

VE 320 Summer 2019

Introduction to Semiconductor Devices

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Lecture 14

MOSFET (Chapter 11)

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

Previously, current saturation for NMOSFET:

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

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

$$I_D(\text{sat}) = WC_{\text{ox}}(V_{GS} - V_T)v_{\text{sat}}$$

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

Electric field: 10^4 V/cm, that is $V_{DS}=1$ V across $1\mu\text{m}$ channel length

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

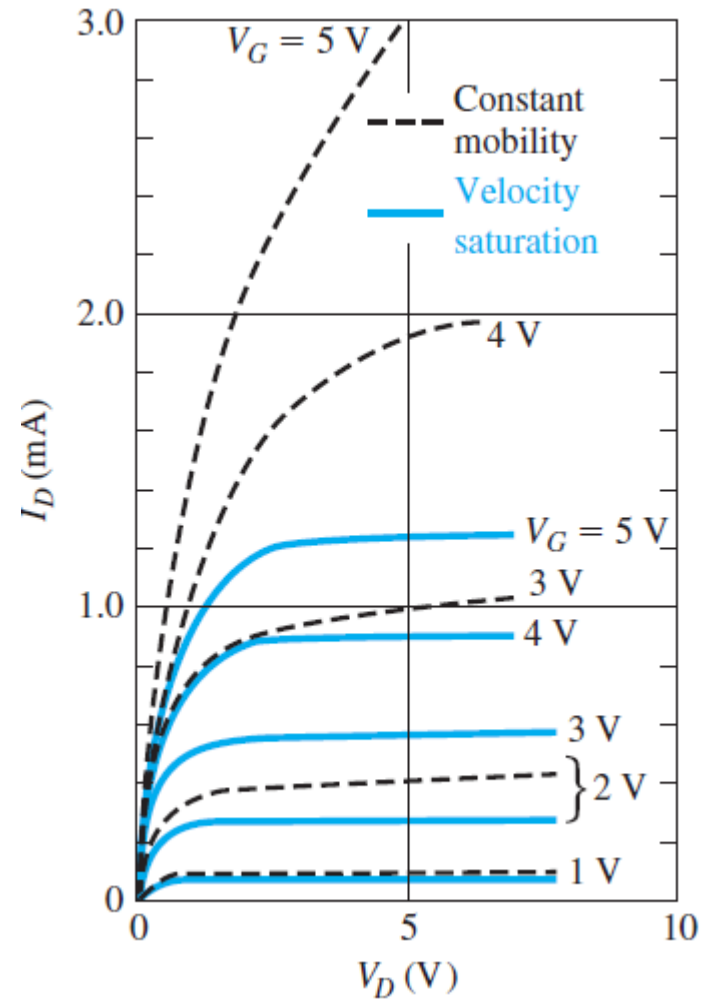
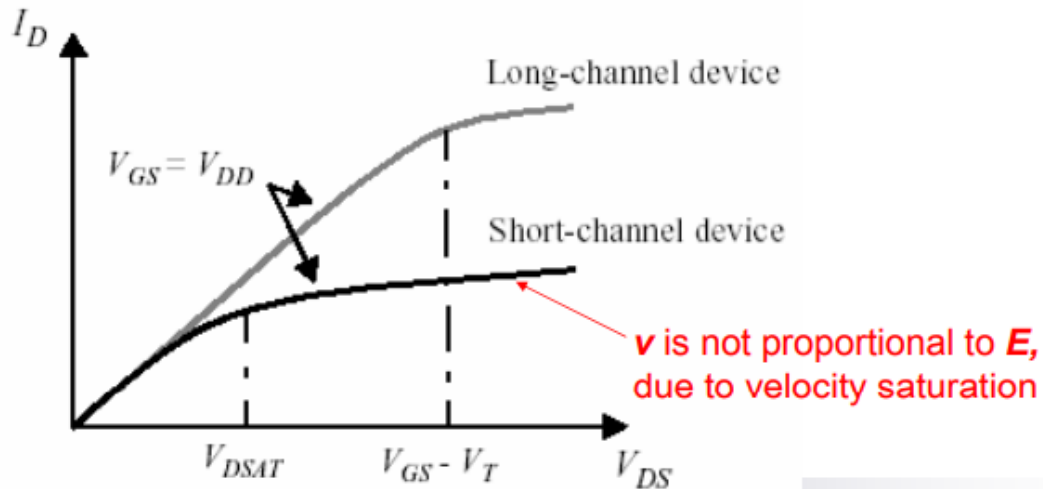
$$\mu = \frac{\mu_{\text{eff}}}{\left[1 + \left(\frac{\mu_{\text{eff}} E}{v_{\text{sat}}}\right)^2\right]^{1/2}}$$

