Progress on III-V 3D Transistors

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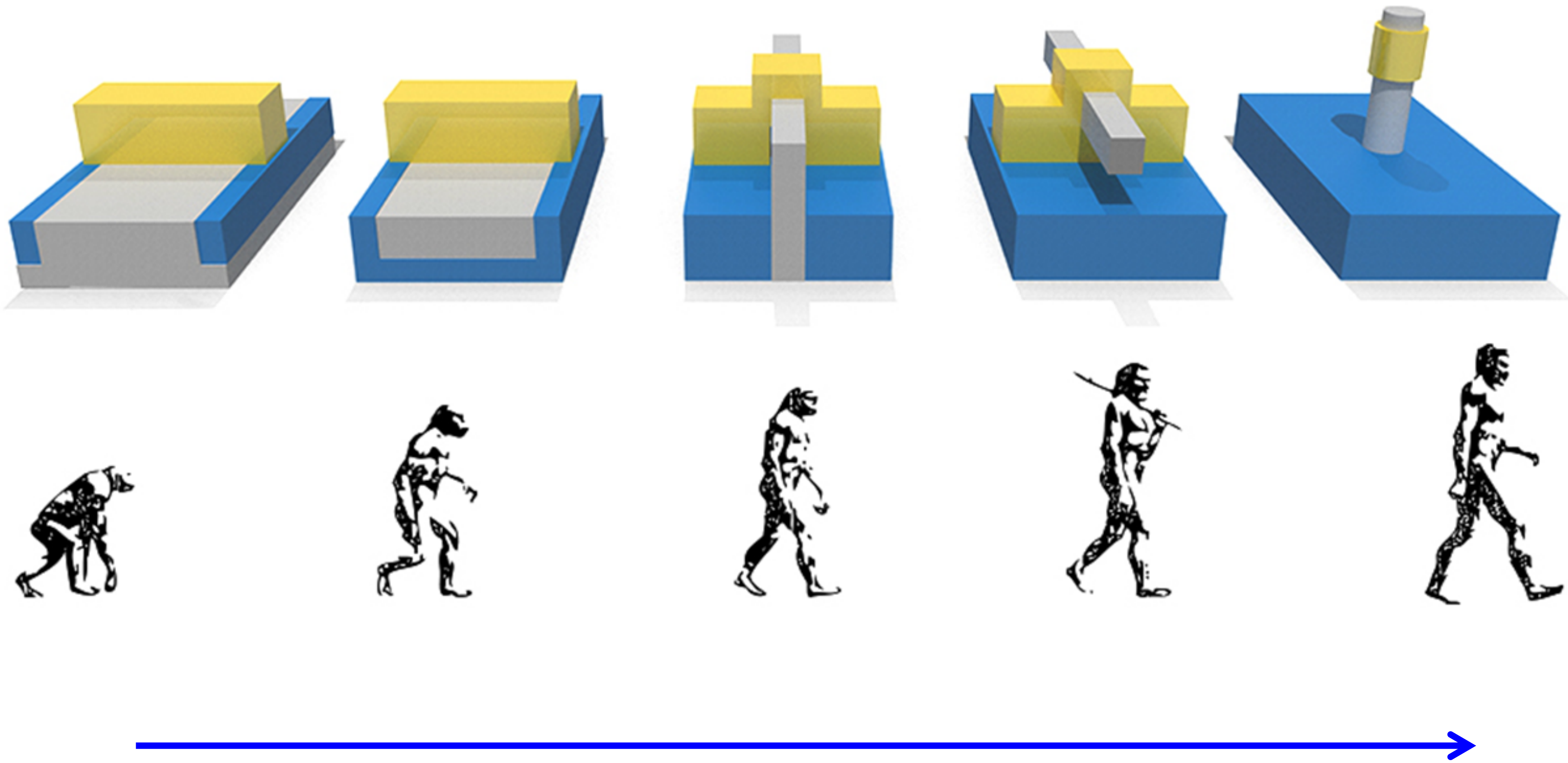
- Labs at MIT: MTL, EBL

Evolution of transistor structure for improved scalability



Enhanced gate control → improved scalability

Studies on InGaAs FinFETs

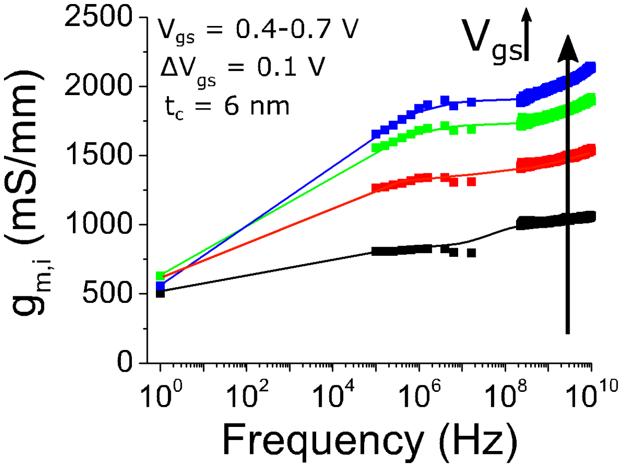
FinFET: Excellent model for 3D MOSFET

1. MOS oxide trapping:
   - Source of instability
   - Masks intrinsic device behavior

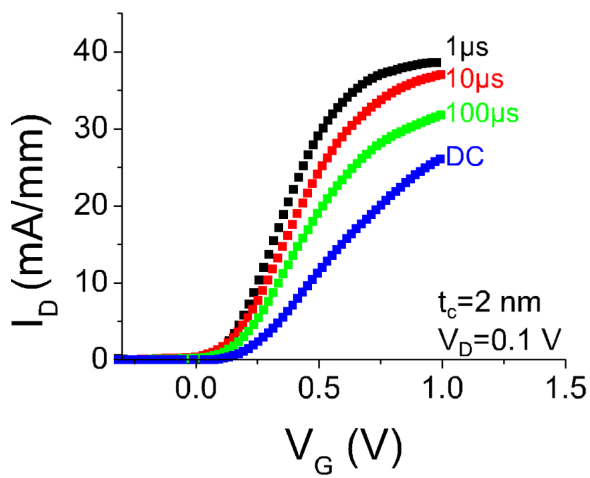
2. Band-to-band-tunneling + bipolar gain:
   - Limitation to OFF state current in narrow bandgap materials

