Physics of Nanoscale Transistors: Lecture 5:

Application to State-of-the-Art MOSFETS

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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)
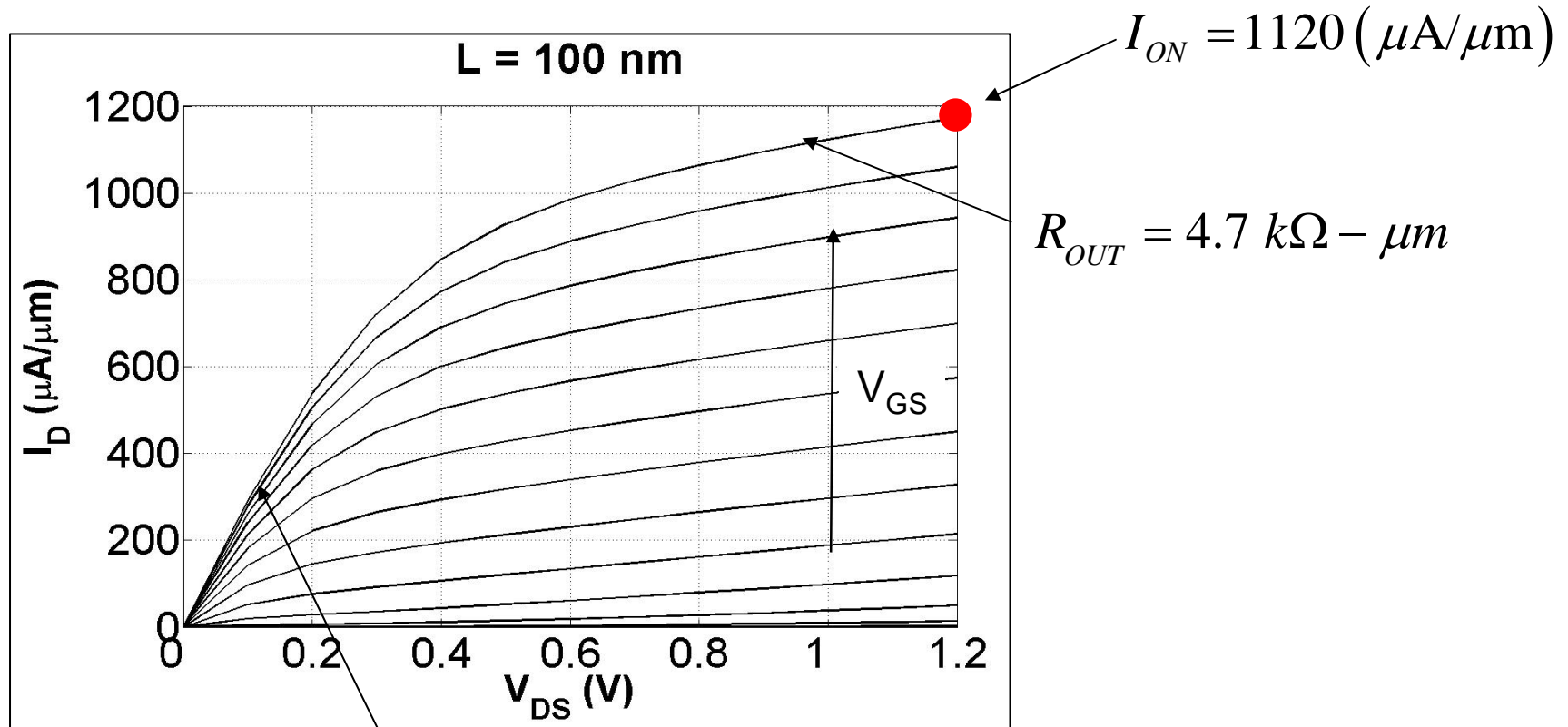
outline

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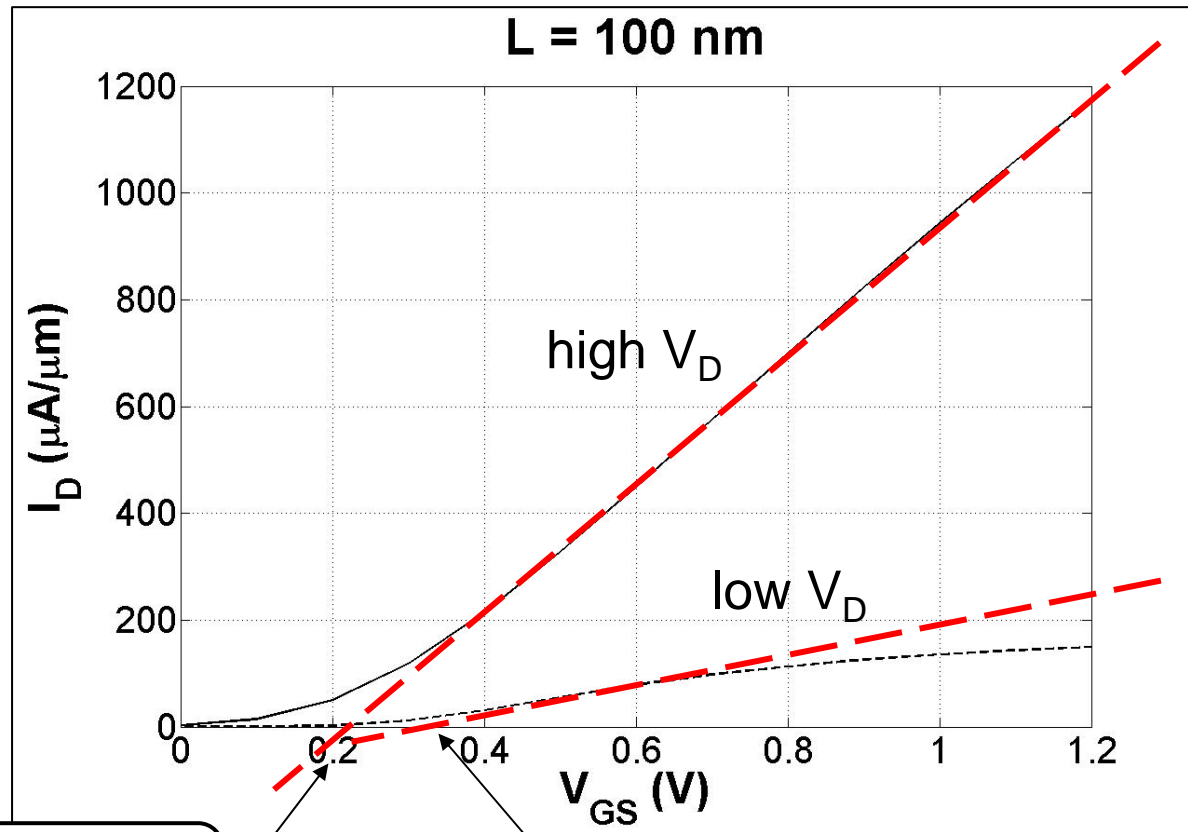
1) Nitrided gate oxide ($k = 5$, $t_{inv} = 2.2$ nm)
2) Polysilicon gate
3) $V_{DD} = 1.2$V
4) Not intentionally strained
5) All measurements at $T \sim 300$K
6) Minimum mask channel length = 100 nm

