VE 320 Fall 2021

Introduction to Semiconductor Devices

Instructor: Rui Yang （杨睿）

Office: JI Building 434

rui.yang@sjtu.edu.cn

Lecture 14

MOSFET
(Chapter 11)

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

Previously, current saturation for NMOSFET:

$$V_{DS} = V_{DS}(\mathrm{sat}) = V_{GS} - V_T$$

When velocity saturation occurs: $I_{D(sat)}$ is smaller than the ideal case

$$I_D(\mathrm{sat}) = W C_{\mathrm{ox}} (V_{GS} - V_T) \upsilon_{\mathrm{sat}}$$

Typical saturation velocity for Si: 10^7 cm/s

Electric field: 10^4 V/cm, that is V_{DS}=1 V across 1μm channel length

$I_{D(sat)}$ is a linear function with V_{GS}, instead of the square law

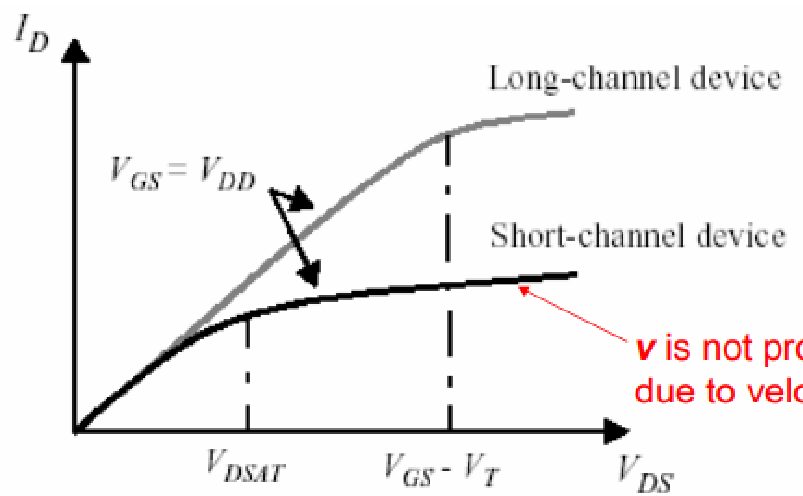
$$\mu = \frac{\mu_{\mathrm{eff}}}{\left[1 + \left(\frac{\mu_{\mathrm{eff}} \mathrm{E}}{\upsilon_{\mathrm{sat}}}\right)^2\right]^{1/2}}$$

Transconductance $g_{ms} = \frac{\partial I_D(\mathrm{sat})}{\partial V_{GS}} = W C_{\mathrm{ox}}\, \upsilon_{\mathrm{sat}}$ Not dependent on V_G or V_D

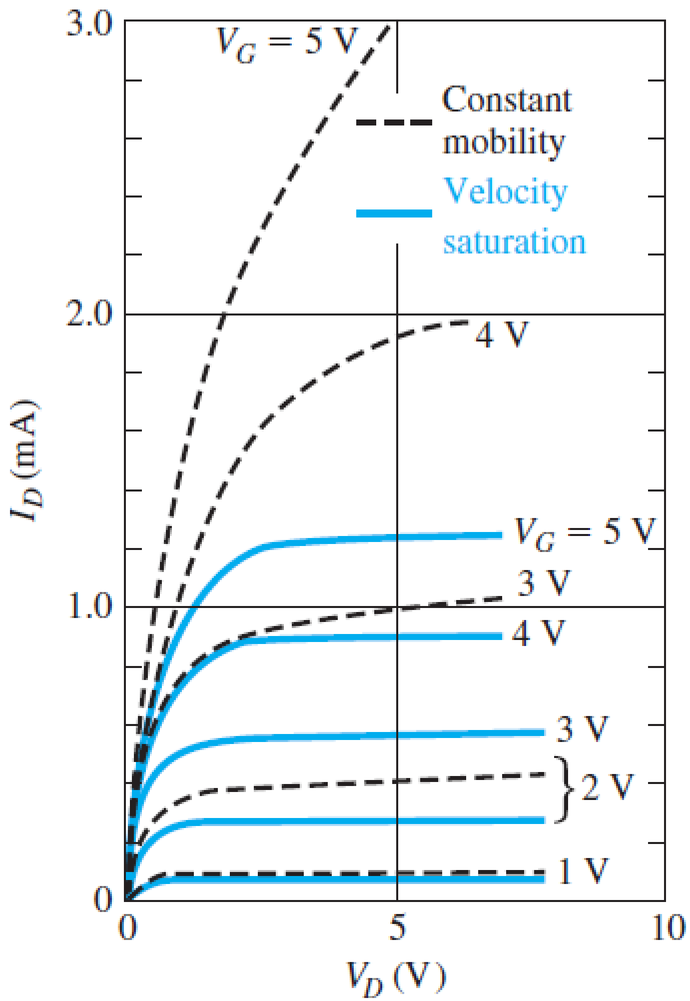
Cutoff frequency (ignore parasitic) $f_T = \frac{g_m}{2\pi C_G} = \frac{W C_{\mathrm{ox}} \upsilon_{\mathrm{sat}}}{2\pi (C_{\mathrm{ox}} W L)} = \frac{\upsilon_{\mathrm{sat}}}{2\pi L}$