Transconductance $g_{ms} = \frac{\partial I_D(\text{sat})}{\partial V_{GS}} = WC_{\text{ox}} v_{\text{sat}}$ Not dependent on V_G or V_D

Cutoff frequency (ignore parasitic) $f_T = \frac{g_m}{2\pi C_G} = \frac{WC_{\text{ox}} v_{\text{sat}}}{2\pi (C_{\text{ox}} WL)} = \frac{v_{\text{sat}}}{2\pi L}$

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field



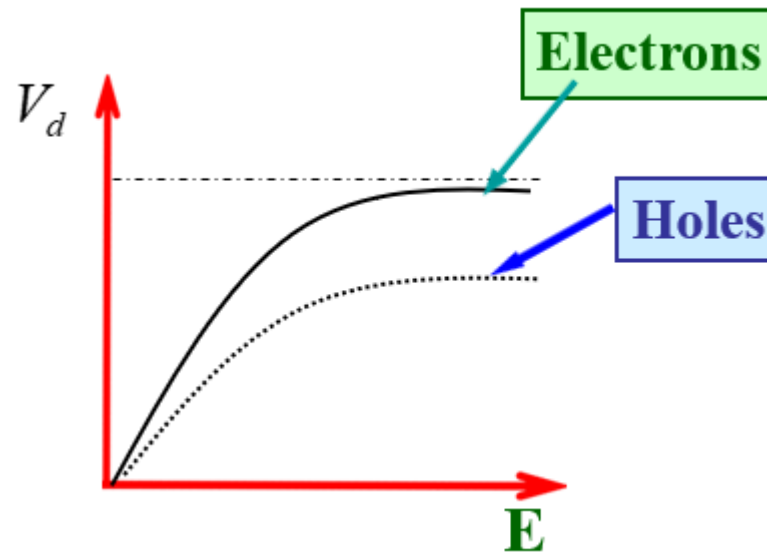
MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

Small velocity: drift velocity $v = \mu E$

But v cannot increase forever...