   Minimum physical channel length (SEM) = 85 nm

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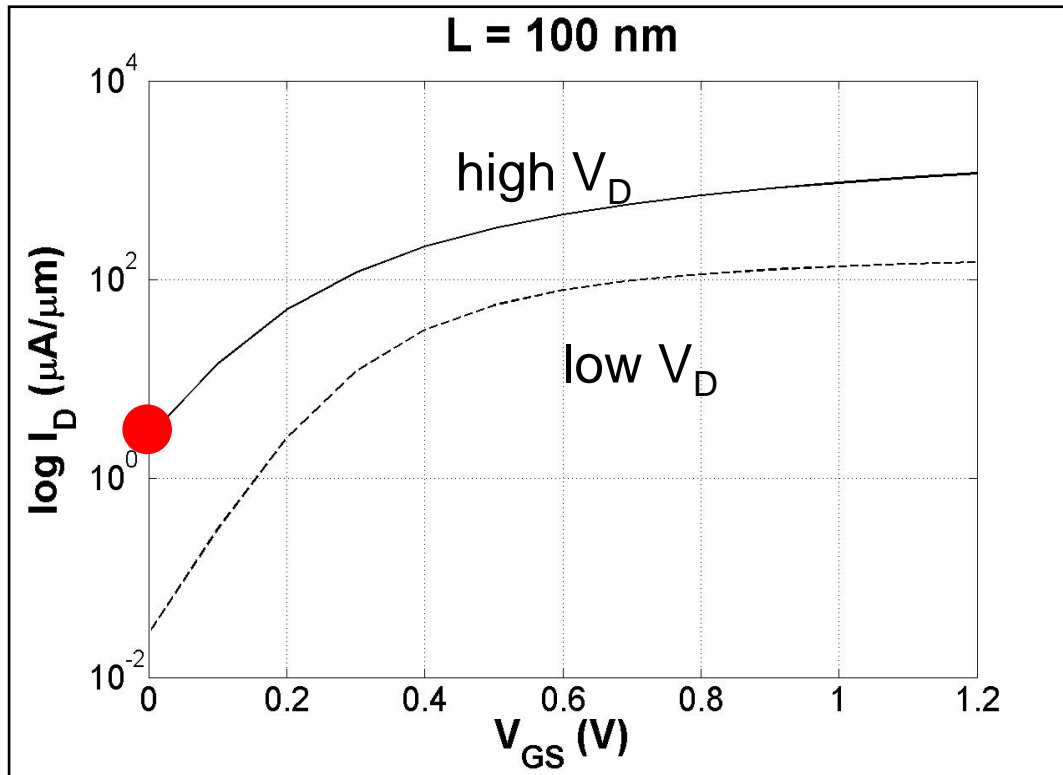
NMOS common source characteristics

L = 100 nm

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

$R_{OUT} = 4.7 \; k\Omega - \mu m$

$R_{CH} = \dfrac{V_{DS}}{I_D} = 340 \left(\Omega - \mu m \right)$

Transfer characteristics

L = 100 nm

I_D ($\mu A/\mu m$)

V_{GS} (V)

high V_D

low V_D

$V_{TSAT} = 0.26$ V

$V_{TLIN} = 0.28$ V

Log$_{10}$ I$_D$ vs. V$_{GS}$

L = 100 nm

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

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

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

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Transcendence
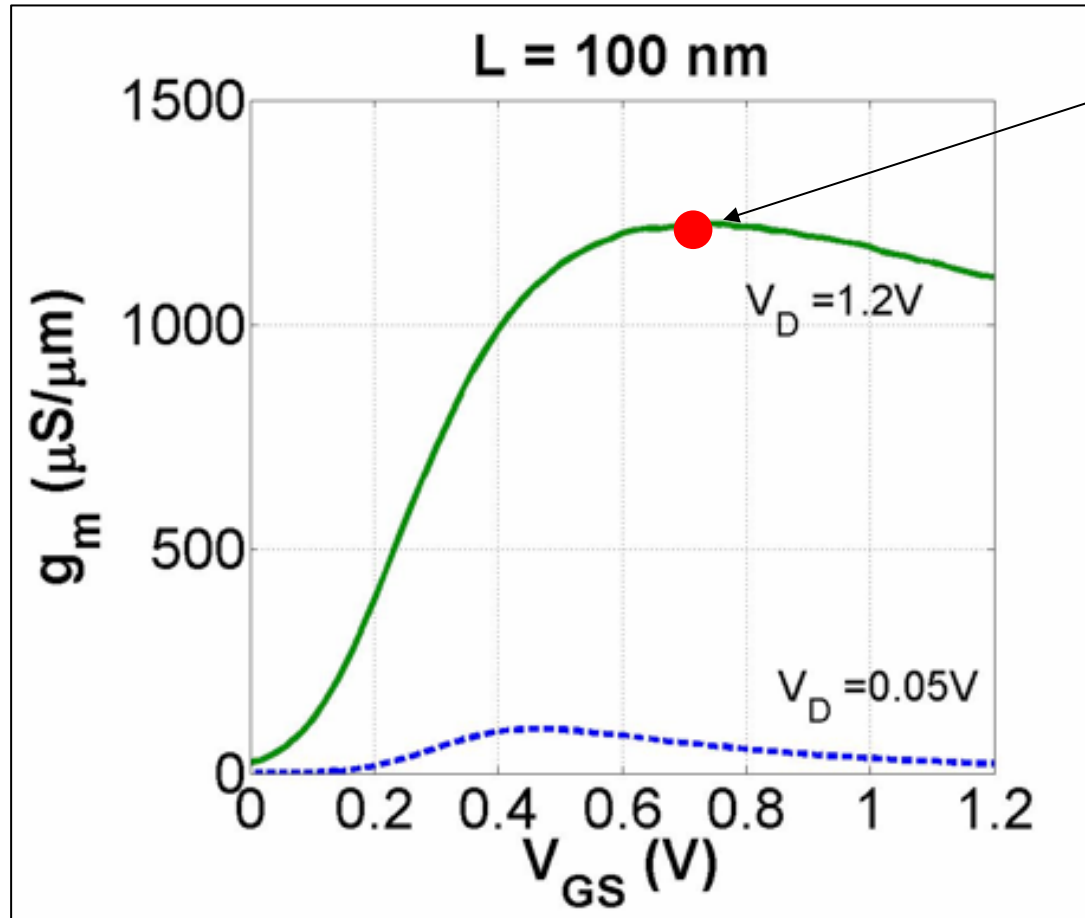
$$\ddot{g}_m = 1225 \left(\mu S / \mu m \right)$$

$$g_m \equiv \frac{\partial I_{DS}}{\partial V_{GS}} \bigg|_{V_{DS}}$$

summary

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

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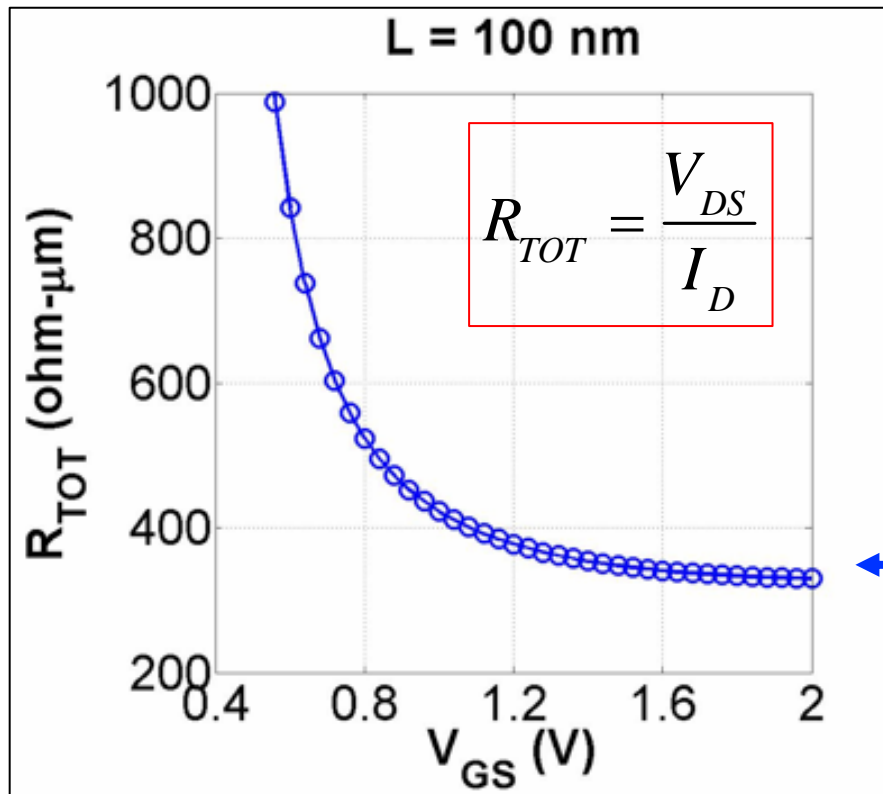
outline

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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.

