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Electron delay analysis and image charge effect in AlGaN/GaN HEMTs on HR-Si(111)

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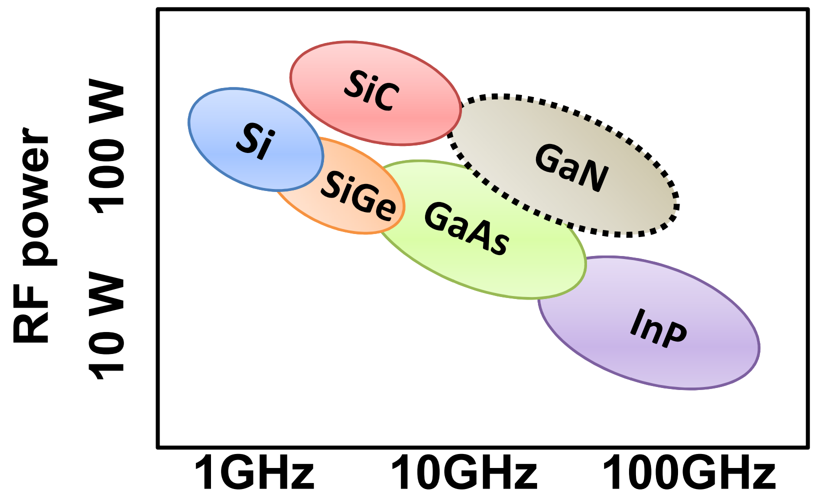
Introduction

This study regards the physical analysis of AlGaN/GaN HEMTs

Why AlGaN/GaN HEMTs ?

- High power at high frequency
- High Breakdown Voltage (BV)
- 2DEG with good electrical properties



How to determine the key factors in order to improve the frequency performance of AlGaN/GaN HEMTs ?

Transit time & small signal analysis !

Mirroring coefficient (α) extraction

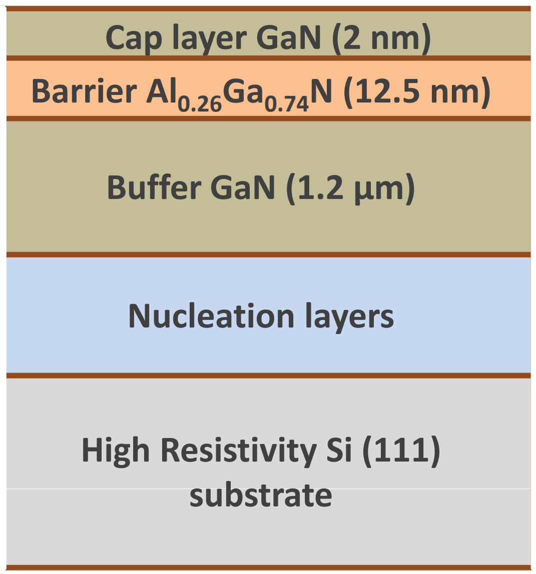
Outline

1) **Device structure and fabrication**
    - Material
    - Process
2) **Device characterization**
    - DC & RF characteristics
    - Transit time analysis
3) **Image charges extraction**

