

NCN@Purdue - Intel Summer School: July 14-25, 2008

Physics of Nanoscale Transistors: Lecture 5:

Application to State-of-the-Art MOSFETS

Changwook Jeong and Mark Lundstrom

Network for Computational Nanotechnology

Purdue University

West Lafayette, Indiana USA

outline

- 1) **Objectives**
- 2) Measured I-V characteristics
- 3) Treatment of series resistance
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) Summary

objectives

- 1) To compare measured, device performance metrics to the values expected from ballistic theory.
- 2) To discuss and interpret the results.
- 3) To identify experimental uncertainties in extracting and interpreting parameters.

(Thanks to Shuji Ikeda of ATDF for supplying these devices in Dec. 2007)

outline

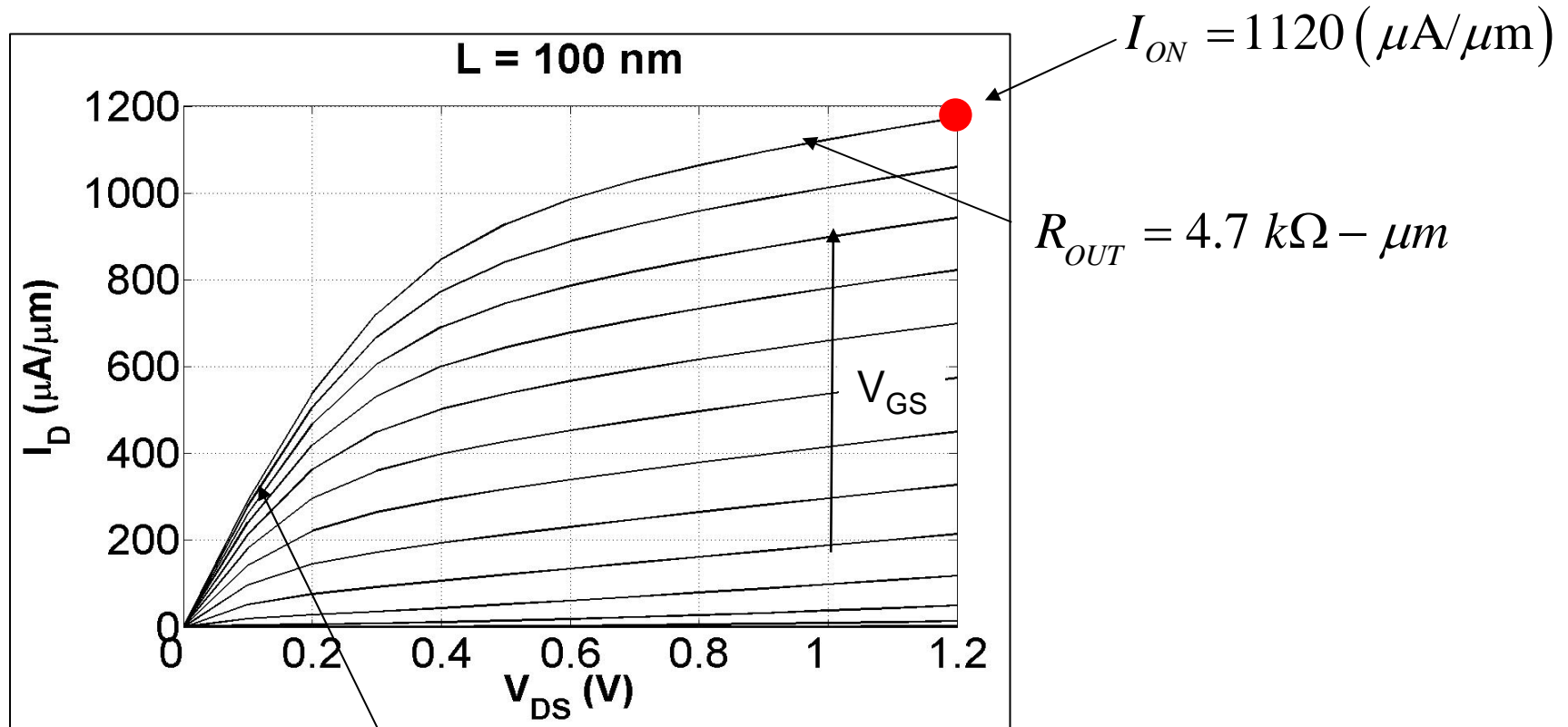
- 1) Objectives
- 2) Measured I-V characteristics**
- 3) Treatment of series resistance
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) Summary

technology parameters

- 1) Nitrided gate oxide ($k = 5$, $t_{inv} = 2.2$ nm)
- 2) Polysilicon gate
- 3) $V_{DD} = 1.2V$
- 4) Not intentionally strained
- 5) All measurements at $T \sim 300K$
- 6) Minimum mask channel length = 100 nm
Minimum physical channel length (SEM) = 85 nm

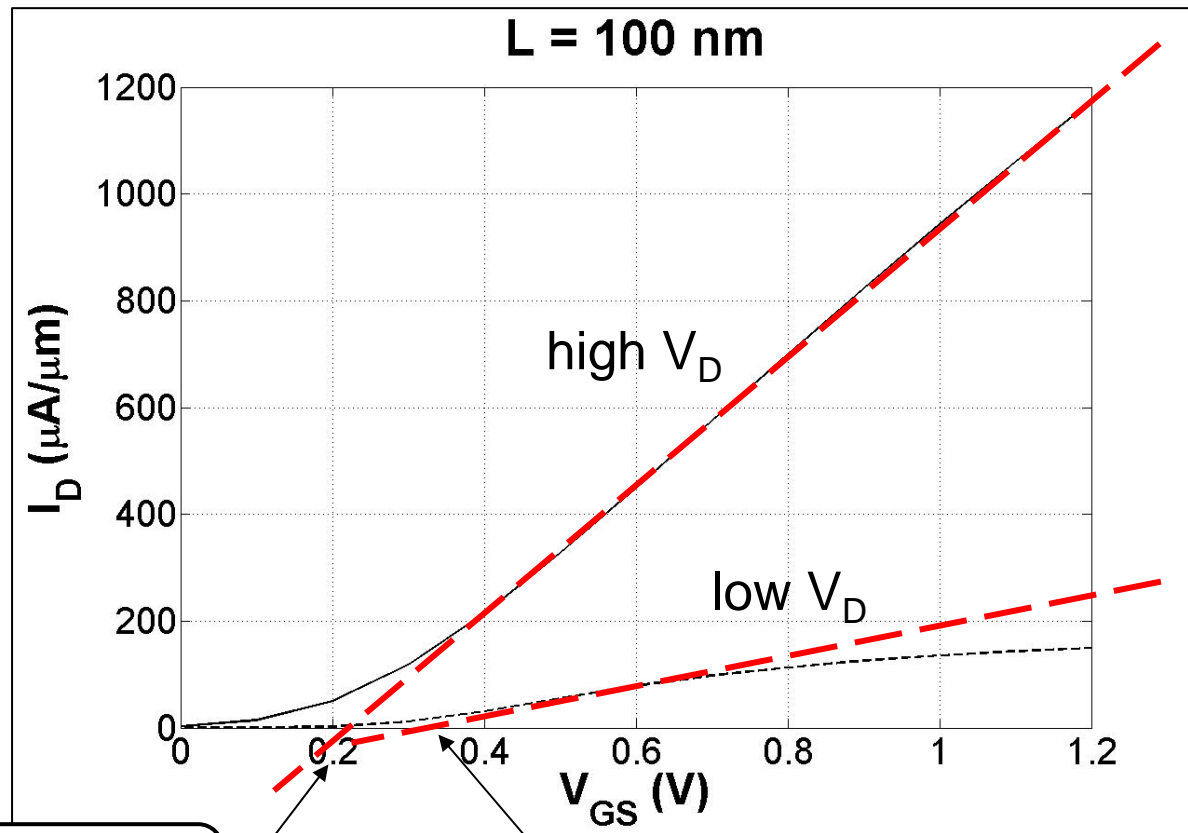
(Thanks to Shuji Ikeda of ATDF for supplying these devices in Dec. 2007)