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field



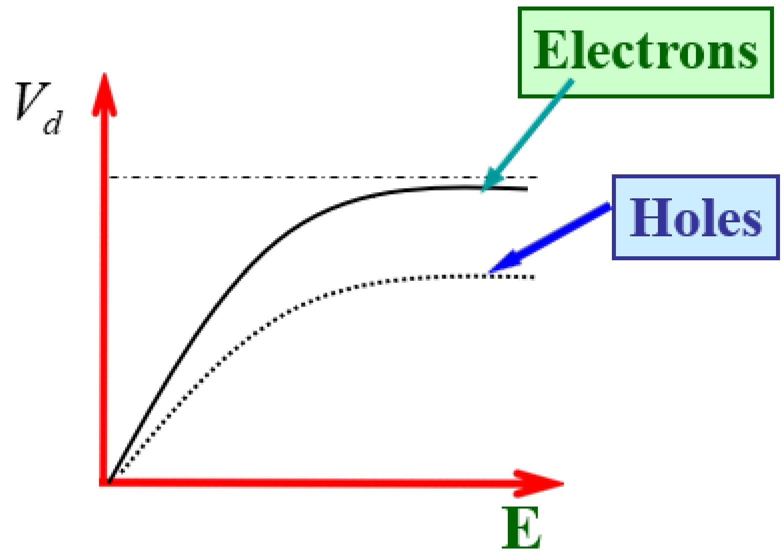
v is not proportional to ***E*,**
due to velocity saturation



MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

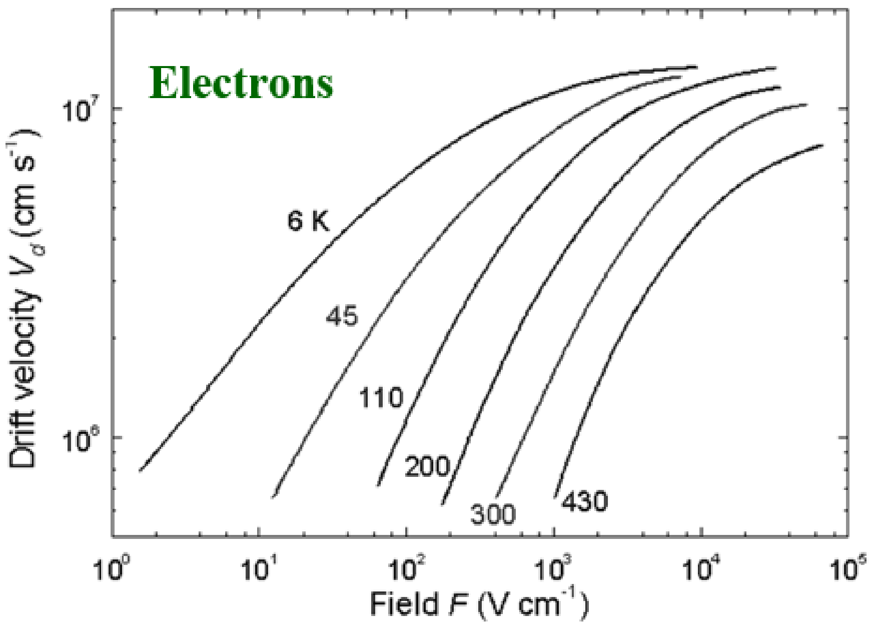
Small velocity: drift velocity $v=\mu E$
But v cannot increase forever…
Large velocity: μ is not a constant

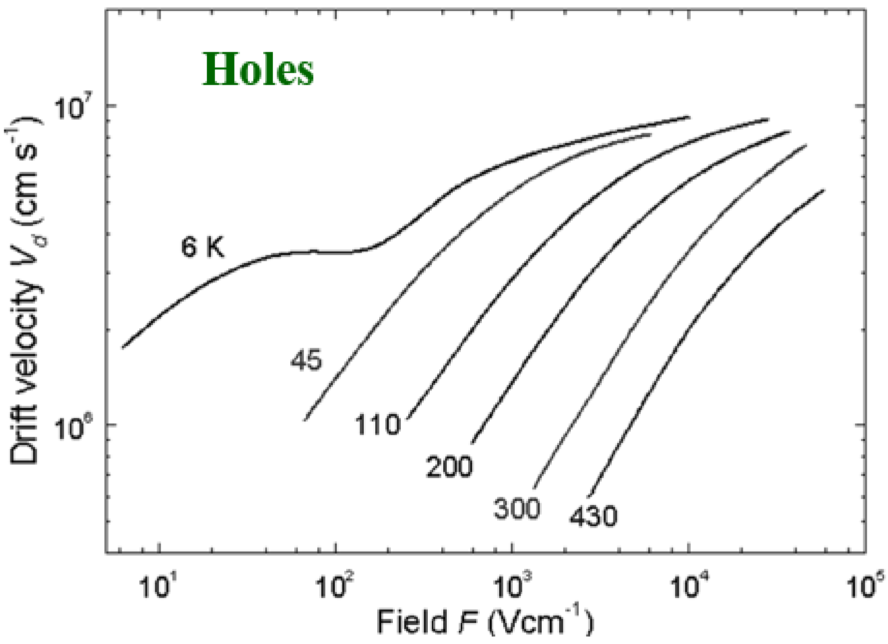


MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

Temperature-dependent v_{sat}





MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

We can measure mobility of transistors, how to measure velocity v_{sat}?