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series resistance

$$R_{TOT} = \frac{V_{DS}}{I_D}$$

L = 100 nm

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

From shift and ratio measurement:

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

$$R_{TOT} = R_{CH} + R_{BALL} + R_{SD}$$
$$= 320\Omega - \mu m$$

From BSIM simulator:

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

series resistance bounds

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

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 Ω-μm.

$$R_{CH}\Big|_{V_{GS}=2} \cong R_{BALL} + R_{CH} + R_{SD} = 320 \rightarrow R_{SD} \leq 280\left(\Omega - \mu m\right)$$
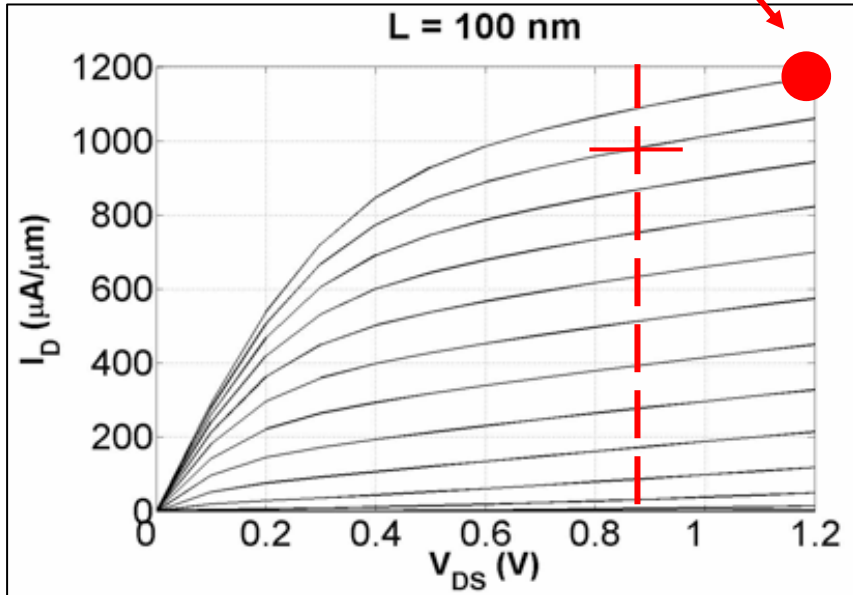
$$\text{BSIM: } R'_{SD} = 200 \rightarrow R_{SD} \approx 140\left(\Omega - \mu m\right)$$

Given the approximations involved, we will assume:

$$R_{SD} = 200 \pm 50\left(\Omega - \mu m\right)$$
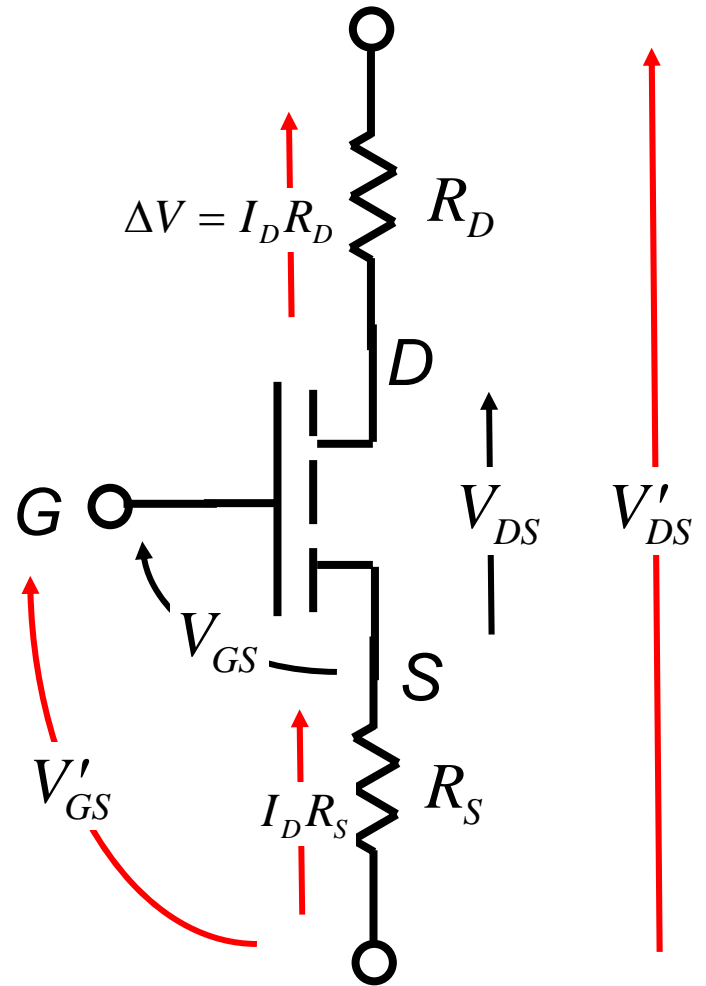
Series resistance has a significant effect

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

L = 100 nm

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

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

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

$$\Delta V = I_D R_D \qquad R_D$$

$$V_{DS} \qquad V'_{DS}$$

$$V_{GS}$$

$$V'_{GS} \qquad I_D R_S \qquad R_S$$

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$$R_S = R_D \approx 100 \, \Omega - \mu m$$

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2) Measured I-V characteristics
3) Series resistance
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5) Saturated region analysis
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channel resistance analysis (V_{GS} = 1.2V)

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

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

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

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

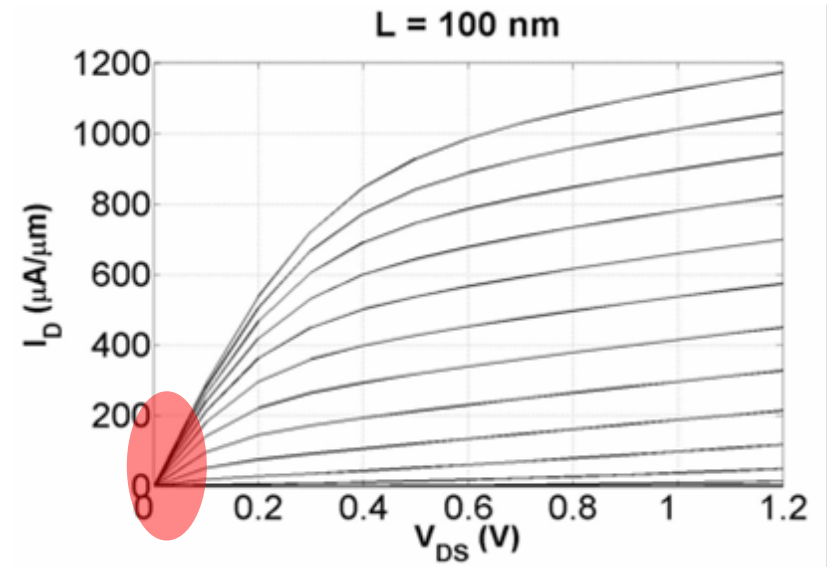2) What is the mobility?