NMOS common source characteristics



$$R_{CH} = \frac{V_{DS}}{I_D} = 340 (\Omega - \mu\text{m})$$

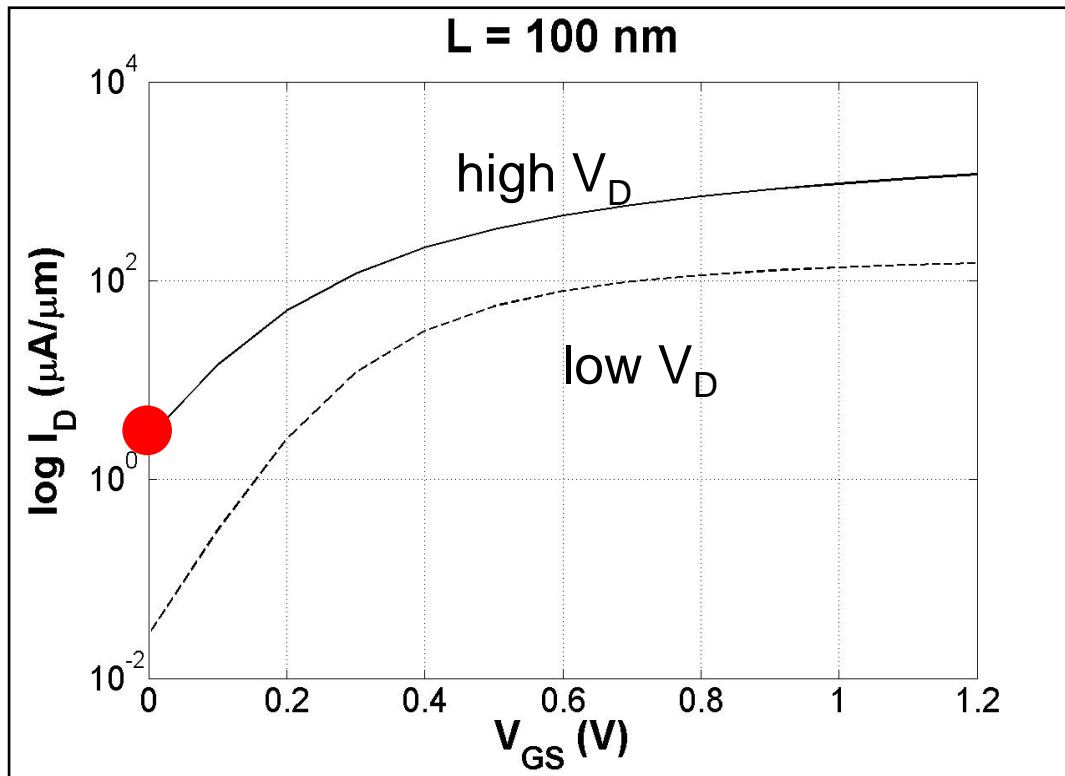
Transfer characteristics



$$V_{TSAT} = 0.26 \text{ V}$$

$$V_{TLIN} = 0.28 \text{ V}$$

Log₁₀ I_D vs. V_{GS}

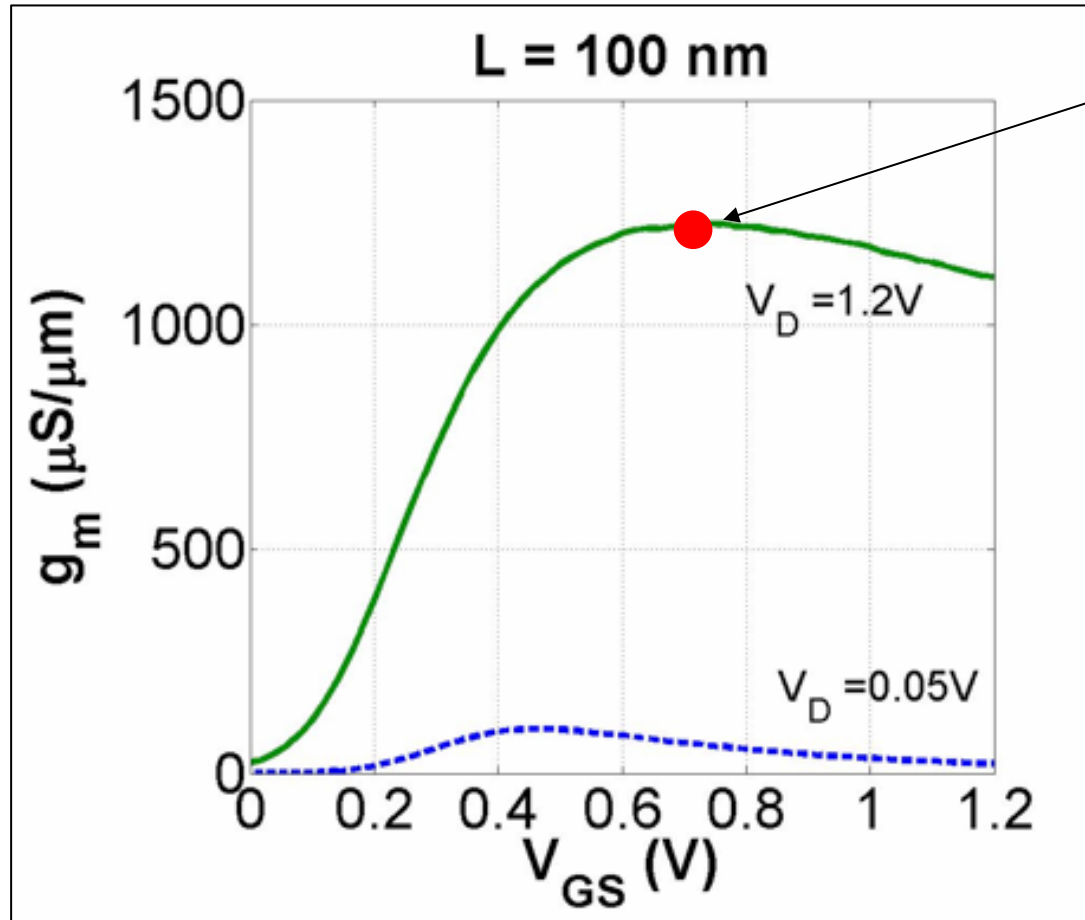


$$I_{OFF} = 0.95 (\mu\text{A}/\mu\text{m})$$

$$S = 110 (\text{mV}/\text{dec})$$

$$DIBL = 170 (\text{mV}/\text{V})$$

Transconductance



$$g_m = 1225 (\mu\text{S}/\mu\text{m})$$

$$g_m \equiv \left. \frac{\partial I_{DS}}{\partial V_{GS}} \right|_{V_{DS}}$$

summary

parameter	value (extr.)
V_{TSAT} (V)	0.26
V_{TLIN} (V)	0.28
I_{ON} ($\mu\text{A}/\mu\text{m}$)	1120
I_{OFF} ($\mu\text{A}/\mu\text{m}$)	0.95
S (mV/dec)	110
$DIBL$ (mV/V)	170
R_{CH} ($\Omega - \mu\text{m}$)	340
R_{OUT} ($\Omega - \mu\text{m}$)	4700
g_{mMAX} ($\mu\text{S}/\mu\text{m}$)	1225

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) Series resistance**
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) Summary

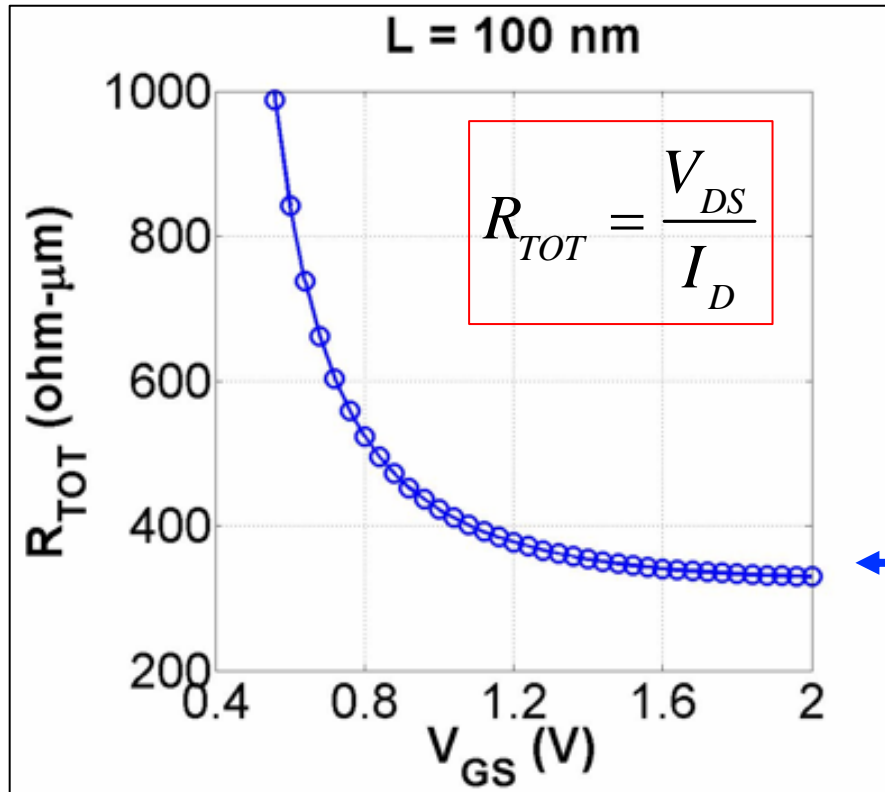
series resistance

To analyze the device, we want to compare the **intrinsic device** to a hypothetical ballistic device. To do so, we must measure the series resistance so that we can de-embed the intrinsic device.

There are many techniques to deduce the series resistance from measured IV data but it is **very difficult** for modern, short channel MOSFETs because of the underlying assumptions of these techniques are no longer well-satisfied.

