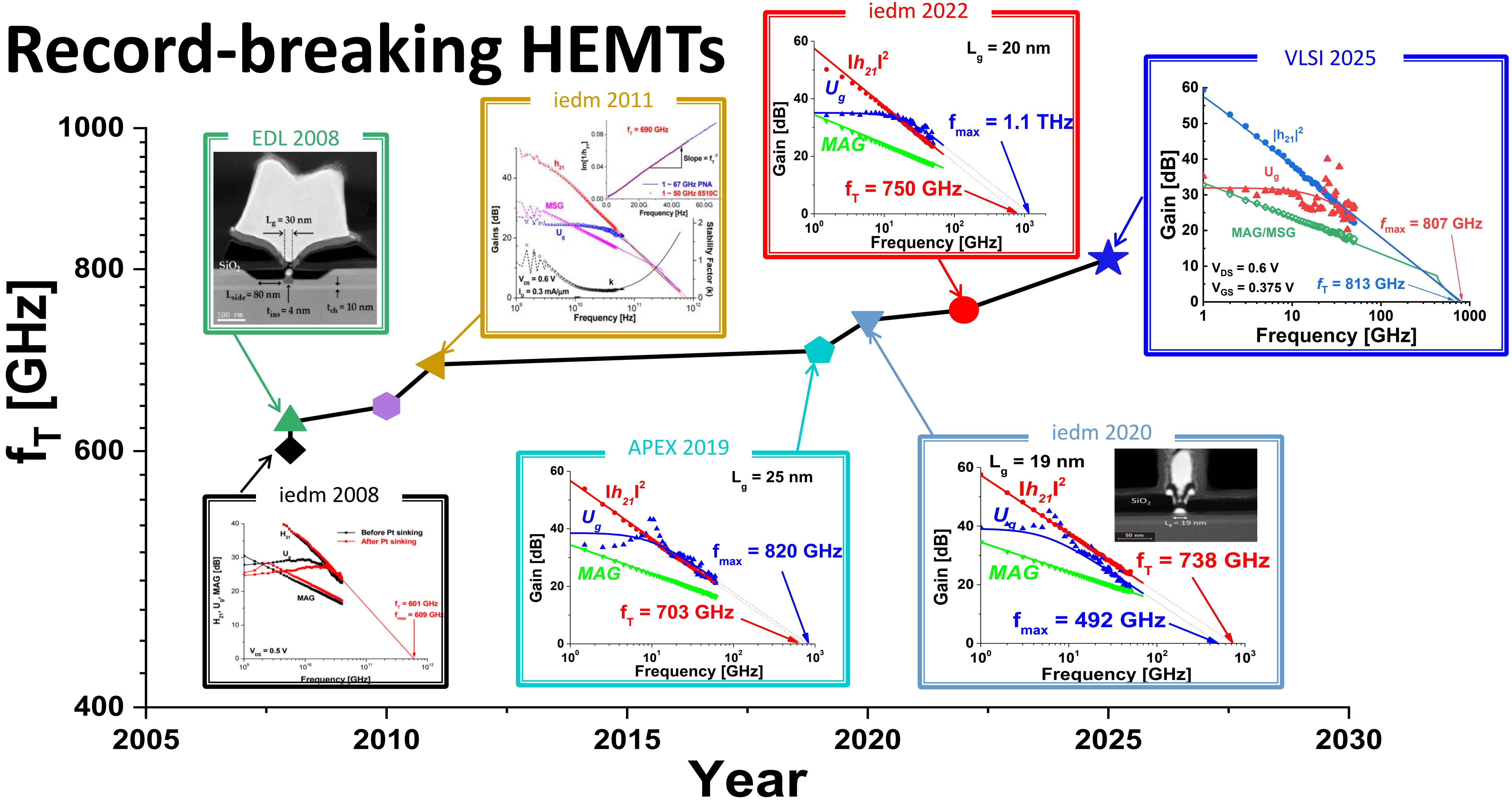
- **2005~2008: Post-doc & research-scientist at MIT**
  - Working with Prof. del Alamo and Prof. Antoniadis
  - InGaAs for future logic funded by Intel

- **2008~2012: MTS at Teledyne Scientific**
  - InGaAs HEMTs on InP funded by DARPA
  - GaN HEMTs on Si/SiC funded by DARPA

- **2012~2014: Manager at SEMATECH**
  - III-V/Ge on Si: Heterogeneous Integration
  - InGaAs MOSFET, 2D path-finding and ALE

- **2015~now: KNU**

# Record-breaking HEMTs




Reported record-breaking HEMT technologies several times for the past two decades

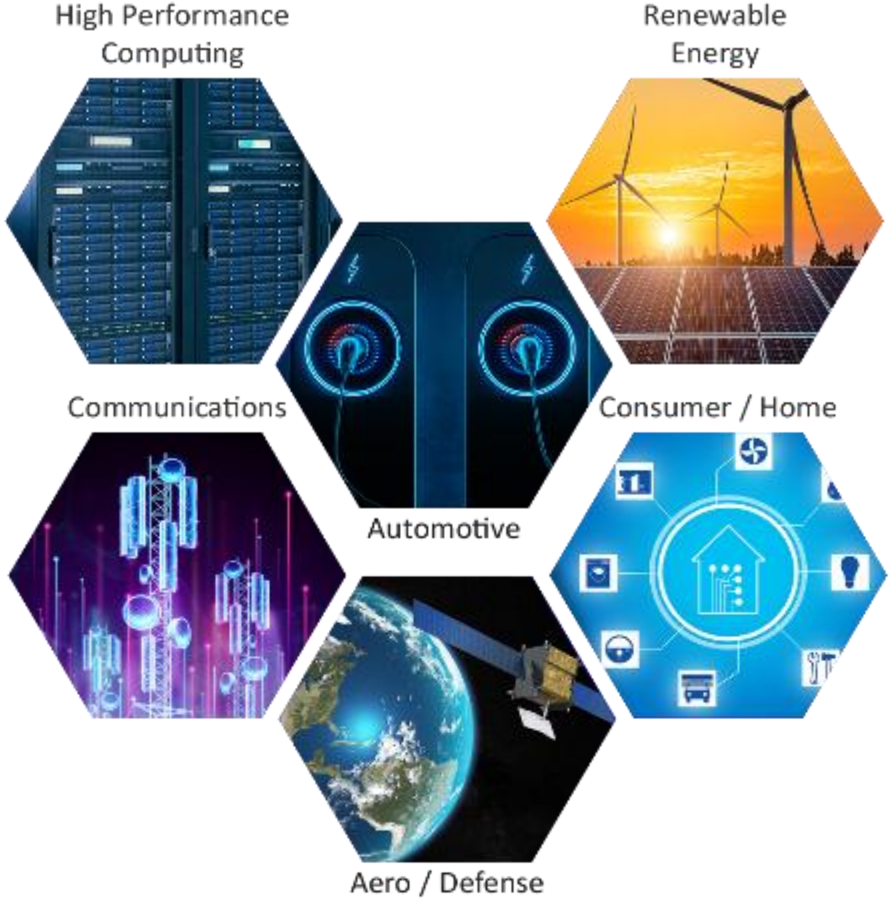
# Outline

1. Introduction, background and motivation
2. Device technology
3. DC & RF characteristics
4. Analysis on $f_T$ and $f_{max}$ & Benchmarking
5. Conclusion