1. Anomalies in InGaAs MOSFETs

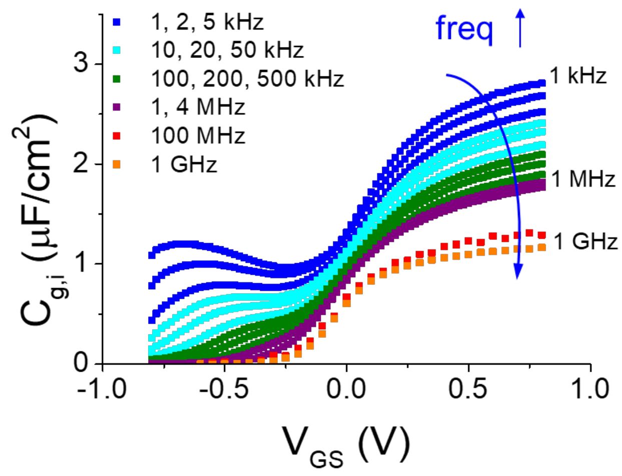
Long-channel InGaAs planar MOSFETs:



g_m frequency dispersion



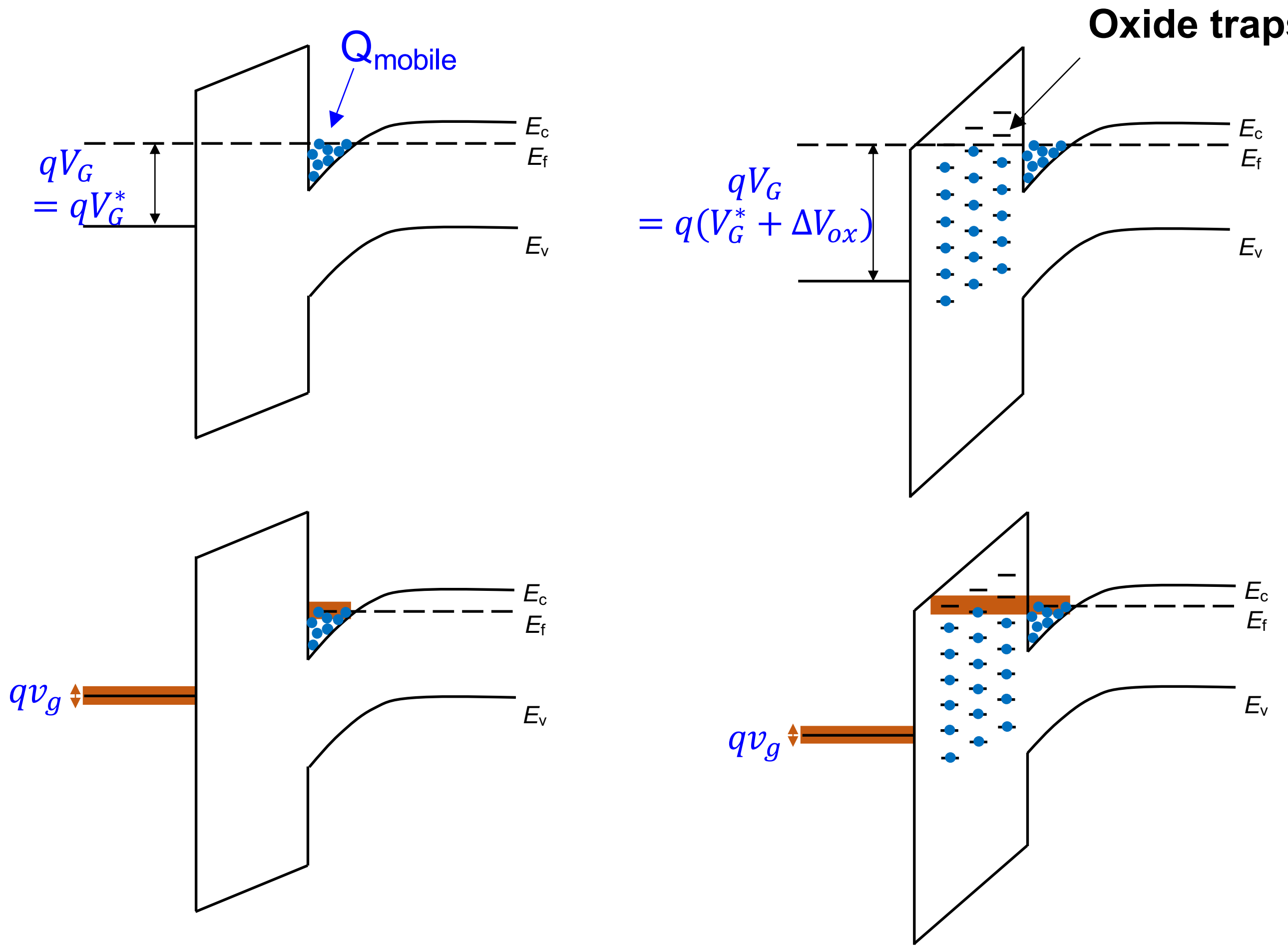
Pulsed vs. DC I-V



C_g frequency dispersion

Cai, VLSI Tech 2019

Physics:
Slow Electron Trapping in Gate Oxide



V_t shifts positively

→ $V_G = V_G^* + \Delta V_{ox}$

(stretch-out)

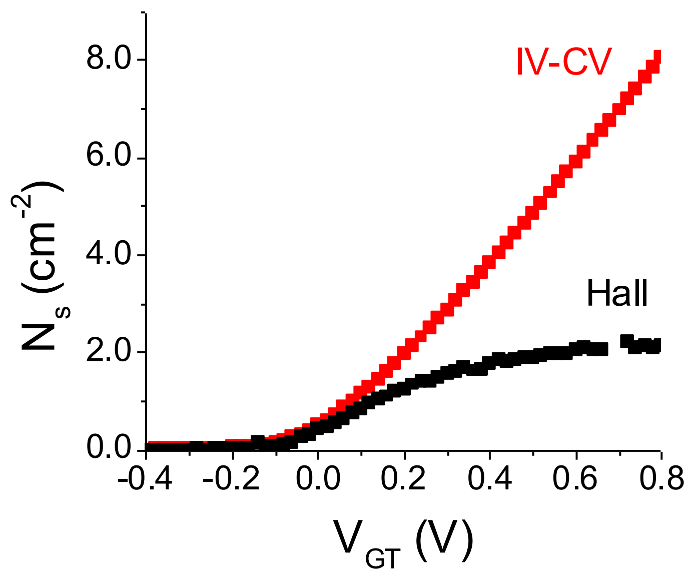
$Q_g > Q_{mobile}$

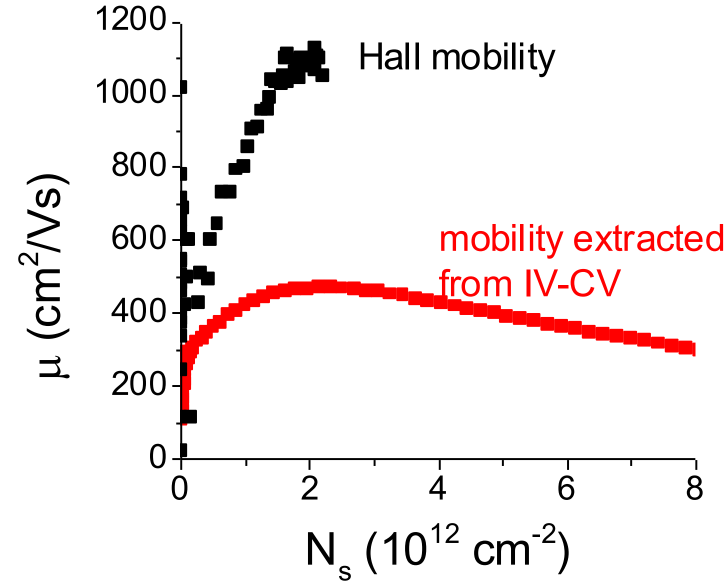
$Q_g = qN_s + qN_{ox}$

(frequency dependent)

Charge-Control Relation in the Presence of Oxide Trapping

InGaAs planar MOSFETs: IV-CV (4 MHz) vs. Hall





- Conventional IV-CV overestimates N_s and underestimates μ
- Hall: cannot be easily applied to 3D device structures

→ New method to determine charge-control relationship needed!