Our analysis of the measured results will be limited by our uncertain knowledge of the value of the series resistance.

series resistance



From shift and ratio measurement:

$$R_{SD} \approx 100 \Omega - \mu\text{m}$$

$$\begin{aligned} R_{TOT} &= R_{CH} + R_{BALL} + R_{SD} \\ &= 320 \Omega - \mu\text{m} \end{aligned}$$

From BSIM simulator:

$$R_{SD} = 200 \Omega - \mu\text{m}$$

$$R_{TOT} = R_{CH}(V_{GS}) + R_{BALL}(V_{GS}) + R_{SD}$$

series resistance bounds

$$R_{BALL} (V_{GS} = 2 \text{ V}) W = \frac{(2k_B T / q) \mathcal{F}_0(\eta_{F1})}{Q_I(0) v_T \mathcal{F}_{-1/2}(\eta_{F1})} \approx 40 \Omega - \mu m$$

For high V_G , we find that the ballistic channel resistance is approximately constant, and for Si parameters (100), single subband, $m^* = 0.19$, its value is about $40 \Omega\text{-}\mu m$.

$$R_{CH} \Big|_{V_{GS}=2} \cong R_{BALL} + R_{CH} + R_{SD} = 320 \rightarrow R_{SD} \leq 280 (\Omega - \mu m)$$

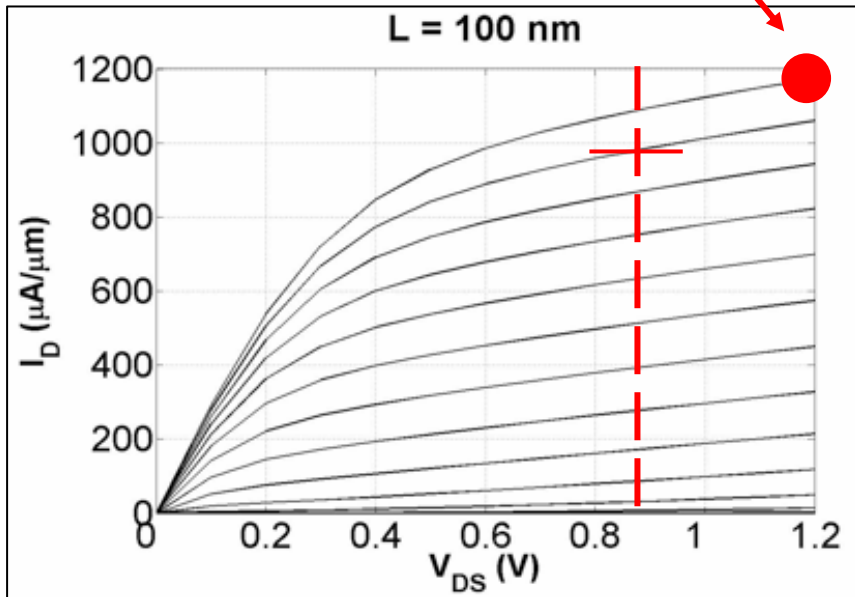
$$\text{BSIM: } R'_{SD} = 200 \rightarrow R_{SD} \approx 140 (\Omega - \mu m)$$

Given the approximations involved, we will assume:

$$R_{SD} = 200 \pm 50 (\Omega - \mu m)$$

Series resistance has a significant effect

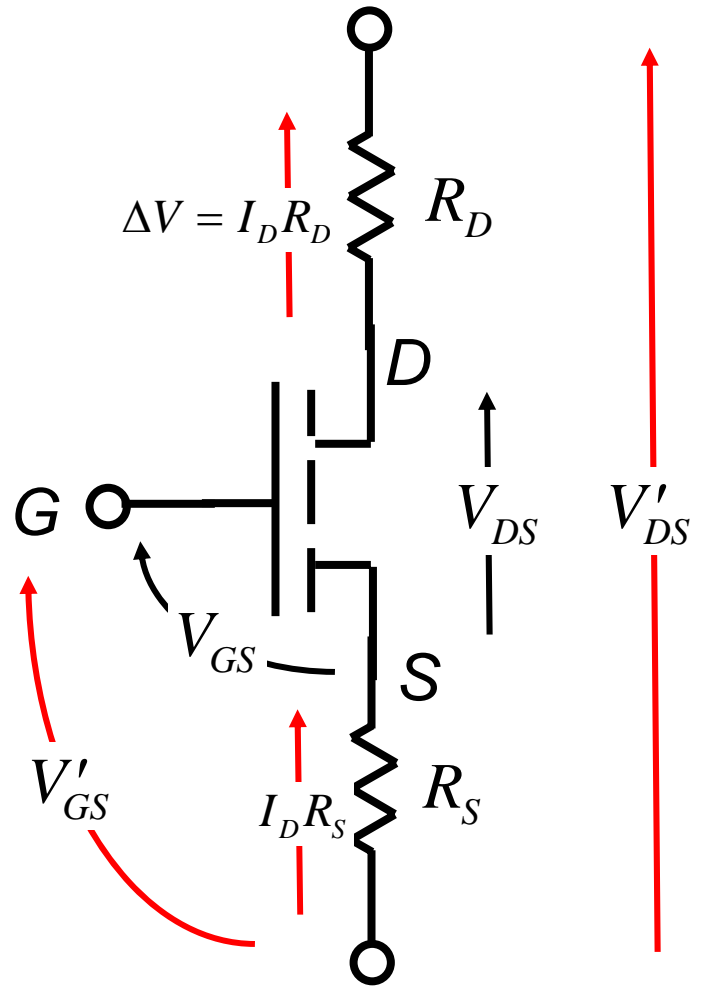
$$I_{ON} = 1120 (\mu\text{A}/\mu\text{m})$$



$$\Delta V = 100 \times 1120 \times 10^{-6} = 0.11\text{V}$$

$$V_{DS} = 1.2 - 0.22 = 0.88\text{V}$$

$$V_{GS} = 1.2 - 0.11 = 1.09\text{V}$$



$$R_S = R_D \approx 100 \Omega - \mu\text{m}$$

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) Series resistance
- 4) Linear region analysis**
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) Summary

channel resistance analysis ($V_{GS} = 1.2V$)

$$R_{CH}(V_{GS}) = R_{TOT}(V_{GS}) - R_{BAL}(V_{GS}) - R_{SD}$$

$$R_{SD} = 200 \pm 50 (\Omega - \mu m)$$

$$R_{CH}(V_{GS} = 1.2 \text{ V}) = 140 \pm 50 (\Omega - \mu m)$$

- 1) What is the inversion layer charge in the linear region?
- 2) What is the mobility?

inversion layer charge

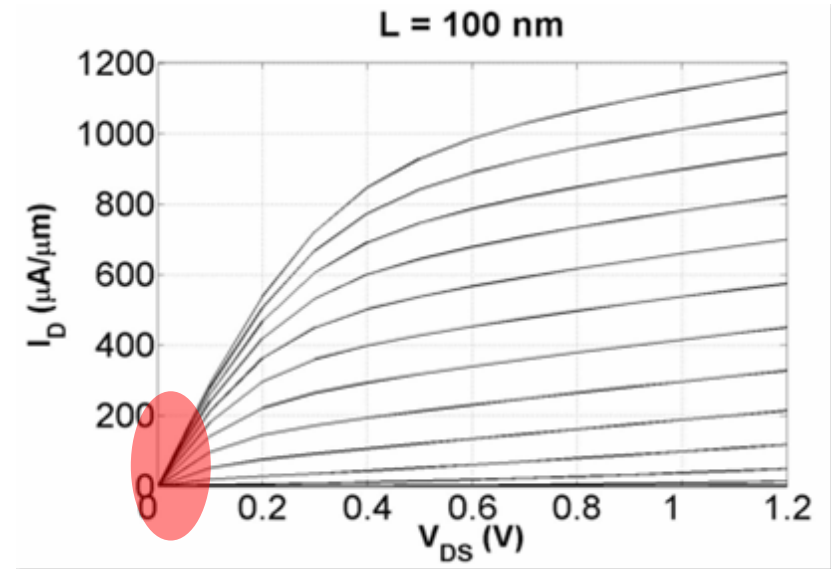
$$Q_I(0) = C_{ox} (V_{GS} - V_T)$$

$$C_{ox} = \frac{\epsilon_{ox}}{T_{inv}} = 1.544 \times 10^{-6} \text{ F/cm}^2$$

$$V_{GS} = V'_{GS} - I_D R_S \approx V'_{GS}$$

$$V_T = V_T(\text{lin}) = 0.28 \text{ V}$$

$$Q_I(0)/q ; 8.9 \times 10^{12} \text{ cm}^{-2}$$



How accurate is this estimate?
(Will discuss in Sec. 7.)