# GaN Devices for RF and Beyond

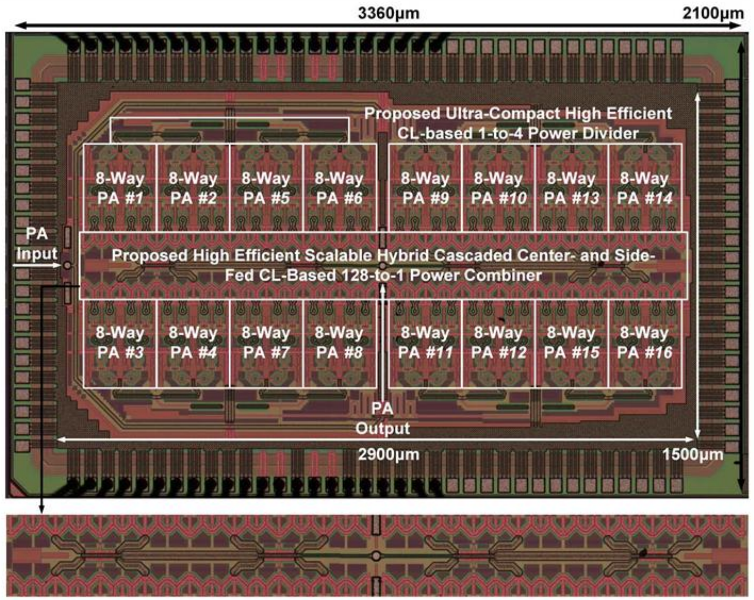

## Efficient & High Data Rate Design

1. Terabits/sec Data Rates
2. Less Spectrum Crowding
3. Smaller Circuit Footprint

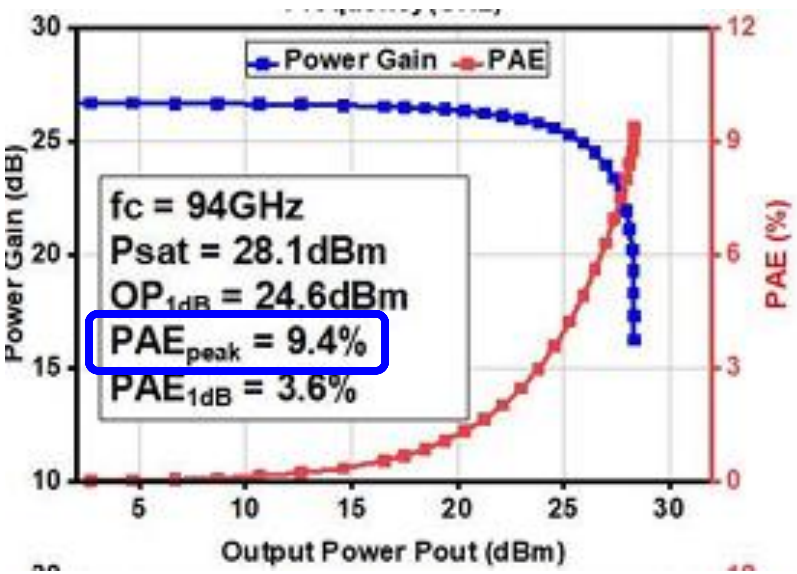



# Inefficiency in Sub-THz Si CMOS PAs

**Si CMOS**



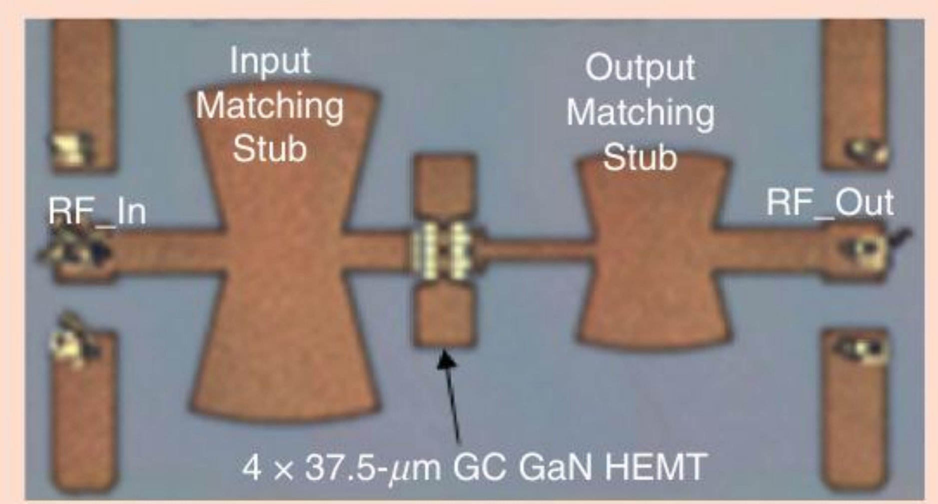

**128-way power Combiner!**



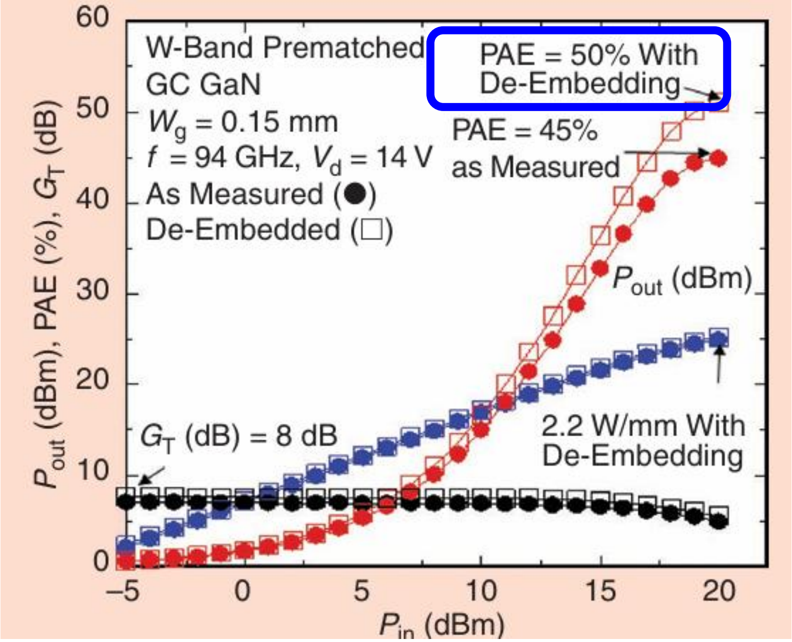

**128 devices in 65nm CMOS**

ISSCC-2022

**GaN**




**GaN HEMTs w/ Mini-FP Graded barrier**

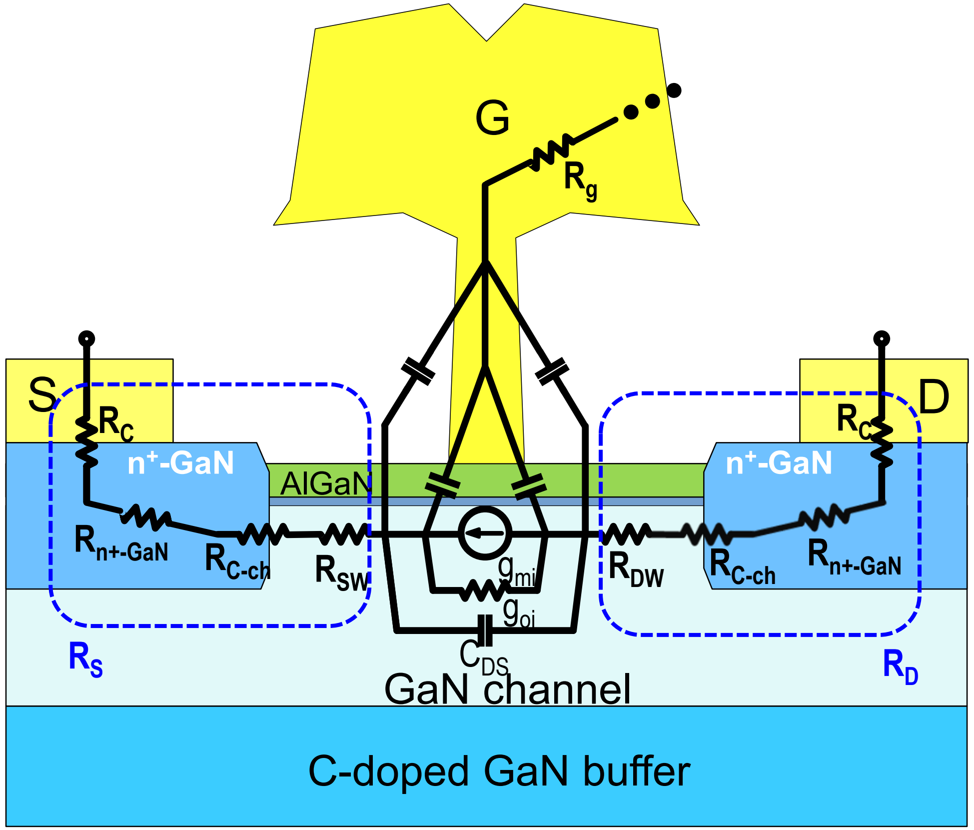



**Single Device Performance!**

- **5x better PAE**
- **Improved Linearity**
- **Low NF at W-band**

MGWL-2022

# Moving to Sub-THz GaN HEMTs & *How?*




RF FOMs (Figures of merit),

$$f_T = \frac{1}{2\pi} \frac{g_{mi}}{C_{gs} + C_{gd} + g_{mi}(R_s + R_D)\{C_{gd} + (C_{gs} + C_{gd})\frac{g_{oi}}{g_{mi}}\}}$$

$$f_{max} = \frac{f_T}{2\sqrt{(R_i + R_s + R_g) \cdot g_{oi} + (2\pi f_T) \cdot R_g \cdot C_{gd}}}$$