$$v_d = \frac{\mu F}{[1 + (\mu F / v_{sat})^{\gamma}]^{1/\gamma}}$$

γ is a fitting factor with values between 0.6 to 2, F is the electric field

Drift velocity v_d can be measured $v_d = J/(en)$

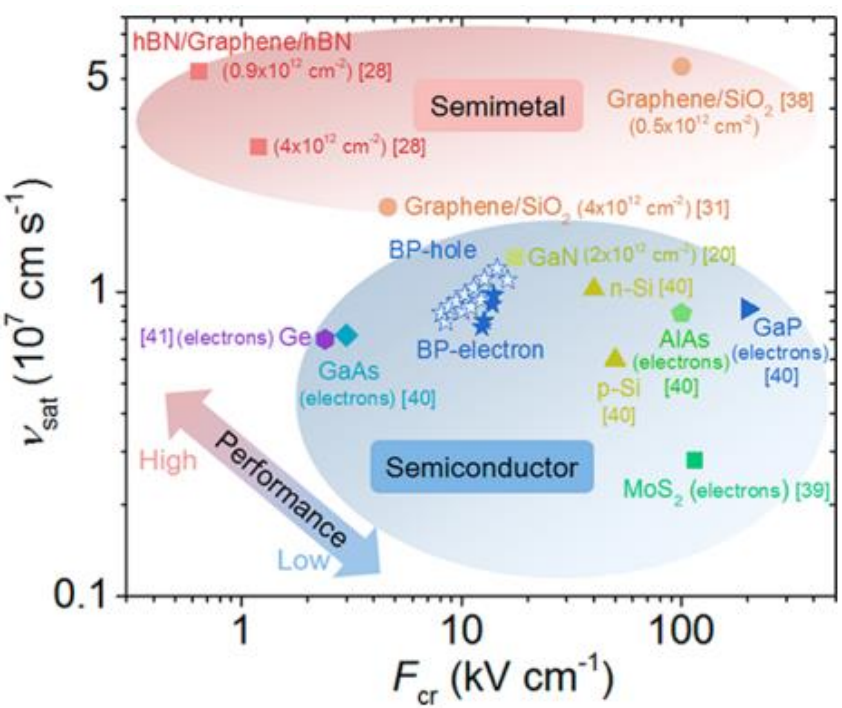
Then perform fitting, with v_{sat} and γ as the fitting parameters

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

We can measure mobility of transistors, how to measure velocity v_{sat}?

$$v_d = \frac{\mu F}{[1 + (\mu F / v_{sat})^{\gamma}]^{1/\gamma}}$$



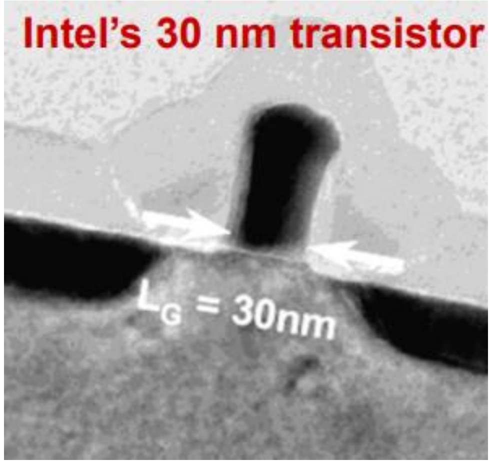
MOSFET: Ballistic transport

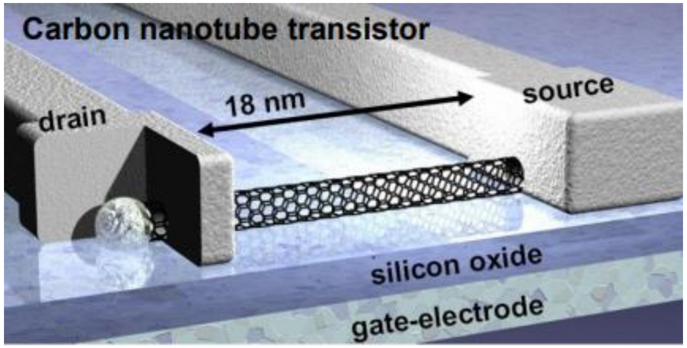
Still: Short channel MOSFETs

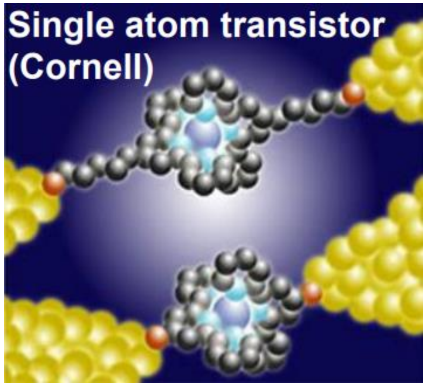
In long channel device, channel length L » mean free path l

In short channel device, channel length L < mean free path l, then a large fraction of carriers travel from S to D without experiencing a scattering event: ballistic transport

Carriers with ballistic transport travel faster than the average drift velocity or the saturation velocity
Can lead to very fast devices