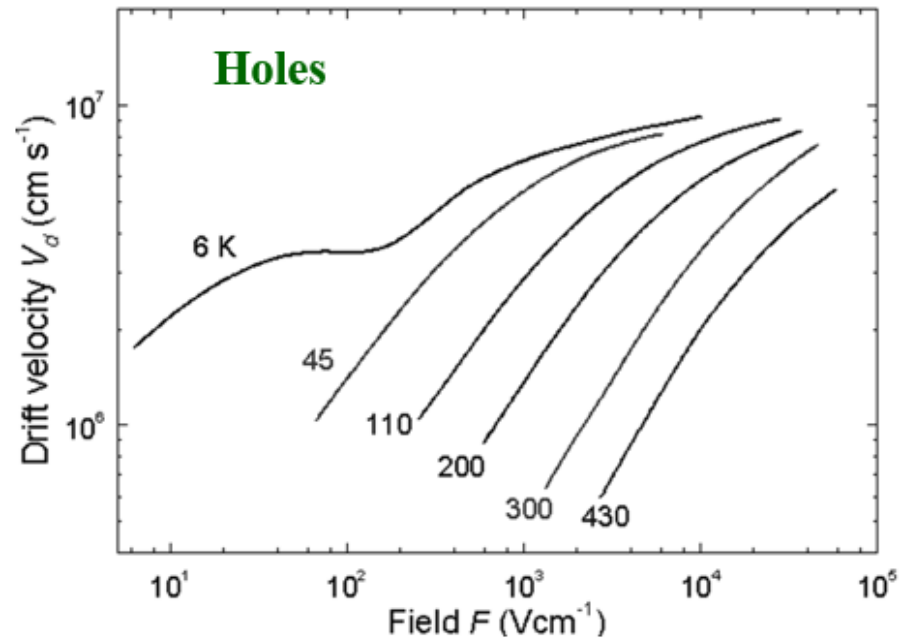
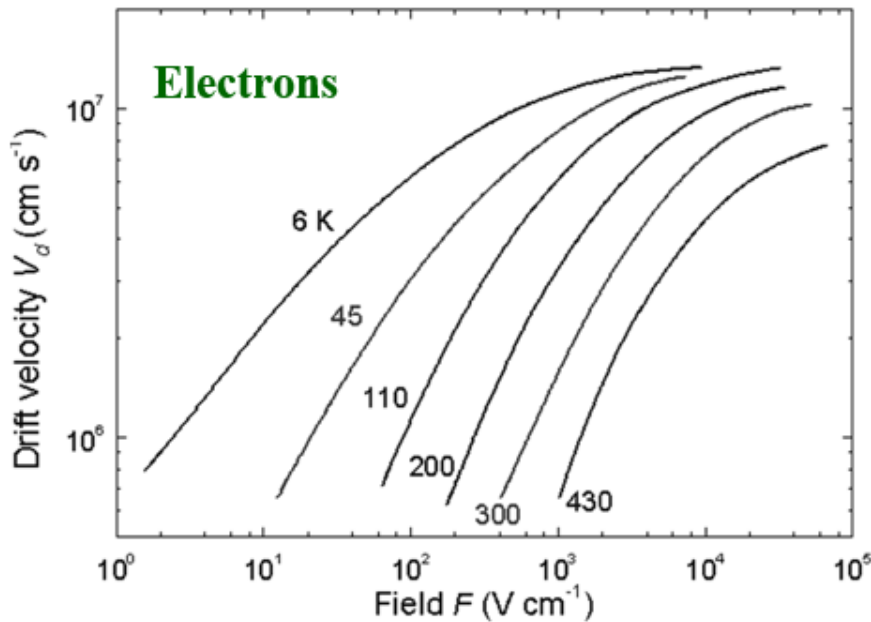
Large velocity: μ is not a constant



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} ?

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

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

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

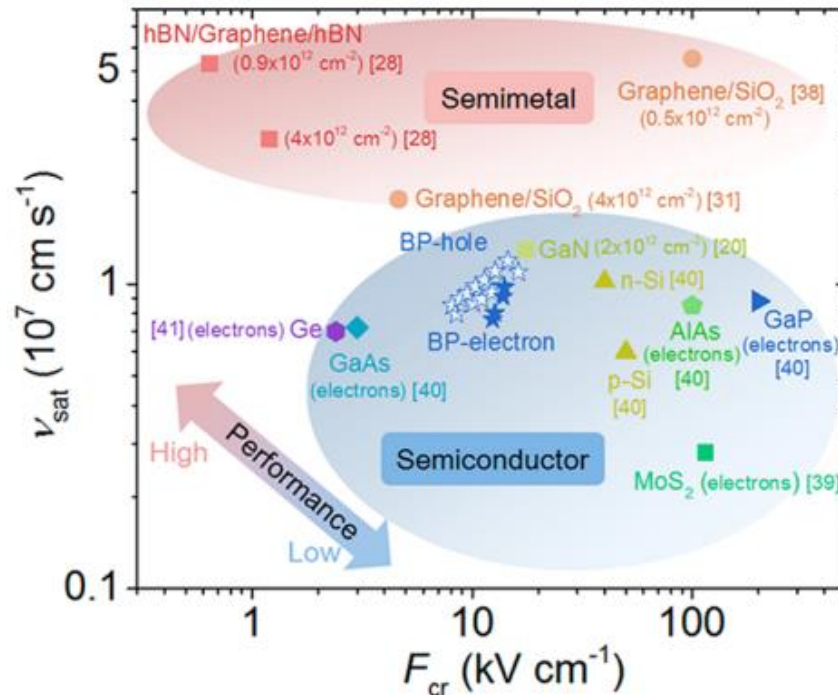
Then perform fitting, with v_{sat} and γ as the fitting parameters