measuring mobility

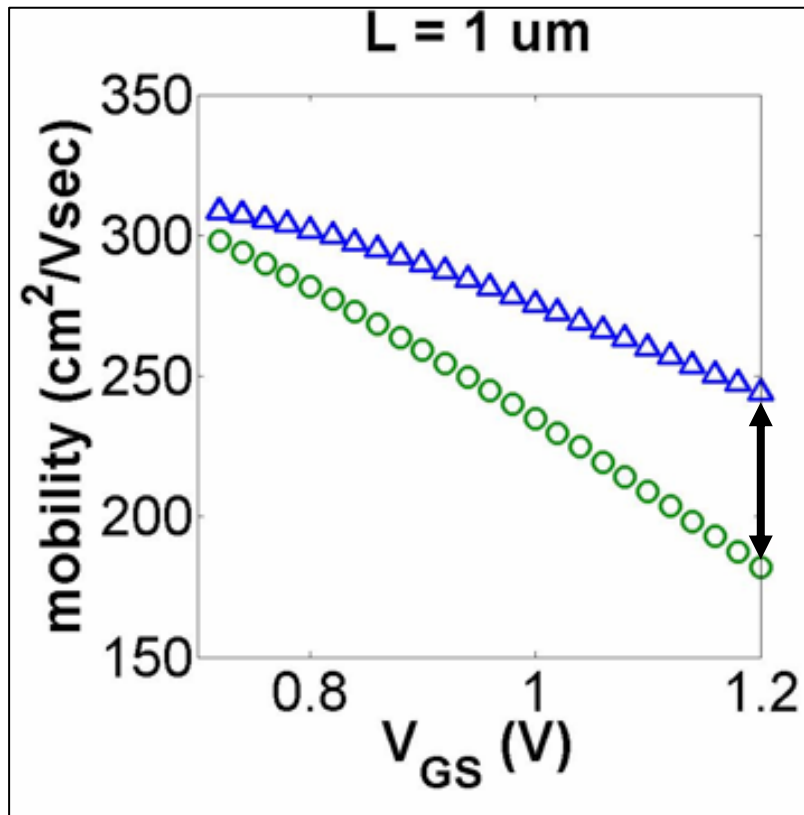
Two methods:

$$\text{i) } \mu_{eff} = \frac{L_{mask}}{W_{mask} (R_{TOT} - R_{BALL} - R_{SD}) C_{ox} (V_{GS} - V_T)}$$

(Sensitive to R_{SD} and to the ballistic resistance.)

$$\text{ii) } \mu_{eff} = \frac{1}{W_{mask} (\partial R_{TOT} / \partial L_{mask}) C_{ox} (V_{GS} - V_T)}$$

measured mobility

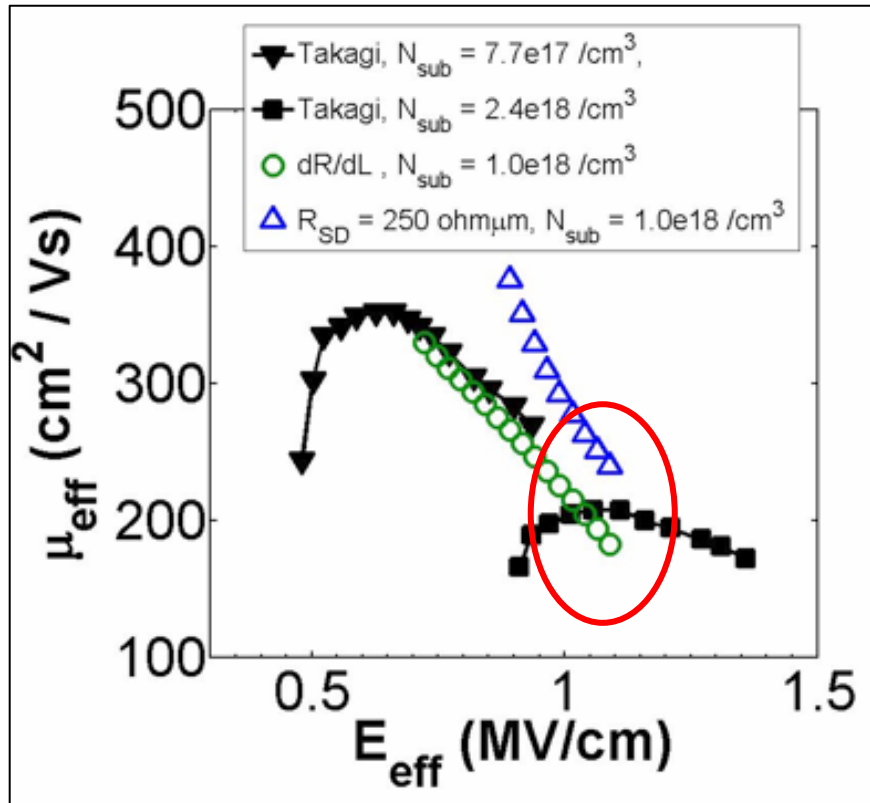


$$\mu_{eff} = \frac{L_{mask}}{W_{mask} (R_{TOT} - R_{SD}) C_{ox} (V_{GS} - V_T)}$$

$$\mu_{eff} = \frac{1}{W_{mask} (\partial R_{TOT} / \partial L_{mask}) C_{ox} (V_{GS} - V_T)}$$

Are these results consistent with the expected universal mobility curve?

universal mobility



$$E_{eff} = \frac{q(N_{dep} + 0.5 \cdot N_{inv})}{\epsilon_{si}}$$

where

$$qN_{inv} = \int_0^{V_{GS}} C_{GC} dV_{GS}$$

$$qN_{dep} = \sqrt{4q\epsilon_{si}\Phi_B N_{sub}}$$

$$\Phi_B = (k_B T / q) \ln(N_{sub} / n_i)$$

(Takagi et al, *IEEE TED* **41**, 2357-2362, 1994)

mobility and mean-free-path

The mobility inferred from measurements on a long channel transistor:

$$188 < \mu_{eff} < 248 \text{ (cm}^2\text{/V-s)}$$

is consistent with the expected, universal mobility.

What mfp do we deduce from the mobility?

From Lecture 4:

$$\mu_n = \frac{v_T \lambda_0}{2 k_B T / q} \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right] \longrightarrow 15 < \lambda_0 < 19 \text{ nm}$$

Linear region summary ($V_{GS} = 1.2V$)

- 1) Series resistance is a significant part of the total channel resistance.

$$R_{TOT} = 340 \left(\Omega - \mu m \right) \quad R_{SD} \approx 200 \pm 50 \left(\Omega - \mu m \right)$$

$$R_{CH} \left(L=100 \text{ nm}, V_{GS} = 2 \text{ V} \right) \approx 140 \pm 50 \left(\Omega - \mu m \right)$$

- 2) The mobility inferred from the measurements is consistent with the expected, universal mobility.

$$188 < \mu_{eff} < 248 \left(\text{cm}^2 / \text{V-s} \right)$$

- 3) The measured mobility implies a mfp of:

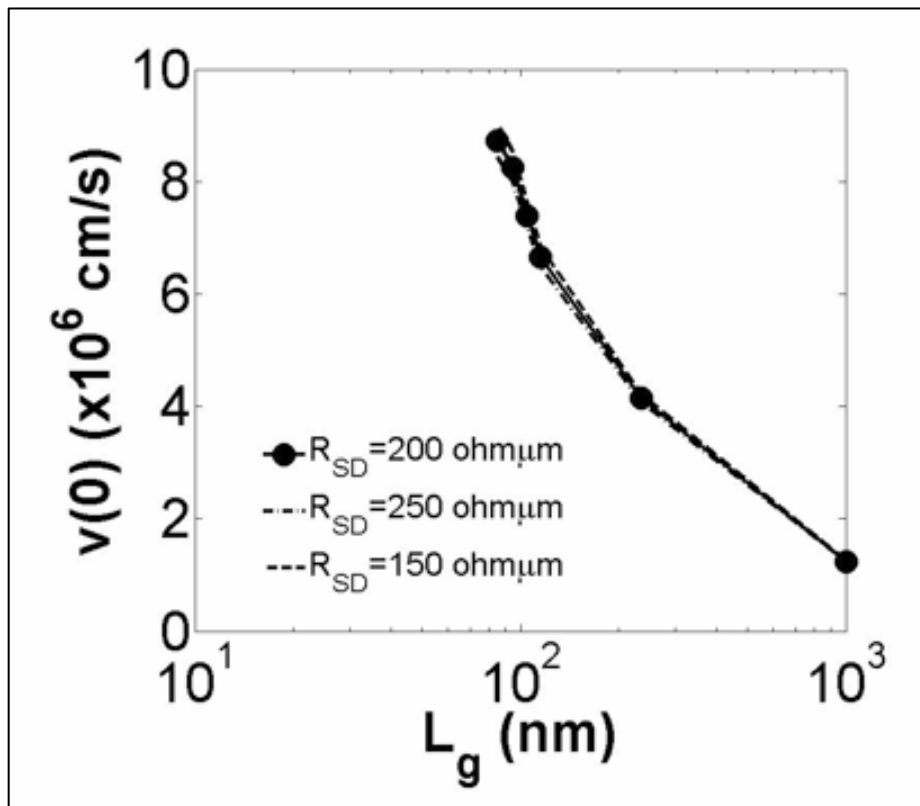
$$15 < \lambda_0 < 19 \text{ nm}$$

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) Series resistance
- 4) Linear region analysis
- 5) Saturated region analysis**
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) Summary

velocity at the beginning of the channel

Under high drain bias = 1.2V



$$\langle v(0) \rangle = \frac{I_{ON}}{WQ_I(0)}$$

$$Q(0)/q \approx 7.9 \times 10^{12} \text{ cm}^{-2}$$

$$\langle v(0) \rangle = 8.7 \times 10^6 \text{ cm/sec at } 100\text{nm}$$

$\pm 25\%$ variation in $R_{SD} \rightarrow$
 $\pm 4\%$ variation in $\langle v(0) \rangle$

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) Series resistance
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit**
- 7) Discussion
- 8) Summary

channel resistance analysis ($V_{GS} = 1.2V$)

$$R_{CH} = 140 \pm 50 (\Omega - \mu m)$$

- 1) How significant is the ballistic resistance?
- 2) What is the transmission?
- 3) How does the mobility compare to the ballistic mobility?
- 4) How many modes conduct?