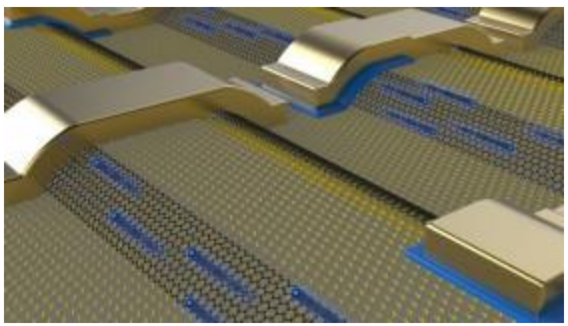
MOSFET: Ballistic transport

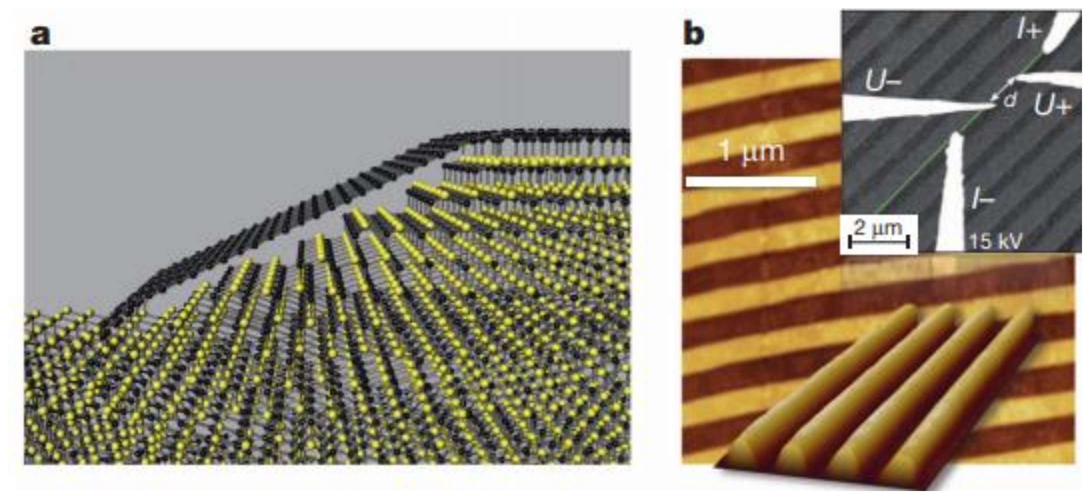
Still: Short channel MOSFETs

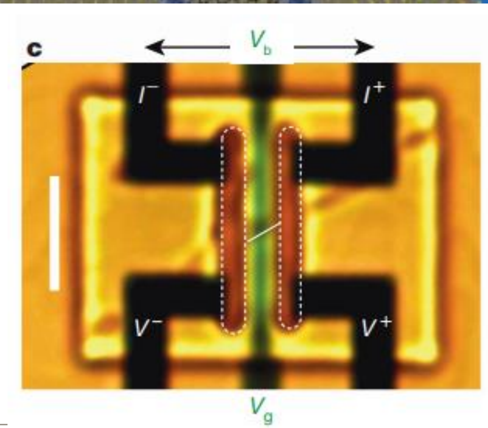
LETTER

doi:10.1038/nature12952

Exceptional ballistic transport in epitaxial graphene nanoribbons







Graphene nanoribbons 40 nm wide, grown on SiC

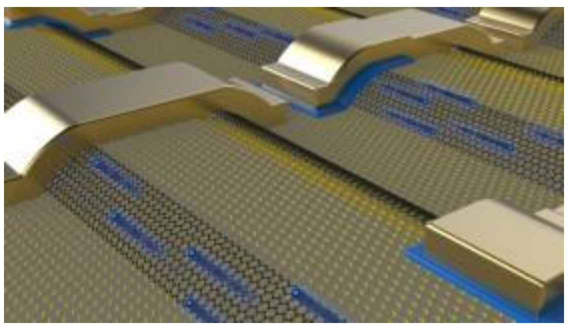
MOSFET: Ballistic transport

Still: Short channel MOSFETs

LETTER

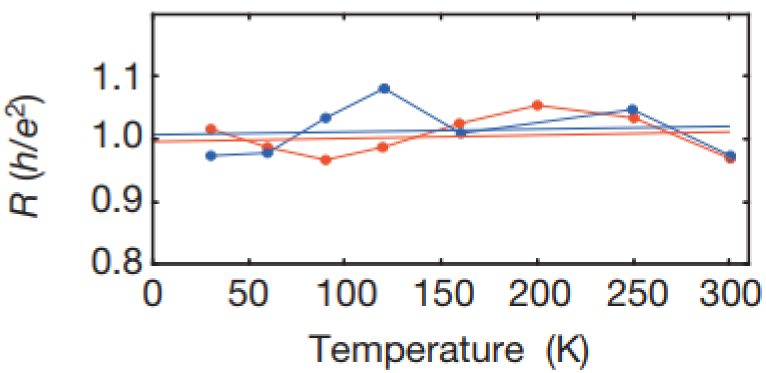
doi:10.1038/nature12952

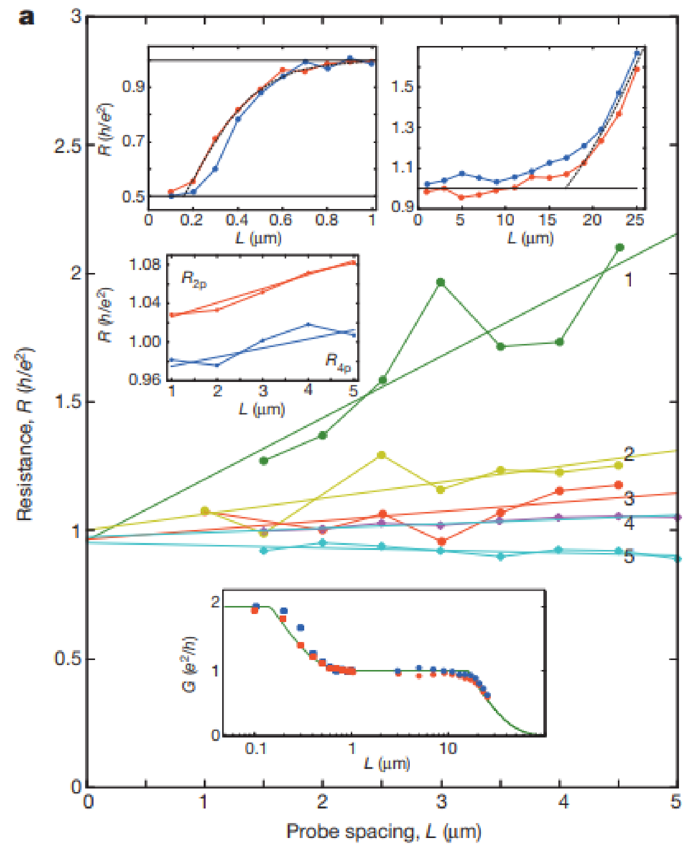
Exceptional ballistic transport in epitaxial graphene nanoribbons