MOSFET: Velocity saturation

Short channel MOSFETs, large electric field

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



MOSFET: Ballistic transport

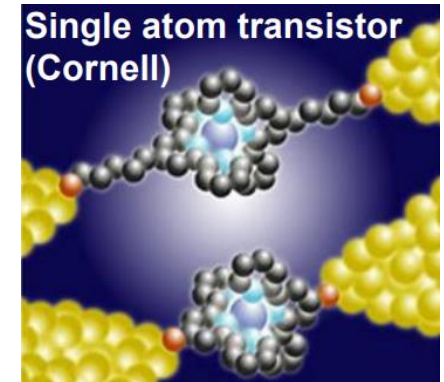
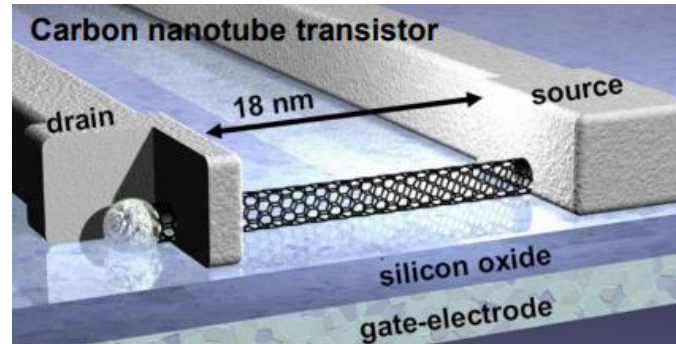
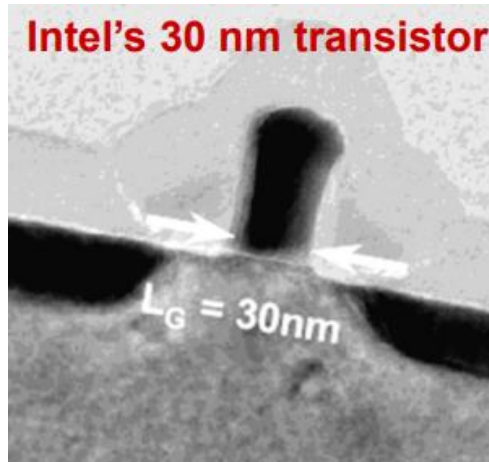
Still: **Short channel** MOSFETs

In long channel device, channel length $L \gg$ 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