Conclusion & Perspective

Material

Epitaxy was grown by MOCVD

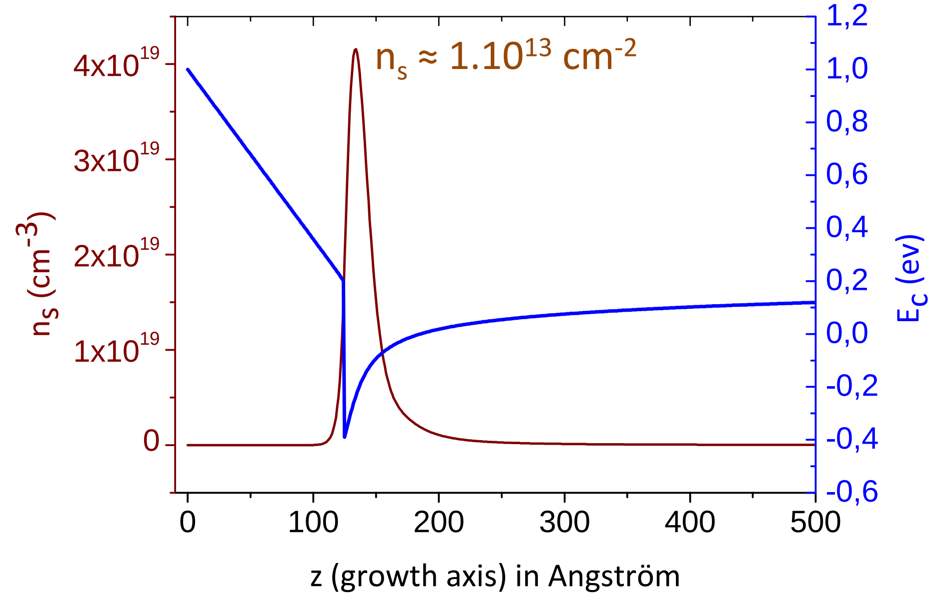


van der Pauw Measurement

- High sheet carrier density (n_s=1.17 10^{13} cm^{-2})
- High carrier mobility (µ=2000 $cm^2.V^{-1}.s^{-1}$)
- Low sheet resistance ($R_\square$=314Ω)

GOOD AGREEMENT ☺

Band diagram



Process

❖ Ohmic contacts

- Ti/Al/Ni/Au metal stack (12/200/40/100 nm)
- Rapid Thermal Annealing : 850°C for 30s

$R_c = 0.45\ \Omega.mm$ and $\rho_c = 10^{-6}\ \Omega.cm^2$

❖ Isolation

He^+ ion multiple implantation

Isolation current < 10 nA at 100V (5µm spacing)

❖ Schottky contacts

- Ti/Al/Ti metal stack
- Tri-layer resist stack (PMMA/Copolymer/PMMA)
- Double-T-shaped gate with 90 nm footprint by electron beam lithography

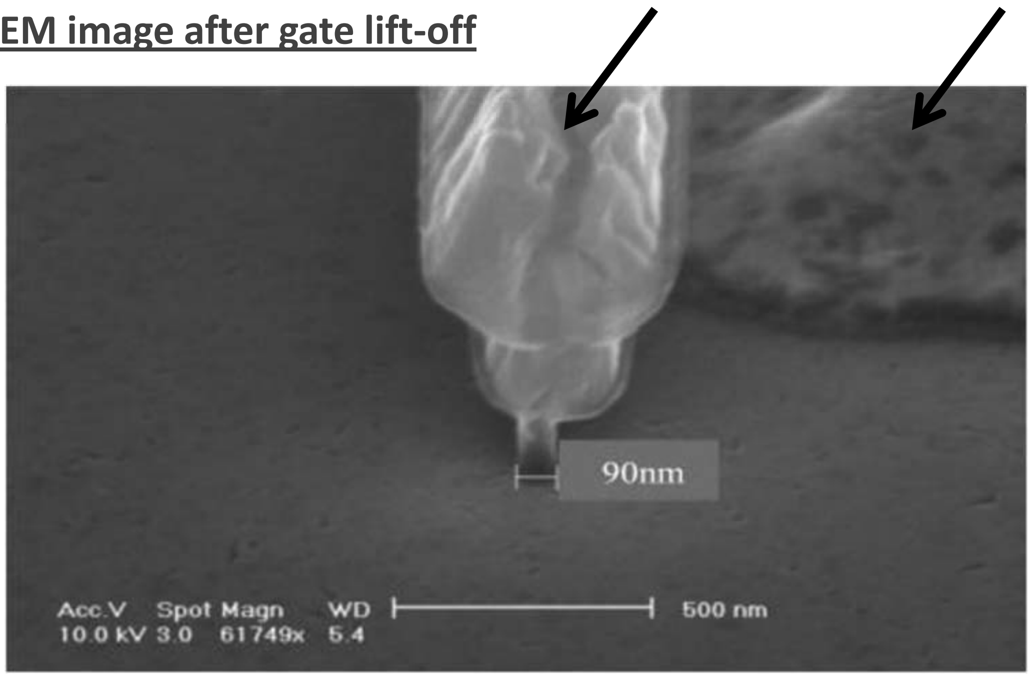
❖ Passivation

SiN (50nm) deposited by PECVD at 300°C

❖ Contact pads Ti/Au (30/100 nm)