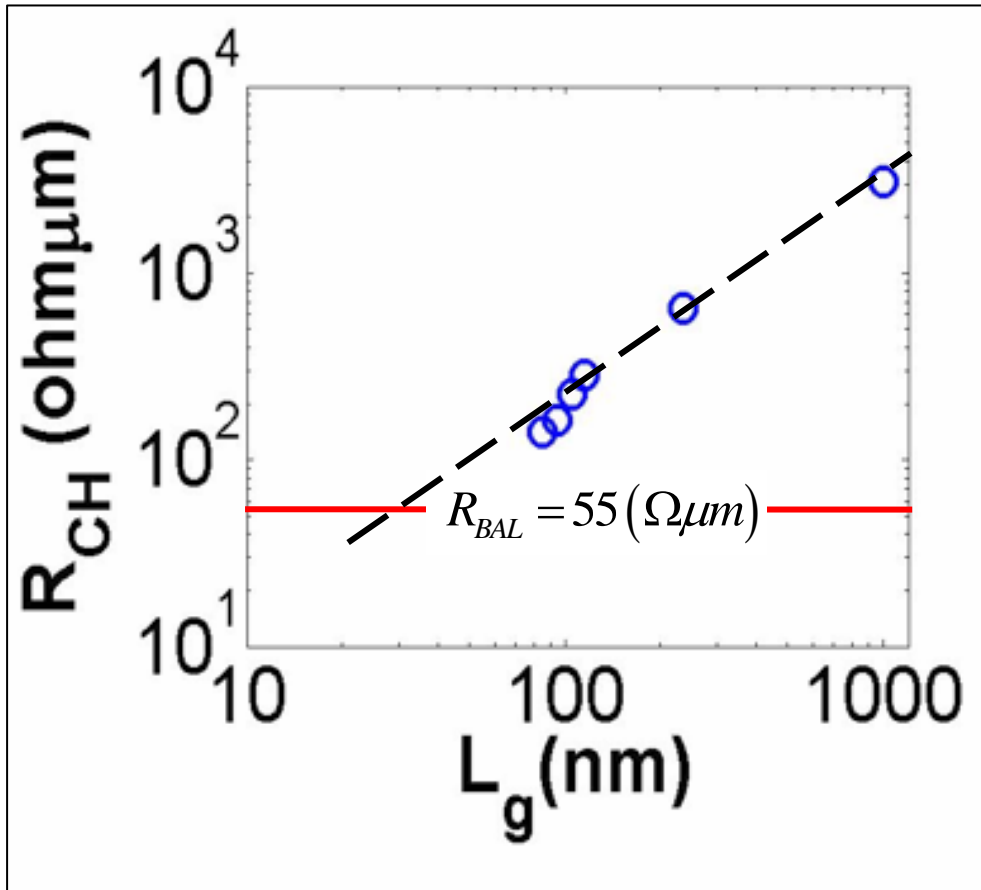
ballistic resistance

1) How significant is the ballistic resistance at $V_{GS} = 1.2V$?

$$R_{BALL} W = \frac{(2k_B T / q) \mathcal{F}_0(\eta_{F1})}{Q_I(0) v_T \mathcal{F}_{-1/2}(\eta_{F1})} \approx 55 \Omega - \mu m$$

$$R_{CH}(\text{meas}) = 140 \pm 50 (\Omega - \mu m) \approx 2 - 4 \times R_{CH}(\text{ball})$$

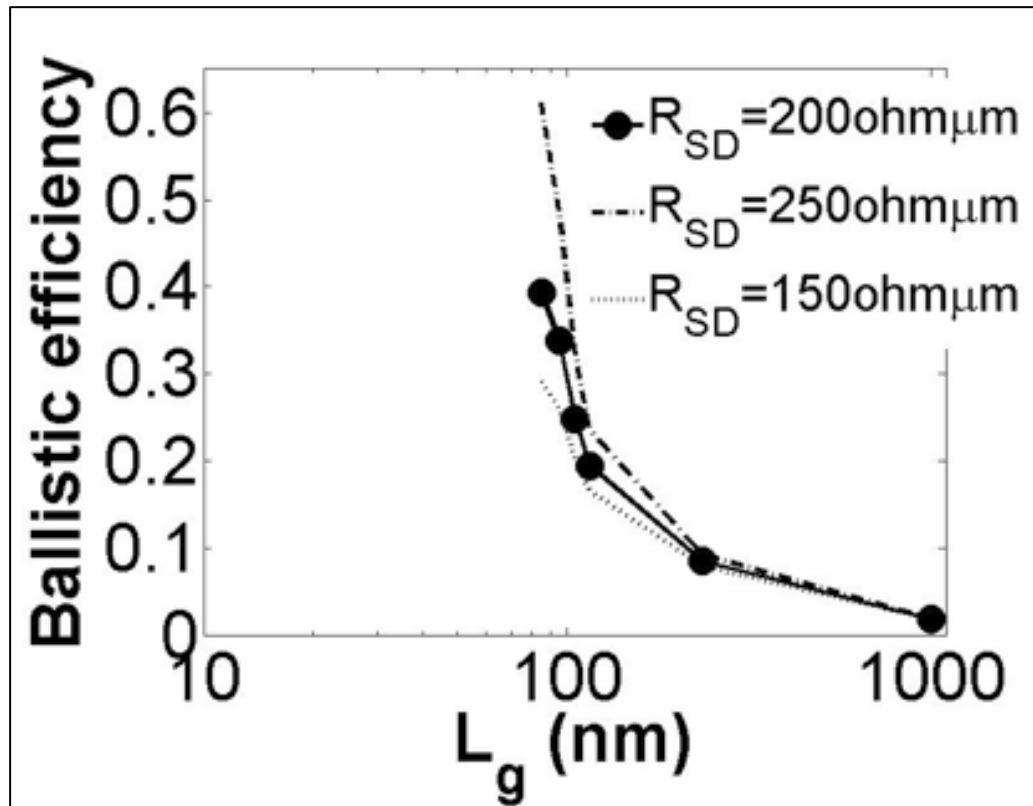
L_g dependence of R_{ch}



As L continues to decrease, R_{CH} will saturate at the ballistic resistance.

Because of the higher mobilities, this may be seen in III-V FETs before it is seen in Si MOSFETs.

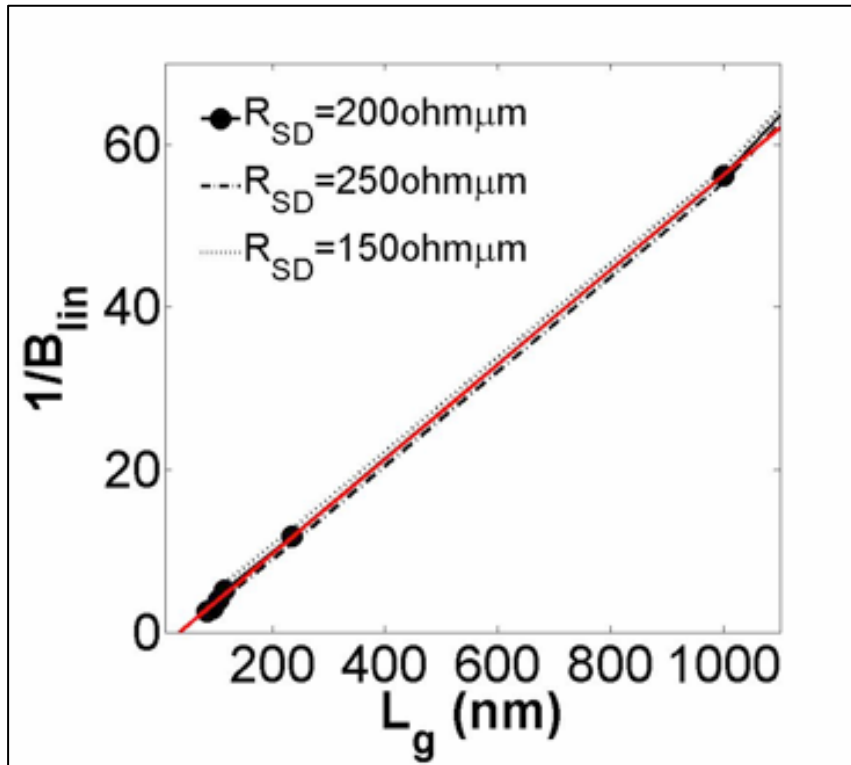
transmission vs. channel length



$$B_{lin} = \frac{I_{Dlin}(\text{meas})}{I_{Dlin}(\text{ball})} = T$$

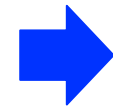
$$0.3 < T_{lin}(100 \text{ nm}) < 0.6$$

mfp from T vs. channel length



$$B_{lin} = T_{lin} = \frac{\lambda_0}{\lambda_0 + L}$$

$$\frac{1}{B_{lin}} = 1 + \frac{L}{\lambda_0}$$



$$\lambda_0 = 17 \text{ nm}$$

Independent of R_{SD}

$$T_{lin} \approx \frac{\lambda_0}{\lambda_0 + L} = \frac{17}{17 + 85} = 0.17$$

transmission recap

We can deduce T in the linear region three different ways:

1) From the linear region current:

$$T = I_{Dlin}(\text{meas}) / I_{Dlin}(\text{ball}) \rightarrow 0.3 < T < 0.6$$

2) From the mfp deduced from the mobility:

$$T = \lambda_0 / (\lambda_0 + L) \quad 15 < \lambda_0 < 19 \text{ nm} \rightarrow 0.15 < T < 0.19$$

3) From the mfp deduced from $1/B_{lin}$ vs. L :

$$T = \lambda_0 / (\lambda_0 + L) \quad \lambda_0 \approx 17 \text{ nm} \rightarrow T \approx 0.17$$

channel resistance analysis

$$R_{CH} (V_{GS} = 1.2 \text{ V}, L = 100 \text{ nm}) = 140 \pm 50 (\Omega - \mu m)$$

- 1) How significant is the ballistic resistance?
- 2) What is the transmission?
- 3) How does the mobility compare to the ballistic mobility?**
- 4) How many modes conduct?

mobility and ballistic mobility

The mobility inferred from measurements on a long channel transistor:

$$188 < \mu_{eff} < 248 \text{ (cm}^2/\text{V-s)}$$

is consistent with the expected, universal mobility.

How does this compare to the ballistic mobility?

From Lecture 4:

$$\mu_B = \frac{v_T L}{2k_B T / q} \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$

for $Q_I(0) = 8.9 \times 10^{12} \text{ cm}^{-2}$

$$\mu_B \approx 3370 \text{ cm}^2/\text{V-s} \gg \mu_{eff}$$

number of conducting channels at $V_{GS} = 1.2V$

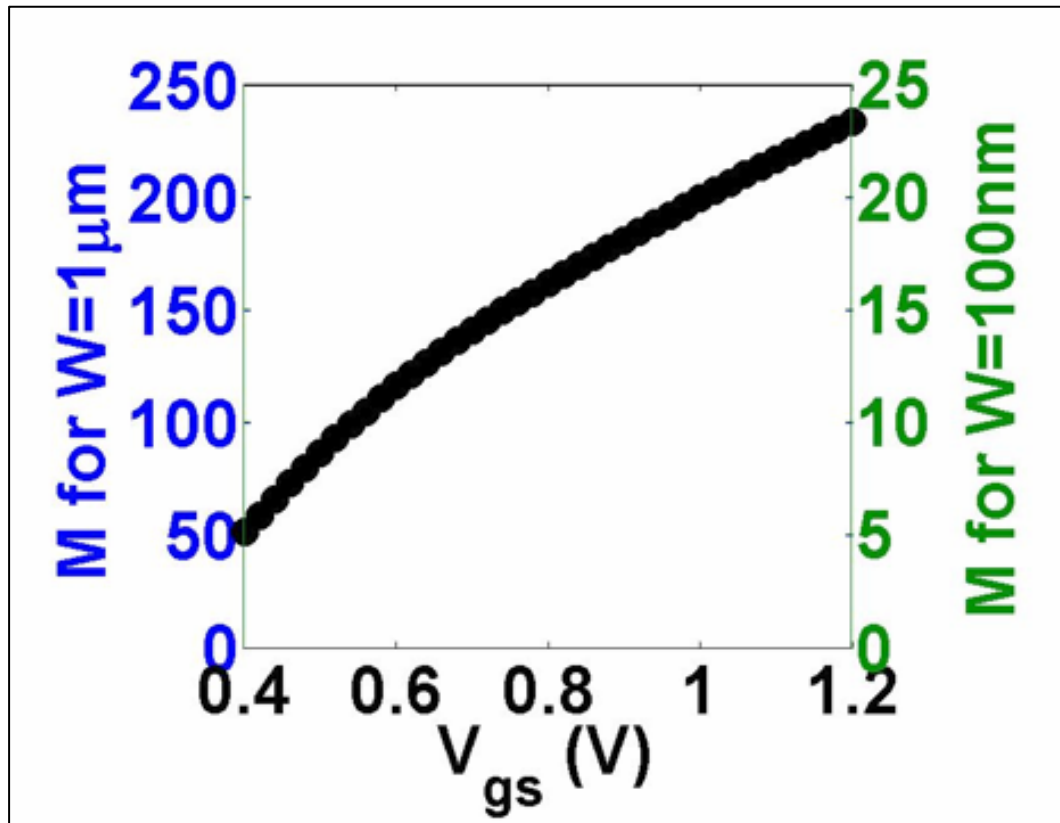
$$G_{CH} = \frac{1}{R_{CH}} = \left(WQ_I(0) \frac{v_T}{(2k_B T/q)} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right] \equiv M_{eff} \frac{2q^2}{h}$$

$$M_{eff} = \frac{h}{2q^2} \left(\frac{WQ_I(0)v_T}{2k_B T/q} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$

For $V_{GS} = 1.2V$:

$$\left. \begin{array}{l} Q_I(0) = 8.9 \times 10^{12} \text{ cm}^{-2} \\ \left[\mathcal{F}_{-1/2}(\eta_{F1}) / \mathcal{F}_0(\eta_{F1}) \right] = 0.54 \end{array} \right\} \longrightarrow M_{eff} = 230 / \mu\text{m}$$

number of conducting channels



Near threshold, a narrow width MOSFET has only a few conducting channels

linear region summary ($V_{GS} = 1.2V$)

- 1) For this $L = 85\text{nm}$ device, the ballistic mobility is much greater than the actual mobility:

$$\mu_{BALL} \approx 3370 \text{ (cm}^2/\text{V-s)} \gg \mu_{eff} \approx 248 \text{ (cm}^2/\text{V-s)}$$

- 2) Because of the uncertainties in series resistance and mobility, it is best to deduce T from a plot of $1/B_{lin}$ vs. L :

$$T(100 \text{ nm}) \approx 0.17$$

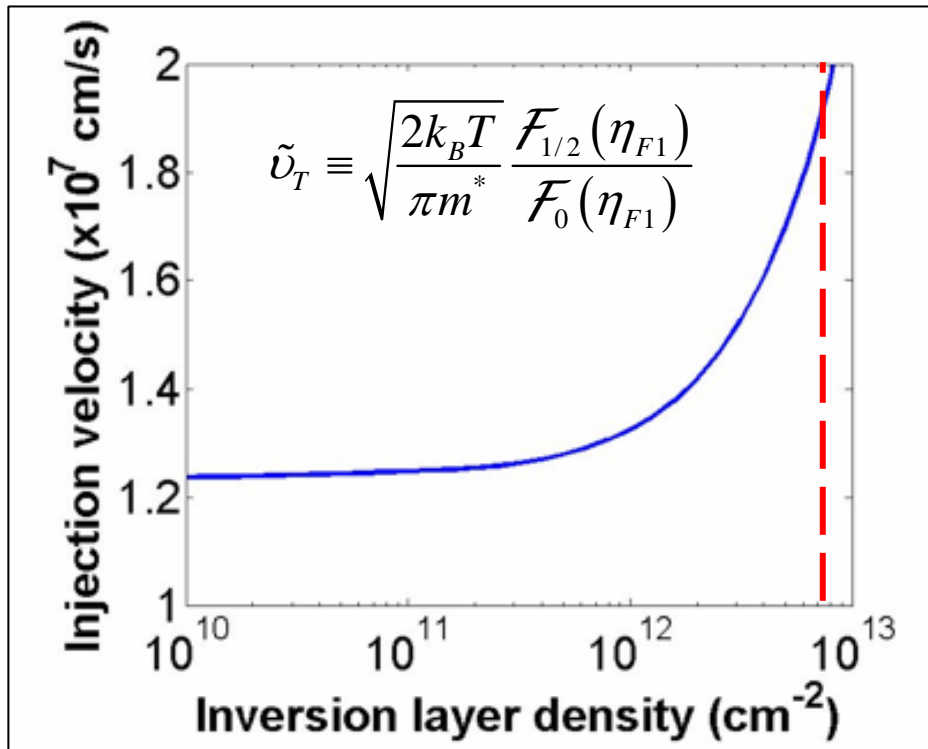
- 3) **But**, there are also uncertainties in interpretation (e.g. assumption that a single subband is occupied, parabolic bands, etc.)

saturation region analysis ($V_{GS} = 1.2V$)

At low V_{DS} : $T(100 \text{ nm}) \approx 0.17$

What is T at high V_{DS} ?

ballistic injection velocity



Since we know inversion layer density, we can just read off the ballistic injection velocity.

$$Q(0)/q \approx 7.9 \times 10^{12} \text{ cm}^{-2}$$

$$\langle \tilde{v}_T \rangle = 1.9 \times 10^7 \text{ cm/sec}$$

Since we know actual velocity,

$$\langle v(0) \rangle = 8.7 \times 10^6 \text{ cm/sec at } 100\text{nm}$$

we can estimate the ballistic ratio:

$$B_{sat} = \frac{I_{ON}}{I_{ON}(\text{ball})} = \frac{\langle v(0) \rangle}{\tilde{v}_T}$$