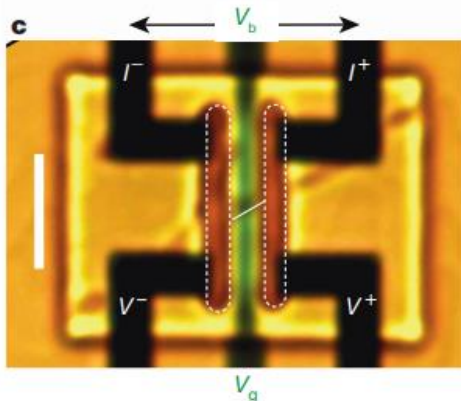
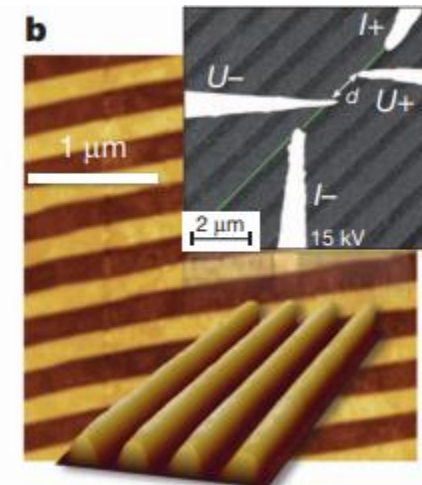
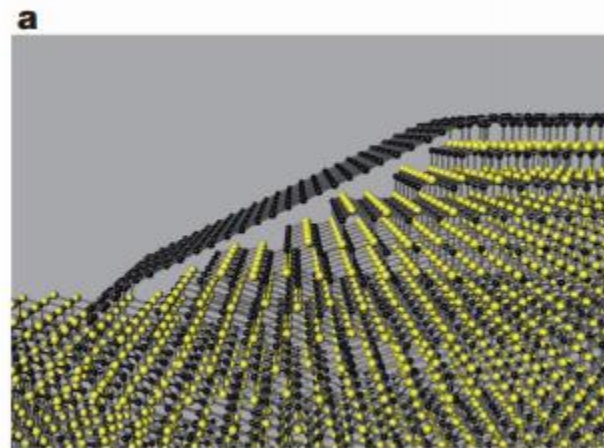
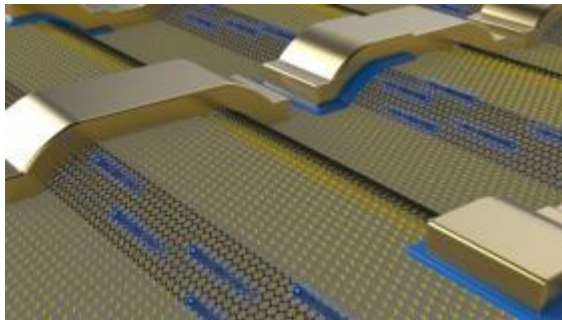
MOSFET: Ballistic transport