New RF-I_D Method for Charge-Control Relation

Conventional IV-CV method integrates charge in voltage:

Overestimated at MHz frequency

Overestimated due to DC stretch-out

$$Q_n = qN_s = \int C_g dV_G$$

New method integrates charge in current:

$$Q_n = qN_s = \int \underbrace{C_{gi} \frac{1 + g_{di} R_{sd}}{g_{mi}}} dI_D$$

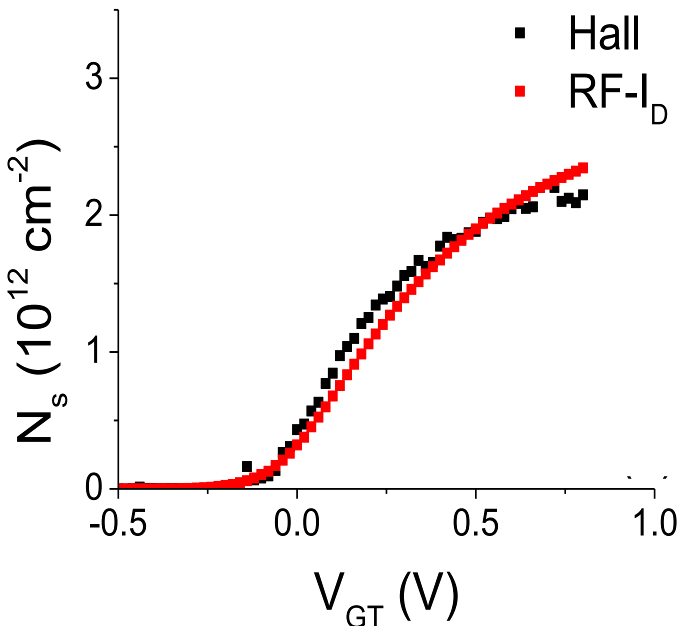
1/(carrier velocity) estimated at 1 GHz

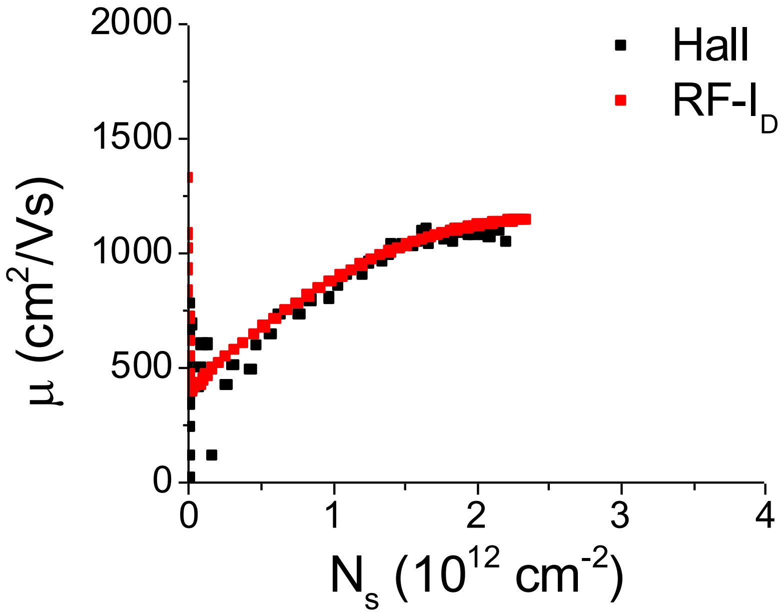
Does not contain stretch-out

C_{gi}, g_{mi}, g_{di} estimated from S-parameter measurements in the GHz regime where oxide traps are unresponsive

RF-I_D vs. Hall Measurements

InGaAs planar MOSFETs (t_c=4 nm)

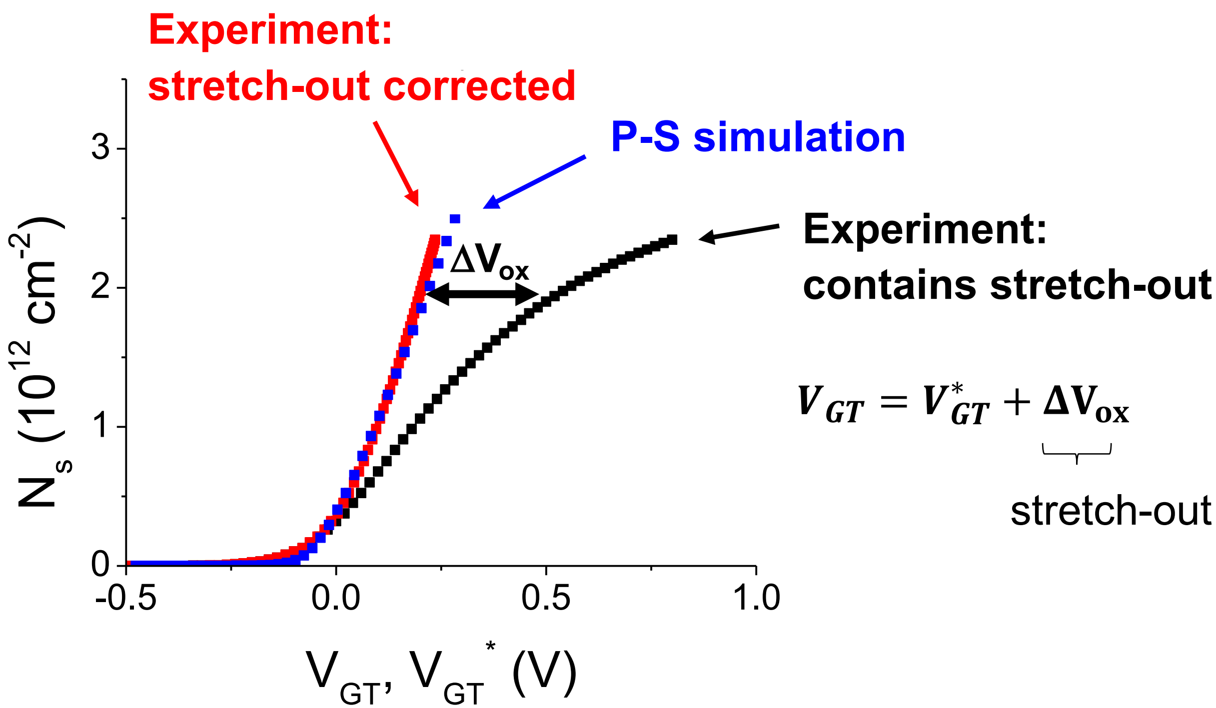




- Excellent agreement with Hall measurements!
- Peak mobility > 1000 $cm^2/V \cdot s$ for t_c = 4 nm!