Ballistic ratio in saturation ($L = 100\text{nm}$)

$$\langle \tilde{v}_T \rangle = 1.9 \times 10^7 \text{ cm/sec}$$

$$\langle v(0) \rangle = 8.7 \times 10^6 \text{ cm/sec at } 100\text{nm}$$

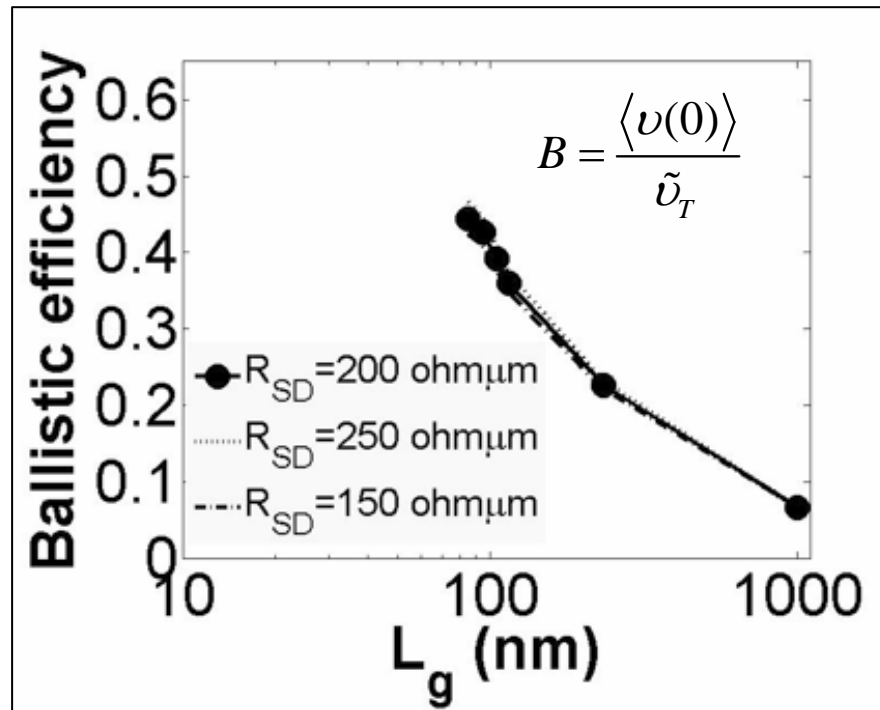
$$B_{sat} = \frac{\langle v(0) \rangle}{\tilde{v}_T} \approx 0.45$$

$$B_{sat} = \frac{T}{2-T} \rightarrow T = 0.62$$

The $L = 100\text{nm}$ transistor operates at about 45% of ballistic limit.

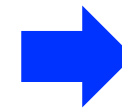
In saturation, $T \sim 0.62$

ballistic ratio in saturation vs. channel length



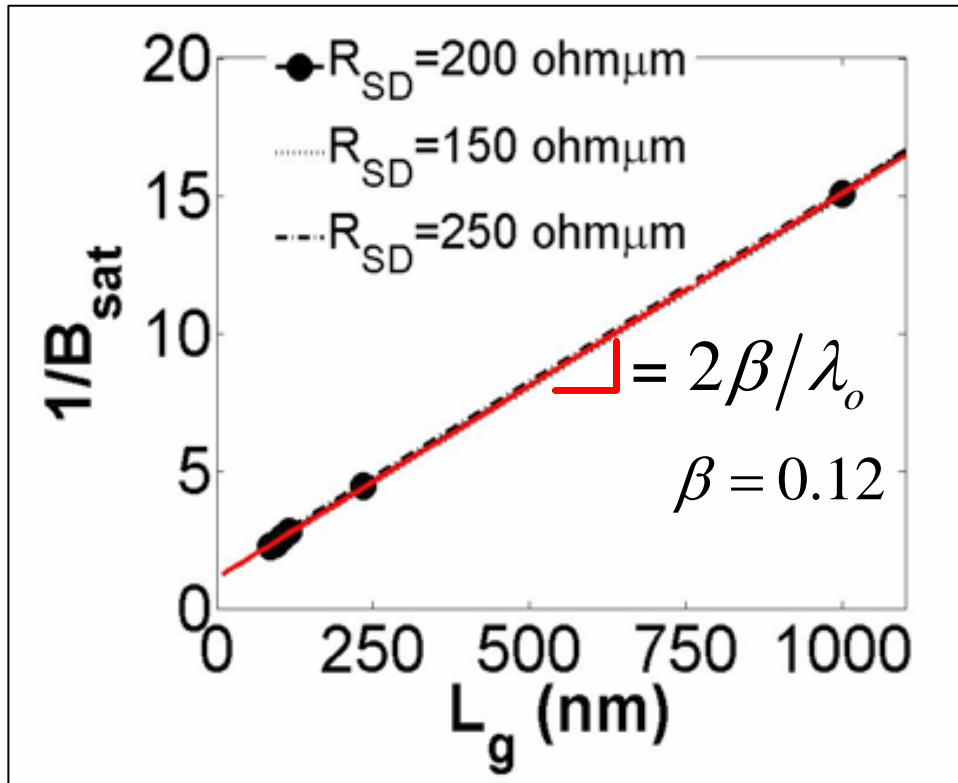
Under high drain bias = 1.2V

$\pm 25\% R_{SD}$



$\pm 4.7\% \langle v(0) \rangle$

critical length analysis



$$B_{sat} = \frac{T}{2-T} = \frac{\lambda_0}{\lambda_0 + 2l}$$

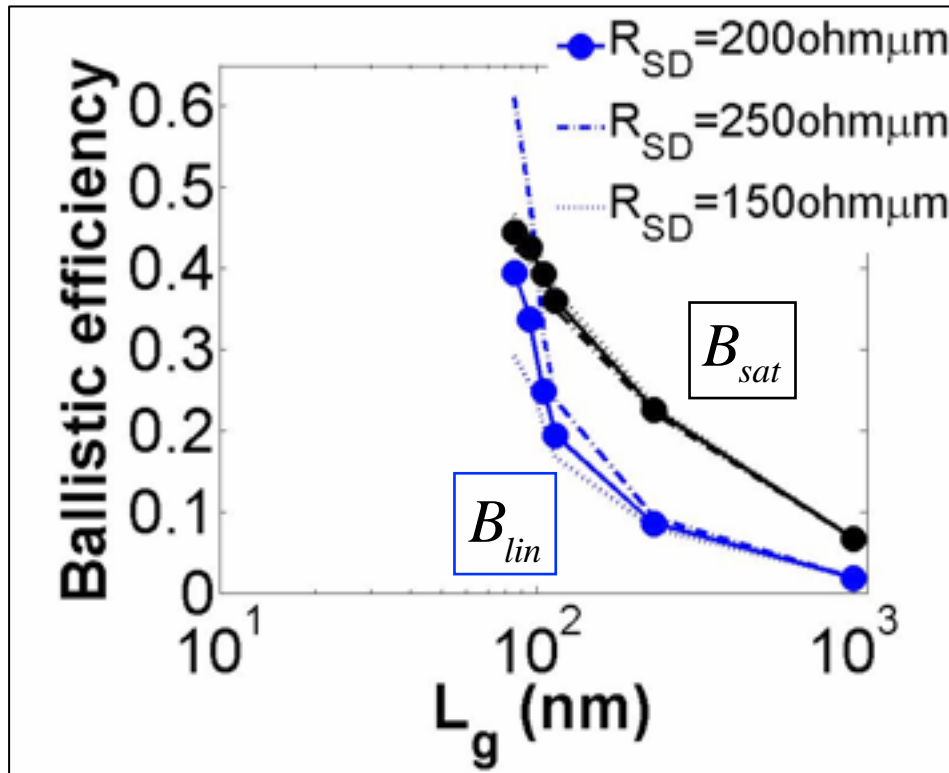
$$l = \beta L$$

$$\frac{1}{B_{sat}} = 1 + \frac{2l}{\lambda_0} = 1 + \frac{2\beta}{\lambda_0} L$$

$$l = 0.12 \times L$$

The existence of a short, critical region of the channel is confirmed.

channel length scaling: linear vs. saturation



$$B_{lin} = \frac{\lambda_o}{L + \lambda_o}$$

$$B_{sat} = \frac{\lambda_o}{\lambda_o + 2l} = \frac{\lambda_o}{\lambda_o + 2\beta L}$$