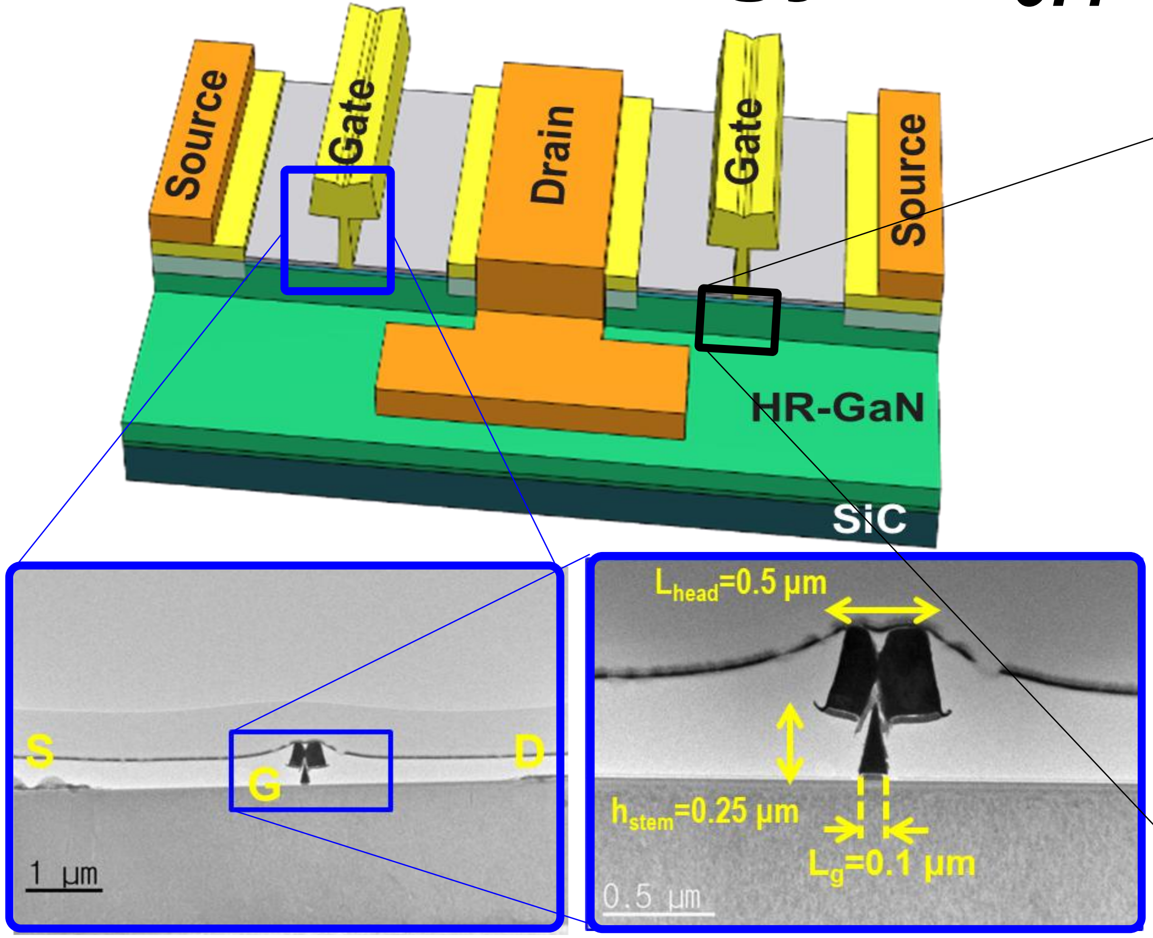
$$NF_{min} \approx 1 + K_f \cdot f \cdot \sqrt{\frac{4\pi^2 \cdot (C_{gs} + C_{gd})^2 \cdot (R_g + R_s)}{g_m}}$$

For multi-discipline applications, it is critical to improve $f_T$, $f_{max}$ & $NF_{min}$.

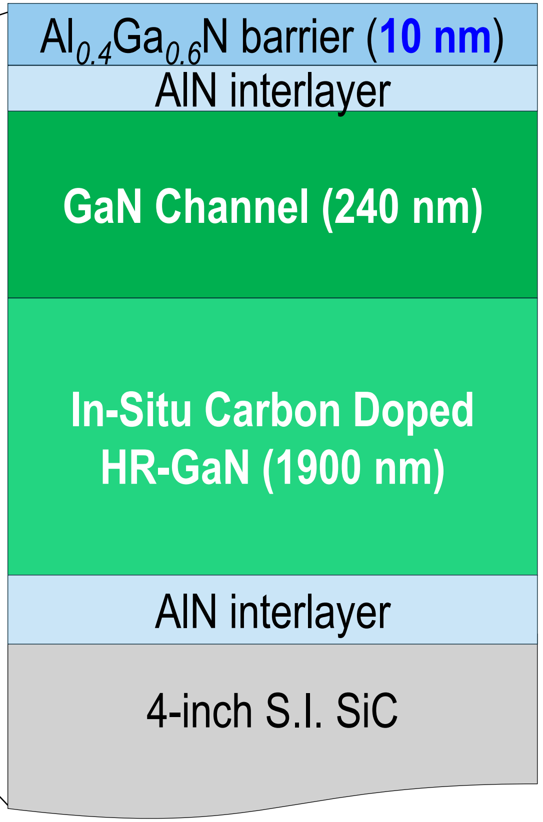
**Goals**: ① To demonstrate sub-THz GaN HEMTs w/ ***$f_{max}$* ~ 500 GHz**.

② To explore **the ultimate scaling limit on *$f_{max}$***.

# Device technology: $Al_{0.4}Ga_{0.6}N/GaN$ HEMTs on SiC




< Epi structure >

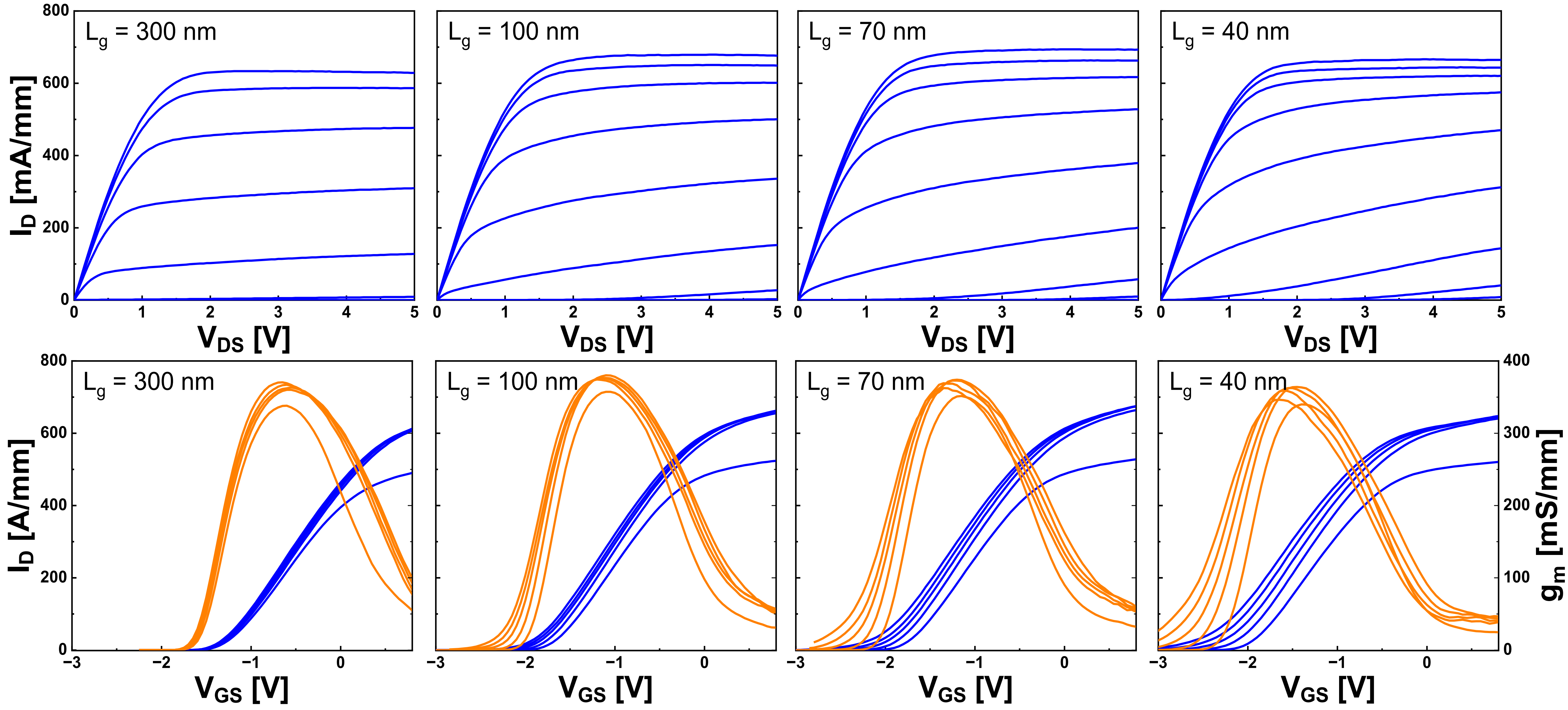



< Fabrication process >

- **Mesa isolation:**
  $Cl_2$-based ICP etching
- **Ohmic formation:**
  1) Ti/Al/Ni/Au deposition
  2) RTA Annealing
- **Pad formation:**
  Ti/Au deposition
- **Surface passivation:**
  $SiN_x$ deposition by PECVD
- **T-gate formation:**
  1) ZEP/PMGI/ZEP coating
  2) E-beam lithography
  3) Gate $SiN_x$ opening
  4) Ni/Au deposition

