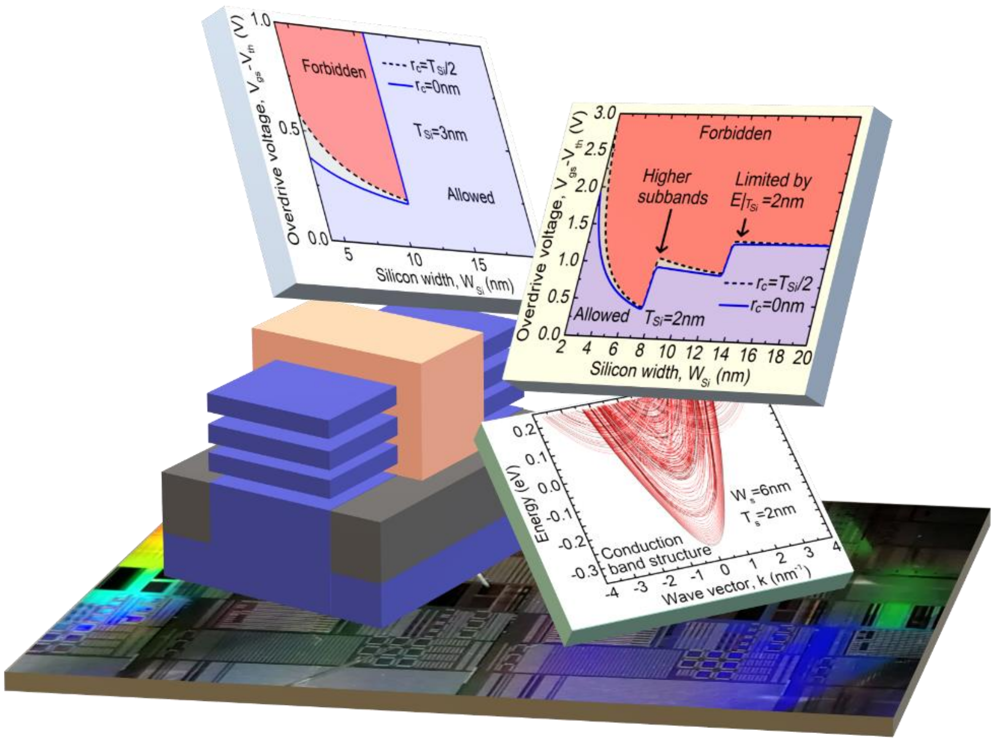
Compact Modeling for Gate-All-Around FET Technology



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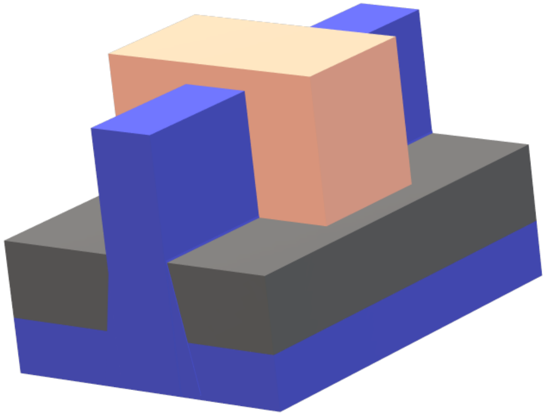
FinFETs to GAAFETs

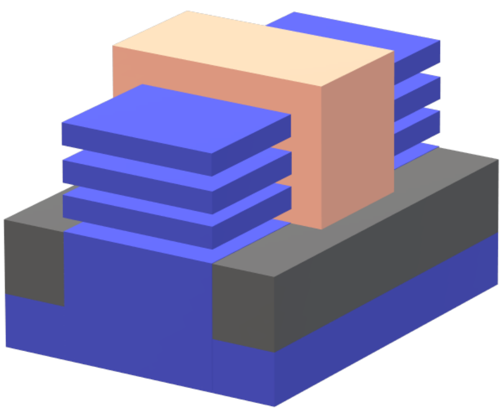
- **FinFETs:** used from 22nm to 5nm nodes [2]

Better electrostatic control

- **Continued scaling**: gate on all four sides : gate-all-around (GAAFETs)
- GAAFETs a.k.a: Nanosheet FETs (IBM), MBCFETs(Samsung)
- Samsung has announced use of GAAFETs for 3nm node (3GAE) [1]
- TSMC has announced the same for 2nm node [2]



FinFET



GAAFET

[1]P. Kushwaha et.al., "Design Optimization Techniques in Nanosheet Transistor for RF Applications", *IEEE Transactions on Electron Devices*, Vol. 67, Issue 10, Oct. 2020.
[2] https://samsungatfirst.com/mbcfet/
[3] M.Lapedus, "New Transistor Structures At 3nm/2nm", [Online]: https://semiengineering.com/new-transistor-structures-at-3nm-2nm/

Compact Model

- **BSIM-CMG111.1.0:** Industry standard model: include Nanosheet specific compact model (Jan. 2021)

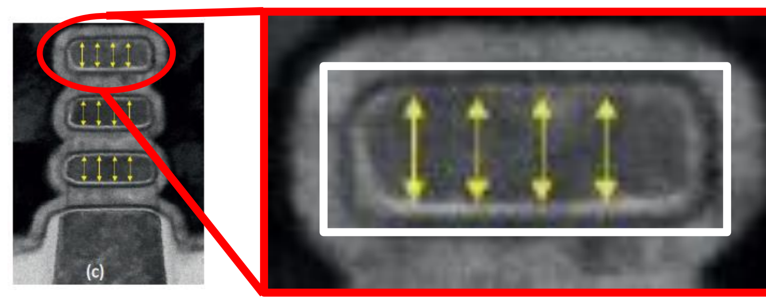
- **History:**
  - BSIM-CMG: Common-multi-gate FETs
  - Modules for double-gate, tri-gate/FinFETs, quadruple gate
  - CMG 105: GEOMOD 2 and 3 for quadruple gate and cylindrical gate.
  - CMG 109 and 110: GEOMOD 4: Unified Model for all channel shapes **including round corners**

GAAFET Variability

GEOMOD=5: specific GAAFET module

- computes GAAFET electrostatics based on TGAA, WGAA and NGAA.
- $DWs_{1|2|3}$, $DAch_{1|2|3}$ for fixed (among sheet layers, corner rounding…) and random geometry variations.