Process

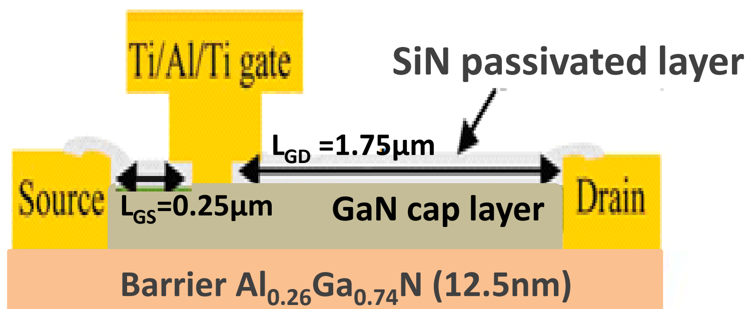
SEM image after gate lift-off



Double-T-shaped gate

Narrow gate foot with large cross-sectional area and close to the source contact

- Reduction of gate resistance R_g
- Low parasitic capacitance C_{gs} and C_{gd}
- High extrinsic transconductance g_m



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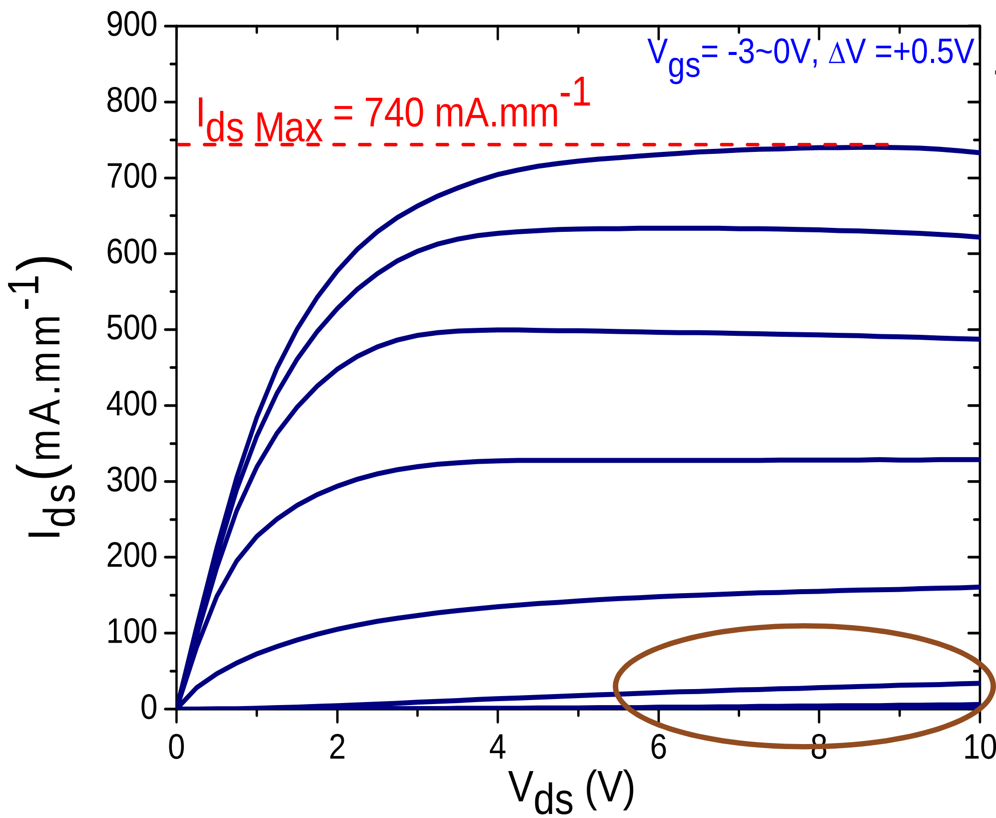
DC characteristics