Still: Short channel MOSFETs

LETTER

doi:10.1038/nature12952

Exceptional ballistic transport in epitaxial graphene nanoribbons



Graphene nanoribbons 40 nm wide, grown on SiC

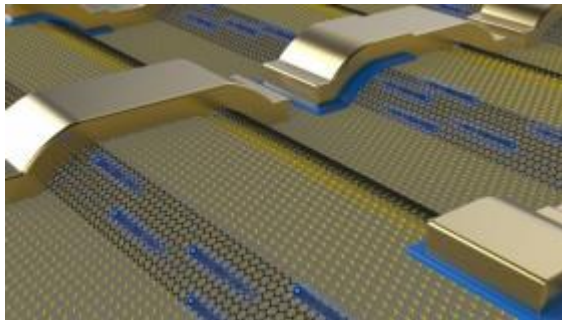
MOSFET: Ballistic transport

Still: Short channel MOSFETs

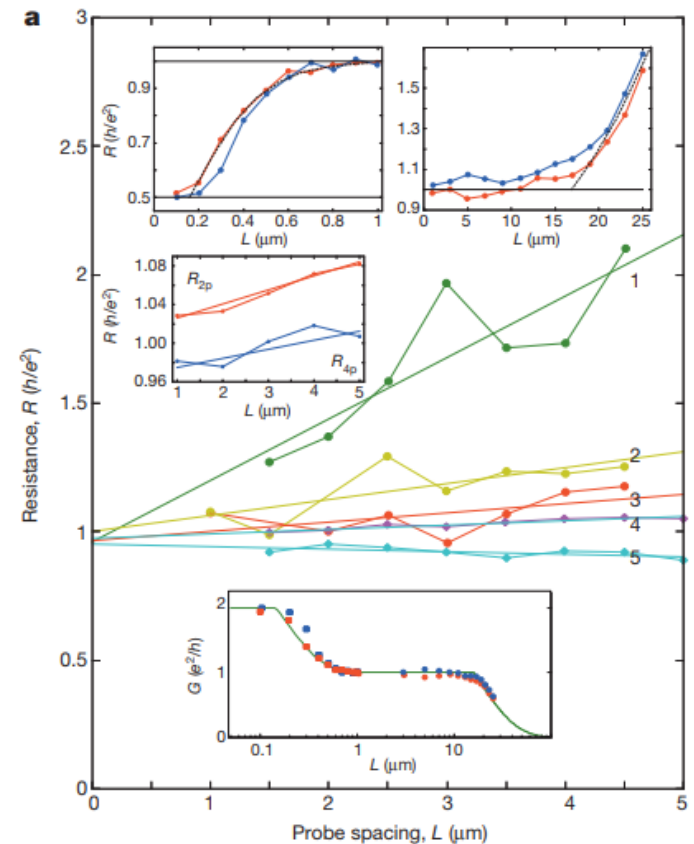
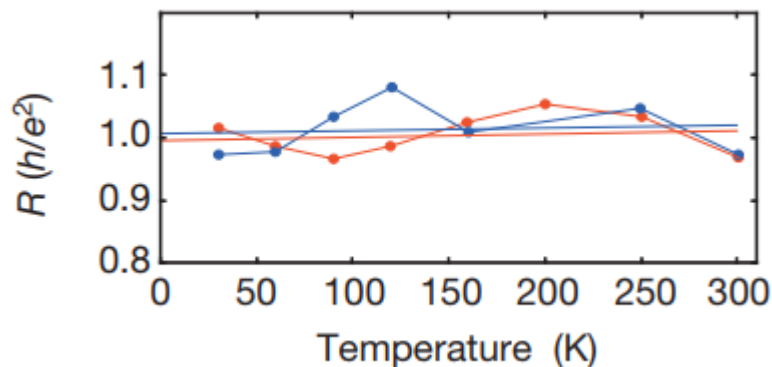
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Exceptional ballistic transport in epitaxial graphene nanoribbons



Ballistic for length
scale of more than
 $10\ \mu\text{m}$
 $R_s < 1\ \Omega/\text{sq}$