Comparison to Theory

Stretch-out correction: $$V_{GSi}^{*} = \int \frac{1 + g_{di} R_{sd}}{g_{mi}} dI_D$$

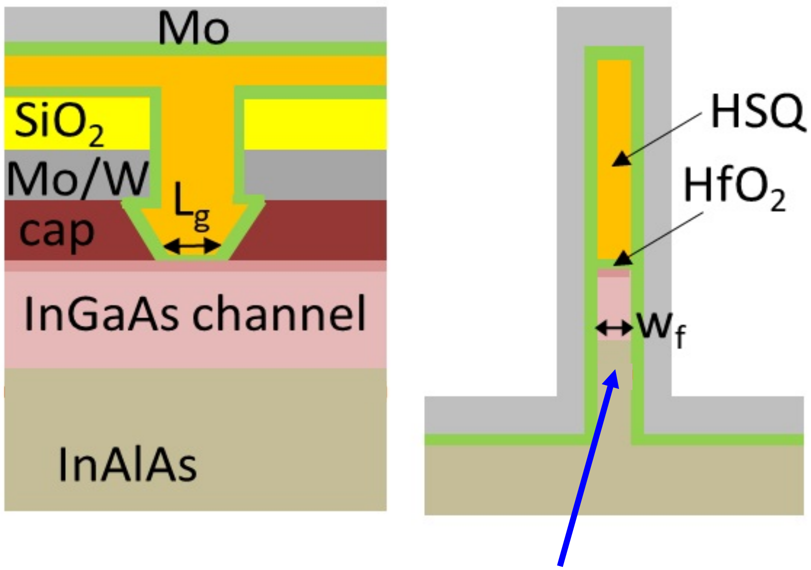


$$V_{GT} = V_{GT}^{*} + \Delta V_{ox}$$

stretch-out

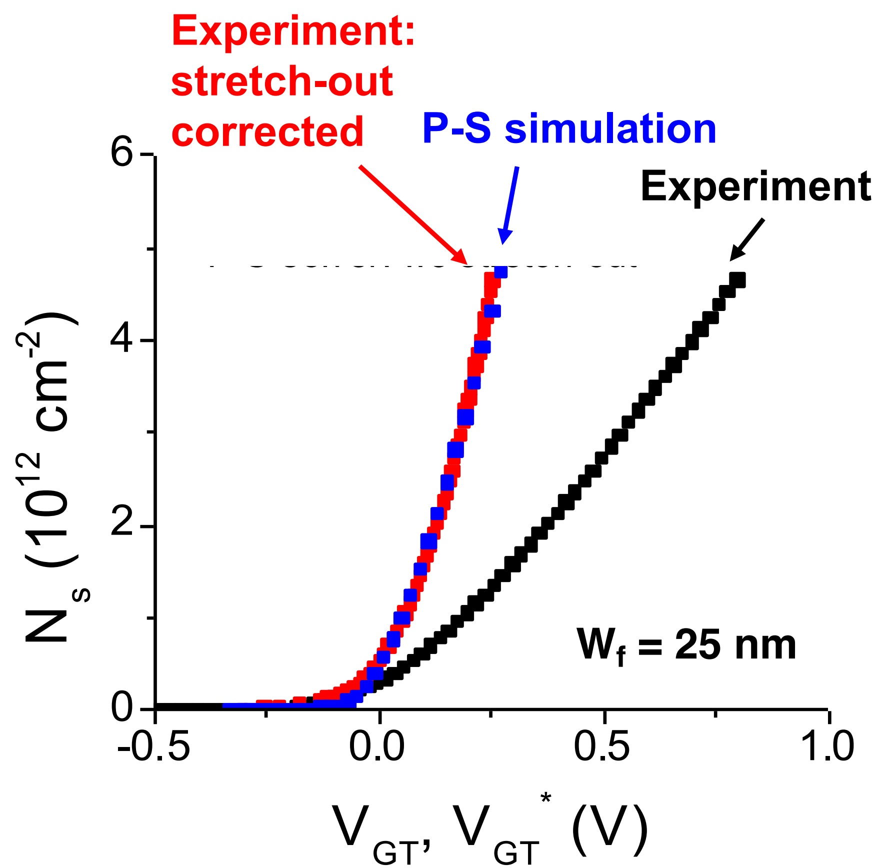
After stretch-out correction, N_s characteristics show excellent agreement with P-S simulations!

Application to InGaAs FinFETs



$In_{0.53}Ga_{0.47}As$ channel

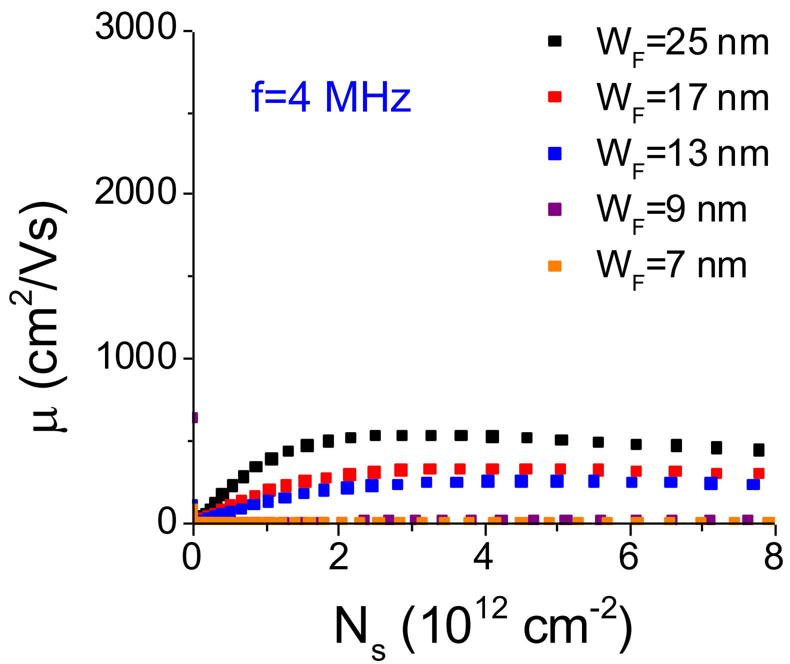
W_f between 7 and 25 nm



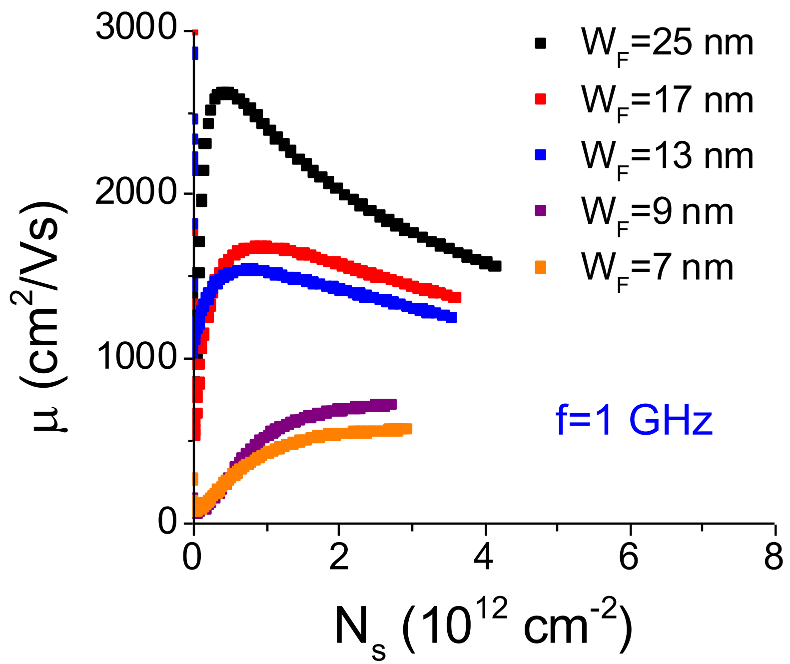
After stretch-out correction, N_s characteristics show excellent agreement with P-S simulations!