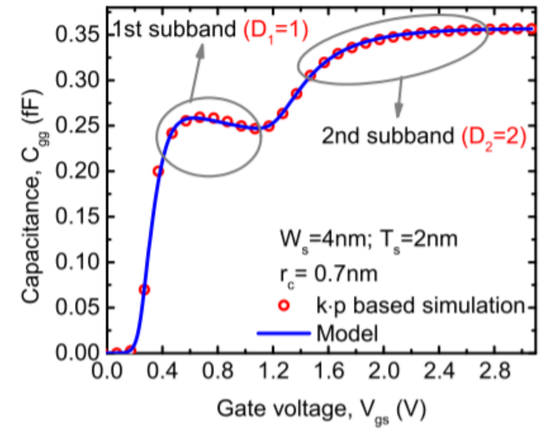
GEOMOD=4 can be used to input A_{ch}, W and C_{ins} directly

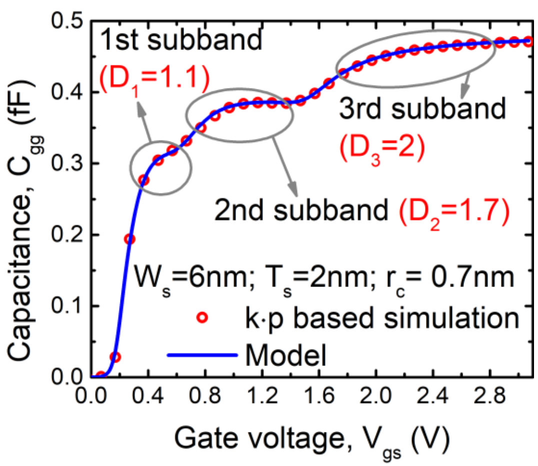


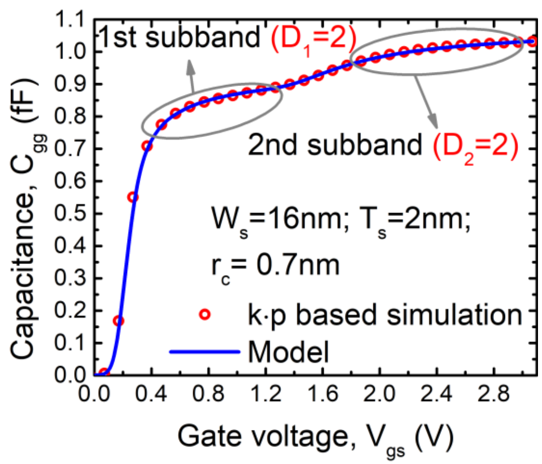
[1] C. W. Yeung, "Channel geometry impact and narrow sheet effect of stacked nanosheet," in IEDM Tech. Dig., Dec. 2018, pp. 28.6.1–28.6.4

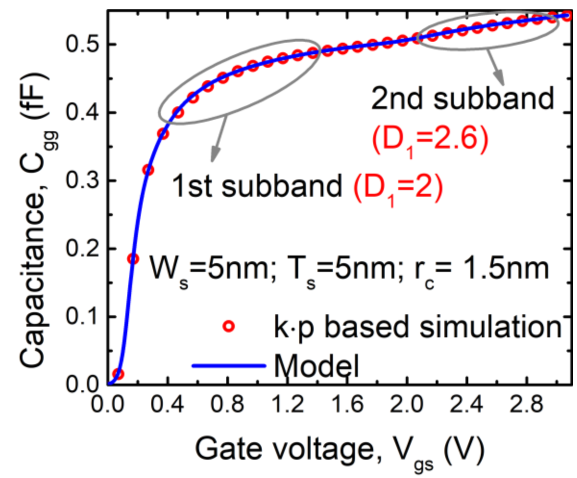
Quantum confinement: geometry dependence

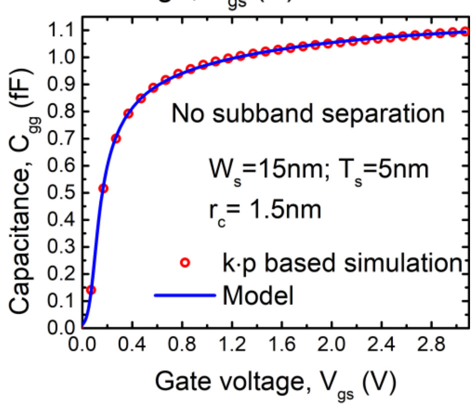
- Geometry dependence:
  - Subband energies (subband separation)
  - Effective mass and band-gap
  - Electrostatic dimension
  - Density of states









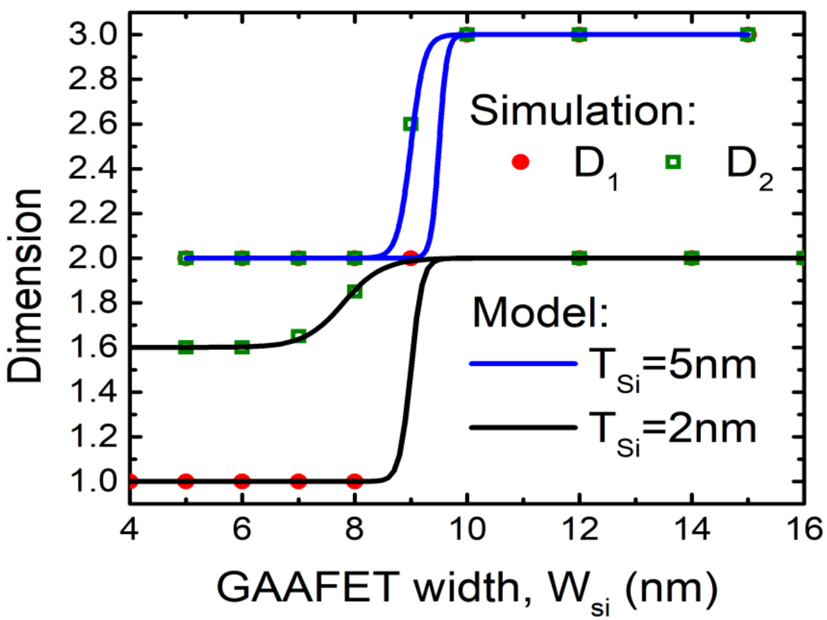


Negligible effect for larger cross-sections

[1] A. Dasgupta et.al., "BSIM Compact Model for Quantum Confinement in Advanced Nanosheet FETs", IEEE Transactions on Electron Devices, Vol. 67, Issue 2, Feb. 2020.