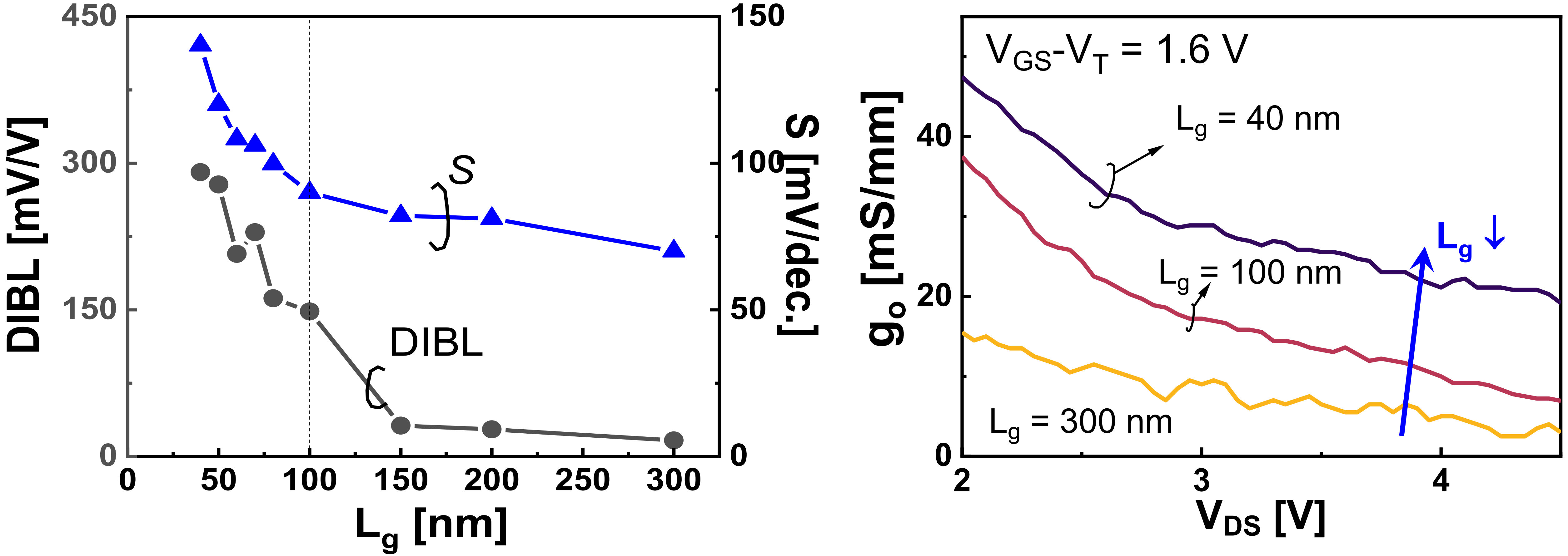
- Full 4-inch wafer-level integration with alloyed S/D contacts: $\boldsymbol{\rho_c < 3\times10^{-6}\ \Omega\cdot cm^2}$
- Aggressively scaled devices with $L_g$ **from 300 nm to 40 nm** & $t_{barrier}$ **~ 11 nm**

# $L_g$ scaling behavior: Output, transfer & $g_m$




$g_{m\_max}$ @$V_{DS}$ = 5 V | 370 mS/mm | **380 mS/mm** | 374 mS/mm | 364 mS/mm

# Short-channel effects (*SCEs*): *DIBL*, *S*, $g_{o\_ext}$

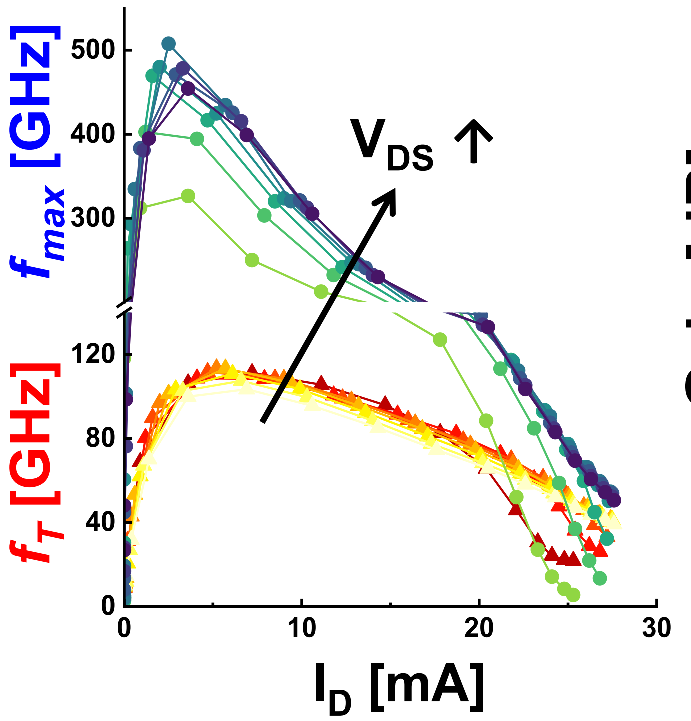



- Short-channel effects (*SCEs*) kicked in @$L_g$ ~100 nm and below.

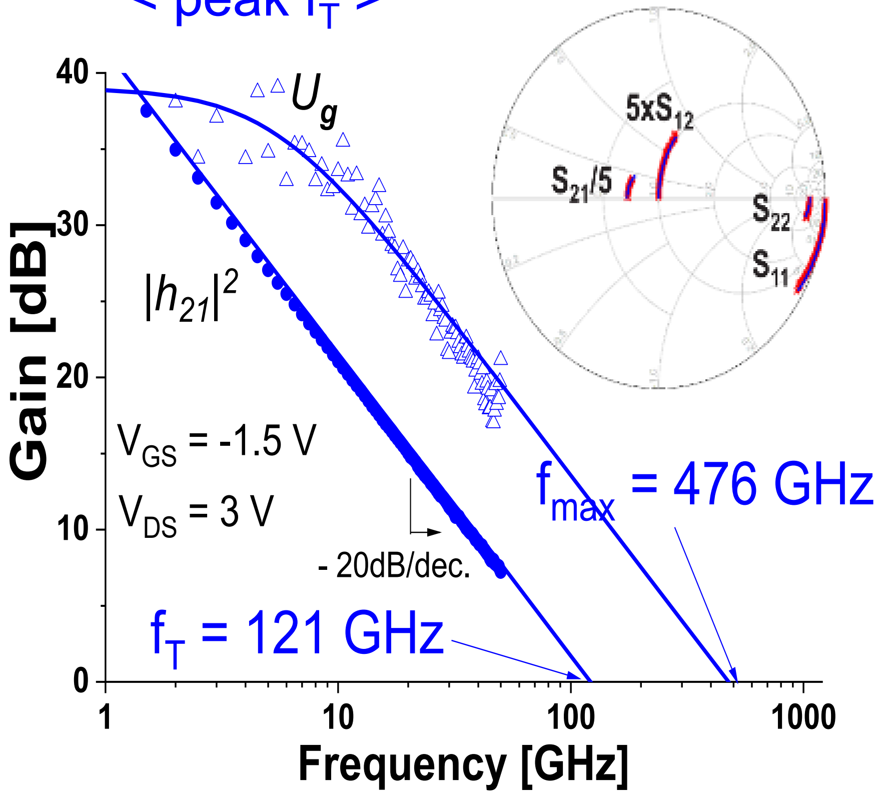
  ⇒ **Enlarged $g_o$**, causing to degrade $f_{max}$ (*will be discussed*)