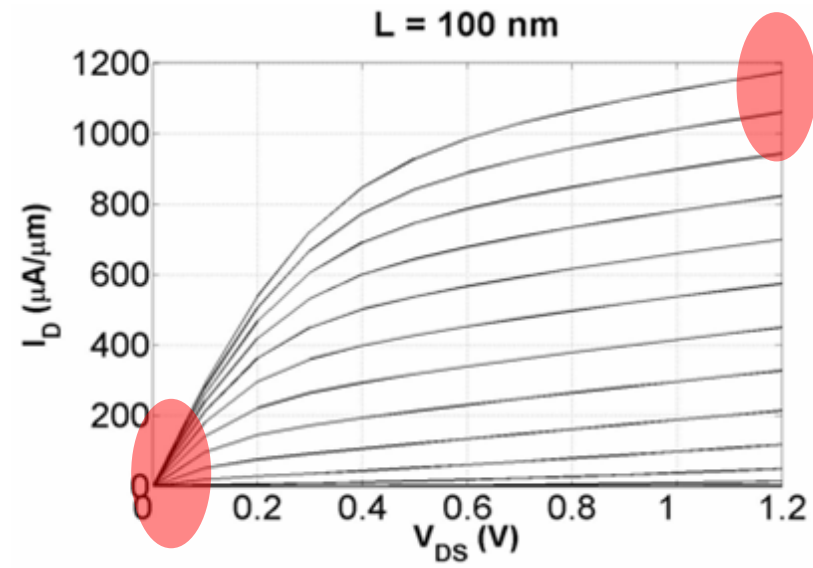
where $\beta \sim 0.12$

B_{lin} drops off faster with increasing channel length than does B_{sat}

comparison to ballistic limit summary

$$T \approx 0.17$$

$$\lambda_0 \approx 17 \text{ nm}$$



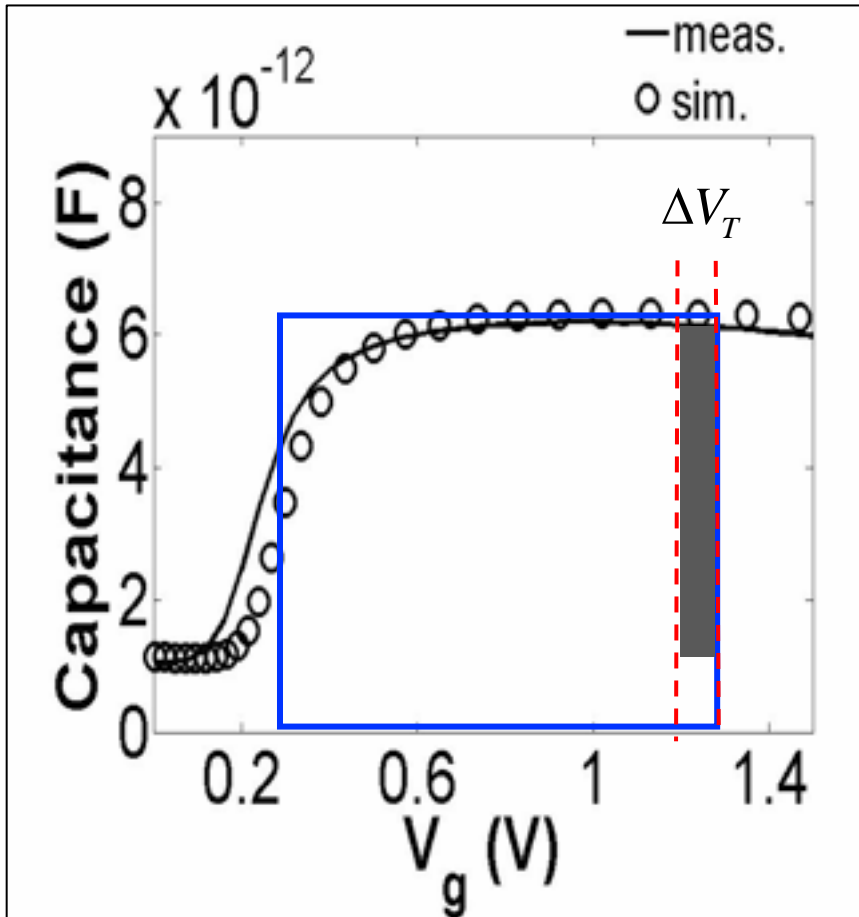
$$T \approx 0.62$$

$$l = 0.12 \times L$$

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) series resistance
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion**
- 8) Summary

how accurate is $Q_i(0) = C_{ox}(V_{GS} - V_T)$?



$$Q(0) = \int_0^{V_{GS_short}} C_{GC} / (L_{long} \times W_{long}) dV_{GS}$$

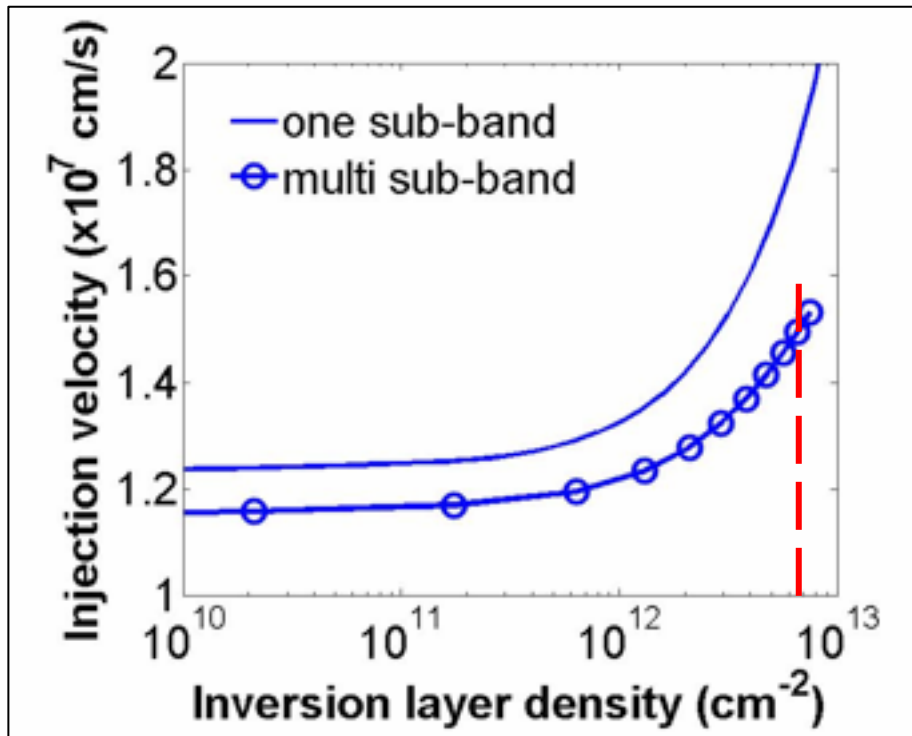
$$V_{GS_short} = V_{GS_long} + \Delta V_T (DIBL + SCE) - I_{ON} R_S$$

$$\square Q(0) = C_{ox} (V_{GS_short} - V_T)$$

$$\square 1.25 \times \text{'exact'}$$

$$Q(0)/q; 7.9 \times 10^{12} \text{ cm}^{-2} \Rightarrow \\ = 6.3 \times 10^{12} \text{ cm}^{-2}$$

how good is the single sub-band approximation?



$$Q(0)/q = 6.3 \times 10^{12} \text{ cm}^{-3}$$

$$v_T^o = 1.9 \times 10^7 \text{ cm/sec}$$

(single subband)

$$v_T^o = 1.5 \times 10^7 \text{ cm/sec}$$

(multi subband)

implications

- 1) $Q_I = C_{ox} (V_{GS} - V_T)$ over-estimates the inversion charge by ~25%

$$\langle v(0) \rangle = \frac{I_{ON}}{WQ_I(0)} \quad 8.7 \times 10^6 \rightarrow 1.1 \times 10^7 \text{ cm/s}$$

- 2) Single subband assumption over-estimates the ballistic injection velocity by ~27%

$$B_{sat} = \frac{\langle v(0) \rangle}{v_o} = 0.45 \rightarrow 0.73 \quad T = 0.62 \rightarrow T = 0.85$$

outline

- 1) Objectives
- 2) Measured I-V characteristics
- 3) Series resistance
- 4) Linear region analysis
- 5) Saturated region analysis
- 6) Comparison to ballistic limit
- 7) Discussion
- 8) **Summary**

linear region analysis

Extraction of T in the linear region is difficult because of uncertainties in the series resistance of short channel MOSFETs.

- 1) Improved R_{SD} measurement techniques would be useful.
- 2) Measurement techniques that eliminate R_{SD} (e.g. our $1/B_{lin}$ v.s L_{mask} approach) are another possibility.

saturated region analysis

Extraction of T in the **saturated region** is difficult because of uncertainties in the measured, average velocity, $\langle v(0) \rangle$ and in the ballistic injection velocity, v_T^0 .

- 1) The inversion layer charge, $Q_I(0)$, of a short-channel MOSFET is difficult to measure.
- 2) The ballistic injection velocity is affected by quantum confinement, bandstructure, strain, etc.

conclusions

- 1) An analysis of modern MOSFET I/V characteristics confirm the general features of the scattering model.
- 2) Extraction of precise numbers for transmission, ballistic efficiency, etc. is clouded by uncertainties in series resistance, physical channel length, mobility of short channel MOSFETs, inversion layer charge, etc.
- 3) Nevertheless, it is clear the modern MOSFETs deliver more than half of the ballistic on-current and much less than half of the ballistic linear current and that under high V_{DS} , a very short 'bottleneck' controls the on-current.