The measurement was performed using an Agilent SMU

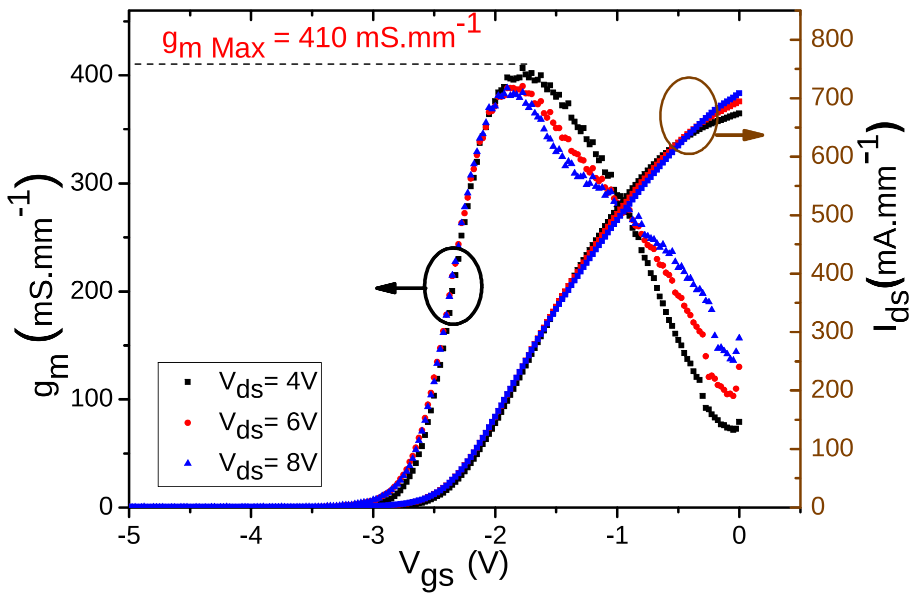


I_{ds}-V_{ds} characteristic of AlGaN/GaN HEMT (L_g = 90nm)

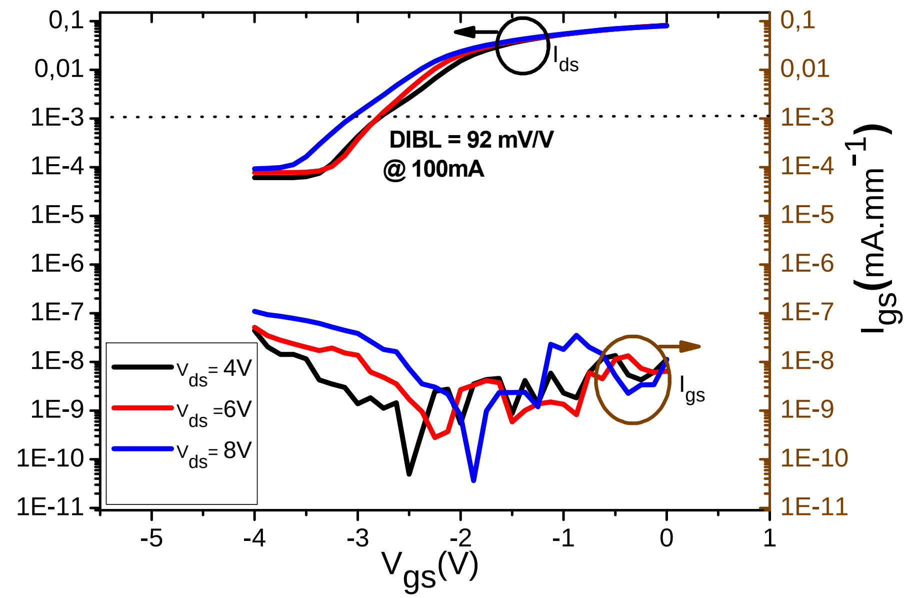
- **Good I_{ds} for $Al_{0.26}Ga_{0.74}N/GaN$**
- **Short channel effects at V_{gs} = -2.5V**

DC characteristic

Transfer characteristics



I_{ds}-V_{gs} characteristic



- $g_{m\ Max}$ = 410 mS.mm^{-1} (ext)
- $V_{pinch\text{-}off}$ = -2.8V

- I_{on} / I_{off} = 10^4
- Good pinch-off not impacted by parasitic gate current leakage
- Short channel effect (DIBL = 92 mV/V)