# RF characteristics: $L_g$ = 70 nm

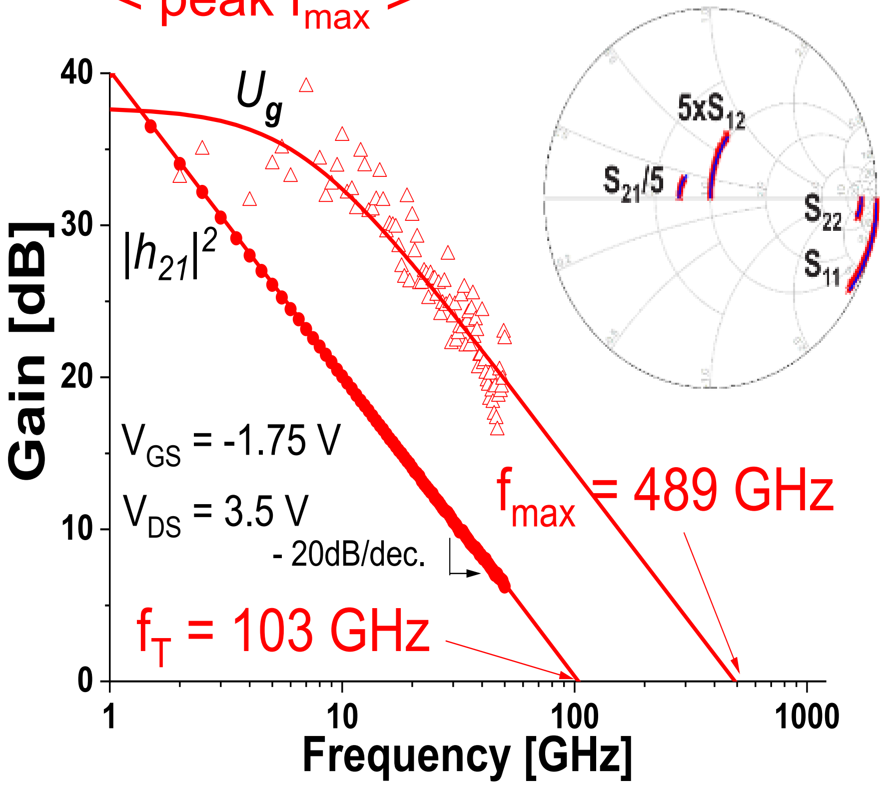
< $f_T$, $f_{max}$ vs. $I_D$ >




< peak $f_T$ >



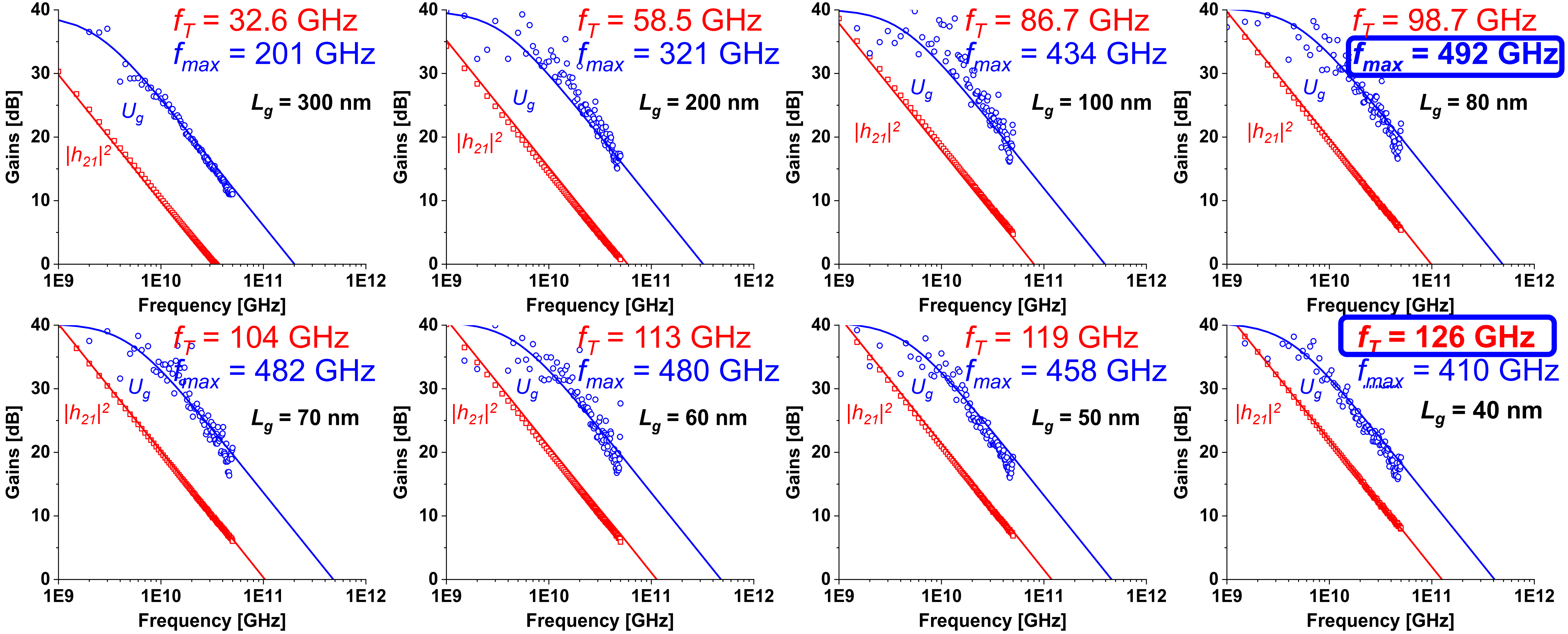

< peak $f_{max}$ >




| $V_{GS}/V_{DS}$ [V] | $R_s/R_d$ [Ω] | $R_g$ [Ω] | $g_{mi}$ [mS/mm] | $g_{oi}$ [mS/mm] | $C_{gs}$ [fF/mm] | $C_{gd}$ [fF/mm] | $C_{ds}$ [fF/mm] | $g_{mi}/g_{oi}$ | $C_{gs}/C_{gd}$ | $f_T$ [GHz] | $f_{max}$ [GHz] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -1.5/3 | 19.25 | 1.2 | 445 | 43.8 | 490 | 50.5 | 2.5E-13 | 10.2 | 9.7 | **121** | 476 |
| -1.75/3.5 | 19.25 | 1.2 | 317 | 32 | 405 | 45 | 2.5E-13 | 9.9 | 9.0 | 103 | **489** |

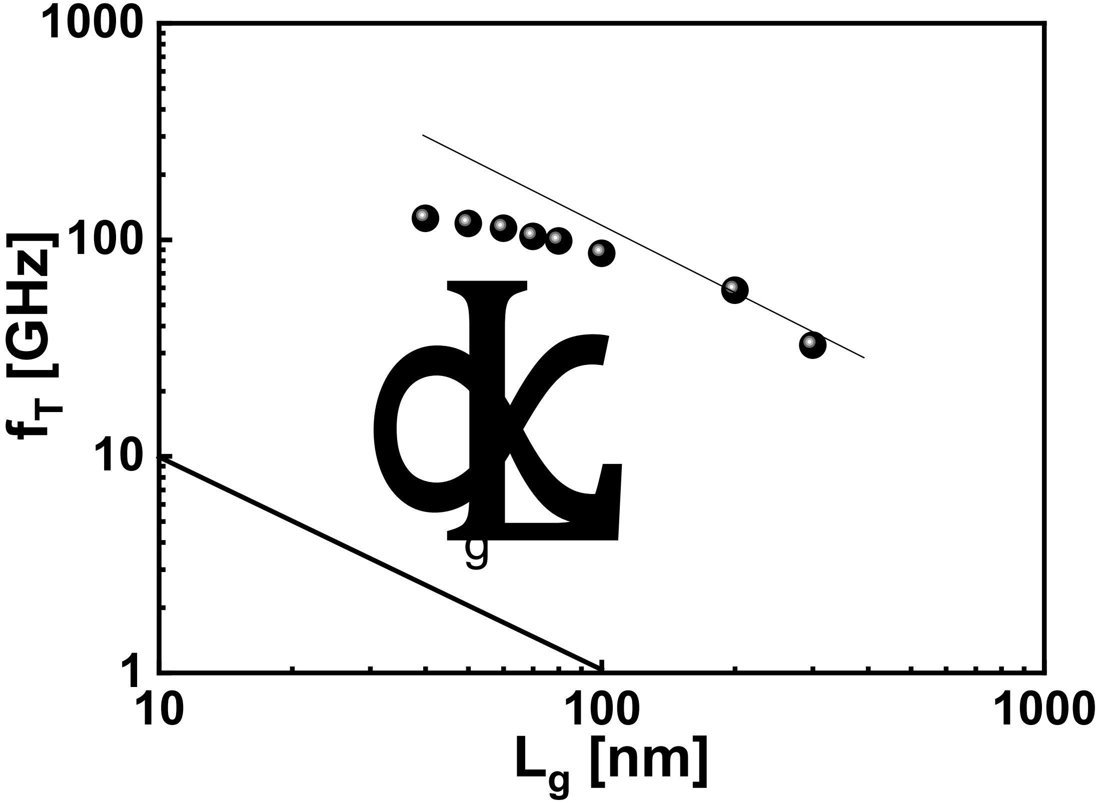
- **Peak $f_T$ = 121 GHz & $f_{max}$ = 489 GHz!**

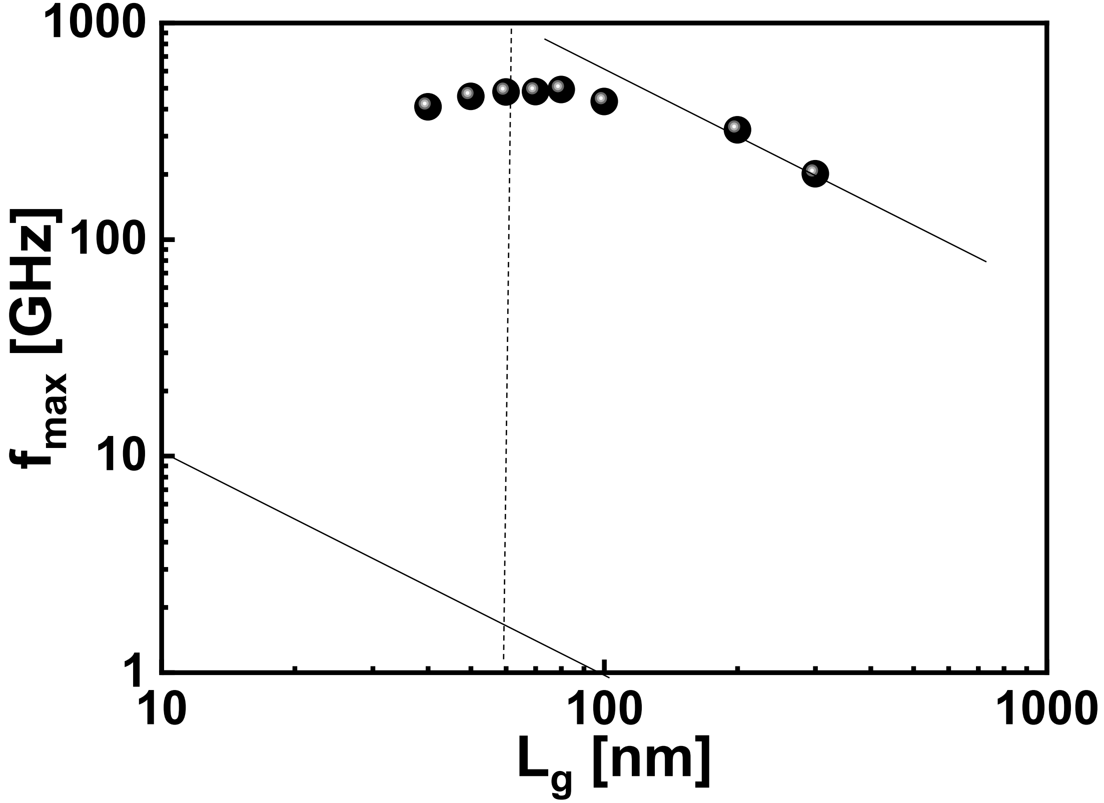
# $L_g$ scaling behavior of $f_T$ & $f_{max}$ (1)