Novel Continuous "Dimension" Model

- Dimension:
  - real GAA-FETs are not categorizable as 1D, 2D or 3D (textbook)
  - W_S and T_S are continuously variable



Compact modeling example:

$$D = D_L + \frac{D_H - D_L}{1 + exp\left(\frac{W_0 - W_S}{R}\right)}$$

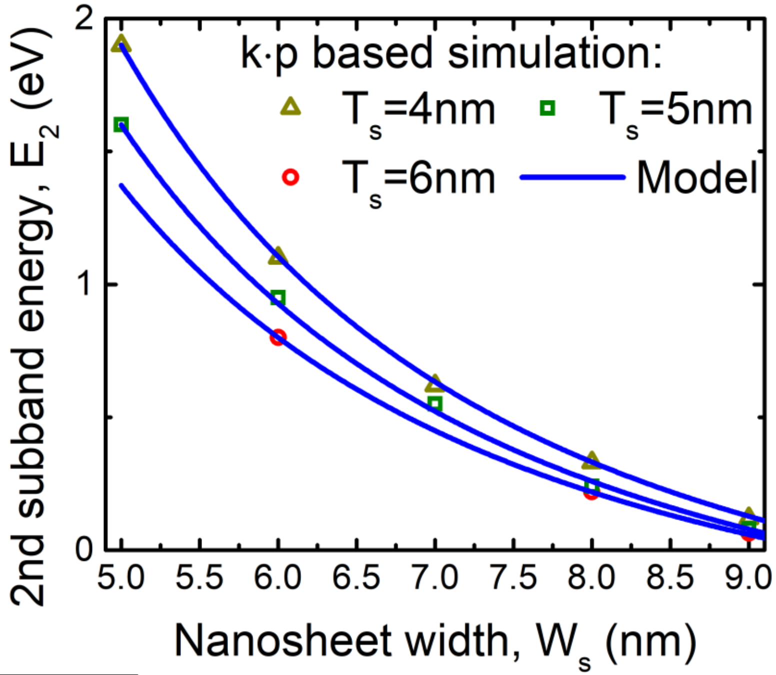
- D_H, D_L, W_0, R: different for each subband
- D_H, D_L, W_0, R scale with cross-section

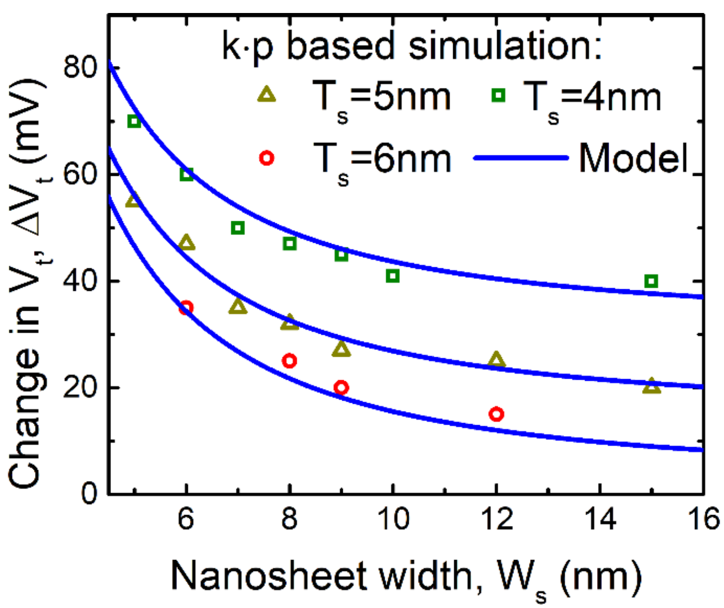
Complex expression

[1] A. Dasgupta et.al., "BSIM Compact Model for Quantum Confinement in Advanced Nanosheet FETs", IEEE Transactions on Electron Devices, Vol. 67, Issue 2, Feb. 2020.

Subbands, threshold voltage

- Subbands, threshold voltage
  - Subbands scale with changing cross-section
  - Subband and band-gap scaling directly influence threshold voltage
  - Requirement: continuous, differentiable, analytical model
  - Complexity: multiple independent variables





Quantum subband model

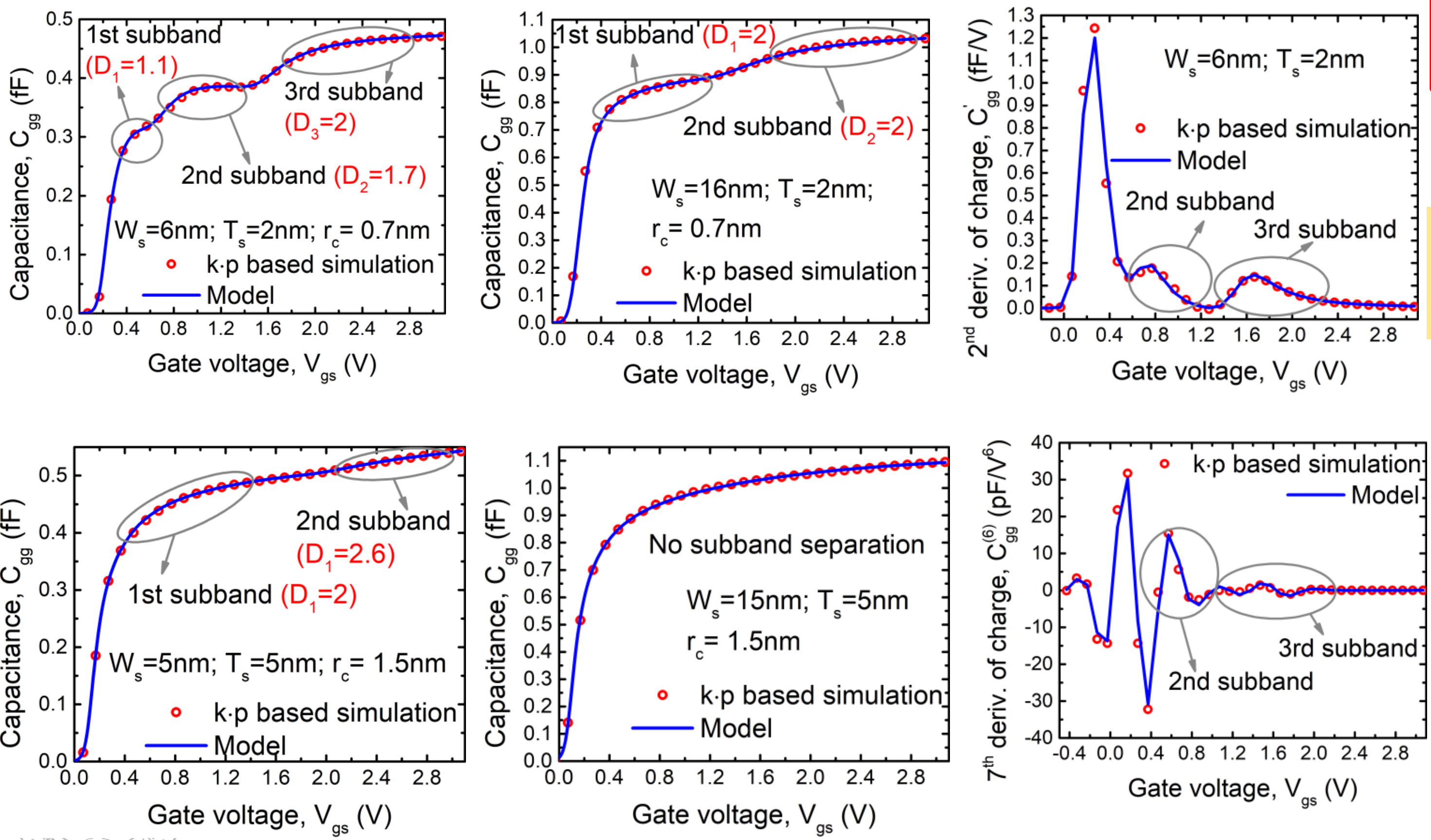
3 subbands included

(First subband is sufficient for thickness > 3nm)