Ballistic for length scale of more than 10 μm

$R_s < 1\ \Omega$/sq



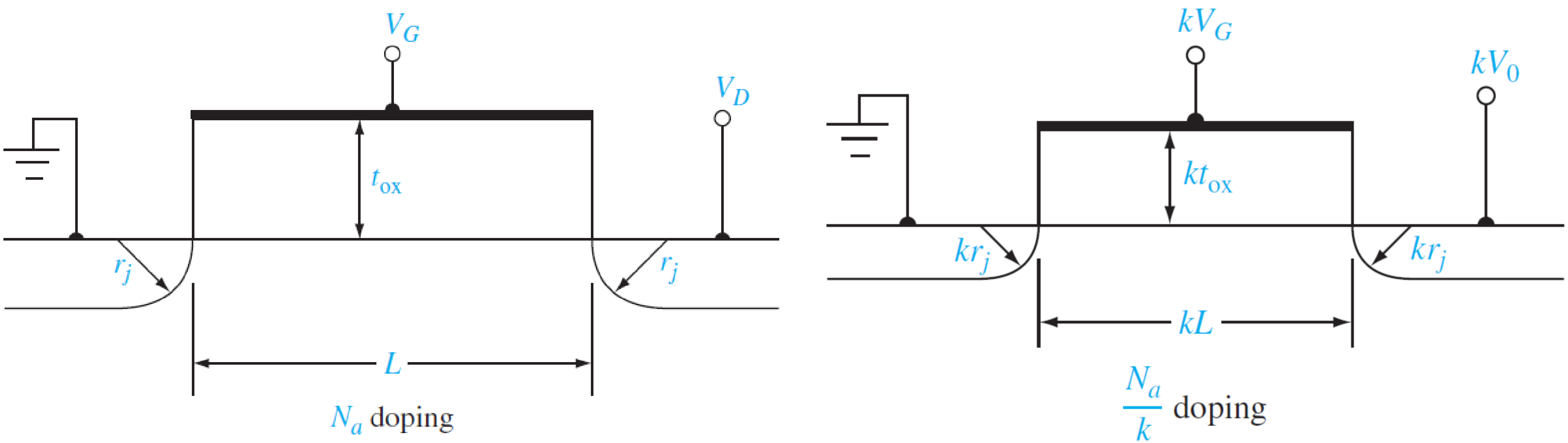


MOSFET: Scaling

MOSFETs continue to scale down, Moore's law

Constant-field scaling: size shrink, and voltage also shrinks. Dennard's law

Original   Scaled



Typically, k 0.7 per generation of a given technology

MOSFET: Scaling

MOSFETs continue to scale down, Moore's law

Constant-field scaling: size shrink, and voltage also shrinks. Dennard's law

	Device and circuit parameters	Scaling factor ($k < 1$)
Scaled parameters	Device dimensions (L, t_{ox}, W, x_j)	k
	Doping concentration (N_a, N_d)	$1/k$
	Voltages	k
Effect on device parameters	Electric field	1
	Carrier velocity	1
	Depletion widths	k
	Capacitance ($C = \epsilon A/t$)	k
	Drift current	k
Effect on circuit parameters	Device density	$1/k^2$
	Power density	1
	Power dissipation per device ($P = IV$)	k^2
	Circuit delay time ($\approx CV/I$)	k
	Power−delay product ($P\tau$)	k^3

MOSFET: Scaling

MOSFETs continue to scale down, Moore's law

Constant-field scaling: size shrink, and voltage also shrinks. Dennard's law

The depletion region width

$$x_D = \sqrt{\frac{2\epsilon(V_{bi} + V_D)}{eN_a}}$$

Since the channel length is being reduced, the depletion widths also need to be reduced.
If the substrate doping concentration is increased by the factor (1/k), then the depletion width is reduced by approximately the factor k since V_D is reduced by k.

Drain current per channel width is nearly a constant

$$\frac{I_D}{W} = \frac{\mu_n \epsilon_{ox}}{2t_{ox}L}(V_G - V_T)^2 \rightarrow \frac{\mu_n \epsilon_{ox}}{2(kt_{ox})(kL)}(kV_G - V_T)^2 \approx \text{constant}$$

I_D scales by k, power reduced by k^2, power density is constant

UNIVERSITY OF MICHIGAN JOINT INSTITUTE 交大密西根学院

MOSFET: Scaling

MOSFETs continue to scale down, Moore's law

Constant-field scaling: size shrink, and voltage also shrinks. Dennard's law

Threshold voltage

$$V_T = V_{FB} + 2\phi_{fp} + \frac{\sqrt{2\epsilon e N_a(2\phi_{fp})}}{C_{ox}}$$

The first two terms are functions of material parameters that do not scale and are only very slight functions of doping concentration

The last term is approximately proportional to $k^{1/2}$, so V_T does not scale

So, shall the voltage be scaled by k?

