Extraction of Virtual-Source Injection Velocity in sub-100 nm III-V HFETs

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Discussions with R. Chau & M. Radosavljevic

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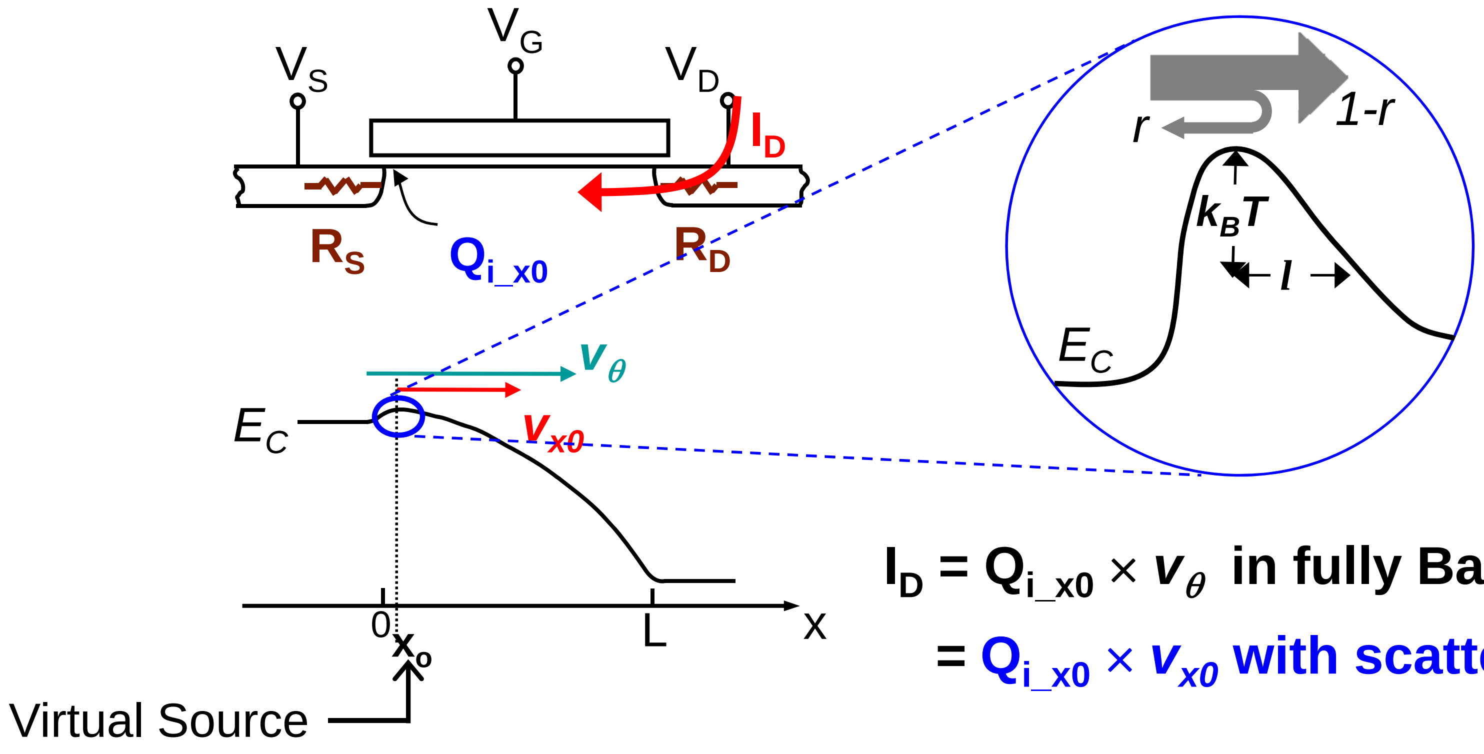
“Virtual Source” Injection Velocity



$I_D = Q_{i\_x0} \times v_\theta$ **in fully Ballistic case**

$= Q_{i\_x0} \times v_{x0}$ **with scattering**

→ v_{x0}: FOM to determine I_D and gate delay (τ).

Goal of this work: measure v_{x0} in III-V channel

Ref: Prof. Lundstrom, Purdue Univ.

v_{x0} - How to extract?

Approaches:

- [1]Inversion charge is linear with V_{GS} for $V_{GS} > V_T$.

$$I_D = Q_{i\_x0} \times v_{x0} = C_{gi} \, (V_{GSi} - V_T) \times v_{x0}$$

$$\rightarrow \; v_{x0} = \frac{I_D}{C_{gi} \, (V_{GSi} - V_T)}$$

Limitation: Linearity assumption underestimates Q_{i_x0}.

- [2]Transconductace method.

$$\frac{\partial(I_D)}{\partial(V_{GSi})} = g_{mi} = C_{gi} \times v_{x0} \rightarrow v_{x0} = \frac{g_{mi}}{C_{gi}}$$

Limitation: Assumes v_{x0} constant with V_{GS}.

Ref: [1]D. A. Antoniadis (IBM Journal-06), [2]G. Dewey (EDL-08)

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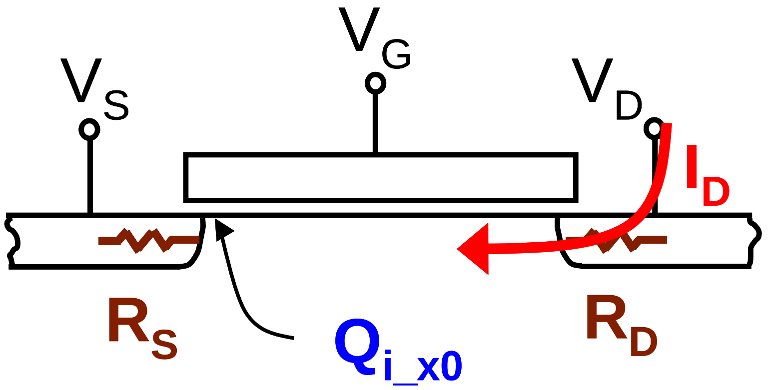
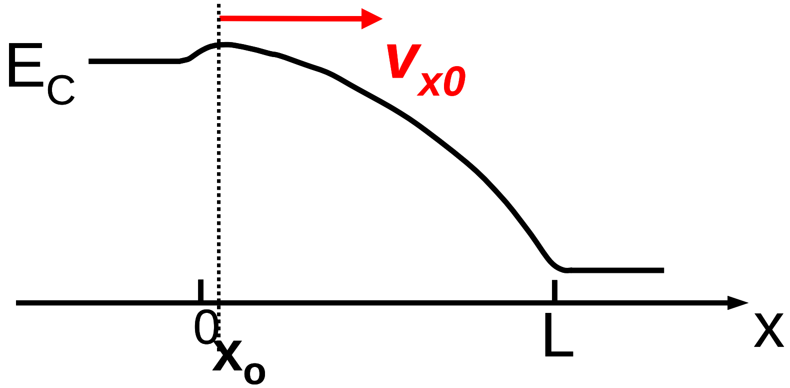
v_{x0} – Proposed Methodology