- As $L_g$↓,
  - $f_T$ continued to increase, but **$f_{max}$ showed its peak at $L_g$ ~ 80 nm.**

# $L_g$ scaling behavior of $f_T$ & $f_{max}$ (2)




- For $L_g$ ~ 300 nm, $f_T \propto 1/L_g \rightarrow f_T$ is governed by ***velocity saturation*.**

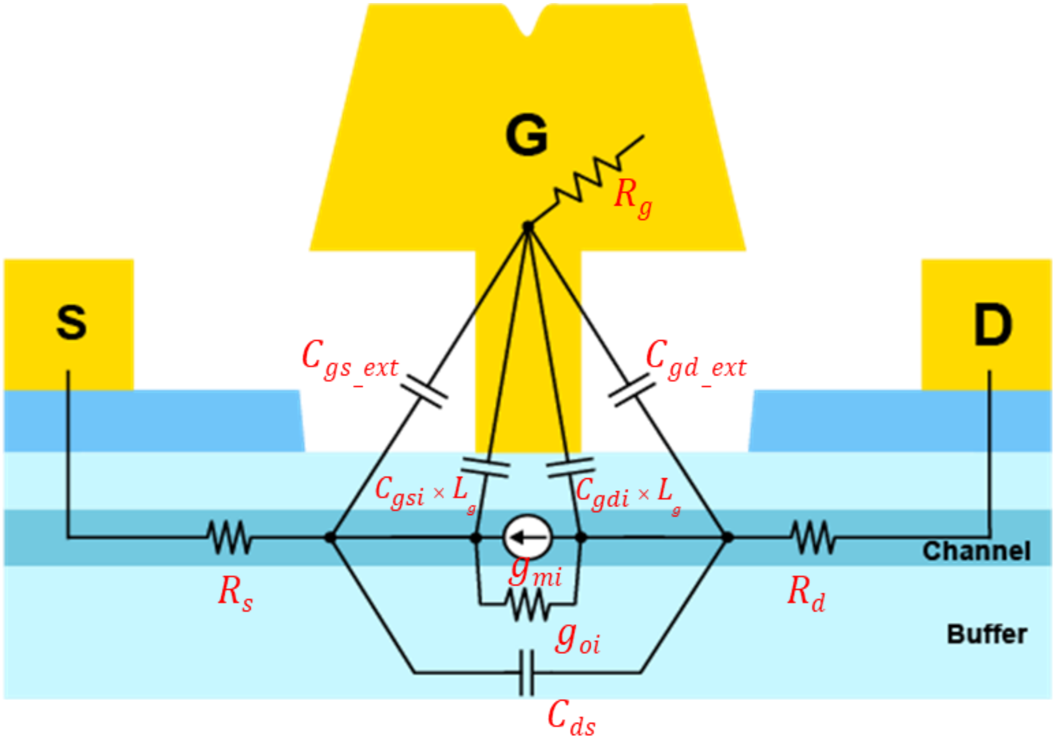
  $\Rightarrow$ helped improve $f_{max}$ accordingly.

- For $L_g$ < 100 nm, $f_T$ started to be dominated by other delay ($\tau_{ext}$).

  $f_{max}$ showed its peak at $L_g$ ~ 80 nm and degraded…

# Analysis of delay time (1)

* Jo *et al.*, IEDM 2020.




First order $f_T$ formula:

$$f_T = \frac{1}{2\pi} \frac{g_{mi}}{C_{gs}+C_{gd}+g_{mi}(R_s+R_d)[C_{gs}+(C_{gs}+C_{gd})\frac{g_{oi}}{g_{mi}}]}$$

$$C_{gs} = C_{gsi} \times L_g + C_{gs\_ext} \quad \& \quad C_{gd} = C_{gdi} \times L_g + C_{gs\_ext}$$

Delay time (τ):

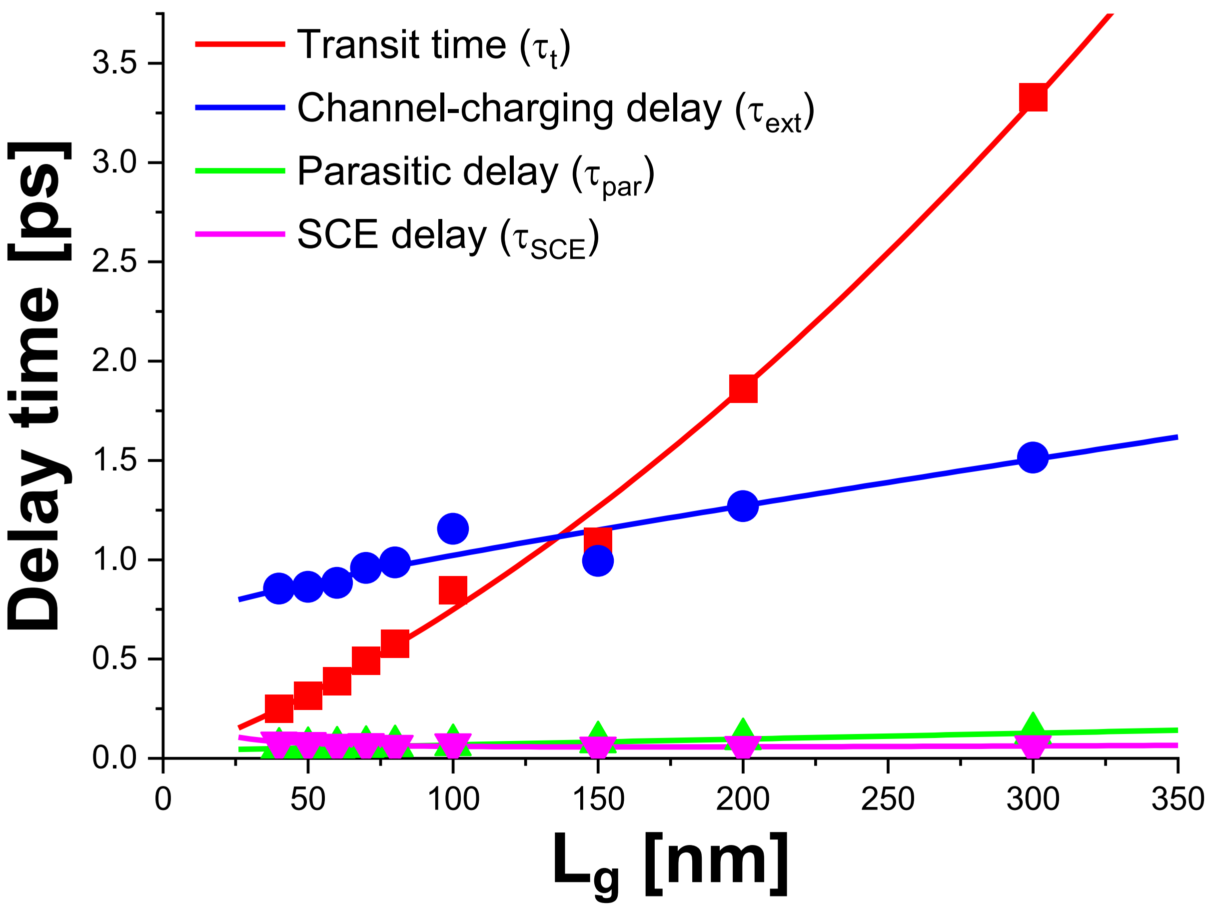
$$\tau = \frac{1}{2\pi f_T} = \frac{C_{gs}+C_{gd}}{g_{mi}} + (R_s + R_d)[C_{gd} + (C_{gs} + C_{gd})\frac{g_{oi}}{g_{mi}}]$$