MOSFET: Scaling

MOSFETs continue to scale down, Moore’s law

Constant-field scaling: size shrink, and voltage also shrinks. Dennard’s law

Threshold voltage

$$V_T = V_{FB} + 2\phi_{fp} + \frac{\sqrt{2\epsilon e N_a (2\phi_{fp})}}{C_{\text{ox}}}$$

The first two terms are functions of material parameters that do not scale and are only very slight functions of doping concentration

The last term is approximately proportional to $k^{1/2}$, so V_T does not scale

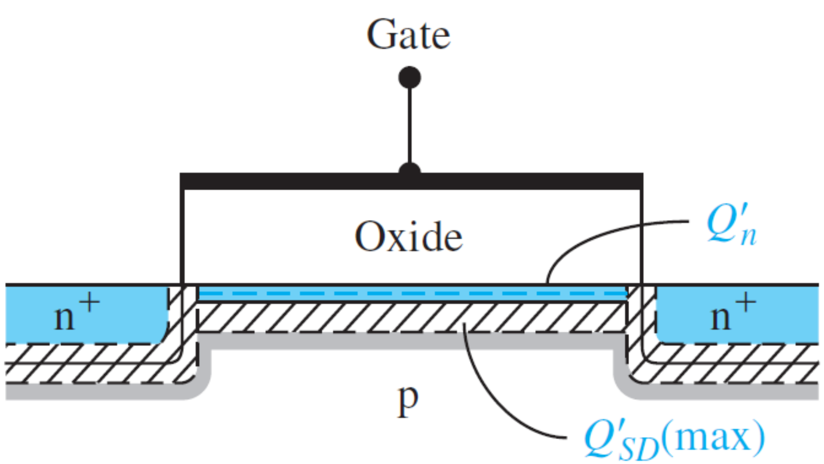
So, shall the voltage be scaled by k?

Actually, increased electric field

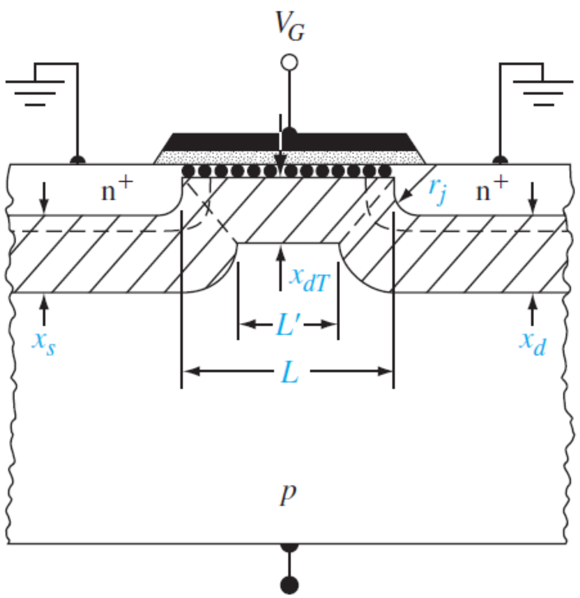
MOSFET: threshold voltage

Threshold voltage $$V_{TN} = \left(|Q'_{SD}(\max)| - Q'_{ss}\right)\left(\frac{t_{ox}}{\epsilon_{ox}}\right) + \phi_{ms} + 2\phi_{fp}$$

Long channel

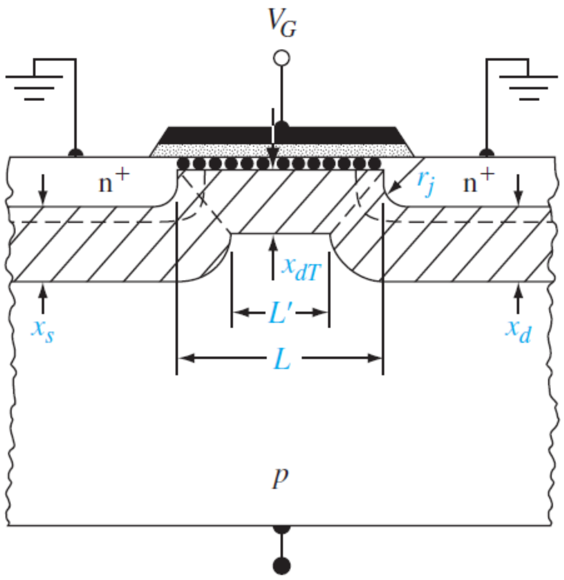


Short channel



MOSFET: threshold voltage

Threshold voltage $$V_{TN} = \left(|Q'_{SD}(\max)| - Q'_{ss}\right)\left(\frac{t_{ox}}{\epsilon_{ox}}\right) + \phi_{ms} + 2\phi_{fp}$$



Diffusion length of the junction r_j

Assume: bulk charge in the trapezoidal region under the gate is controlled by the gate

$$x_s \approx x_d \approx x_{dT} \equiv x_{dT}$$

Bulk charge per unit area

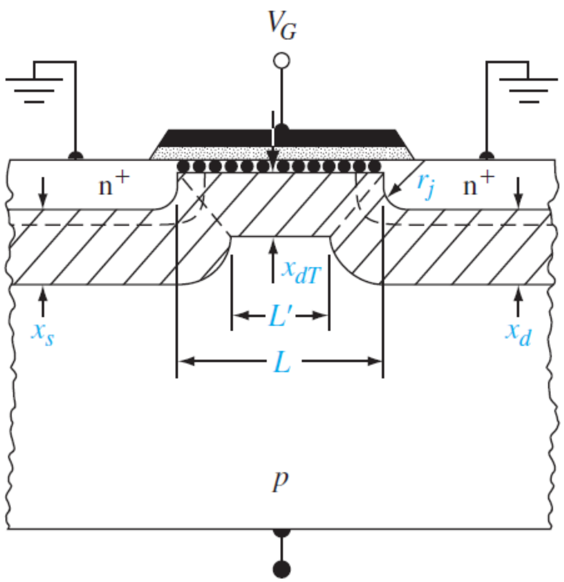
$$|Q'_B| \cdot L = eN_a x_{dT}\left(\frac{L + L'}{2}\right)$$