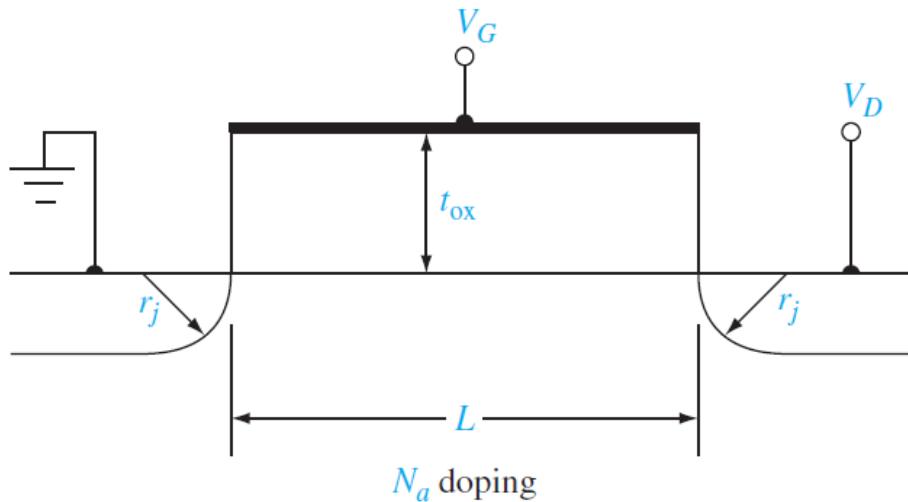


MOSFET: Scaling

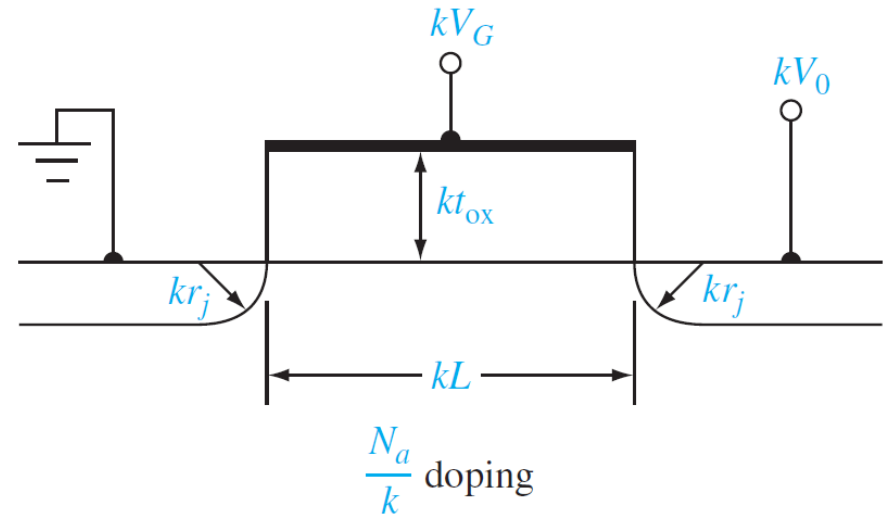
MOSFETs continue to scale down, Moore's law

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

Original



Scaled



Typically, $k \approx 0.7$ 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

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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

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

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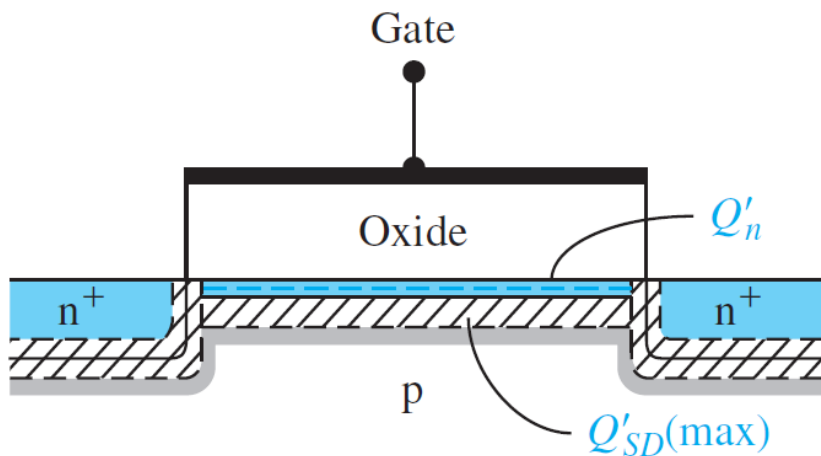
So, shall the voltage be scaled by k ?