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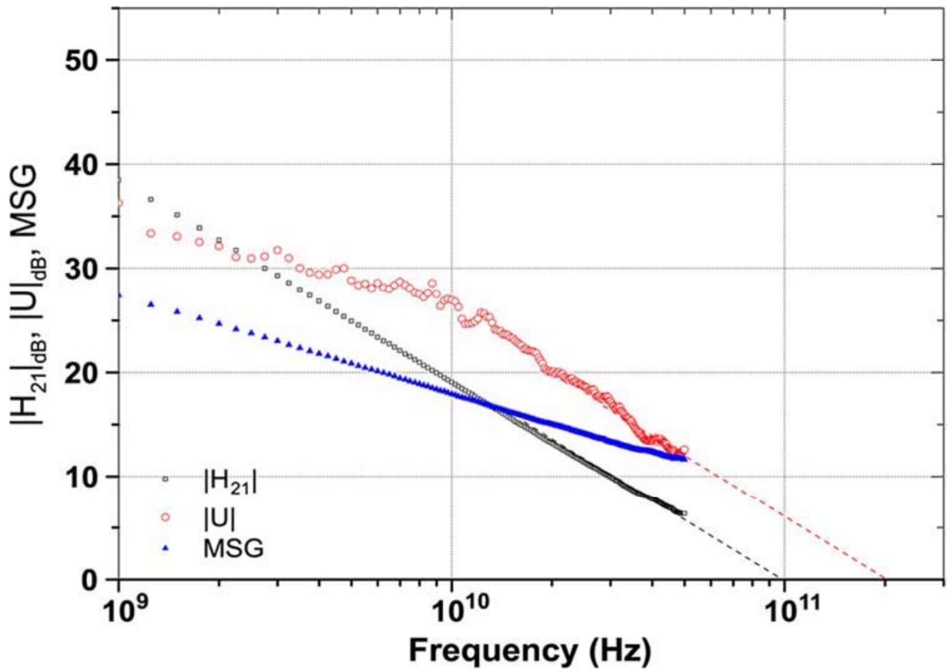
RF characteristic

Transfer characteristics



- Agilent N5245A VNA
- Standard LRRM calibration from 0.25 to 55 GHz
- Open, Short dummy structure de-embbeding method

Current gain $|H_{21}|$ ⟶ F_t = 100 GHz

Mason unilateral gain $|U|$ ⟶ F_{MAX} = 206 GHz

$F_{MAX} / F_t \approx 2$

IEEE Publication as best power gain cut-off frequency (F_{Max}) performance for AlGaN/GaN HEMTs on Si(111) substrate [1]

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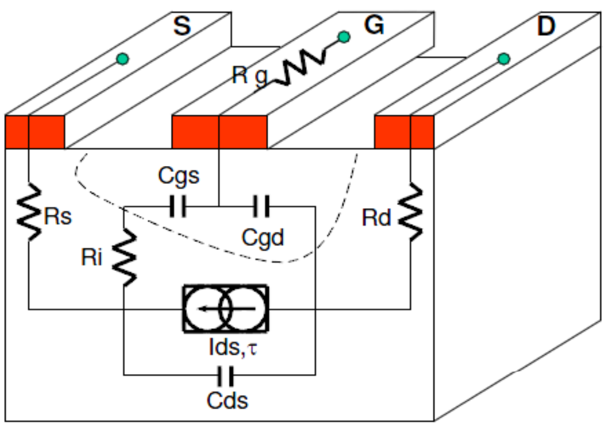
[1] S. Bouzid-Driad et al,"AlGaN/GaN HEMTs on Silicon Substrate With 206-GHz FMAX," IEEE Transactions on Electron Devices, vol. 34, no. 1, January 2013.

Transit time analysis

Total transit time (τ_{total}) is obtained by using Suemitsu Method [1]



Equivalent circuit

$$\tau_{total} = \tau_{int} + \tau_{drain} + \tau_{cc} \; (+\tau_{pads})$$

[illegible]