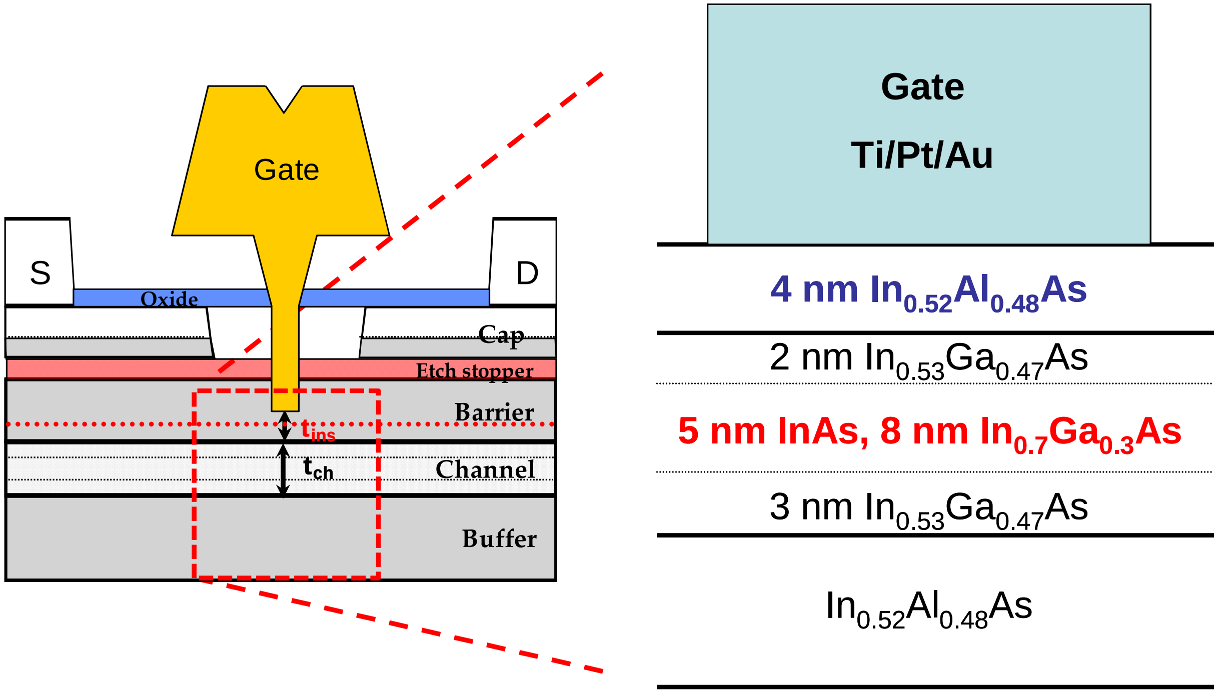


$$I_D = Q_{i\_x0} \times v_{x0}$$

$$\Rightarrow v_{x0} = I_D / Q_{i\_x0}$$

- I_D: Measured Drain Current
- Q_{i_x0}: Sheet Charge Density
  $$\rightarrow Q_{i\_x0} = \int C_{gi}\, d(V_{GS,i})$$
  where C_{gi} @ V_{DS} = 10 mV
- R_s and R_d correction
  $$V_{DSi} = V_{DS} - I_D \times (R_S + R_D)$$
  $$V_{GSi} = V_{GS} - I_D \times R_S$$
- V_T roll-off correction in Q_{i_x0}
- DIBL correction in Q_{i_x0}

Device Technology: III-V HEMT



Gate

Ti/Pt/Au

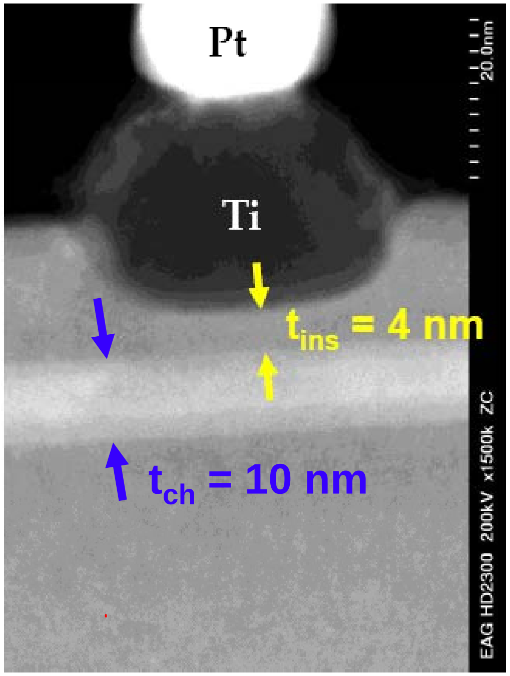
4 nm $In_{0.52}Al_{0.48}As$

2 nm $In_{0.53}Ga_{0.47}As$

5 nm InAs, 8 nm $In_{0.7}Ga_{0.3}As$

3 nm $In_{0.53}Ga_{0.47}As$

$In_{0.52}Al_{0.48}As$



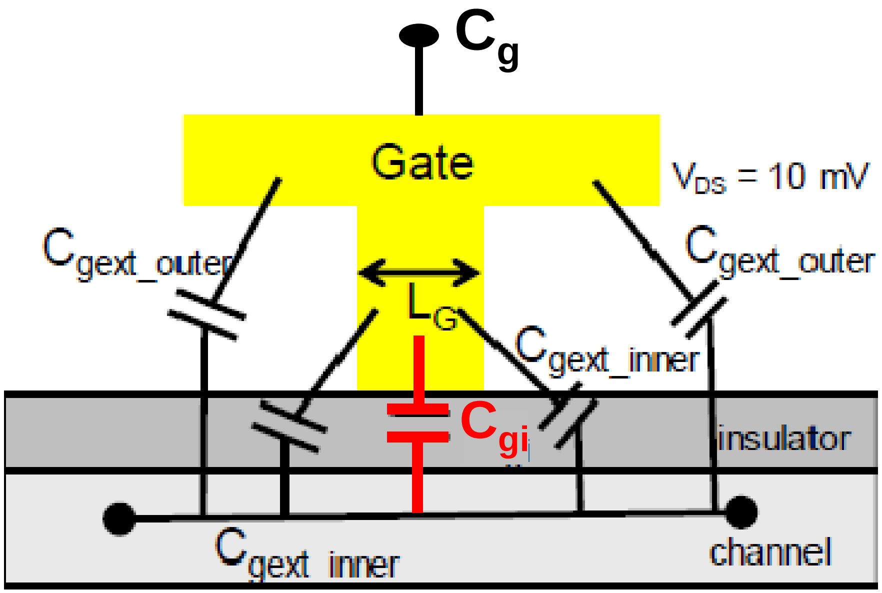
- L_g: 200 nm ~ 30 nm, t_{ins} = ~ 4 nm
- Channel: **$In_{0.53}Ga_{0.47}As$, $In_{0.7}Ga_{0.3}As$, InAs**

Refs: Kim *et al.*, iedm-08, iprm-09

C_{gi} - How to extract in small L_g device?