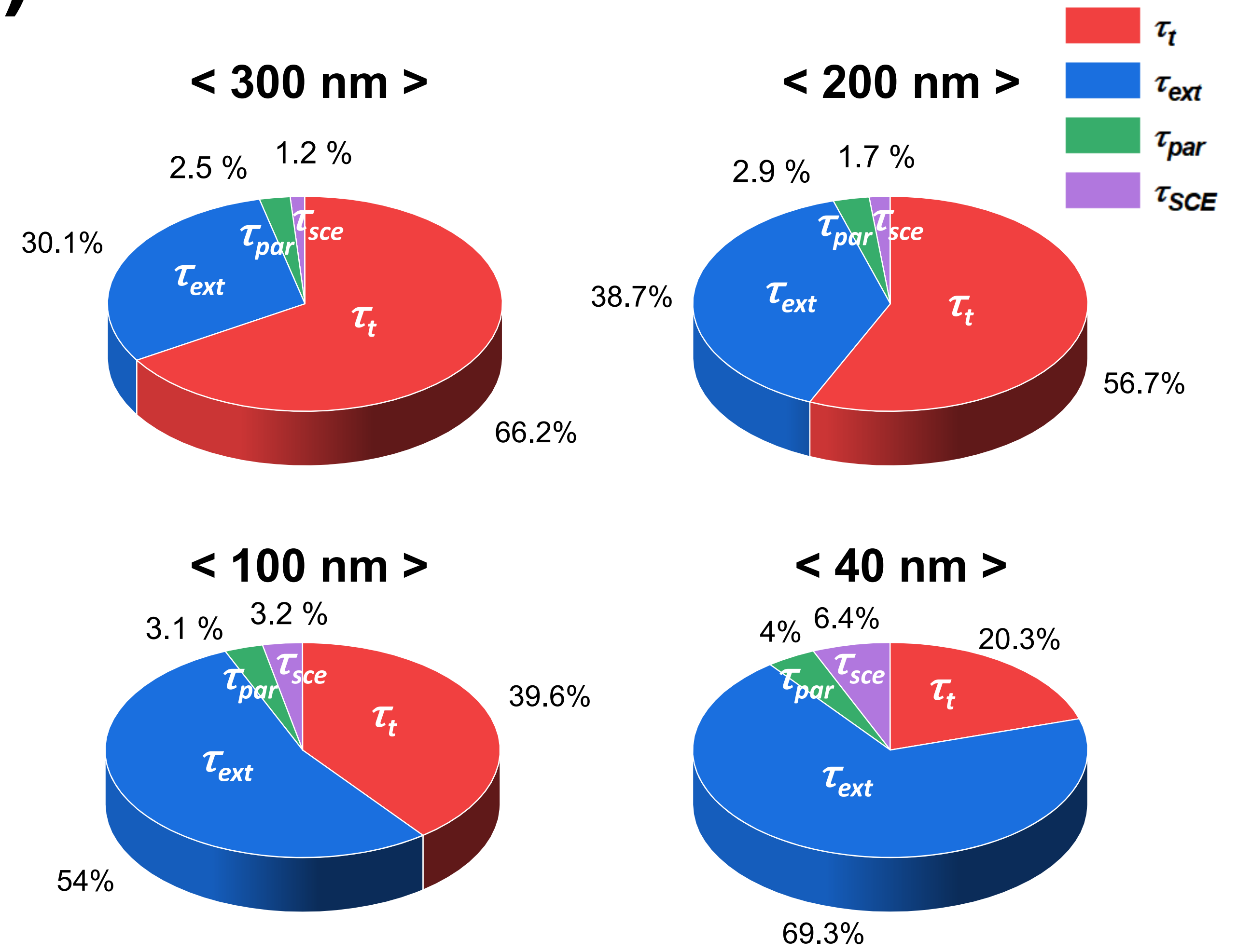
$$= \frac{(C_{gsi} + C_{gdi})}{g_{mi}} \times L_g + \frac{(C_{gs\_ext} + C_{gd\_ext})}{g_{mi}} + (R_s + R_d)\left[C_{gd} + (C_{gs} + C_{gd})\frac{g_{oi}}{g_{mi}}\right]$$

$$= \frac{(C_{gsi} + C_{gdi})}{g_{mi}} \times L_g + \frac{(C_{gs\_ext} + C_{gd\_ext})}{g_{mi}} + (R_s + R_d)C_{gd} + (R_s + R_d)(C_{gs} + C_{gd})\frac{g_{oi}}{g_{mi}}$$

Transit time ($\tau_t$) | Channel-charging delay ($\tau_{ext}$) | Parasitic delay ($\tau_{par}$) | SCE delay ($\tau_{SCE}$)

# Analysis of delay time (2)

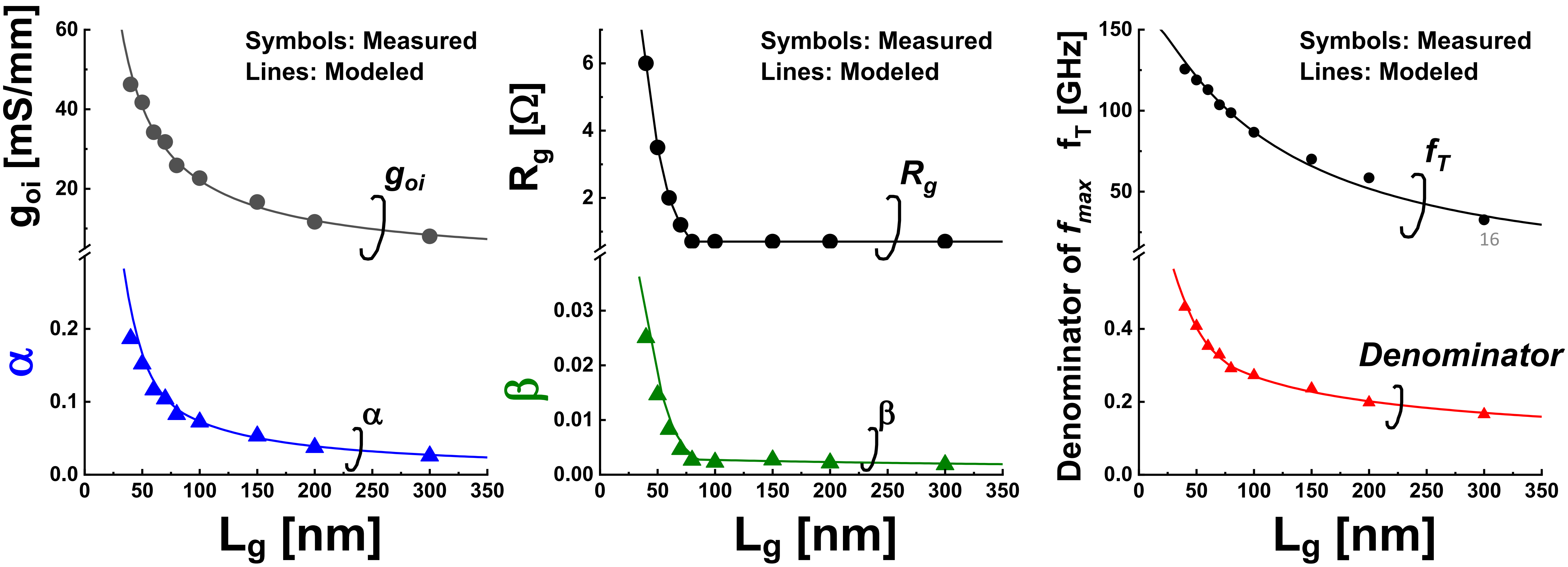



- For $L_g$ ~ 150 nm, reduction of $\tau_T$ helped to improve $f_T$.
- For $L_g$ = 40 nm, $\tau_{ext}$ was the most significant ⇒ ***69 %...***

# How about $f_{max}$?

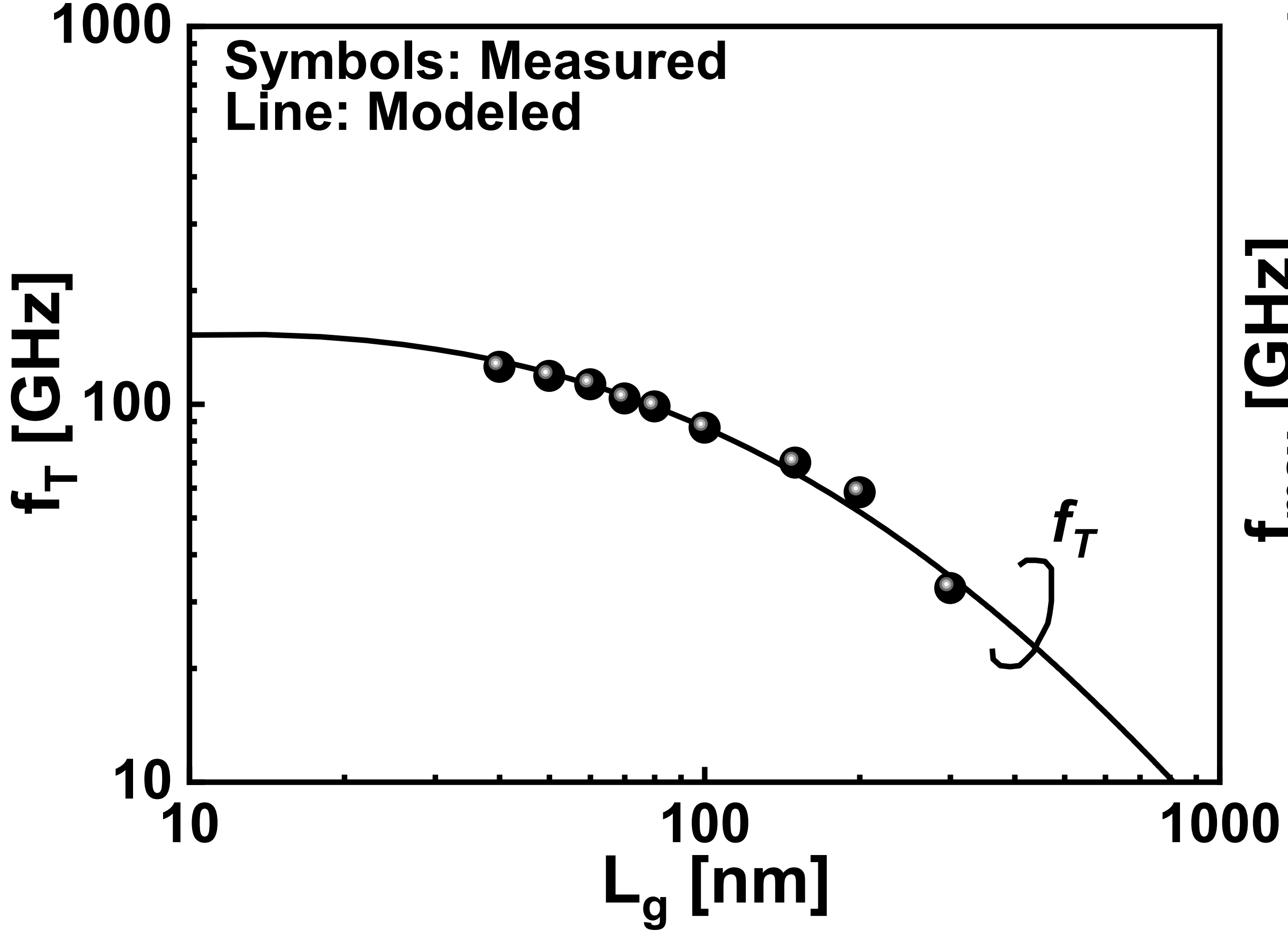
$$f_{max} = \frac{f_T}{\sqrt{\underbrace{4(R_i + R_s + R_g)\cdot g_{oi}}_{\alpha} + \underbrace{4(2\pi f_T)\cdot R_g \cdot C_{gd}}_{\beta}}}$$