From geometry

$$\frac{L + L'}{2L} = \left[1 - \frac{r_j}{L}\left(\sqrt{1 + \frac{2x_{dT}}{r_j}} - 1\right)\right]$$

MOSFET: threshold voltage

Threshold voltage $$V_{TN} = \left(|Q'_{SD}(\max)| - Q'_{ss}\right)\left(\frac{t_{ox}}{\epsilon_{ox}}\right) + \phi_{ms} + 2\phi_{fp}$$



Diffusion length of the junction r_j

Assume: bulk charge in the trapezoidal region under the gate is controlled by the gate

$$|Q'_B| = eN_a x_{dT}\left[1 - \frac{r_j}{L}\left(\sqrt{1 + \frac{2x_{dT}}{r_j}} - 1\right)\right]$$

Since $$|Q'_{SD}(\max)| = eN_a x_{dT}$$

The threshold voltage shift due to short channel

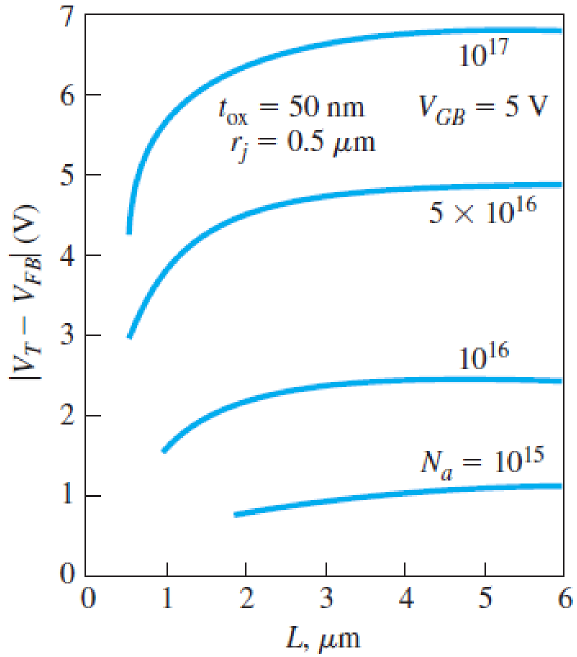
$$\Delta V_T = V_{T(\text{short channel})} - V_{T(\text{long channel})}$$

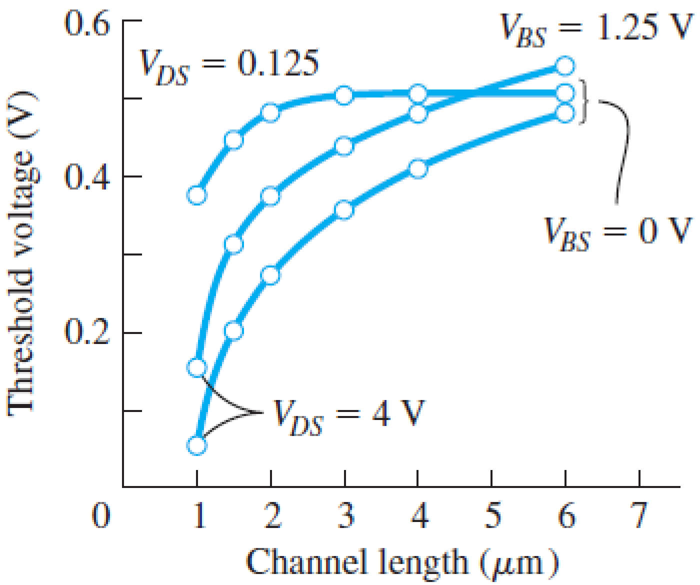
$$\Delta V_T = -\frac{eN_a x_{dT}}{C_{ox}}\left[\frac{r_j}{L}\left(\sqrt{1 + \frac{2x_{dT}}{r_j}} - 1\right)\right]$$

MOSFET: threshold voltage

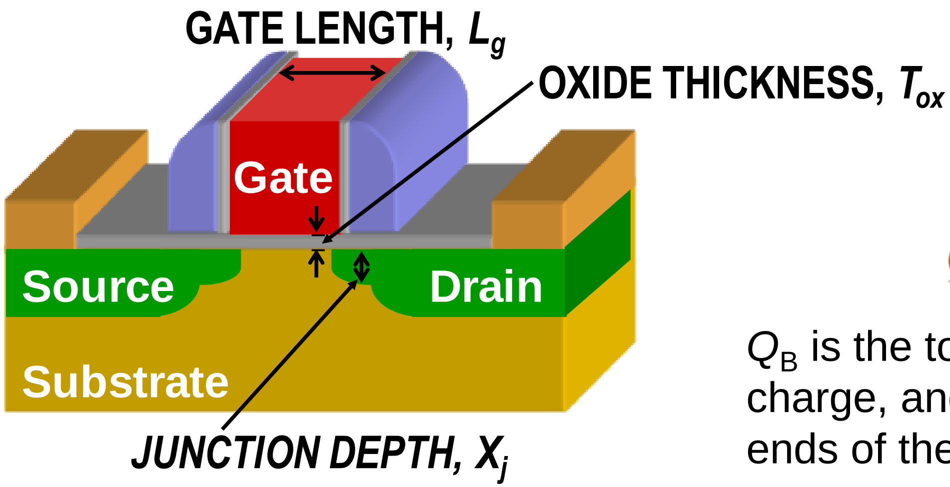
Threshold voltage $$V_{TN} = \left(|Q'_{SD}(\max)| - Q'_{ss}\right)\left(\frac{t_{ox}}{\epsilon_{ox}}\right) + \phi_{ms} + 2\phi_{fp}$$

$$\Delta V_T = -\frac{eN_a x_{dT}}{C_{ox}}\left[\frac{r_j}{L}\left(\sqrt{1+\frac{2x_{dT}}{r_j}} - 1\right)\right]$$