inversion layer charge

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

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

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

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

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

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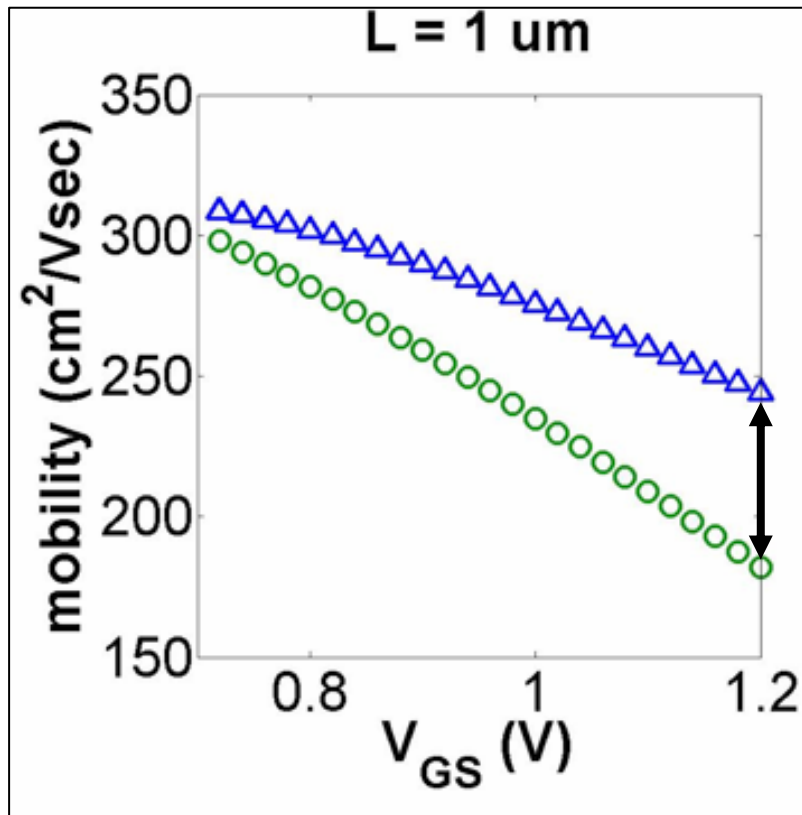(Will discuss in Sec. 7.)

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measuring mobility

Two methods:

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

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

ii) $\mu_{eff} = \dfrac{1}{W_{mask}\left(\partial R_{TOT}/\partial L_{mask}\right)C_{ox}(V_{GS} - V_T)}$
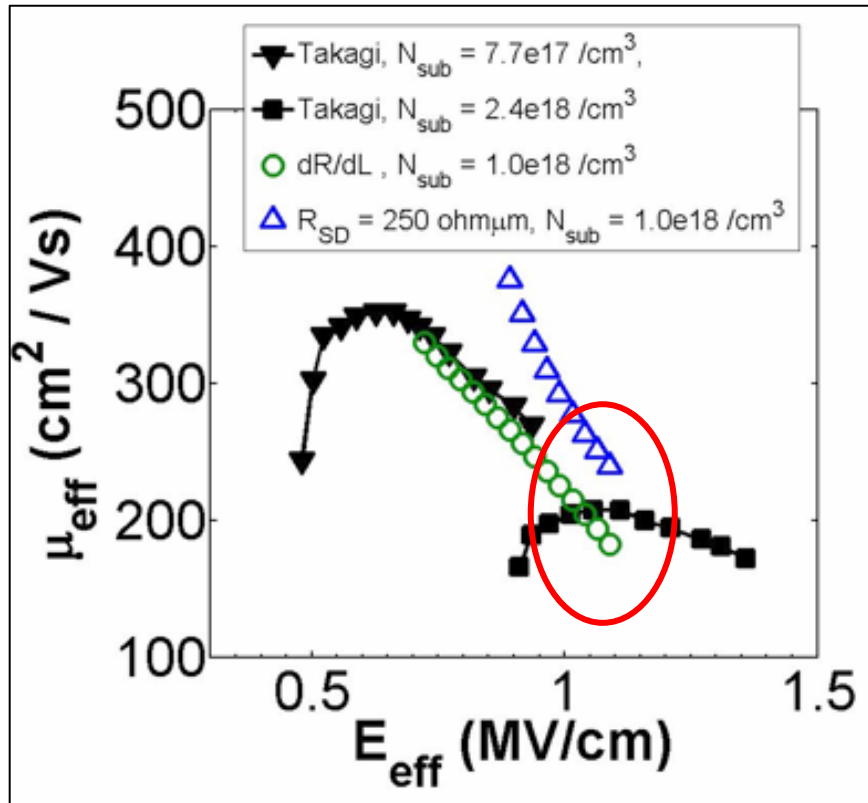
measured mobility

L = 1 um

mobility (cm²/Vsec) vs V_{GS} (V)

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

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

Are these results consistent with the expected universal mobility curve?

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universal mobility

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

where

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

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

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

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

mobility and mean-free-path

The mobility inferred from measurements on a long channel transistor:

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

is consistent with the expected, universal mobility.

What mfp do we deduce from the mobility?

From Lecture 4:

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

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

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:

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

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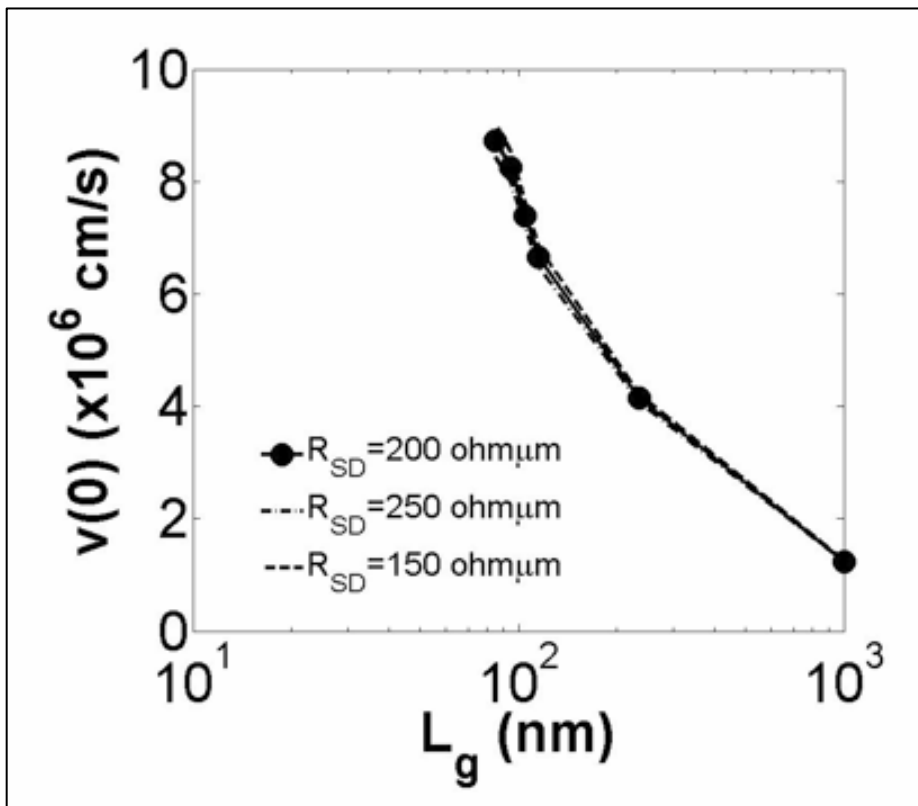# velocity at the beginning of the channel

Under high drain bias = 1.2V

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

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

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

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

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

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

1) How significant is the ballistic resistance?