Mobility in InGaAs FinFETs

Conventional IV-CV



New RF-I_D Method

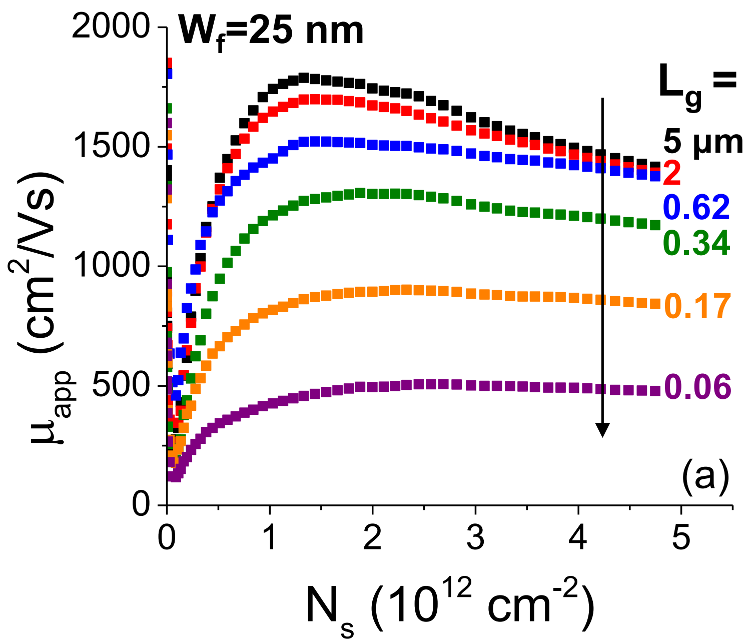


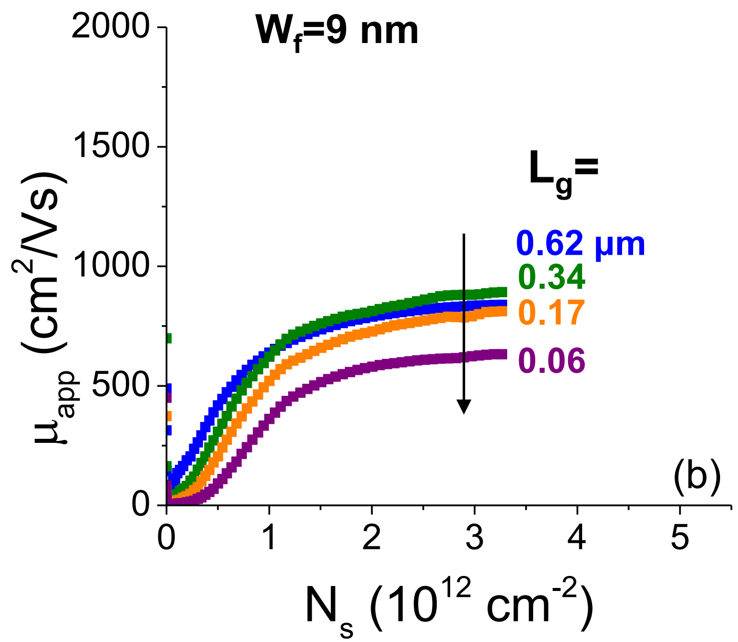
Mobility significantly underestimated in InGaAs FinFETs by IV-CV

- Peak mobility ~ 570 $cm^2/V \cdot s$ for W_f = 7 nm

→ Intrinsic potential of InGaAs much higher than reported so far!

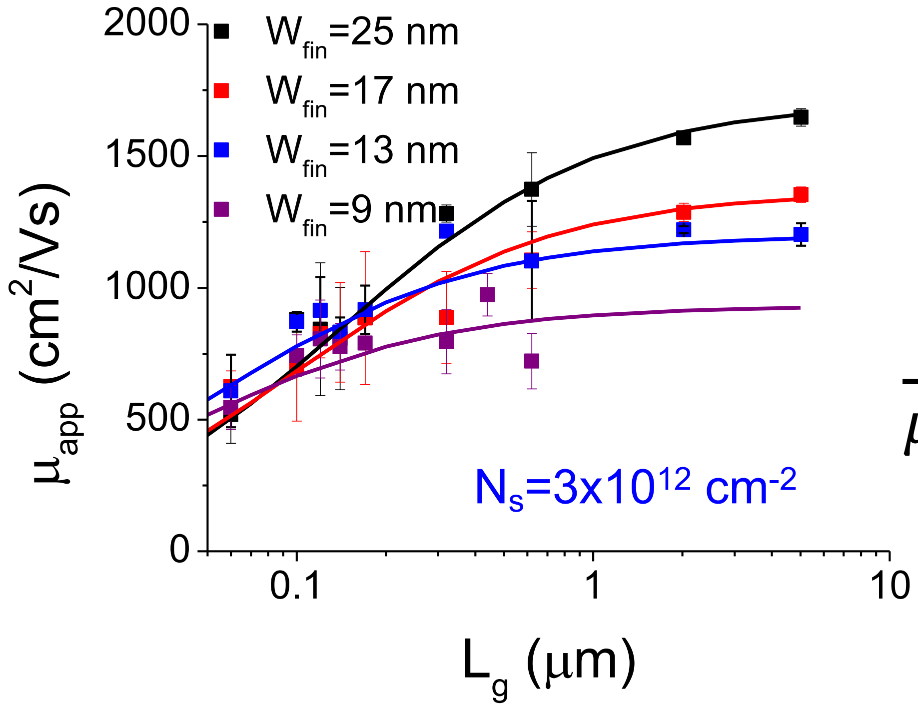
L_g Dependence of Mobility in InGaAs FinFETs





L_g ↓→ μ↓: evidence of ballistic mobility

Evidence of Ballistic Mobility in InGaAs FinFETs



mean-free path

$$\frac{1}{\mu_{app}} = \frac{1}{\mu_{col}} + \frac{1}{\mu_B} = \frac{1}{\mu_{col}}\left[1 + \frac{\lambda}{L_g}\right]$$

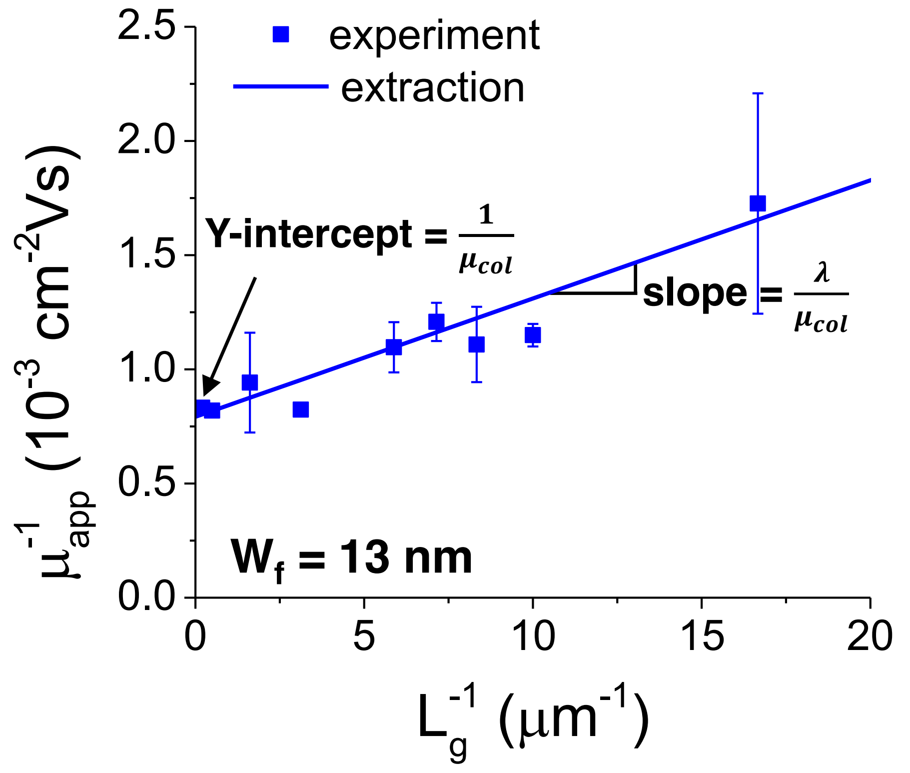
- Long L_g → μ_{col} dominates, independent of L_g
- Short L_g → μ_B dominates, $\mu_B \sim L_g$