C_{gi} → intrinsic gate capacitance per unit area [fF/μm²]

(from S-parameters at linear region, $V_{DS} = 10$ mV)

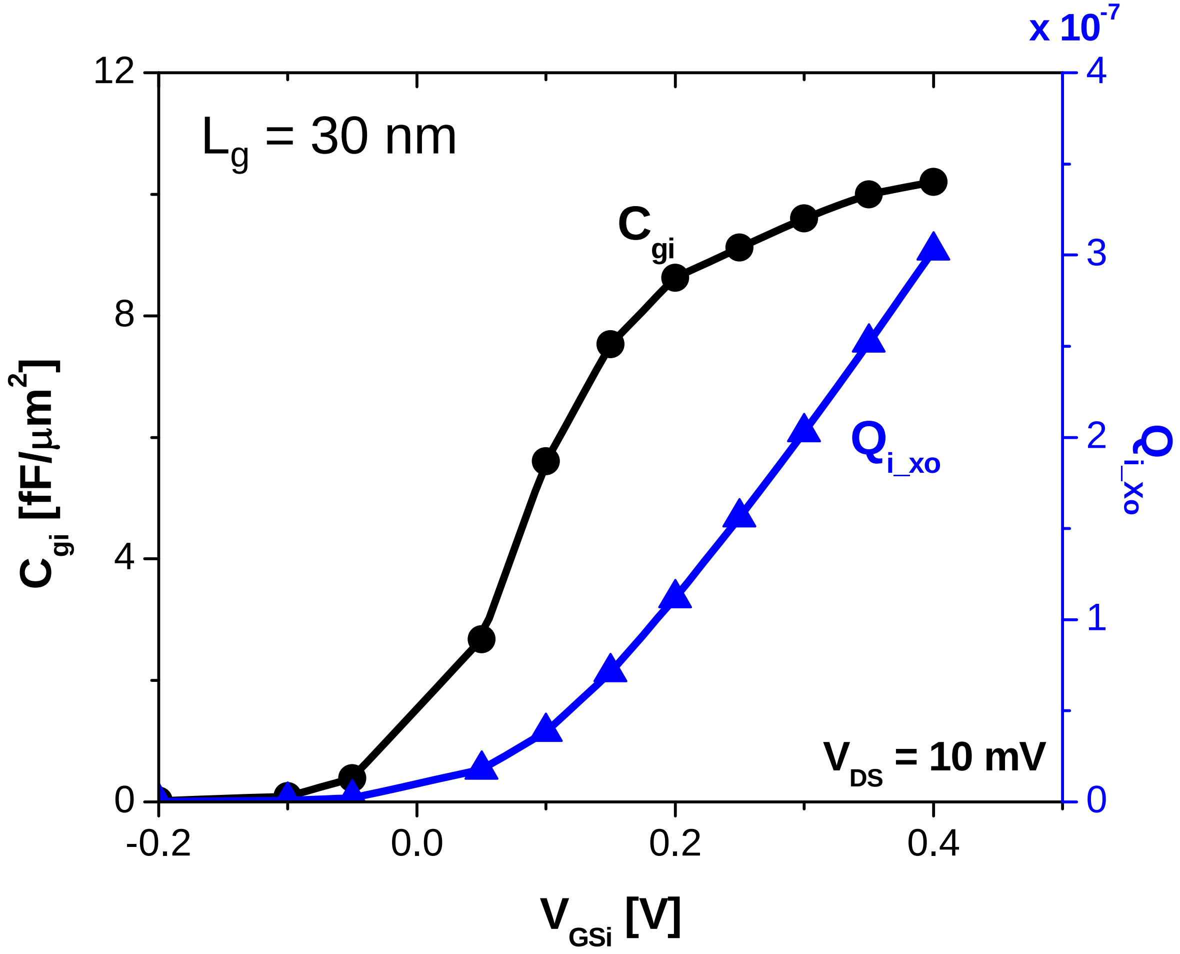


$$C_g = \underbrace{C_{gi} \text{ x } L_g + 2C_{gext\_inner}}_{\propto f(V_{GSi} - V_T)} + \overset{\approx C_g \text{ @ OFF}}{\boxed{2C_{gext\_outer}}}$$

$$\rightarrow C_g - C_g(\text{OFF}) = \boxed{\mathbf{C_{gi} \text{ x } L_g}} + 2C_{gext\_inner}$$