2) What is the transmission?

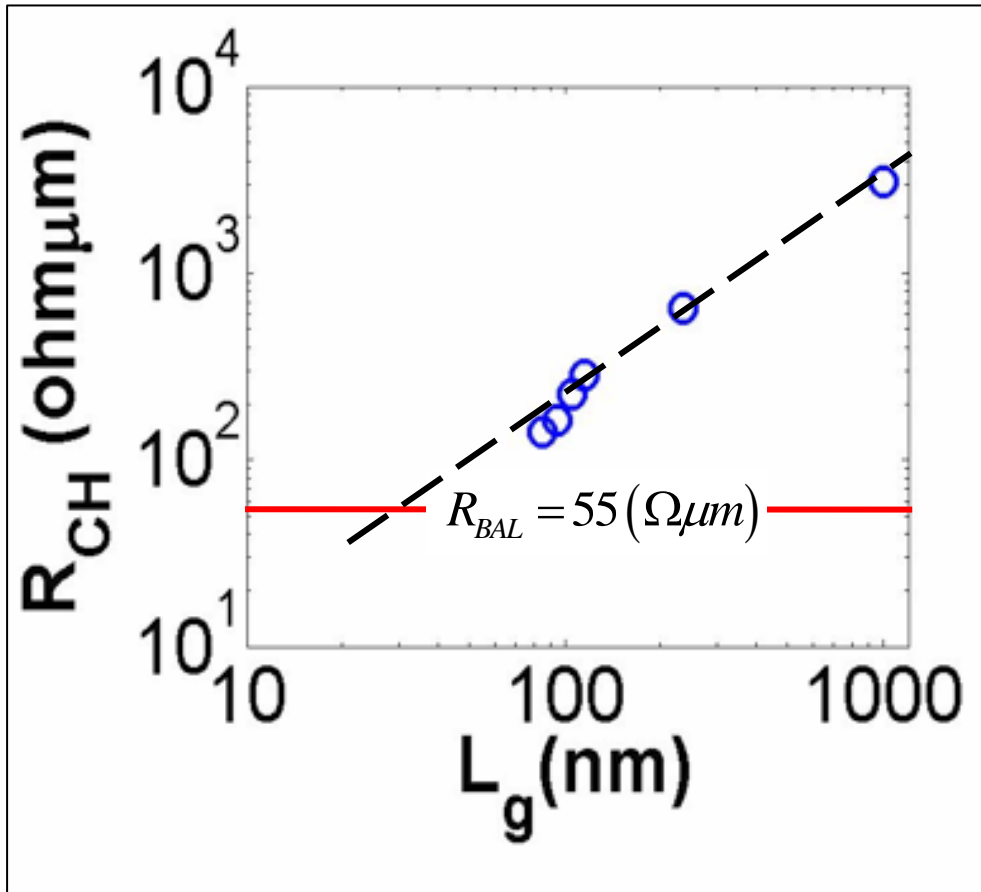3) How does the mobility compare to the ballistic mobility?

4) How many modes conduct?

ballistic resistance

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

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

$$R_{CH}(\text{meas}) = 140 \pm 50\,(\Omega - \mu m) \approx 2 - 4 \times R_{CH}(\text{ball})$$
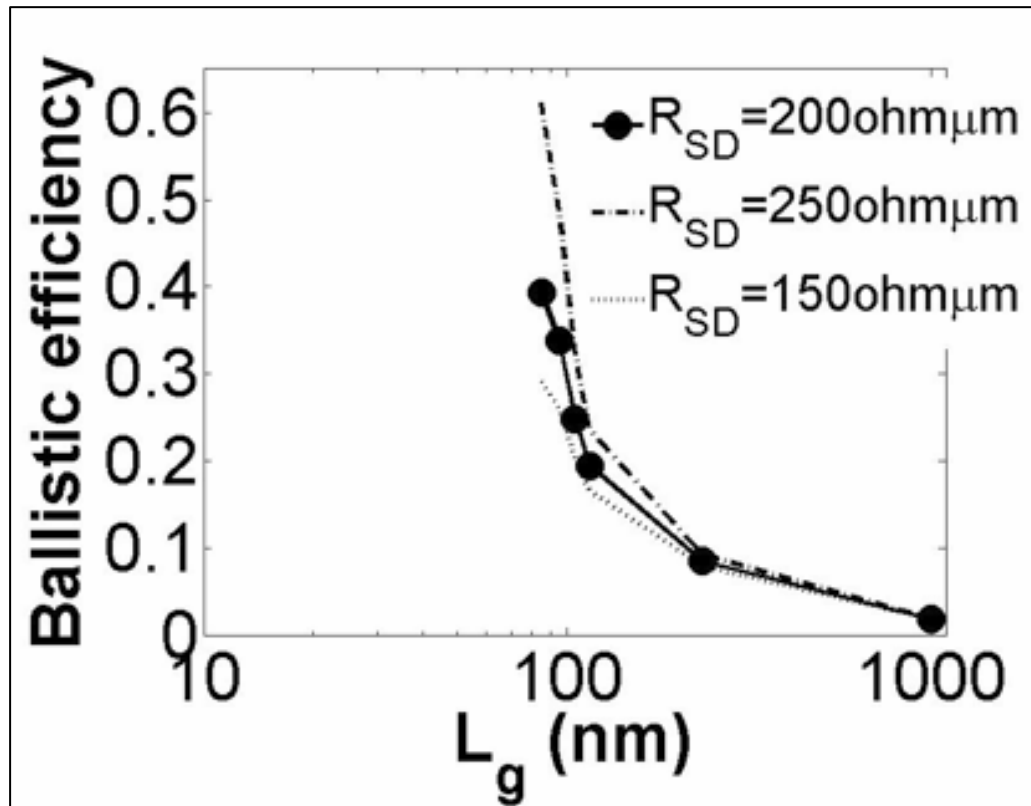
L$_g$ dependence of R$_{ch}$

$$R_{BAL} = 55\,(\Omega\mu m)$$

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.
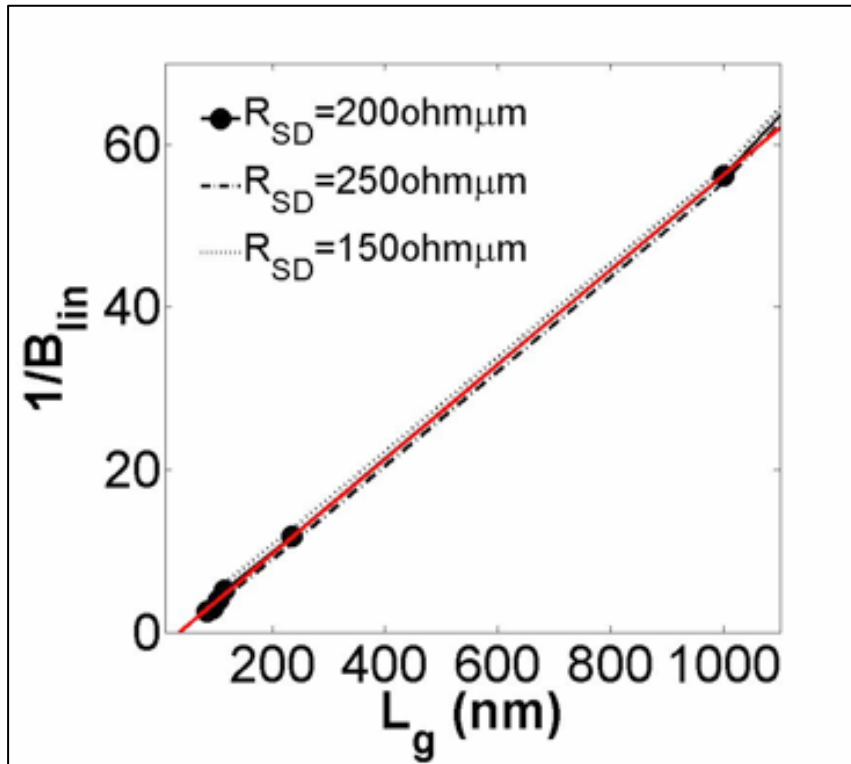
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transmission vs. channel length

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

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

mfp from T vs. channel length

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

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

$$\lambda_0 = 17nm$$

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:

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

2) From the mfp deduced from the mobilty:

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

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

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

channel resistance analysis

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

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:

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

is consistent with the expected, universal mobility.