  → Separation of μ_{col} and μ_B possible

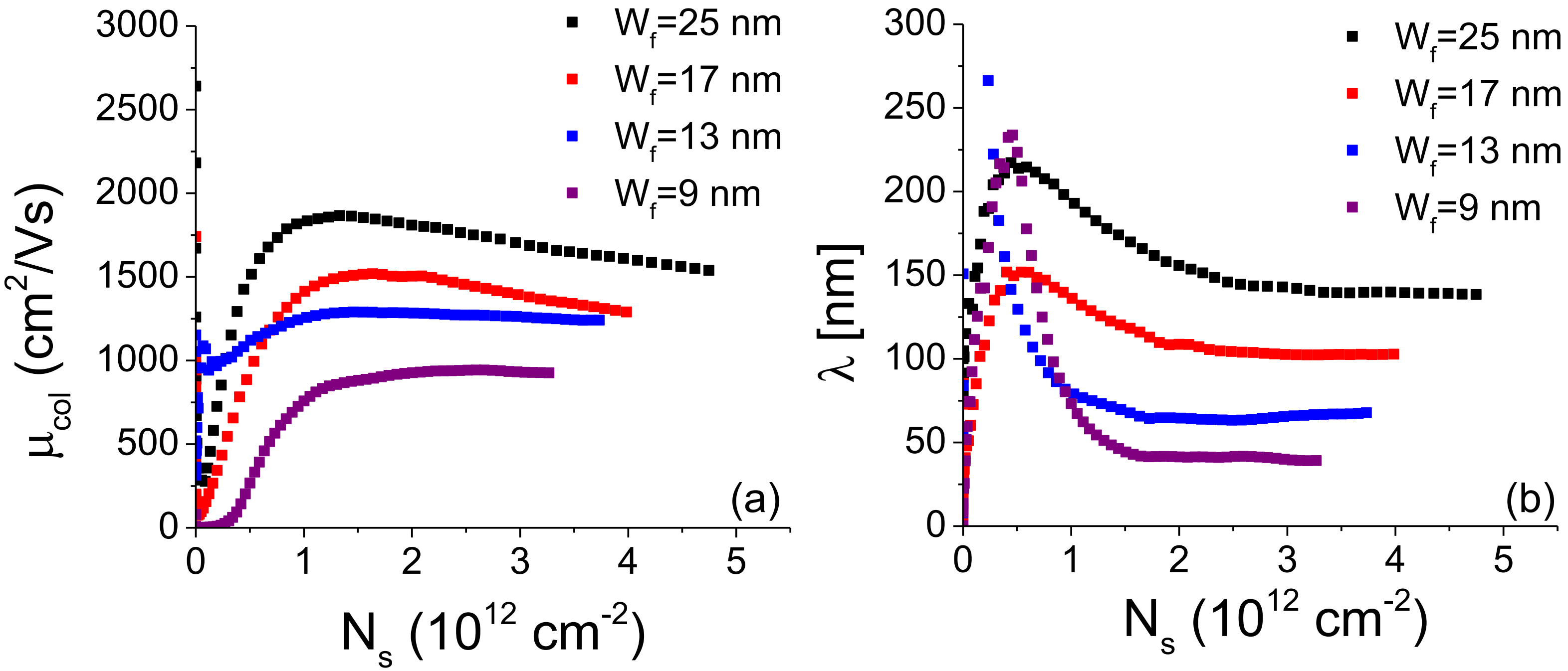
Ballistic Mobility Extraction

$$\frac{1}{\mu_{app}} = \frac{1}{\mu_{col}} + \frac{1}{\mu_B} = \frac{1}{\mu_{col}}\left[1 + \frac{\lambda}{L_g}\right]$$

$N_s = 3 \times 10^{12}\ cm^{-2}$



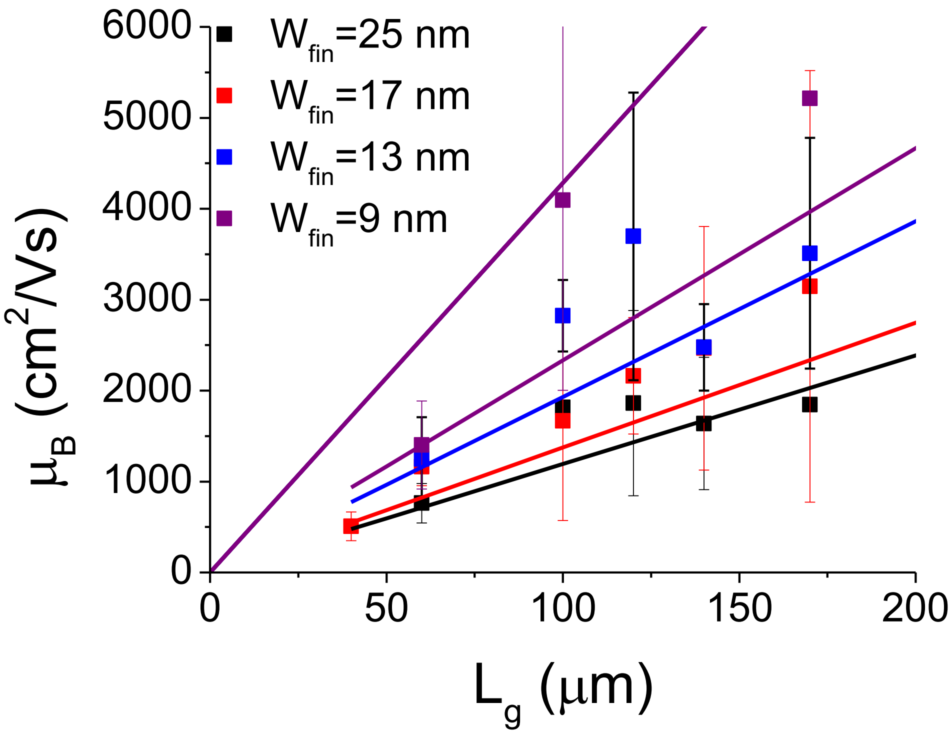
Collision-Limited Mobility and Mean-Free Path