τ_{int} : transit time through the gate region

τ_{drain} : transit time through the depleted region extension towards drain

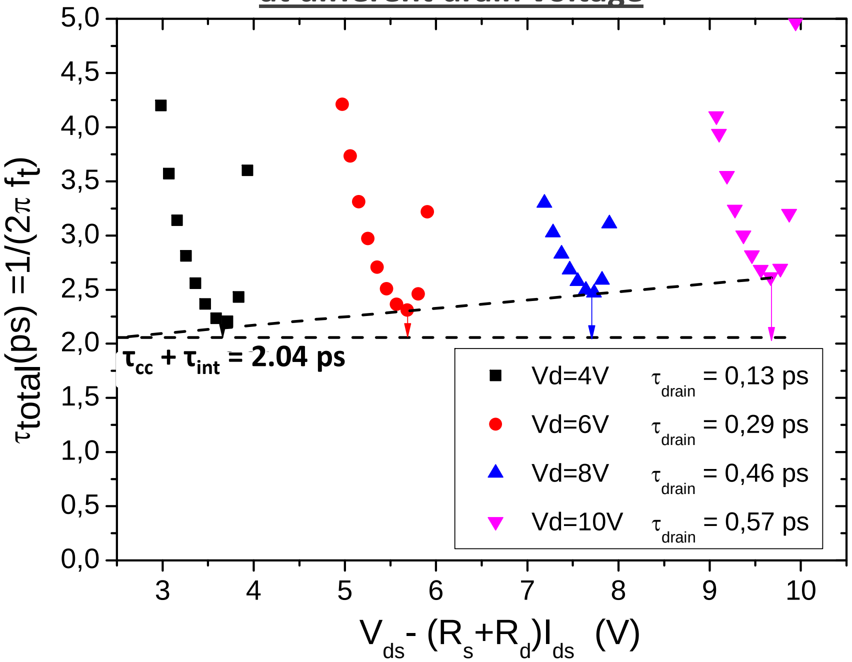
τ_{cc} : transit time due to the contribution of source and drain access resistances and parasitic capacitances

[1] T. Suemitsu et al, "Intrinsic Transit Delay and Effective Electron Velocity of AlGaN/GaN High Electron Mobility Transistors," Japanese Journal of Applied Physics,vol. 44, no. 6, pp. L 211–L 213, January 2005.

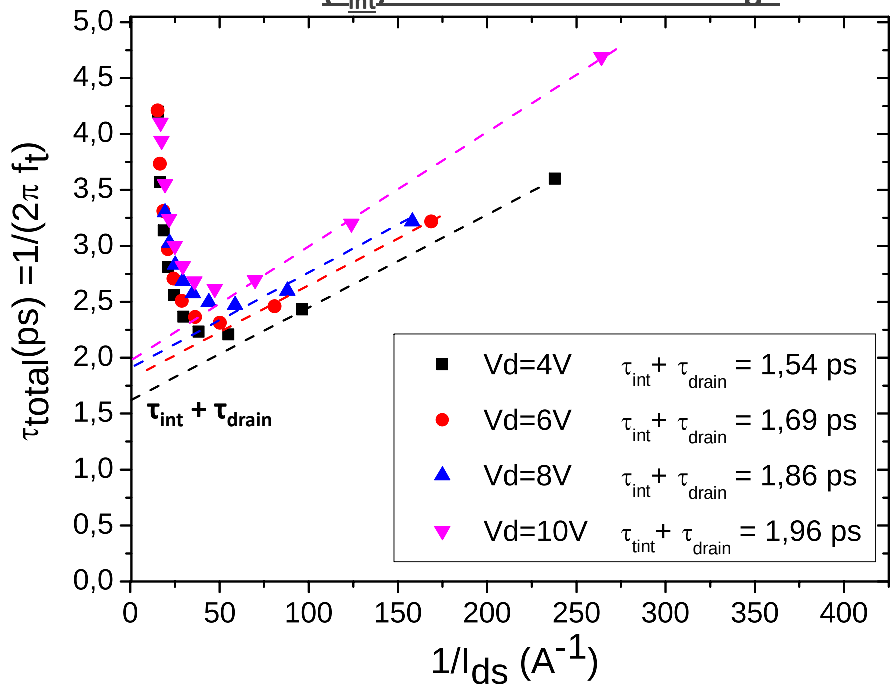
Transit time analysis

Different contributions of transit time were extracted using the cut-off frequencies (F_t) measured for different bias conditions sweeping both V_{gs} & V_{ds}