How does this compare to the ballistic mobility?
From Lecture 4:

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

for $Q_I(0) = 8.9 \times 10^{12} \, \text{cm}^{-2}$ $\boxed{\mu_B \approx 3370 \;\; \text{cm}^2 / \text{V-s} >> \mu_{eff}}$

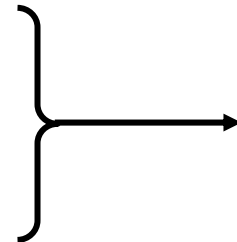# number of conducting channels at V_{GS} = 1.2V

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

$$M_{eff} = \frac{h}{2q^2} \left(\frac{WQ_I(0)\upsilon_T}{2k_B T/q} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$
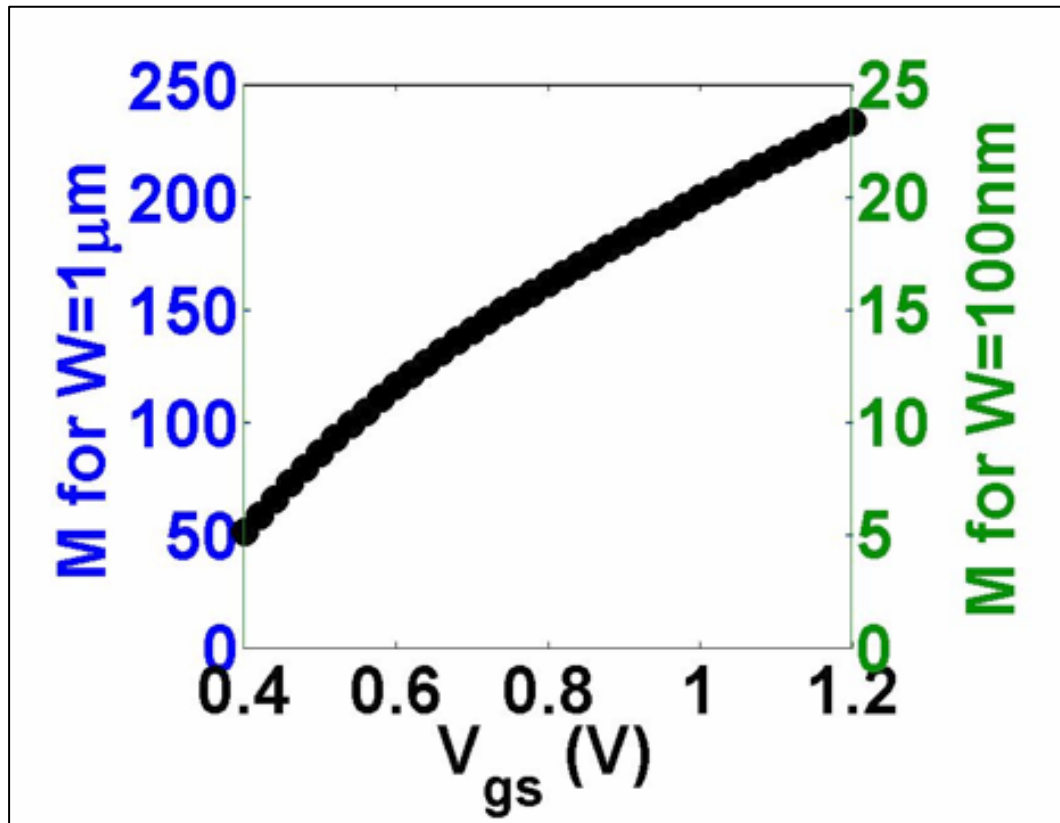
For V_{GS} = 1.2V:

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

$$\left[\mathcal{F}_{-1/2}(\eta_{F1}) / \mathcal{F}_0(\eta_{F1}) \right] = 0.54$$

$$M_{eff} = 230 \ /\mu\text{m}$$

number of conducting channels

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

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

1) For this L = 85nm device, the ballistic mobility is much greater than the actual mobility:

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

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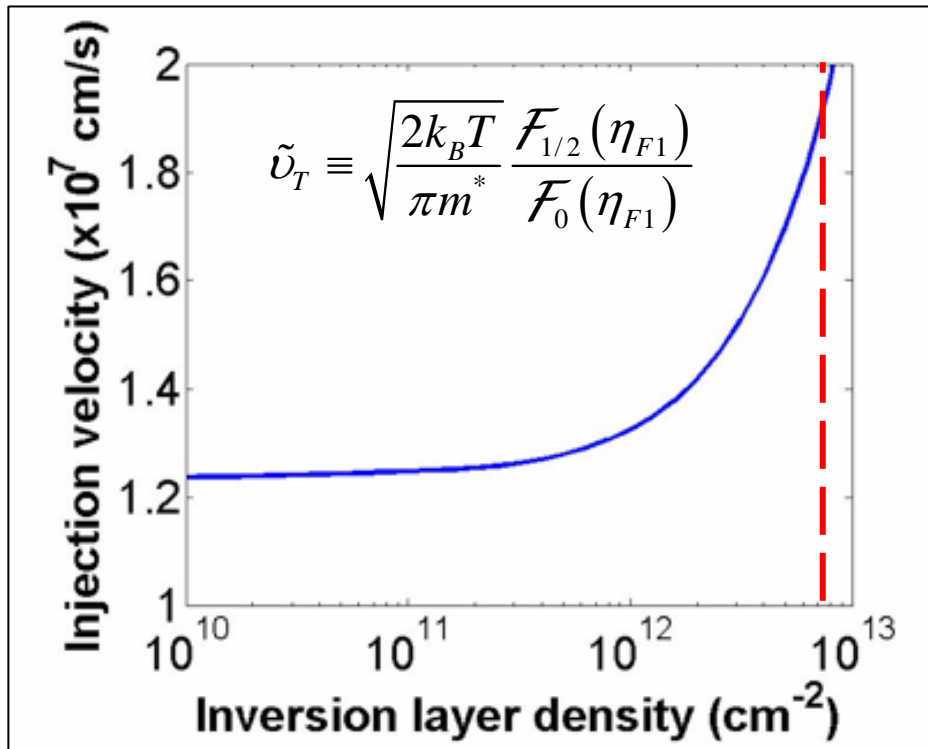
$$T\left(100 \text{ nm} \right) \approx 0.17$$

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

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

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

What is T at high V_{DS}?

ballistic injection velocity

$$\tilde{\upsilon}_T \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

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

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

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

Since we know actual velocity,

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

we can estimate the ballistic ratio:

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

Ballistic ratio in saturation (L = 100nm)