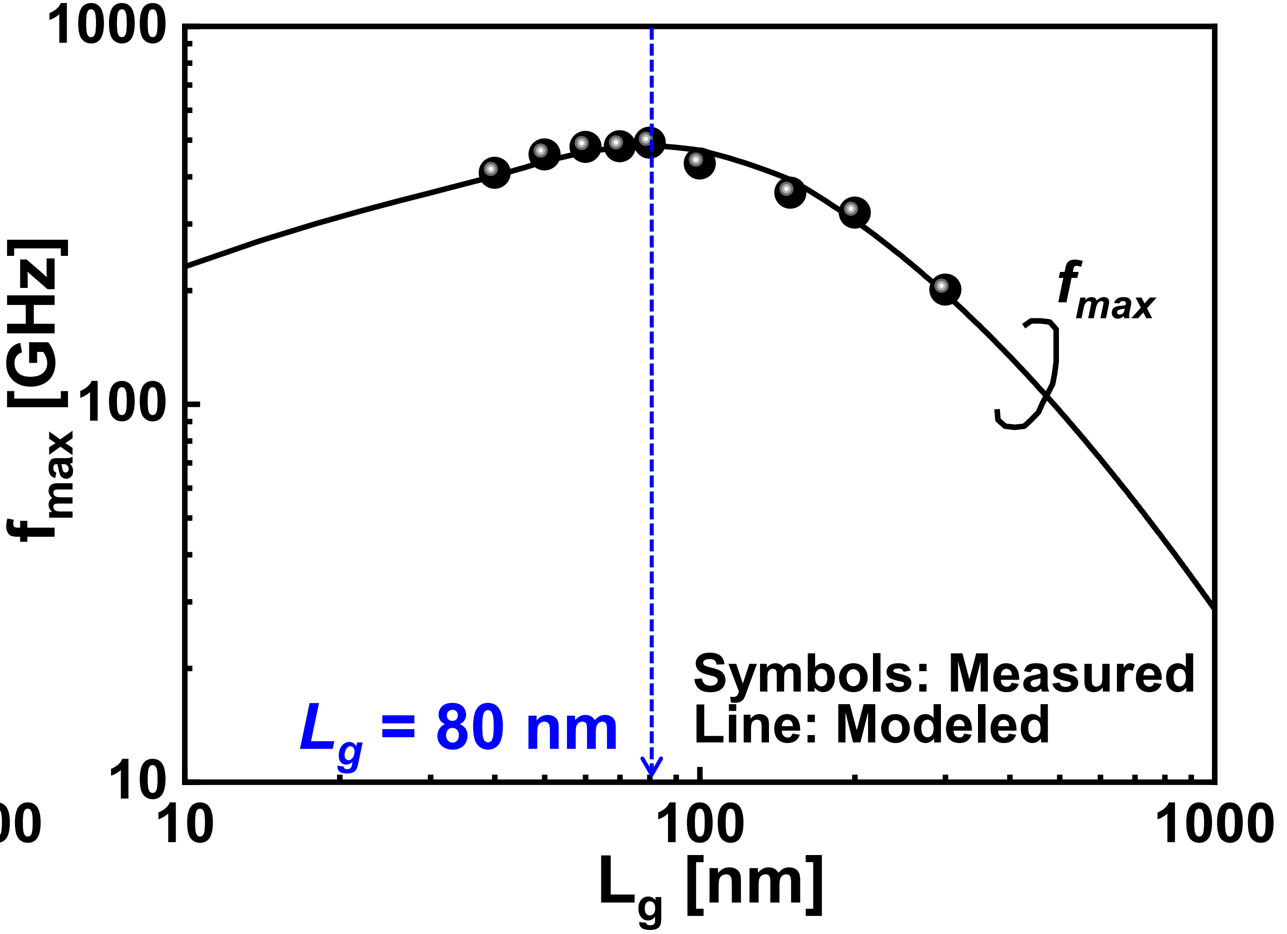



- As $L_g$↓, $f_T$ continued to increase, but the denominator of $f_{max}$ increased.

⇒ This was why no further improvement of $f_{max}$ for $L_g$ < 80 nm.

# Modeled $f_T$ and $f_{max}$ against $L_g$




- The modeled $f_T$ & $f_{max}$ were in excellent agreement with the measured!

# Benchmarking

| | $L_g$ | $t_{ins}$ | $R_{ON}$ | $g_{m\_max}$ | $R_S/R_D$ | $R_g$ | $g_{mi}$ | $g_{oi}$ | $g_{mi}/g_{oi}$ | $C_{gs}$ | $C_{gd}$ | $C_{gs}/C_{gd}$ | $f_T$ | $f_{max}$ | $f_{max}$ x $L_g$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [nm] | [nm] | [Ω-mm] | [mS/mm] | [Ω-mm] | [Ω-mm] | [mS/mm] | [mS/mm] | | [fF/mm] | [fF/mm] | | [GHz] | [GHz] | [GHz-μm] |
| This work | 80 | 10 | 1560 | 391 | 0.77 | **0.028** | 323 | 26 | **12.5** | 445 | 45 | **9.9** | 98.7 | **492** | **39** |
| HRL | 50 | 4 | N/A | 466 | N/A | **N/A** | 466 | 47.6 | **9.8** | 336 | 86 | **3.9** | 170 | **363** | 18.1 |
| HRL | 50 | 8 | N/A | 667 | N/A | **N/A** | 667 | 52.6 | **12.7** | 501 | 200 | **2.5** | 153 | **300** | 15 |
| Taiwan Univ. | 265 | 23.5 | 2.45 | 291 | 0.75/1.01 | **0.21** | 317 | 21.8 | **14.5** | 911 | 122.8 | **7.4** | 43.7 | **126** | 34 |
| Renesas | 160 | 20.5 | N/A | 260 | 0.75/0.82 | **0.32** | 350 | 24.9 | **14.0** | 540 | 83 | **6.5** | 63 | **226** | 36 |
| OMMIC | 90 | 12.5 | N/A | 440 | 0.48/1.09 | **0.66** | 627 | 37 | **16.9** | 734 | 92 | **8.0** | 100 | **206** | 19 |
| Tsing Hua Univ. | 110 | 12 | 2.5 | 189 | 0.98/1.03 | **0.06** | 220 | 28.4 | **7.7** | 660 | 110 | **6** | 60 | **101** | 11 |

- **Among the AlGaN/GaN HEMTs on SiC technologies, highest $f_{max}$ ~ 500 GHz**
  - excellent combination of $g_{mi}/g_{oi}$ ~ 12.5, $C_{gs}/C_{gd}$ ~ 9.9, $R_g$ ~ 0.028 Ω-mm
  - thanks to barrier scaling & excellent T-gate technology

# Conclusion

- Demonstrated sub-THz $Al_{0.4}Ga_{0.6}N$/GaN HEMTs on 4-inch SiC substrate.
  - Full 4-inch wafer-level integration with $L_g$ from 300 nm to 40 nm & $t_{barrier}$ ~ 11 nm.
- $L_g$ = 70 nm device exhibited:
  - $R_{ON}$ = 1.54 Ω·mm, $g_{m\_max}$ = 380 mS/mm & *DIBL* = 148 mV/V, S = 139 mV/dec.

  → *Short-channel effects started to kicked in & Enlarged $g_{o\_ext}$ by x4.*
- Explored $L_g$ scaling behavior of $f_T$ & $f_{max}$.
  - As $L_g$↓ → Helped to reduce $\tau_t$ => **peak $f_T$ = 126 GHz with $L_g$ = 40 nm**.
  - For $L_g$ = 80 nm, **peak $f_{max}$ = 489 GHz**.
- Analyzed the physics-based ultimate scaling limit of $f_T$ & $f_{max}$.
  - $\tau_{ext}$ most significant for further improving $f_T$, calling for $g_{mi}$ improvement!
  - $g_{oi}$ played a critical role in $f_{max}$ → *strict control of SCEs would be most imperative*!

**Highest $f_{max}$, thanks to excellent combination of $g_{mi}/g_{oi}$ ~ 9.9 & $C_{gs}/C_{gd}$ = 9!**

# Thank You