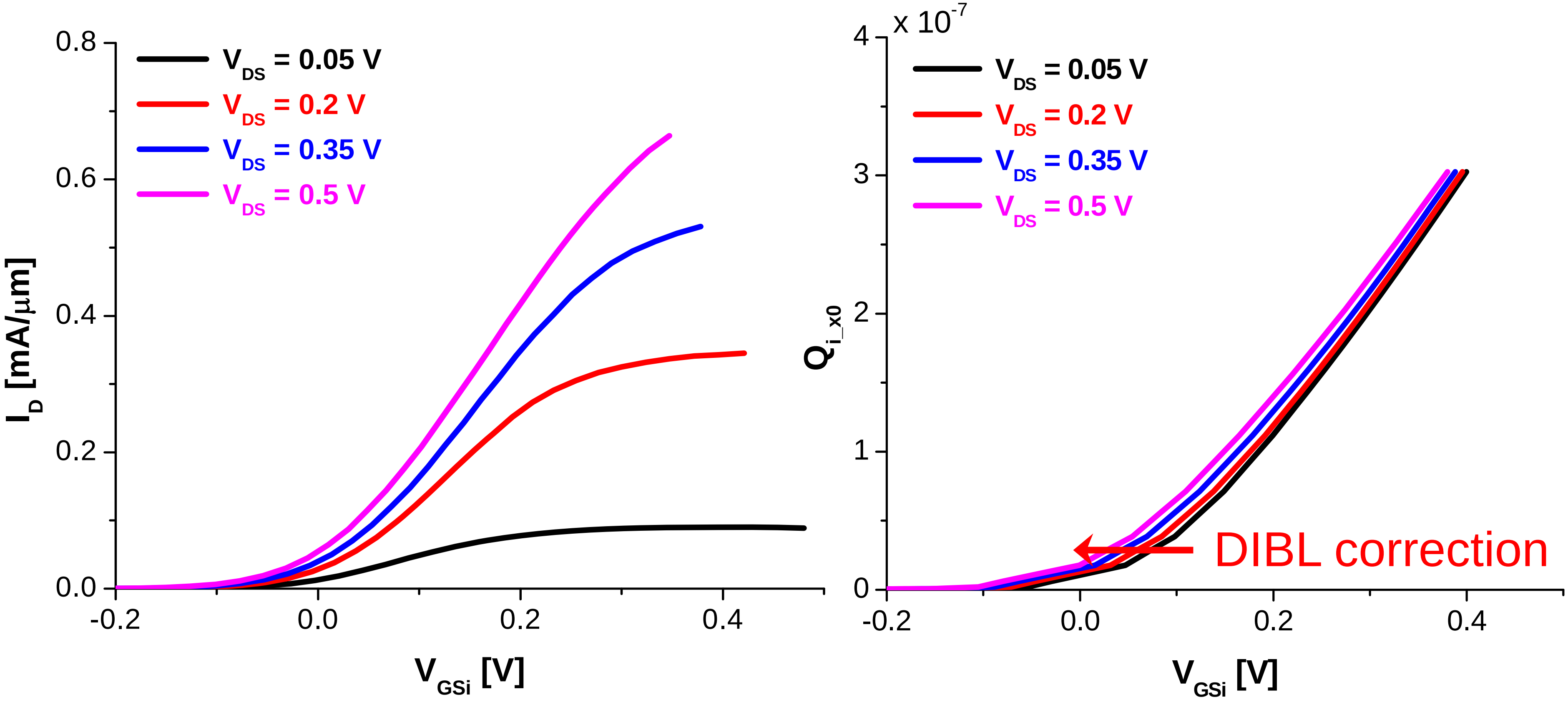
Q_{i_x0} - How to extract?

$$Q_{i\_x0} = \int C_{gi}\, d(V_{GS,i}), \text{ where } C_{gi} \text{ @ } V_{DS} = 10\text{ mV}$$



$v_{x0} = I_D / Q_{i\_x0}$

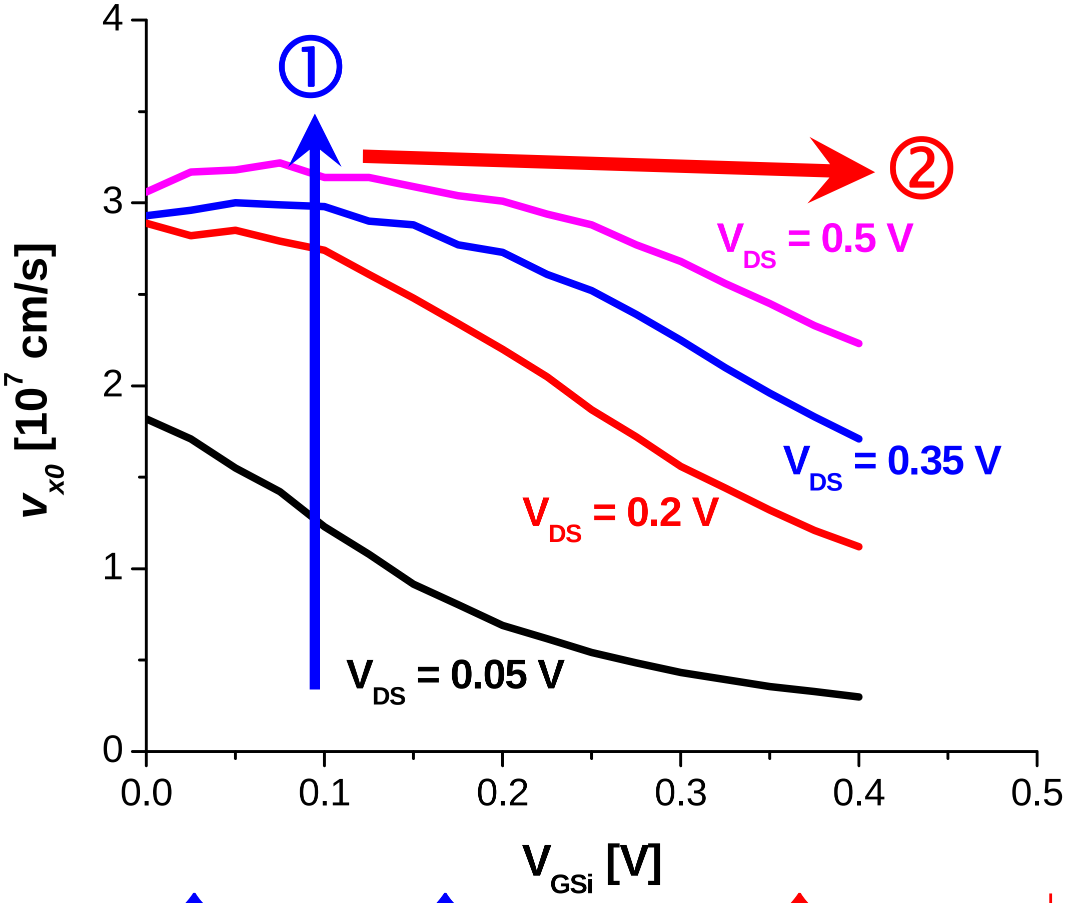
L_g = 30 nm $In_{0.7}Ga_{0.3}As$ HEMTs with t_{ins} = 4 nm



v_{x0} → can be extracted at any bias condition.

As V_{GSi} ↑, less DIBL correction due to V_{DSi} ↓.