Measurement of drain delay time (τ_{drain}) at different drain voltage



Measurement of intrinsic delay time (τ_{int}) at different drain voltage



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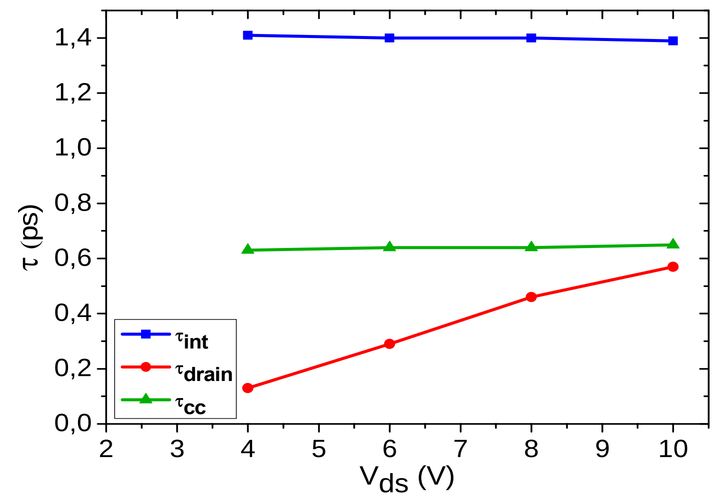
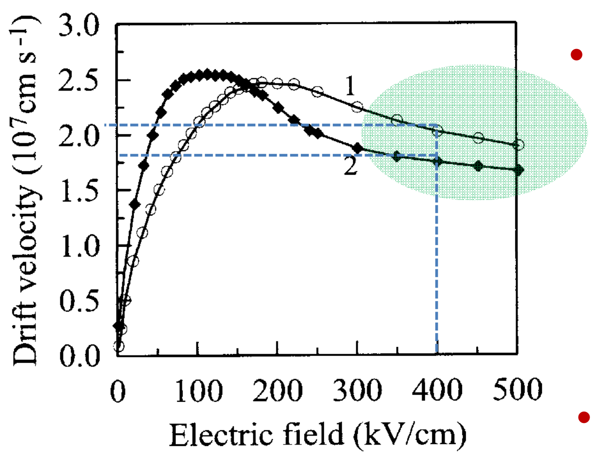
Transit time analysis

Experimental delay time contributions

V_{ds}	4V	6V	8V	10V
τ_{int} (ps)	1.41	1.4	1.4	1.39
τ_{drain} (ps)	0.13	0.29	0.46	0.57
τ_{cc} (ps)	0.63	0.64	0.64	0.65





- τ_{int} does not depend on V_{ds} → saturation electron velocity for V_{ds} > 4 V
  for V_{ds}= 4V E(400 KV/cm) > E_c

☺ Good agreement with theoretical critical electric field

- τ_{drain} increases with V_{ds} due to :
  - extension of drain depletion area
  - self heating effects impacting source and drain resistances

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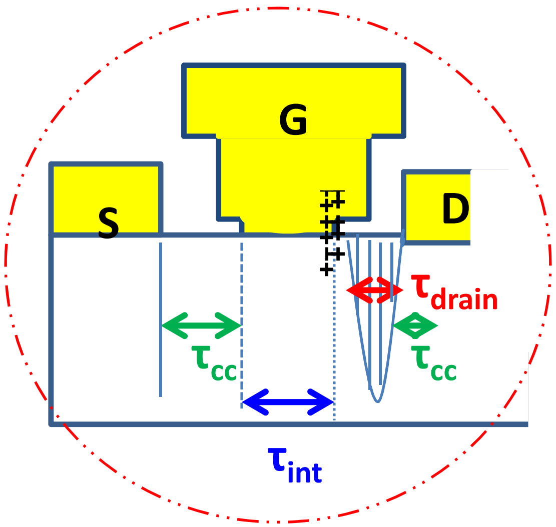
Image charges extraction

- τ_{drain} increases with V_{ds}
- τ_{drain} = time for e^- to cross the depletion region to the drain side of the gate
- This transport of the negative sheet of charges induces image charges (α)

→ τ_{drain} is directly affected by image charges



HEMT structure model

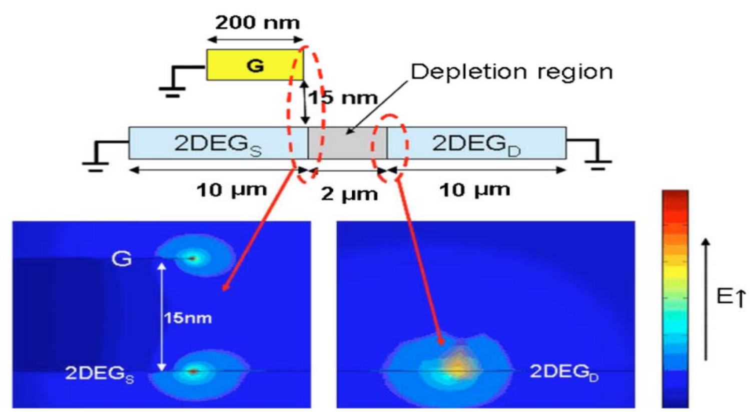


Illustration of HEMT structure model and resulting electric field after redistribution of image charges [1]

[1] T. Palacios et al, "High-power AlGaN/GaN HEMTs for Ka-band applications," IEEE Electron Device Letters, vol. 26, no. 11, pp. 781–783, November 2005.