MOSFET: narrow channel effects



There is an additional space charge region at each end of the channel width, also controlled by gate voltage

$$Q_B = Q_{B0} + \Delta Q_B$$

Q_B is the total bulk charge, Q_{B0} is the ideal bulk charge, and ΔQ_B is the additional bulk charge at the ends of the channel width

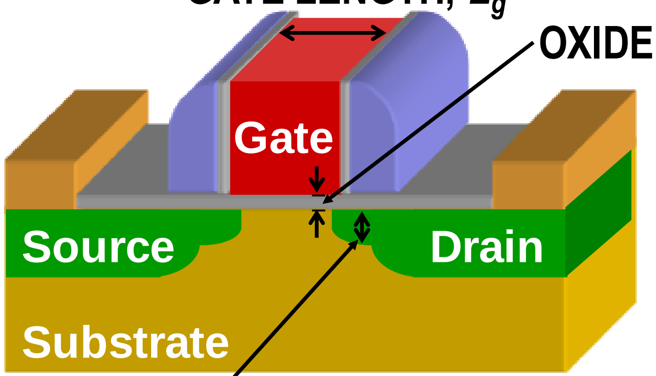
$$|Q_{B0}| = eN_a W L x_{dT}$$

$$\Delta Q_B = eN_a L x_{dT}(\xi x_{dT})$$

ξ is the fitting parameter that accounts for the lateral space charge width

Lateral space charge width may not be the same as the vertical width x_{dT} due to the thicker field oxide at the ends, and /or due to the nonuniform semiconductor doping created by an ion implantation

MOSFET: narrow channel effects



There is an additional space charge region at each end of the channel width, also controlled by gate voltage

$$Q_B = Q_{B0} + \Delta Q_B$$

$$|Q_B| = |Q_{B0}| + |\Delta Q_B| = eN_a\, WL\, x_{dT} + eN_a\, Lx_{dT}\,(\xi x_{dT})$$

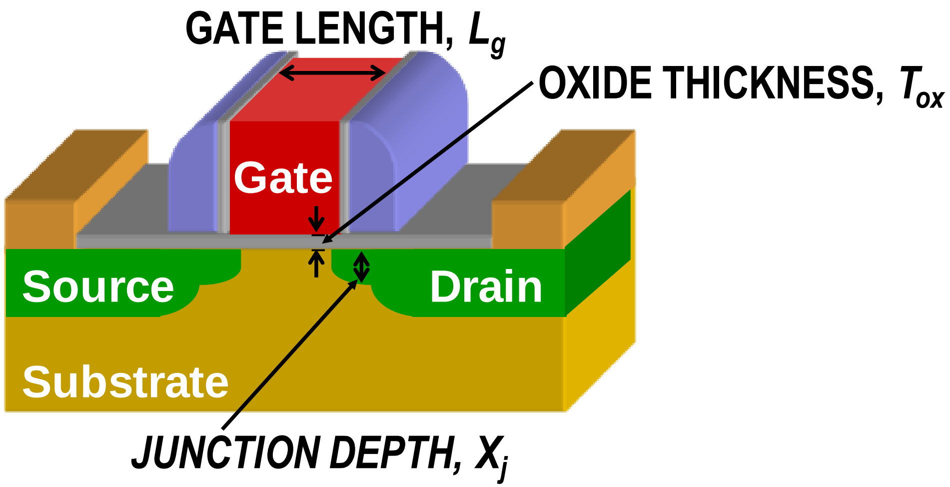
$$= eN_a WL x_{dT}\left(1 + \frac{\xi x_{dT}}{W}\right)$$

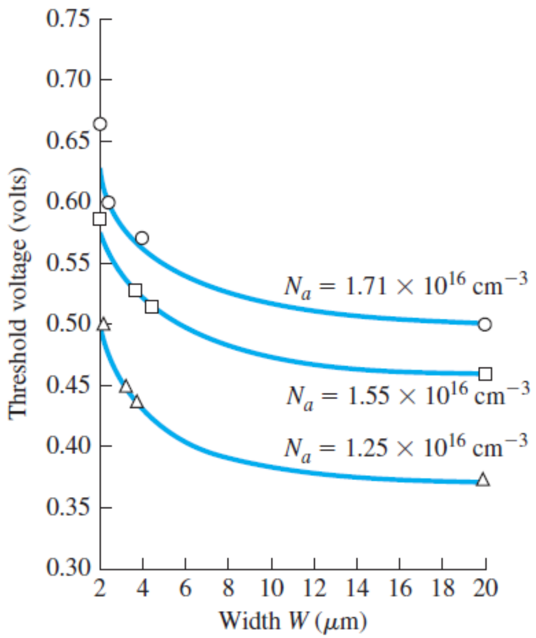
The effect of the end space charge regions becomes significant as the width W decreases and the factor ($\xi\, x_{dT}$) becomes a significant fraction of the width W.

$$\Delta V_T = \frac{eN_a x_{dT}}{C_{ox}}\left(\frac{\xi x_{dT}}{W}\right)$$

The shift in threshold voltage due to a narrow channel is in the positive direction for the n-channel MOSFET.
As the width *W* becomes smaller, the shift in threshold voltage becomes larger.

MOSFET: threshold voltage





Summary