Bias Dependent v_{x0} - 30 nm InGaAs HFET

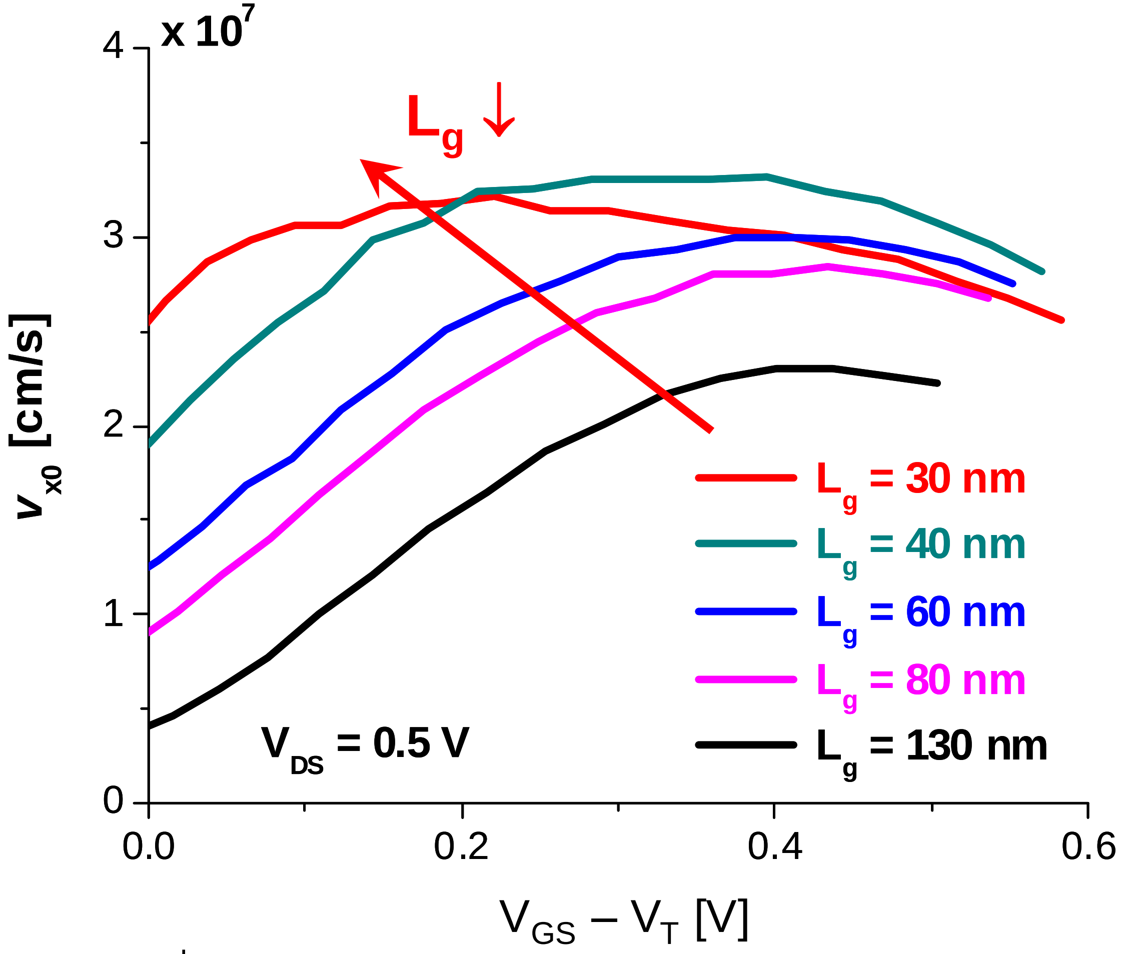


① $V_{DS} \uparrow \rightarrow v_{x0} \uparrow$ ② $V_{GSi} \uparrow \rightarrow v_{x0} \downarrow$

Extracted v_{x0} is ***NOT*** constant with V_{GSi}.

$$\frac{\partial(I_D)}{\partial(V_{GSi})} = \frac{\partial(Q_{i\_x0})}{\partial(V_{GSi})} v_{x0} + Q_{i\_x0} \frac{\partial(v_{x0})}{\partial(V_{GSi})}$$

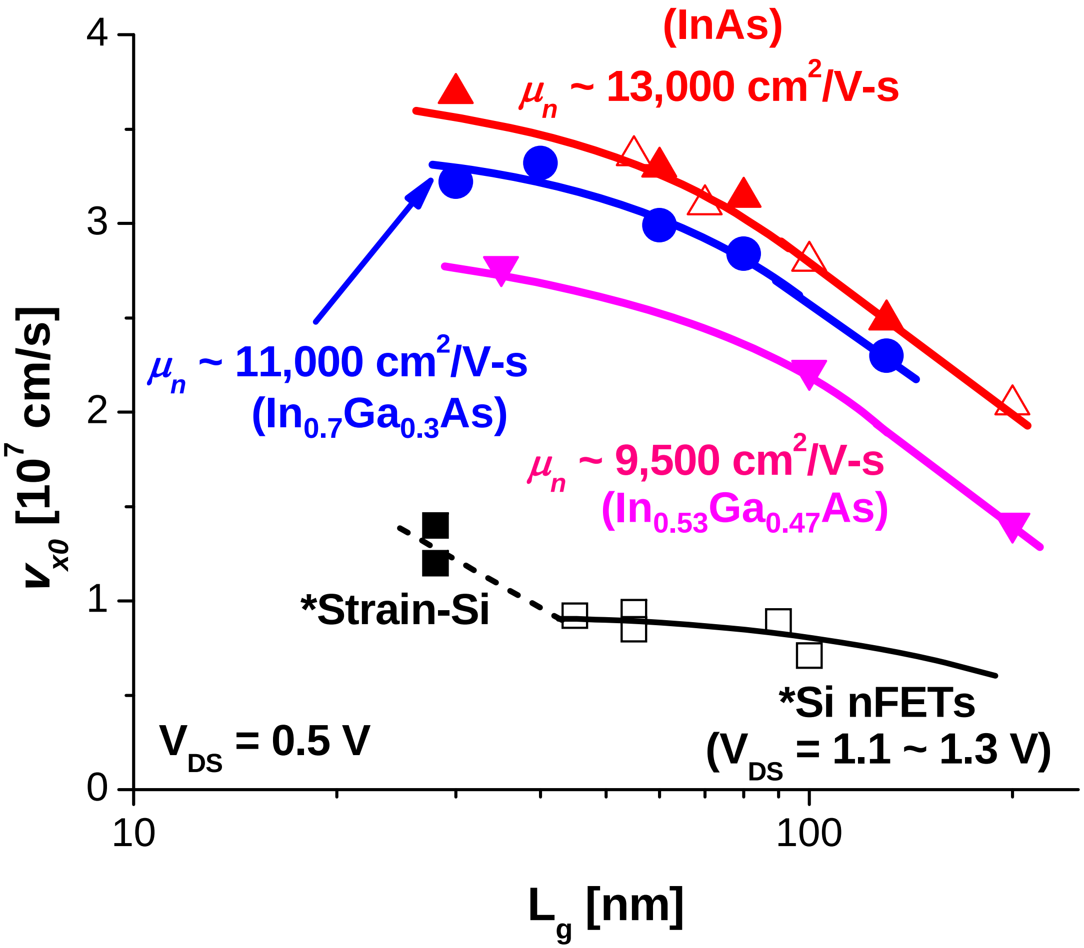
v_{x0} for different L_g



As L_g ↓,

v_{x0} improves and then saturates at L_g ~ 40 nm.