- Charge contribution of 3 subbands added

$$Q = q\sum_i \int_{E_i}^{\infty} g_{D_i}(E)\cdot\frac{1}{1+exp\left(\frac{E-E_f}{kT}\right)}dE = \sum_i N_{Ci} F_{\frac{D_i}{2}-1}\left(\frac{E_f - E_i}{kT}\right)$$

$$\boxed{q\frac{D_i}{(2\pi)^{\frac{D_i}{2}}\Gamma\left(1+\frac{D_i}{2}\right)}\frac{m_i^{*\frac{D_i}{2}}}{\hbar^{D_i}}}$$



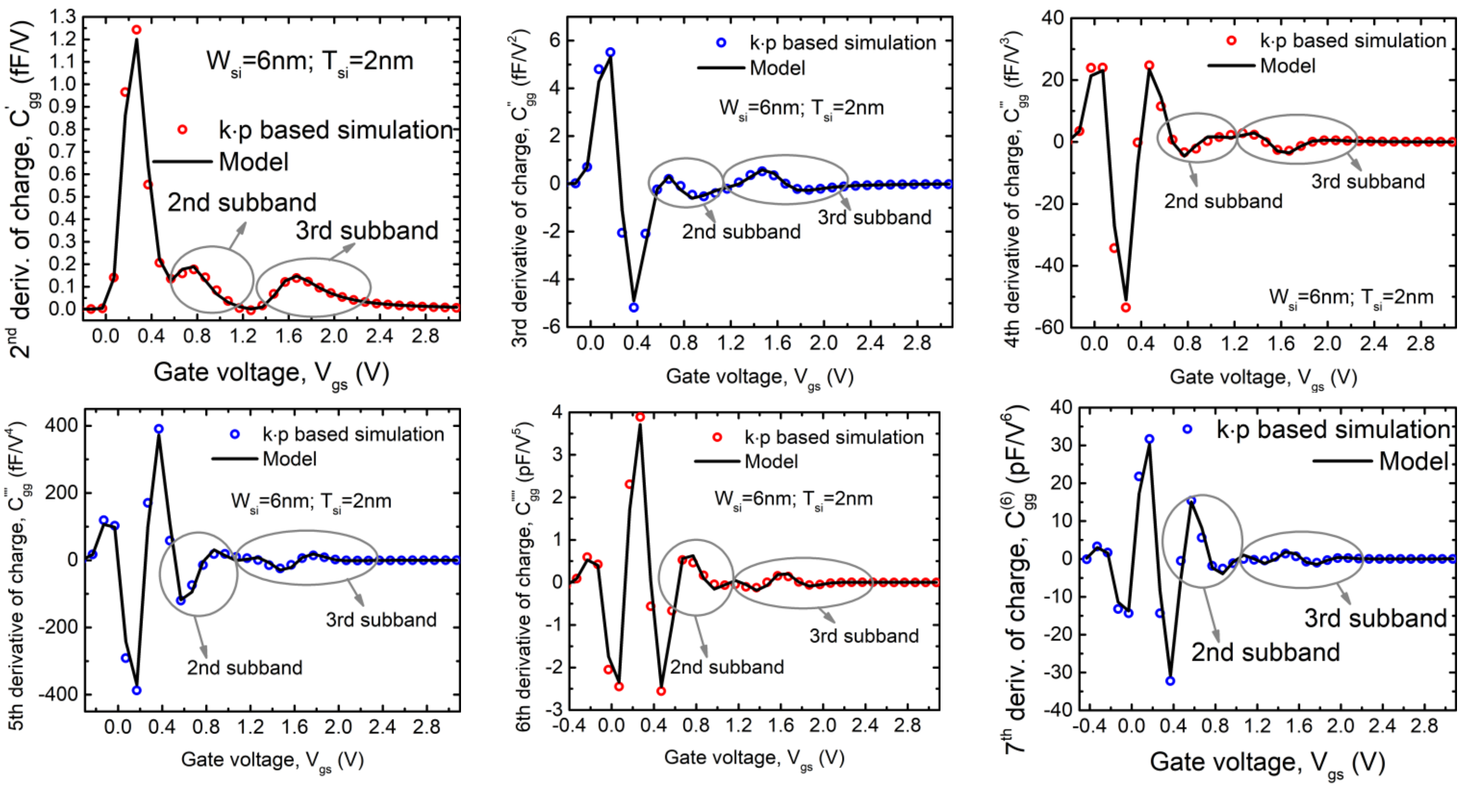
Geometry-dep. confinement effect

Accurate upto 7^{th} deriv. of charge

[1] A. Dasgupta et.al., "BSIM Compact Model for Quantum Confinement in Advanced Nanosheet FETs", IEEE Transactions on Electron Devices, Vol. 67, Issue 2, Feb. 2020.

Derivatives

- Accuracy of derivatives are important
- Computationally efficient compact model accurate up to 7th derivative of charge against quantum simulation
- For accurate simulation of linearity and higher order harmonics



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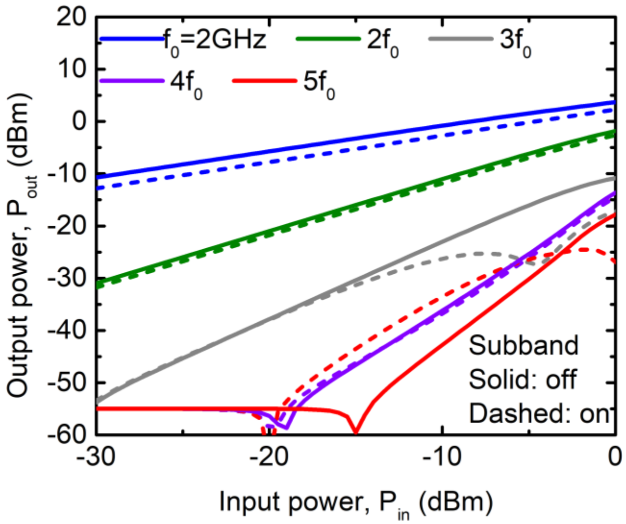
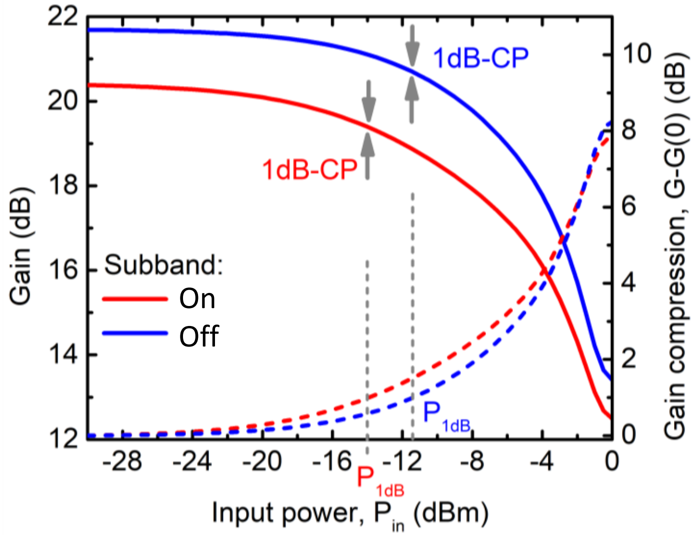
Results: device metrics (RF)