Image charges extraction

τ_{drain} experimentally deduced permits to extract the image charges coefficient [1]

$$\tau_{drain} = \frac{W_D}{\alpha \times v_e}$$

W_D: drain depletion width

V_e: electron effective velocity

α: image charges coefficient

How to extract the effective electron velocity ?

How to extract the drain depletion width ?

[1] T. Palacios et al, “High-power AlGaN/GaN HEMTs for Ka-band applications,” IEEE Electron Device Letters, vol. 26, no. 11, pp. 781–783, November 2005.

Image charges extraction

How to extract the electron velocity used in $\tau_{drain} = \frac{w_D}{\alpha \times v_e}$?

$$v_e = \frac{L_{geff}}{\tau_{int}}$$

L_{geff} : effective gate length

τ_{int}: intrinsic delay time (measured)

No consensus was established about the L_{geff} consideration in the electron effective velocity extraction:

$$L_{geff} = L_g$$

$$v_e = 0.64.10^7 m.s^{-1}$$

$$L_{geff} = L_g + \beta . d_{2DEG}$$ [1]

$$v_e = 0.85.10^7 m.s^{-1}$$

More physical

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[1] P.C. Chao,et al. "DC and Microwave Characteristics of Sub-0.1 -pm Gate-Length Planar-Doped Pseudomorphic HEMT's IEEE Transactions on Electron Devices, vol. 36, no. 3, pp.461-473, March 1989.

Image charges extraction

How to extract the drain depletion width used in $\tau_{drain} = \frac{w_D}{\alpha \times v_e}$?

$$W_D = \sqrt{\frac{2.\varepsilon_r.L_0.V_{GD,i}}{q.n_s}}$$

ε_r : barrier relative Permittivity

$V_{GD,I}$: intrinsic gate-drain voltage

n_S : sheet carrier density

L_0 : width of region where electric fields + lateral spreading of the depletion region are assumed to terminate

L_0 impact W_D and can be obtained using gate-drain breakdown voltage (BV_{gd}) or feedback capacitance (C_{gd}) [1]

Depletion width values

	$W_{D\_calculated}$	$W_{D\_litterature}$
AlGaN/GaN L_g=90 nm	74 -75 nm	54 nm

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[1] K. Higuchi et al" Optimum Design and Fabrication of InAlAs/InGaAs HEMT's on GaAs with Both High BreakdownVoltage and High Maximum Frequency of Oscillation" IEEE Transactions on Electron Devices, vol. 7, pp.1312-1318, July 1999

Image charges extraction

Determination of α after evaluation of v_e and w_D

$$\alpha = \frac{w_D}{\tau_{drain} \times v_e}$$

Mirroring coefficient value

	$\alpha_{experimental}$		$\alpha_{simulation}$
AlGaN/GaN L_g=90 nm	$\alpha(BV_{GD})$	$\alpha\ (C_{gd})$	α
	3.35	**3.19**	**3.0**

Good agreement between experimental method & Monte-Carlo-Simulation [1]

[1] T. Palacios et al, "High-power AlGaN/GaN HEMTs for Ka-band applications," IEEE Electron Device Letters, vol. 26, no. 11, pp. 781–783, November 2005.

Conclusion & Perspective

- ✓ Analysis of the origin of drain delay in AlGaN/GaN HEMTs presenting f_{MAX} at the state of the art
- ✓ τ_{drain} has a detrimental contribution when V_{ds} increases
- ✓ The frequency performance can be further improved at high bias mitigating thermal effects (role of R_s & R_d) and designing innovative topologies / passivation schemes (role of C_{gd})
- ✓ First experimental extraction of the image charges based only in drain delay measurement
- ✓ $\alpha \approx 3$ is in accordance with the predicted results demonstrated by Monte-Carlo simulation

Does the epitaxial stack affects the image charges coefficient ?

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Aknowledgements

Agence Nationale de la Recherche
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Thank you for your attention!

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