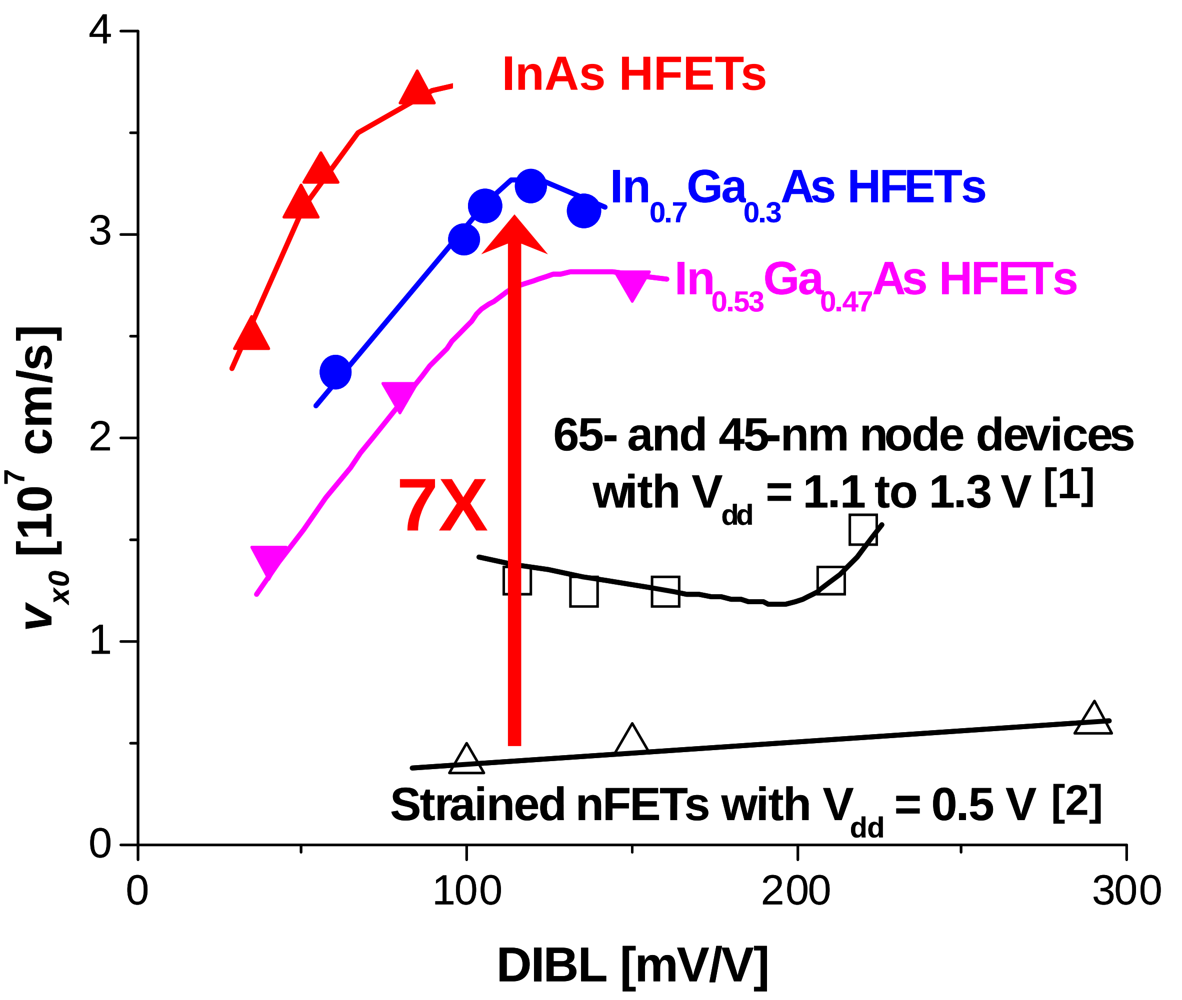
v_{x0} vs. L_g for different channels



- III-Vs shows **2X higher v_{x0}** than Si, even at V_{DS} = 0.5 V.
- As InAs composition ↑, v_{x0} ↑ due to m_e^* ↓.

Ref: *Khakifirooz *et al.*, *TED*, 1674 (08)

v_{x0} vs. DIBL



→ **7X higher v_{x0}** @ DIBL = 100 mV/V, V_{dd} = 0.5 V

Ref: 1)Khakifirooz *et al.*, *TED*, 1674 (08), 2)G. Dewey (*EDL*-08)

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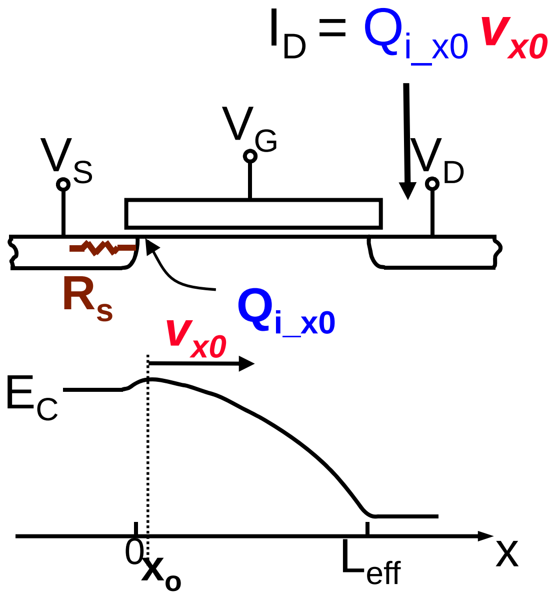
The "Virtual Source" FET Model