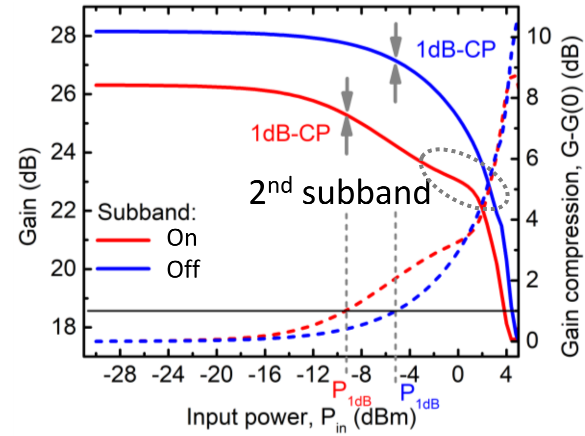
T_{SHEET}=2nm, W_{SHEET}=6nm



T_{SHEET}=2nm, W_{SHEET}=6nm

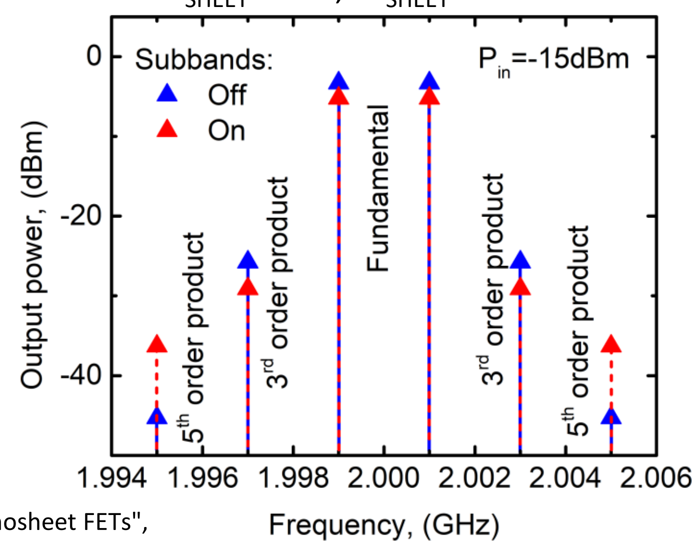


T_{SHEET}=2nm, W_{SHEET}=4nm



- Kinks in output power variation at $3f_0$, $4f_0$ and $5f_0$
- Shift in 1dB compression point
- Effect of subbands seen in gain (larger confinement)
- Lower gain due to lower charge & current at same bias: lower effective DOS
- Major changes in fundamental, 3rd and 5th order products

T_{SHEET}=2nm, W_{SHEET}=6nm



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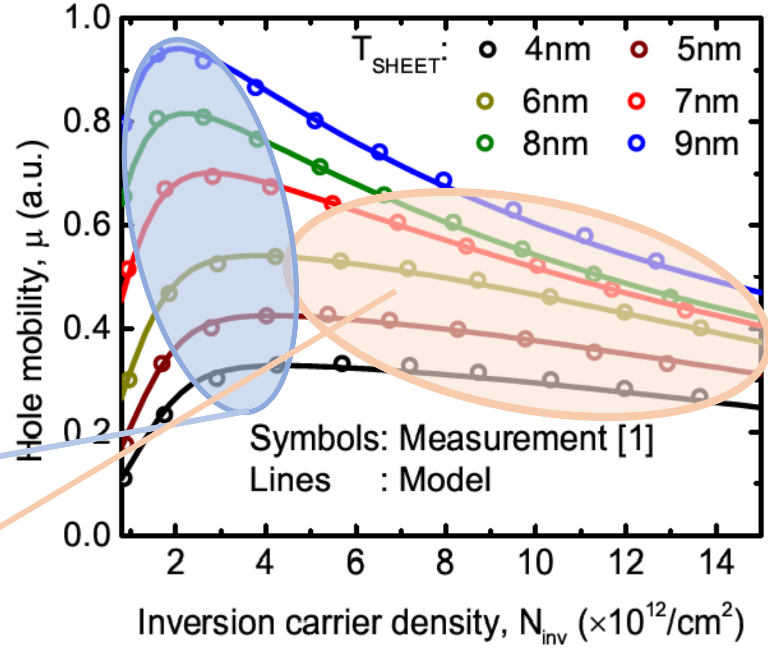
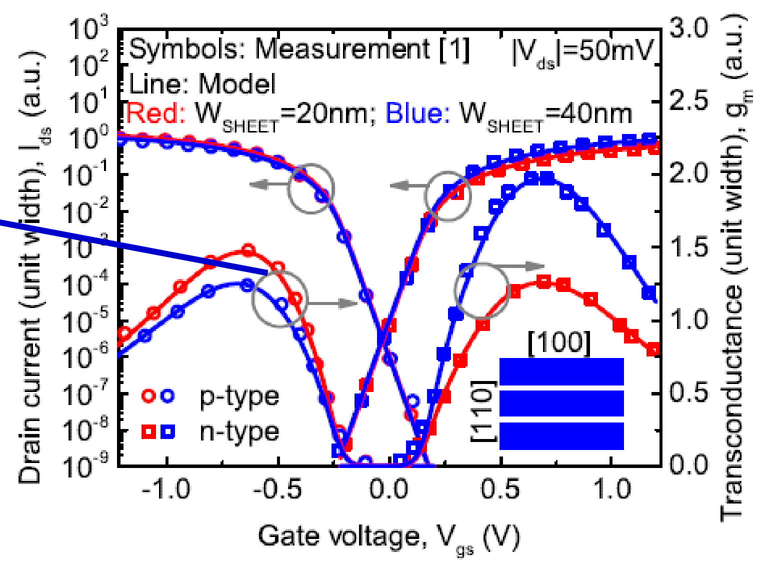
Transport

- New mobility model includes
  - Quantum confinement (Tsheet & Wsheet) effect on effective mass and mobility
  - Modified field dependence based on thickness
  - Different crystal orientations on sides and surface of sheets





[1] C. W. Yeung et.al., "Channel geometry impact and narrow sheet effect of stacked nanosheet", *IEDM*, 2018
[2] A. Dasgupta et.al., "Compact Model for Geometry Dependent Mobility in Nanosheet FETs", *IEEE EDL*, 2020.