- W_f ↓ → μ_{col} ↓
- W_f ↓ → λ ↓

→ reflects sidewall scattering

Ballistic Mobility

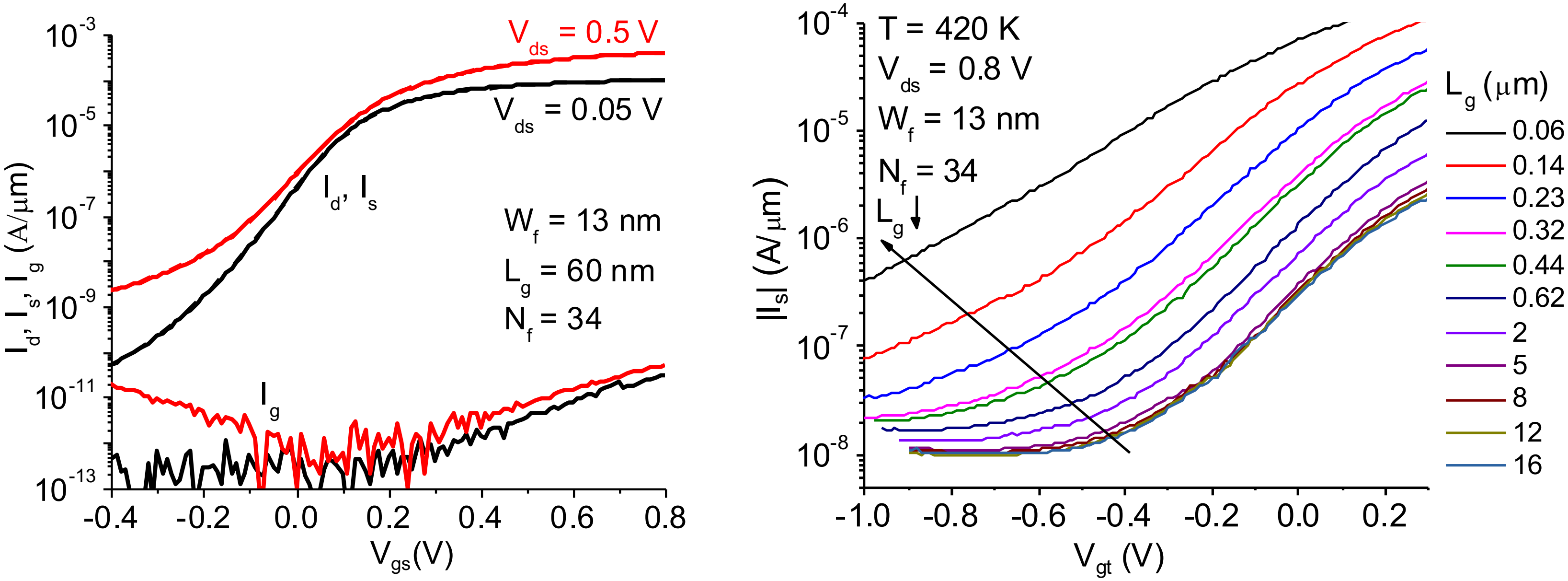


- $L_g \uparrow \rightarrow \mu_B \uparrow$
- $W_f \downarrow \rightarrow \mu_B \uparrow$

$\rightarrow$ effect of quantization + non-parabolicity?

2. Excess Off-State Current in InGaAs FinFETs

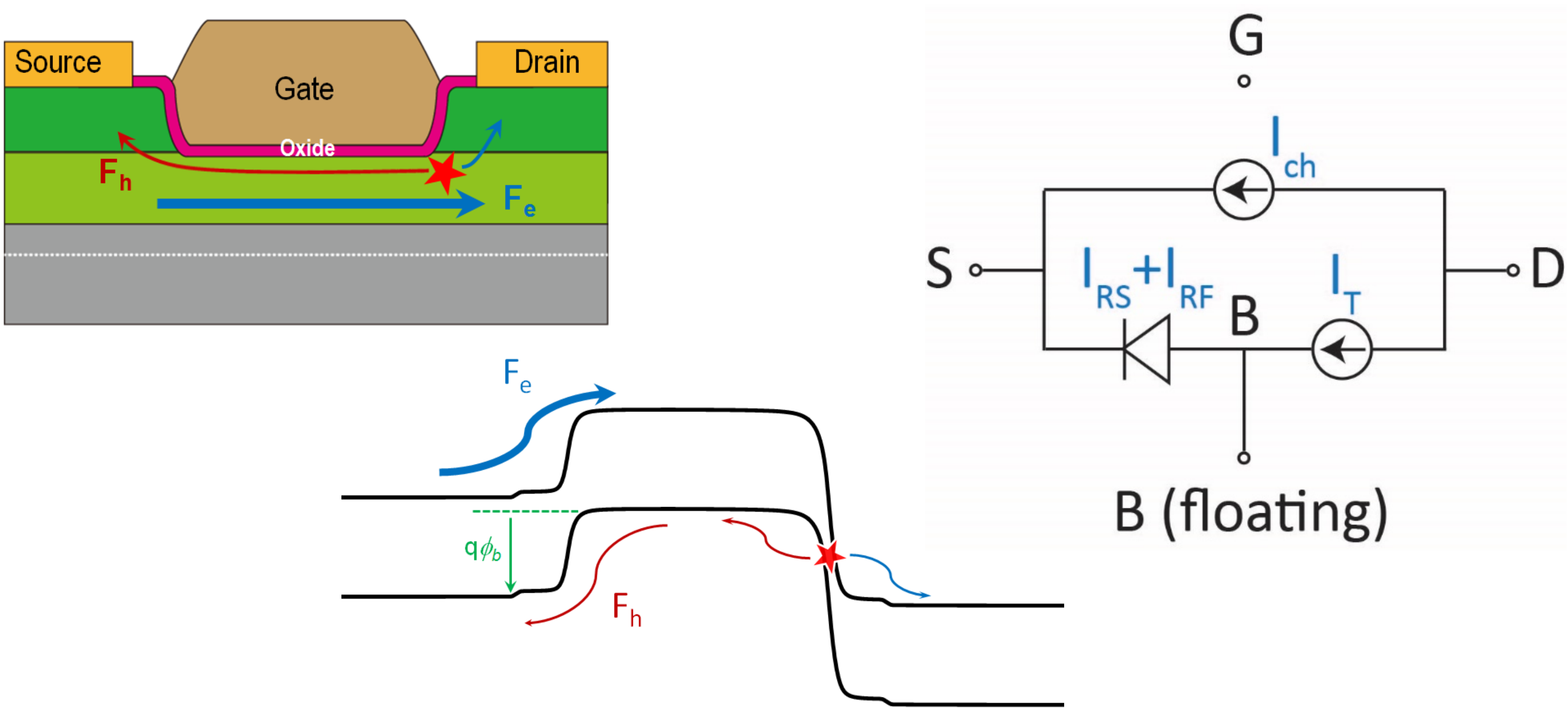
W_f = 13 nm InGaAs FinFET



- Enhanced as V_{ds} ↑
- Strongly enhanced as L_g ↓

Zhao EDL 2018, TED 2019

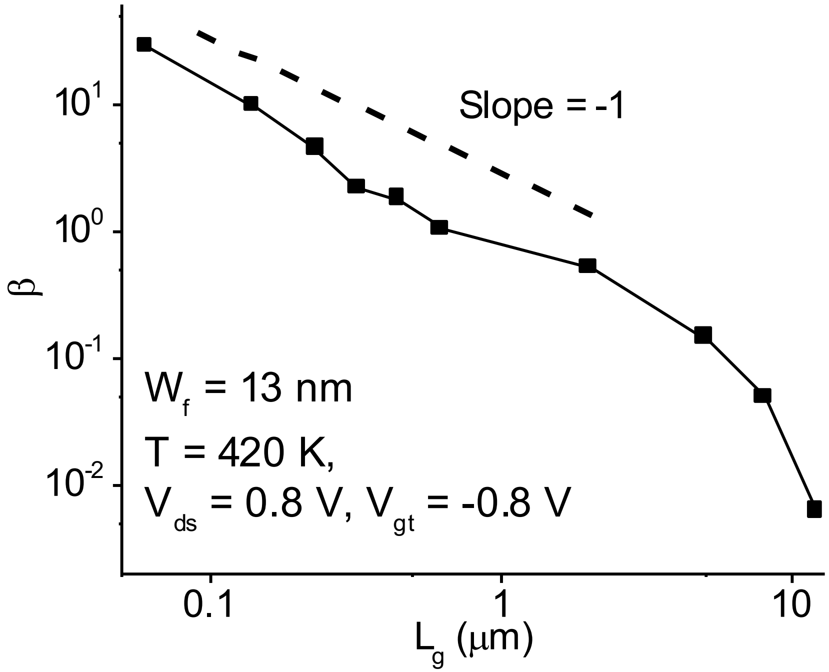
Physics: Band-to-Band Tunneling + Parasitic Bipolar Transistor