- A Simple, Physical Universal-Short Channel FET Semi-empirical Model
  (based on Si MOSFET model [1])

$$I_D = Q_{i\_x0} \times v_{x0\text{-}m} \times F_{sat}$$

F_{sat} : *Semiempirical saturation function*



- **Known Device Parameters**

C_{ox}^{inv} : $Q_{ix0} = C_{ox}^{inv} f(S, V_{GSi}, V_{DSi}, V_t^*)$

δ : $V_t^* = V_{t0} - \delta V_{DSi}$: *DIBL, From* $I_D(V_{DSi})$ *vs.* V_{GSi}

S : *Subthreshold swing: From* $\log(I_D)$ *vs.* V_{GSi}

V_{t0} : *Threshold Voltage at* $V_D \sim 0$ *(from* I_{off} *and DIBL)*

$R_{S,D}$: $V_{GSi} = V_{GS} - I_D R_S$; $V_{DSi} = V_{DS} - 2I_D(R_S + R_D)$

- **Fitted Physical Parameters**

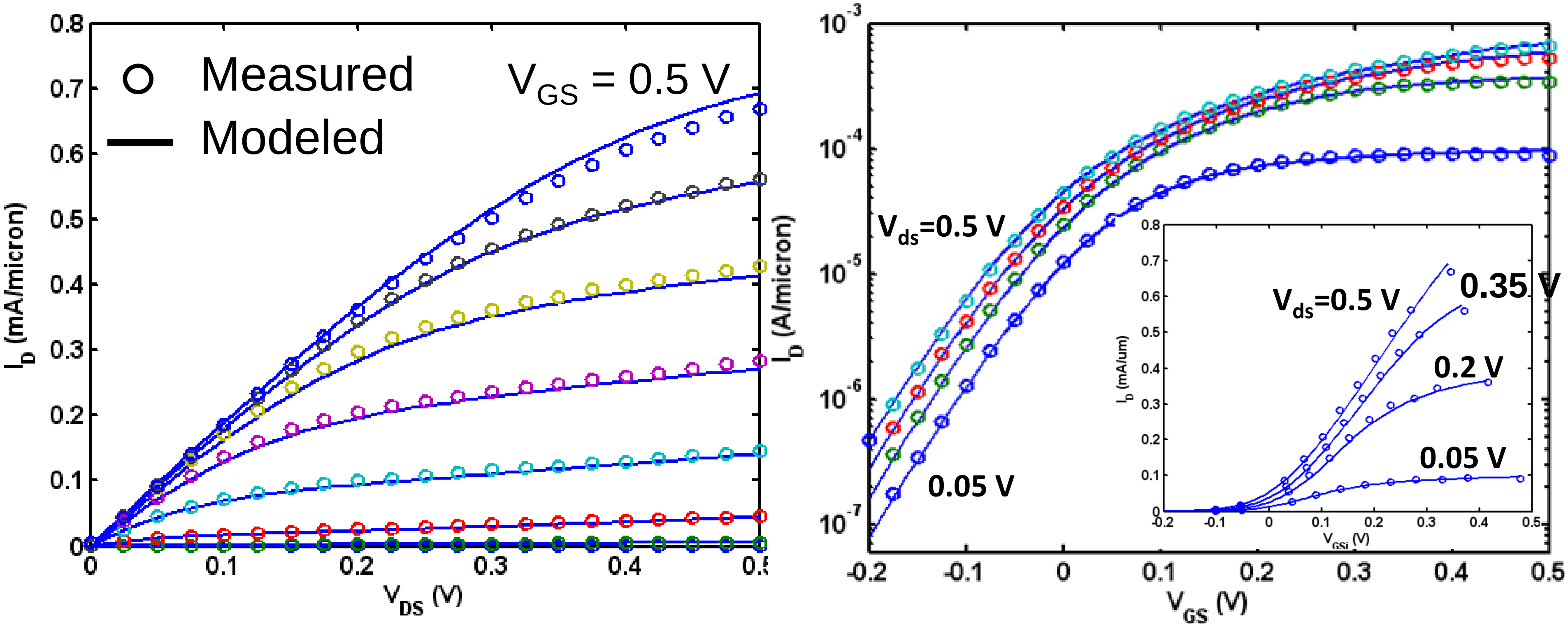
$V_{x0\text{-}m}$: *Maximum carrier velocity at virtual source* $(x = x_0)$

μ_{eff} : *Effective mobility, assumed constant*

[1] Khakifirooz *et al.*, *TED*, 1674 (08)

Comparison - 30 nm $In_{0.7}Ga_{0.3}As$ HFET

Fitting parameters: μ_{eff}, v_{x0m}



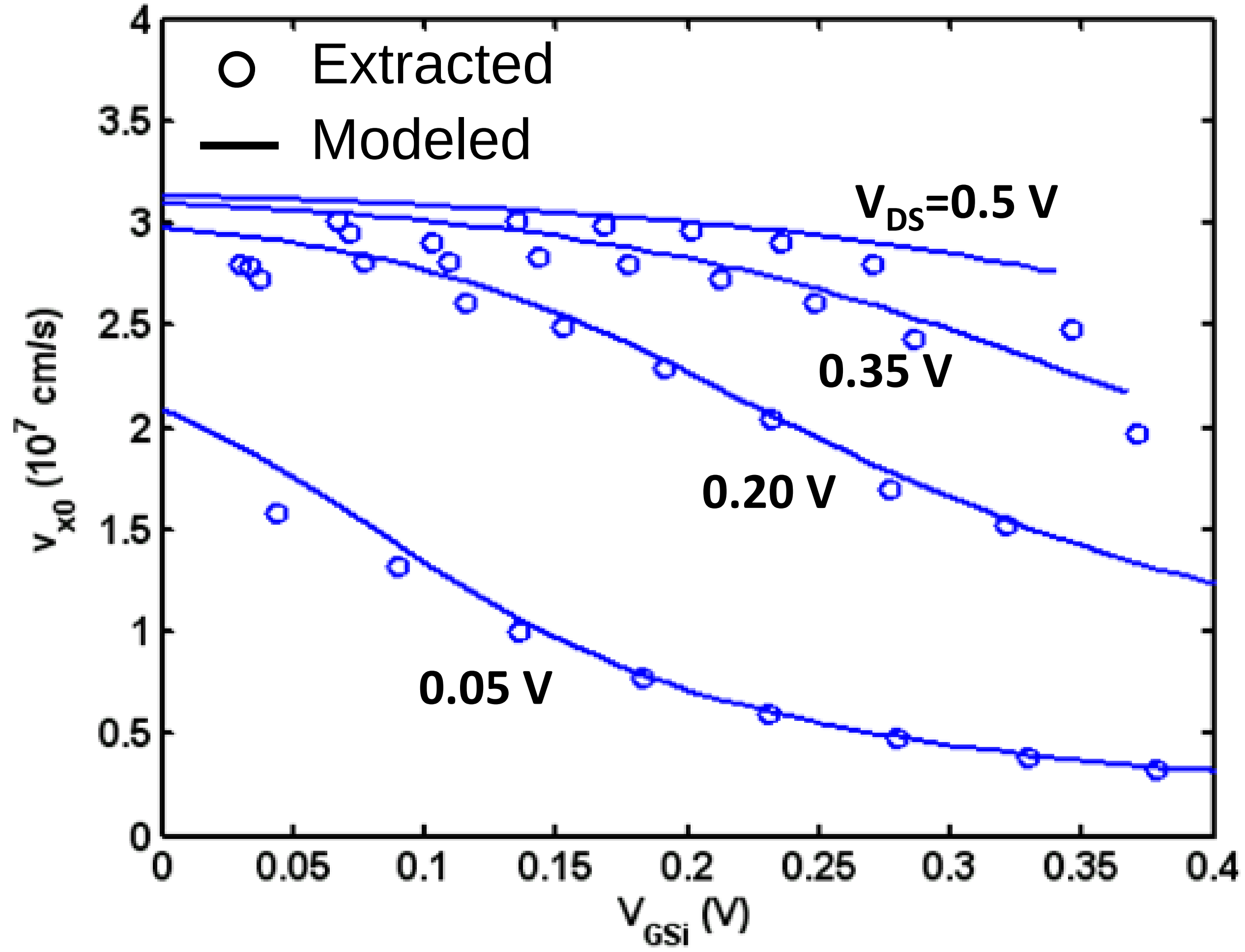
Excellent agreement:

- from linear to saturation, and weak to strong inversion.

- μ_{eff} = 1500 cm^2/Vs, v_{x0m} = 3.1 × 10^7 cm/s

Comparison: $v_{x0} = v_{x0m} \times F_{sat}$

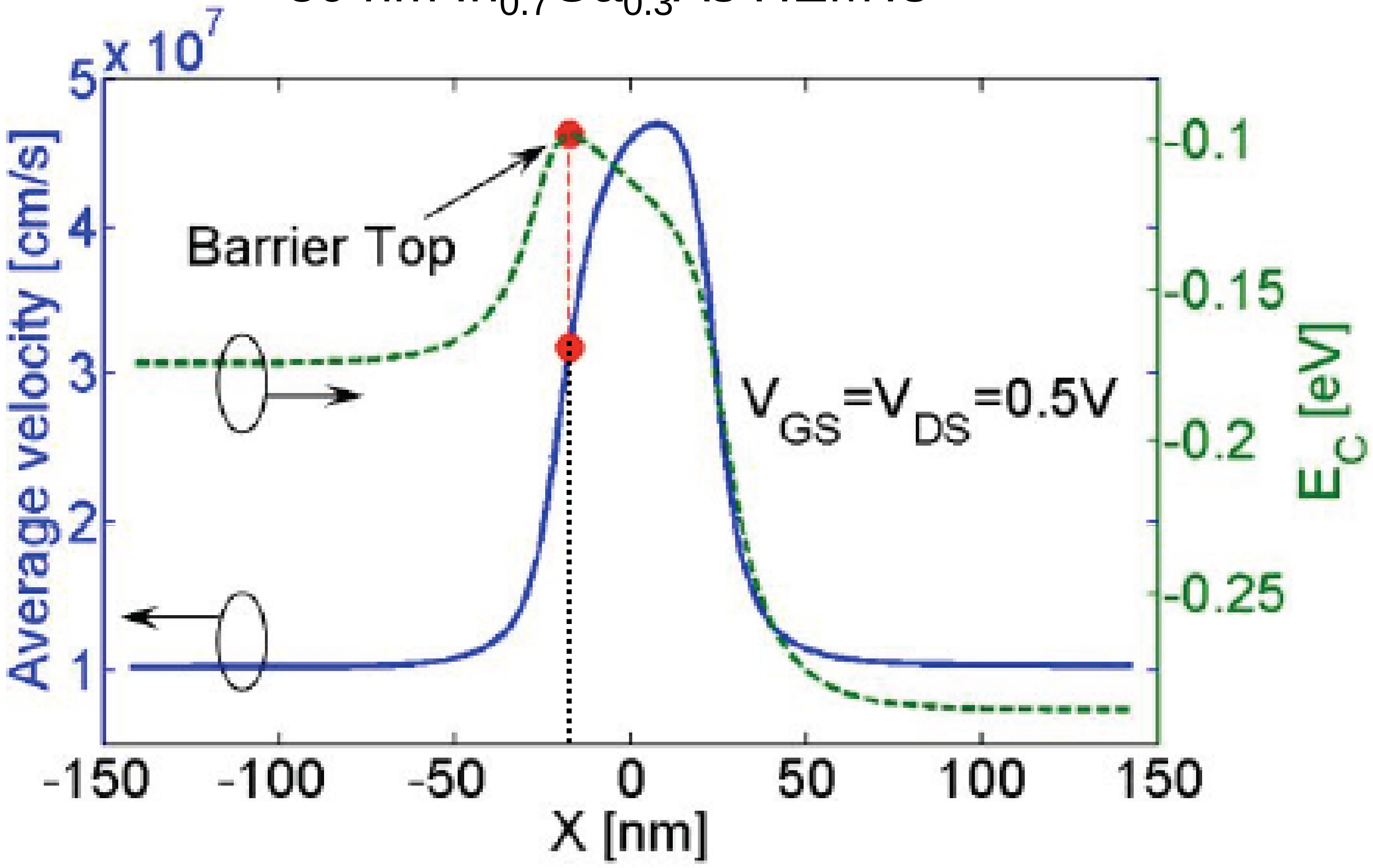
L_g = 30 nm $In_{0.7}Ga_{0.3}As$



→ Excellent agreement with extracted values of v_{x0}.

v_{x0} – NEGF simulation

30 nm $In_{0.7}Ga_{0.3}As$ HEMTs



→ **v_{x0} = 3.1 x 10^7 cm/s**: close to experimental value.

Acknowledgement : Y. Yang and M. S. Lundstrom, Purdue Univ.

Conclusions

- Methodology to extract injection velocity (v_{x0}) at virtual source.
- **Sub-100 nm InGaAs HEMTs**

  - **$v_{x0} > 3 \times 10^7$ cm/s** at $V_{DS} = 0.5$ V for $In_{0.7}Ga_{0.3}As$

  - Peak **$v_{xo} = 3.7 \times 10^7$ cm/s** for InAs sub-channel

  - 7× higher than Si at DIBL = 100 mV/V and $V_{DS} = 0.5$ V
- **"Virtual Source" FET model**

  - Excellent description of I-V characteristics of III-V HEMTs

  with physically meaningful values of v_{x0}.