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

$$\langle \upsilon(0) \rangle = 8.7 \times 10^6 \text{ cm}/\text{sec at 100nm}$$
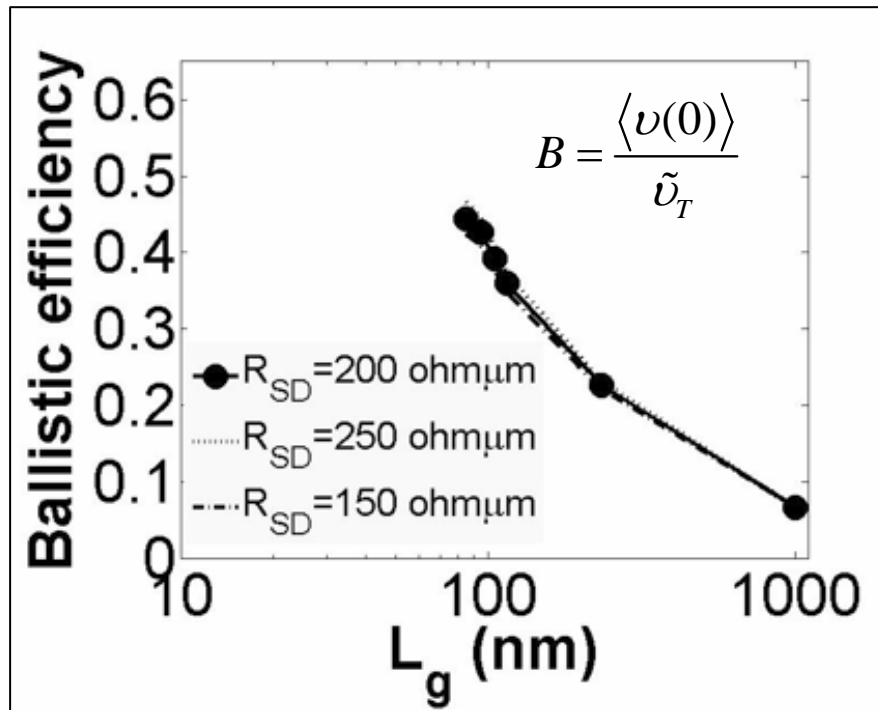
$$B_{sat} = \frac{\langle \upsilon(0) \rangle}{\tilde{\upsilon}_T} \approx 0.45$$

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

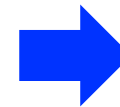The L = 100nm transistor operates at about 45% of ballistic limit.

In saturation, $T \sim 0.62$

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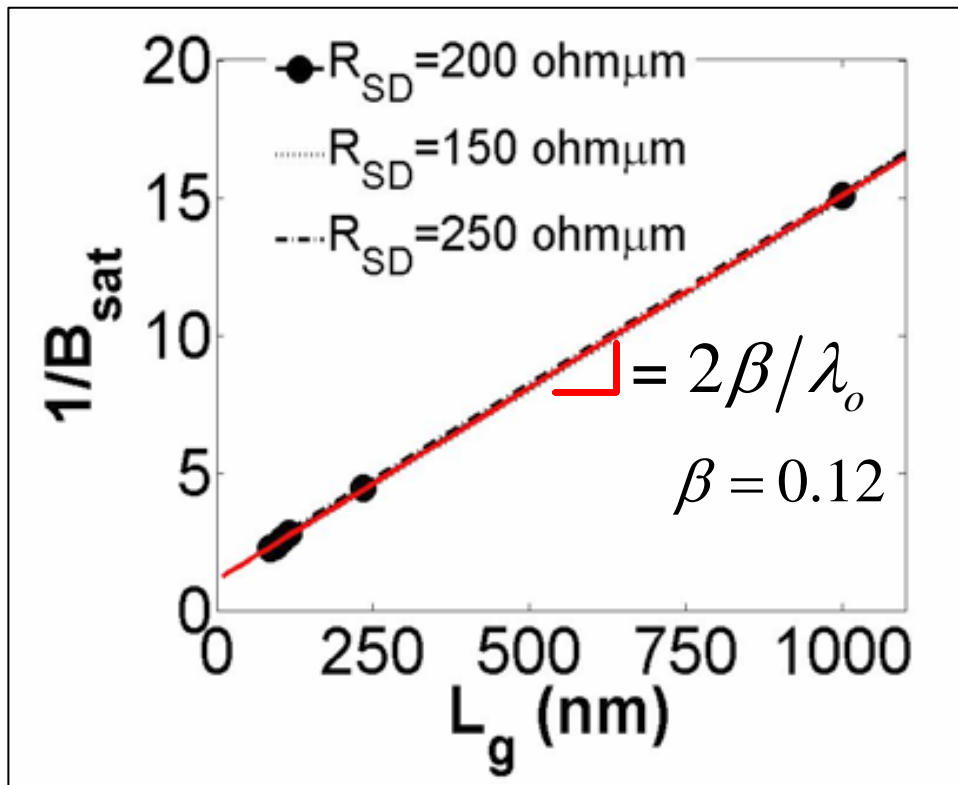nanoHUB.org

ballistic ratio in saturation vs. channel length

$$B = \frac{\langle \upsilon(0) \rangle}{\tilde{\upsilon}_T}$$

$R_{SD}=200$ ohmμm
$R_{SD}=250$ ohmμm
$R_{SD}=150$ ohmμm

Under high drain bias = 1.2V

$$\pm\, 25\% \ \ R_{SD}$$

$$\pm\, 4.7\% \ \ \langle \upsilon(0) \rangle$$

critical length analysis

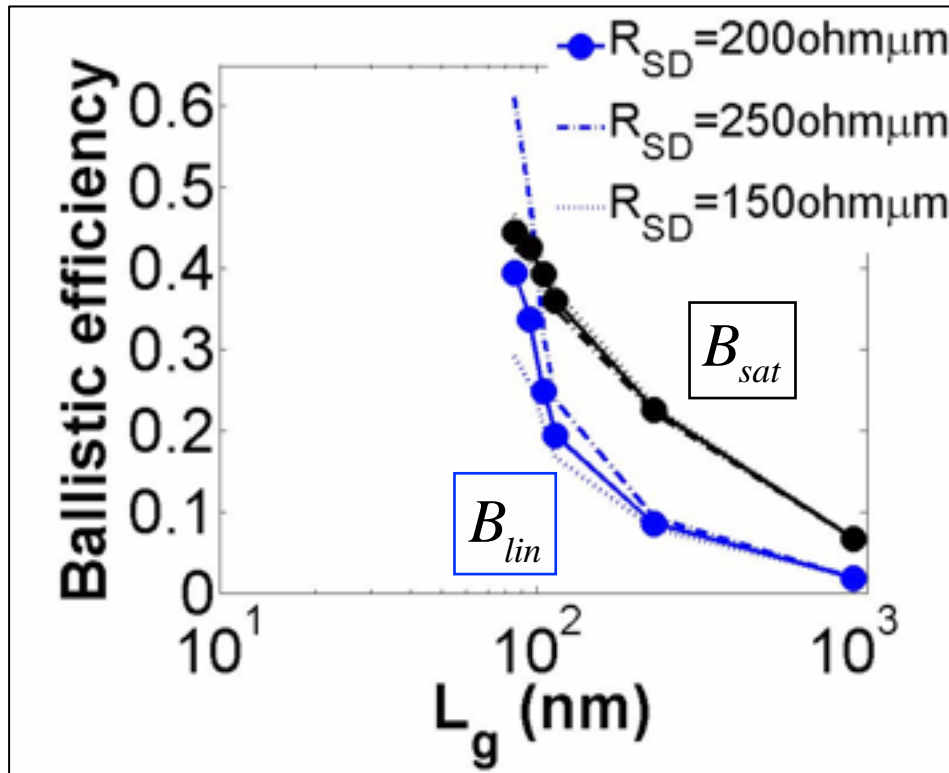$$B_{sat} = \frac{T}{2-T} = \frac{\lambda_0}{\lambda_0 + 2l}$$