Quantum confinement

- Confined effective mass
  - m^* increases with increasing confinement (decreasing T_{SHEET})

$A \sim B/64$

k·p theory: $m^* = \frac{m_0}{1+\frac{B}{E_g}}$ ⟺ Schrodinger's eq: $E_g = E_{g,bulk} + \frac{A}{m^* T_{SHEET}^2}$

$B = \frac{2h^2}{m_0 a_o^2}$: fixed for a material

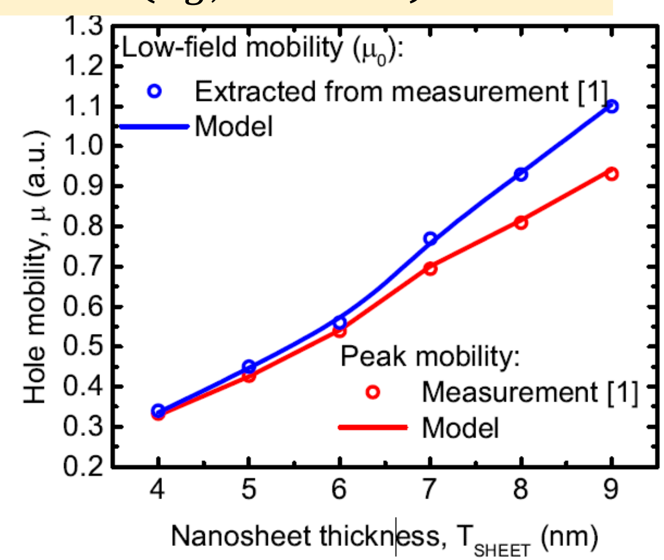
$\kappa_1 = m_0 E_{g,bulk} T_{SHEET}^2 - A$

$$\frac{m^*}{m_0} = \frac{\kappa_1 + \sqrt{\kappa_1^2 + 4A\kappa_2}}{2\kappa_2}$$

$\kappa_2 = m_0 \left(E_{g,bulk} + B\right) T_{SHEET}^2$

- Increase in effective mass ⇒ lower μ

$$\mu_{0,new} = \mu_0 \frac{m_0}{m^*}$$



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Field dependence

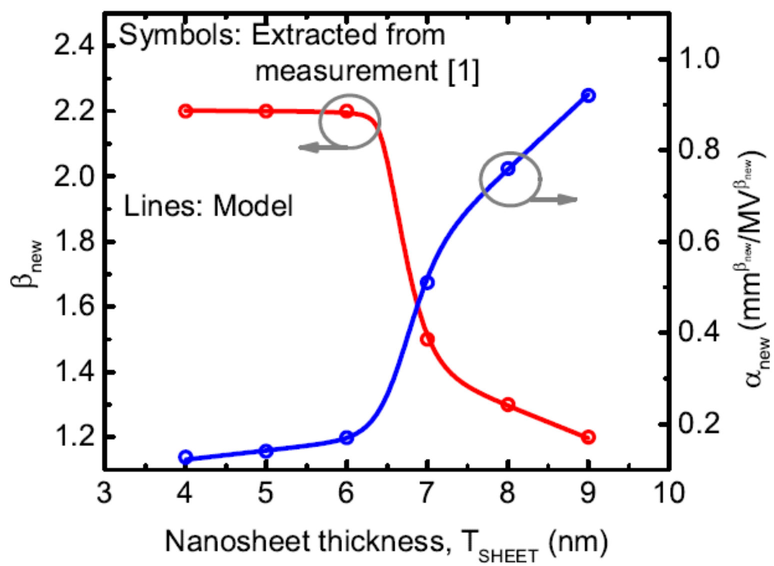
- Existing mobility degradation model: $\mu = \frac{\mu_0}{1+\alpha E_{eff}^{\beta}}$
- Thin Tsheet changes charge centroid and phonon scattering

$$\alpha_{new} = \alpha_0 + \alpha_m T_{SHEET} + \frac{\Delta_0 + \Delta_1 T_{SHEET}}{1 + exp\left(\frac{T_{S0} - T_{SHEET}}{T_{ni}}\right)}$$

$$\beta_{new} = H_{min}\left(\frac{1}{1 + exp\left(\frac{T_{S0} - T_{SHEET}}{T_{ni}}\right)}, \beta_0, \delta\right)$$

$\Delta_1, \Delta_0, T_{S0}, T_{ni}, \alpha_m, \beta_0$ and δ are fixed for a given technology.

H_{min} ensures saturation of centroid location to $T_{SHEET}/2$ assymptotically



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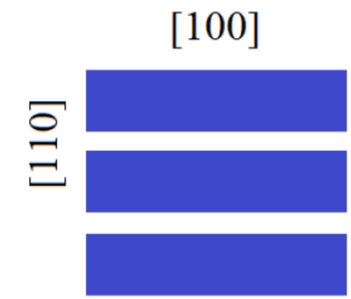
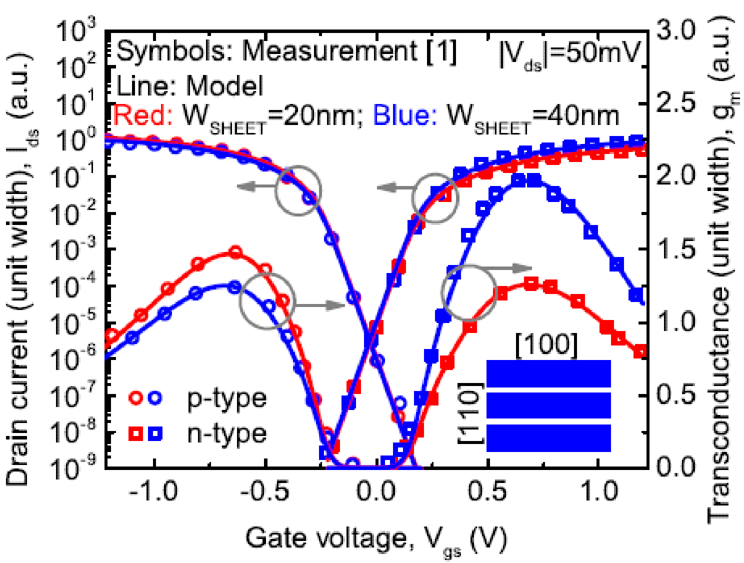
Width effect