- Band-to-band tunneling at drain end of channel
- Bipolar amplification effect
- Similar to floating-body SOI MOSFET

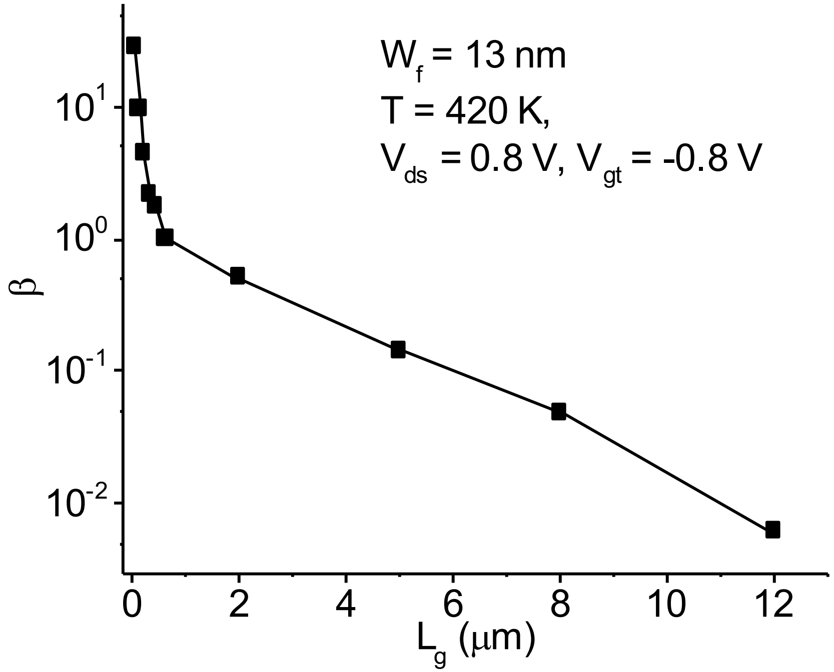
Parasitic Bipolar Current Gain

Short channel regime



- $\beta \approx L_g^{-1}$
- Negligible fin recombination

Long-channel regime

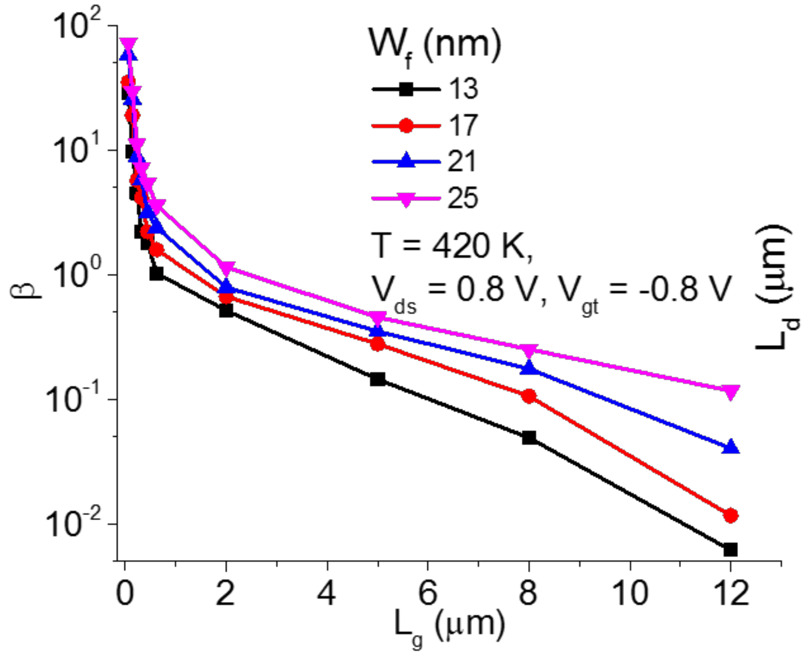


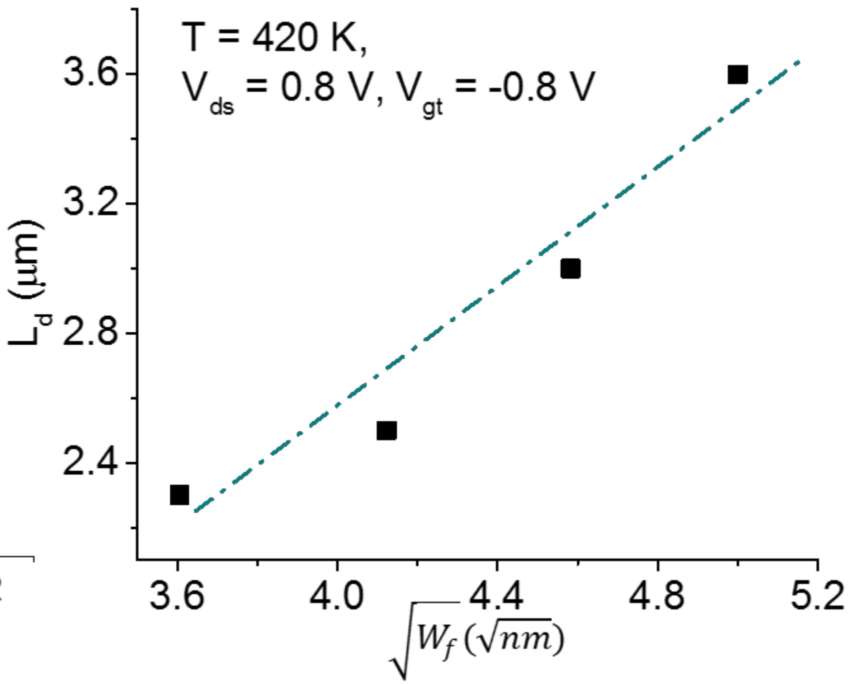
- $\beta \approx \exp(L_g/L_d)$
- Diffusion length: L_d ~ 3 μm

Zhao EDL 2018, TED 2019

Fin-Width Dependence of Diffusion Length

Long-channel regime vs. W_f





$L_d \sim W_f^{1/2}$ reflects dominant surface recombination

$$L_d \approx \sqrt{\frac{D_e W_f}{2S}}$$

Conclusions

Ideal 3D device behavior masked by:

1. extrinsic effects, i.e., gate oxide trapping
   - → grossly distorts charge-control relationship
   - → results in underestimate of mobility
   - → new technique reveals intrinsic device behavior
2. additional intrinsic physics:
   - → band-to-band tunneling
   - → parasitic bipolar amplification
   - → developed techniques to analyze, model