$$l = \beta L$$

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

$$\boxed{l = 0.12 \times L}$$

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

channel length scaling: linear vs. saturation

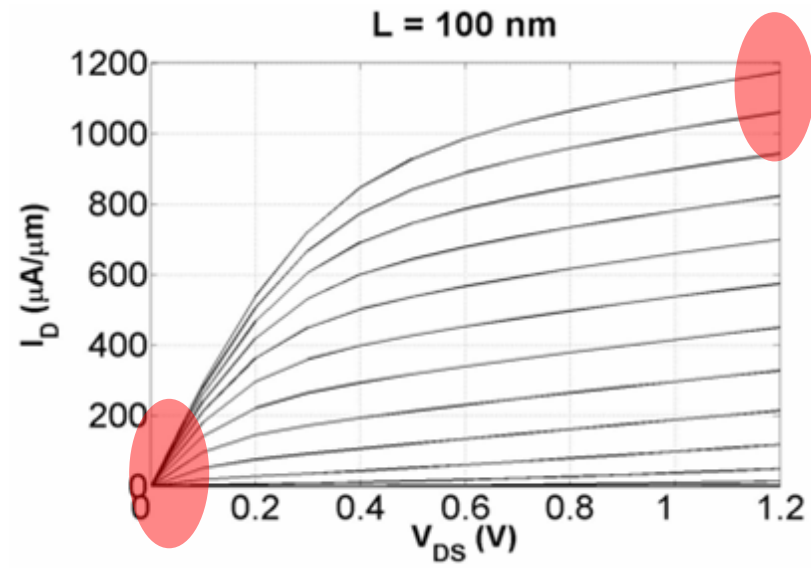
$$B_{lin} = \frac{\lambda_o}{L + \lambda_o}$$

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

where $\beta \sim 0.12$

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

comparison to ballistic limit summary
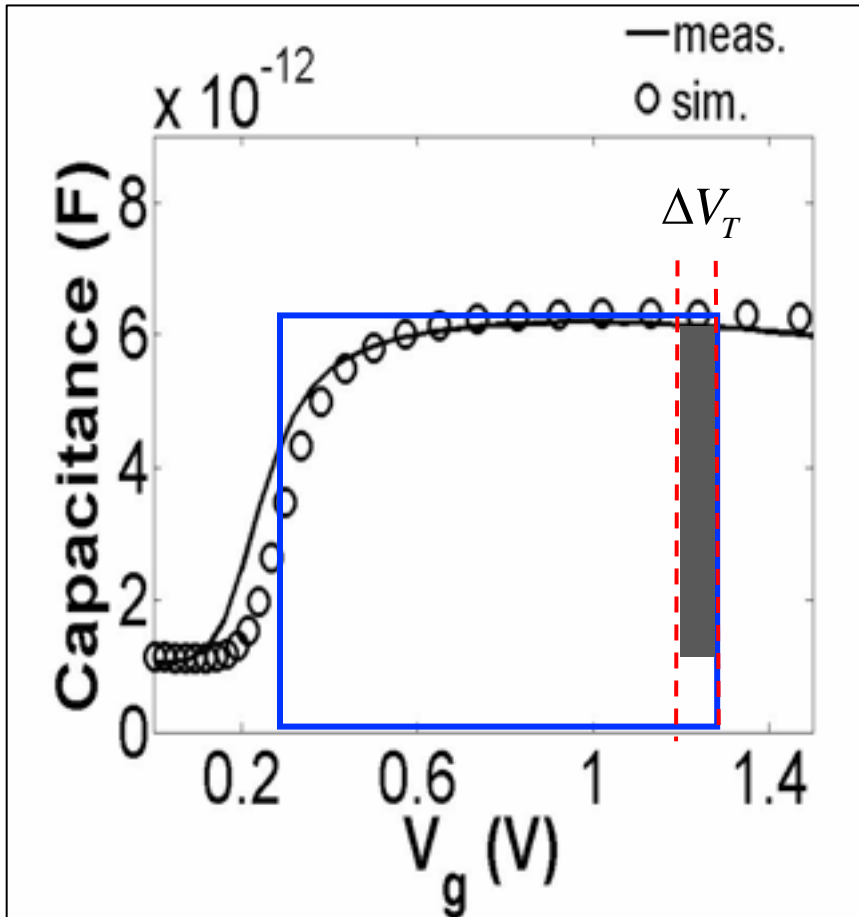

$T \approx 0.62$

$l = 0.12 \times L$

$T \approx 0.17$

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

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

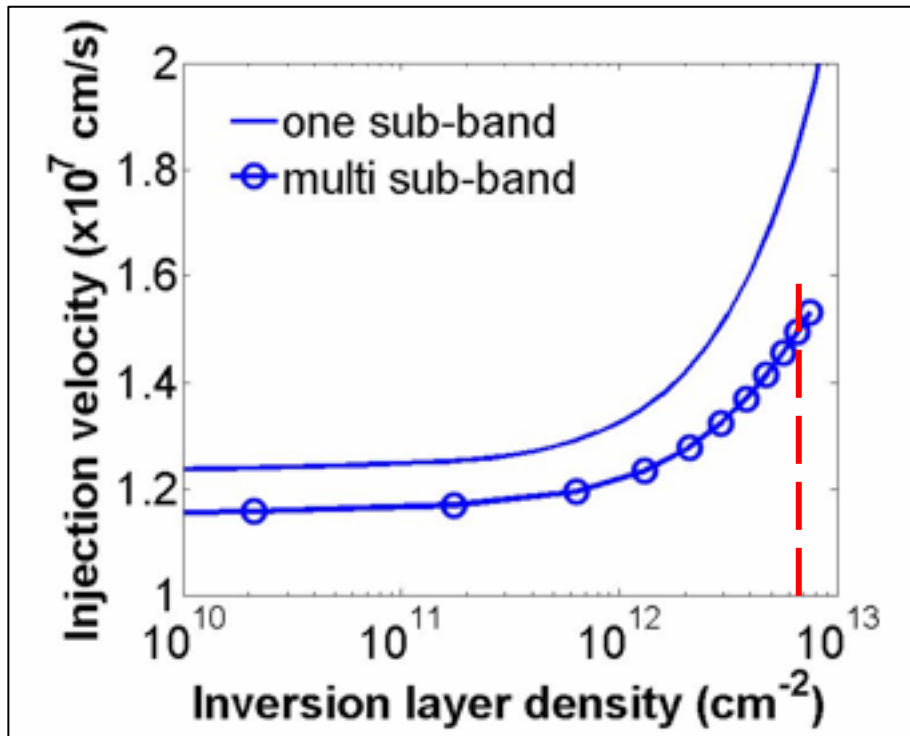$$Q(0) = \int_0^{V_{GS\_short}} C_{GC} \Big/ \left(L_{long} \times W_{long} \right) dV_{GS}$$

$$V_{GS\_short} = V_{GS\_long} + \Delta V_T (DIBL + SCE) - I_{ON} R_S$$

$$\boxed{} \quad Q(0) = C_{ox} \left(V_{GS\_short} - V_T \right)$$

$$\boxed{} \quad 1.25 \times \text{'exact'}$$

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

how good is the single sub-band approximation?

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

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

(single subband)

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

(multi subband)

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implications

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

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

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

$$B_{sat} = \frac{\langle \upsilon(0) \rangle}{\tilde{\upsilon}_T} = 0.45 \rightarrow 0.73 \qquad T = 0.62 \rightarrow T = 0.85$$

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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, $\langle\upsilon(0)\rangle$ and in the ballistic injection velocity, υ_T.

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 *IV* 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.