- Sheet sidewalls and surfaces have different crystal orientations and different mobilities
- Reducing W_{SHEET} changes
  - Relative contribution of sidewall to Id
  - Quantum confined mobilities
- p-type and n-type devices show trends trends
  - P-type: $\mu_{110} > \mu_{100}$
  - n-type: $\mu_{110} < \mu_{100}$



$$\mu_{eff} = \mu_{100}\left(\frac{W_{SHEET}}{W_{SHEET}+T_{SHEET}} + \underbrace{\frac{\mu_{110}}{\mu_{100}}}_{\eta_\mu}\frac{T_{SHEET}}{W_{SHEET}+T_{SHEET}}\right)$$



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Overall mobility model

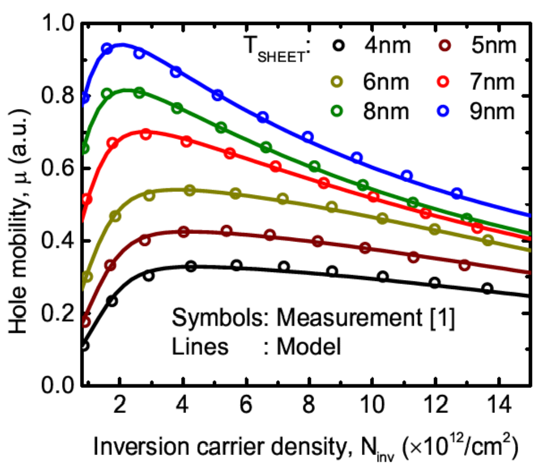
$$\mu_{eff} = \mu_{100}\left(\frac{W_{SHEET} + \eta_\mu T_{SHEET}}{W_{SHEET} + T_{SHEET}}\right)$$

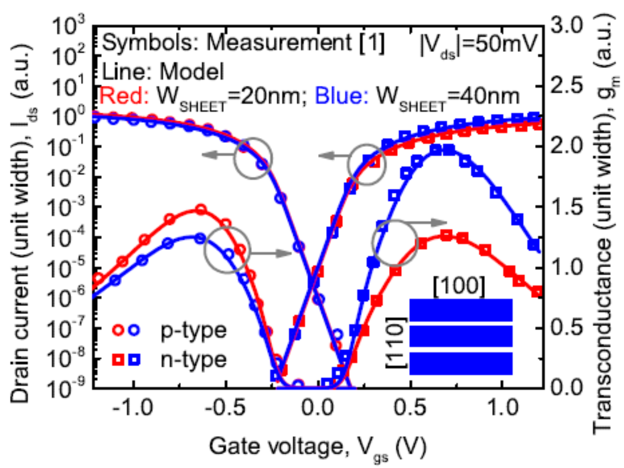
$$\frac{m^*}{m_0} = \frac{\kappa_1 + \sqrt{\kappa_1^2 + 4A\kappa_2}}{2\kappa_2}$$

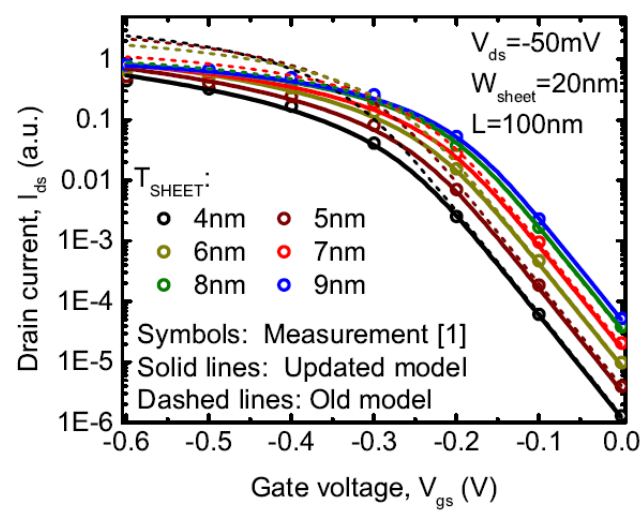
$$\mu = \frac{\mu_{eff}\dfrac{m_0}{m^*}}{1 + \alpha_{new} E_{eff}^{\beta_{new}}}$$

$$\alpha_{new} = \alpha_0 + \alpha_m T_{SHEET} + \frac{\Delta_0 + \Delta_1 T_{SHEET}}{1 + exp\left(\dfrac{T_{S0} - T_{SHEET}}{T_{ni}}\right)}$$

$$\beta_{new} = H_{min}\left(\frac{1}{1 + exp\left(\dfrac{T_{S0} - T_{SHEET}}{T_{ni}}\right)}, \beta_0, \delta\right)$$







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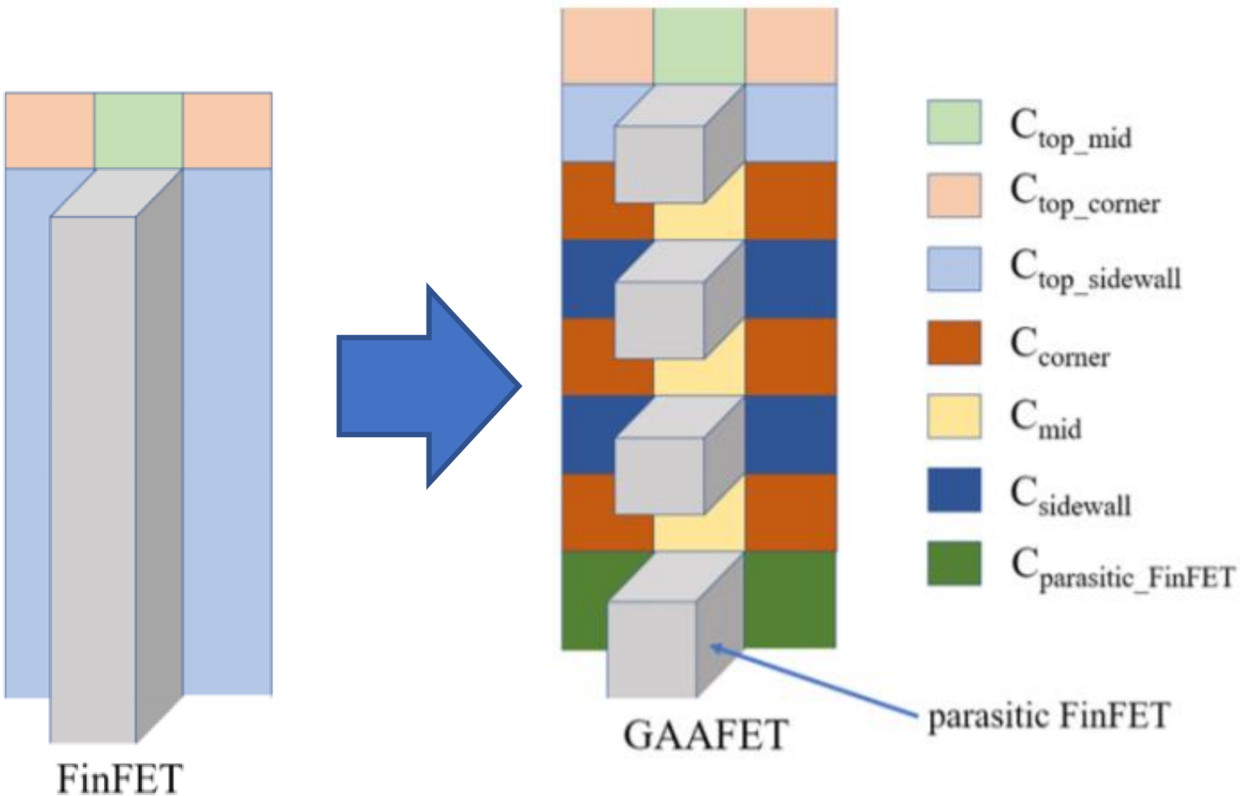
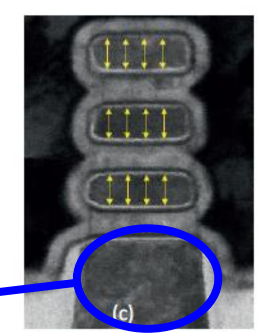
Parasitic capacitances:

- Modified capacitance network : CGEOMOD = 3
- NSHEET and TSUS dependence included
- Parasitic FET accounted for



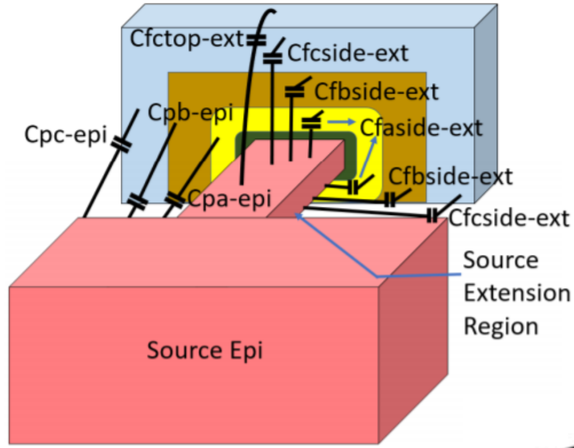


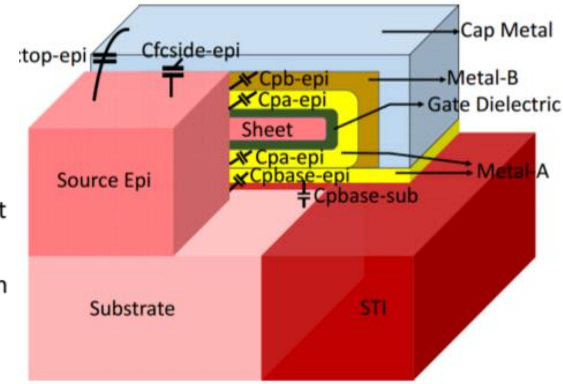
Parasitic FET

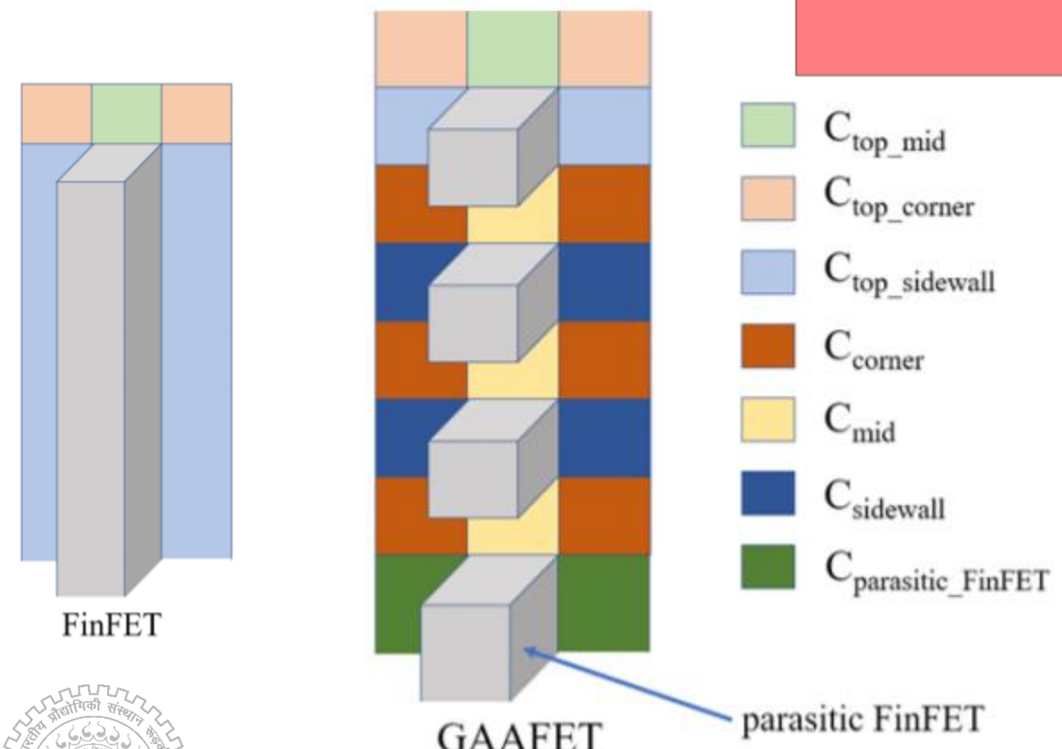
p. 15

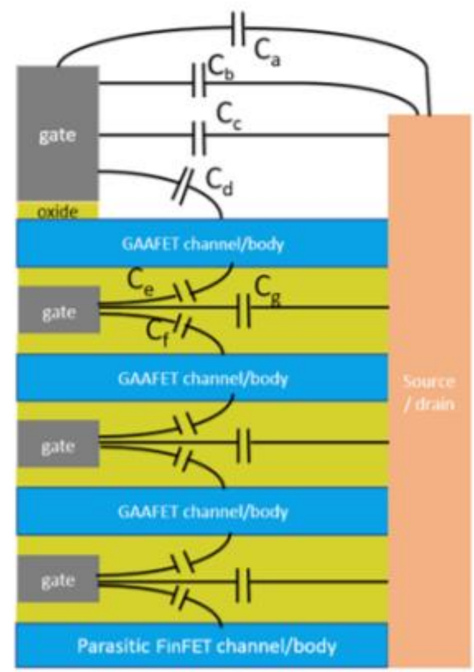
Complete picture

- Multiple parasitic components
- Various sources of fringe-fields









[1] P. Kushwaha, A. Dasgupta, M.-Y. Kao, H. Agarwal, S. Salahuddin, C. Hu, "Design Optimization Techniques in Nanosheet Transistor for RF Applications", *IEEE Transactions on Electron Devices*, Vol. 67, Issue 10, Oct. 2020.

Thank you