Actually, increased electric field

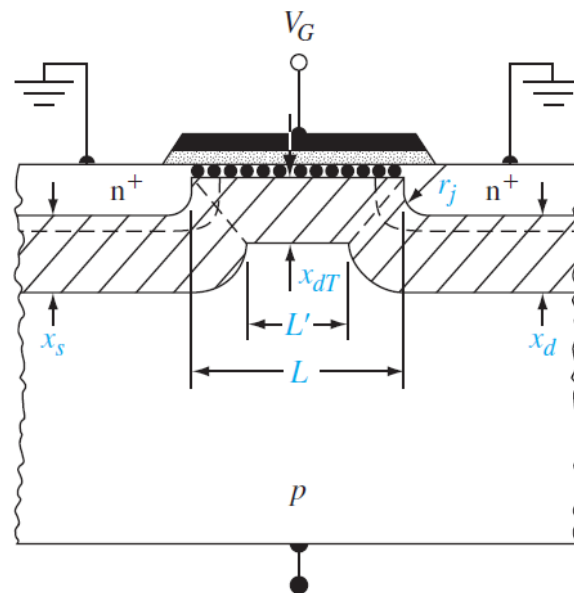
MOSFET: threshold voltage

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

Long channel

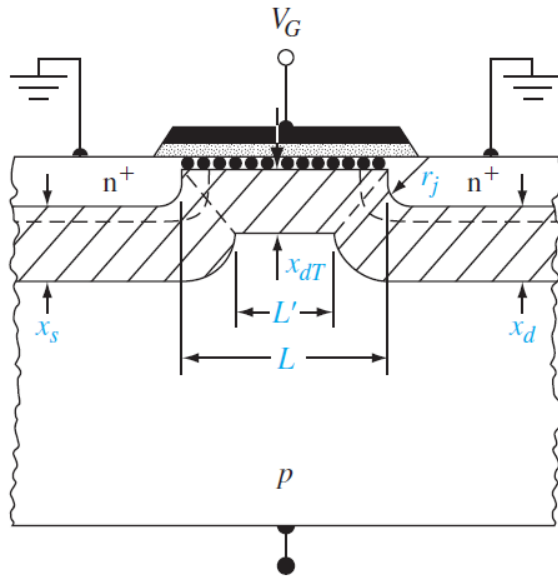


Short channel



MOSFET: threshold voltage

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



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

Diffusion length of the junction r_j

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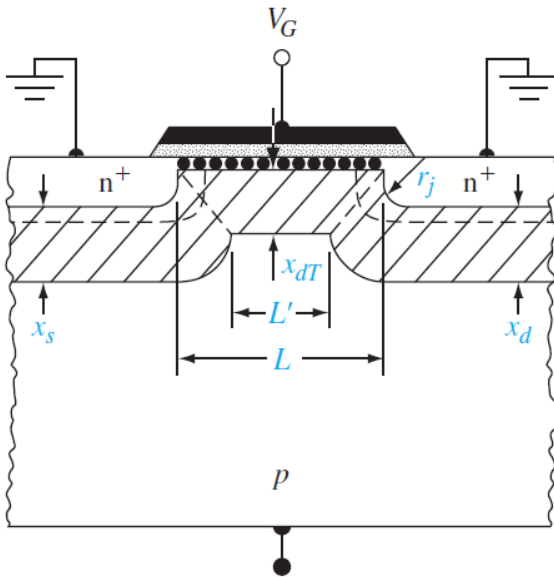
$$|Q'_B| = eN_a x_{dT} \left[1 - \frac{r_j}{L} \left(\sqrt{1 + \frac{2x_{dT}}{r_j}} - 1 \right) \right]$$

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

The threshold voltage shift due to short channel

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

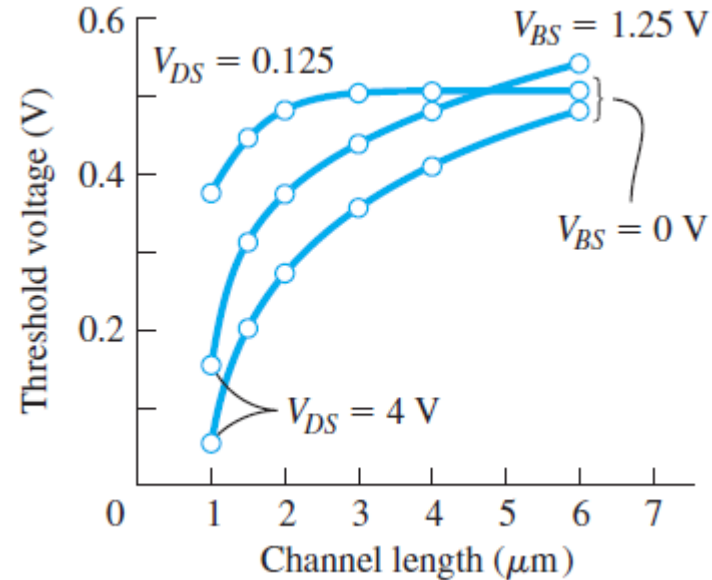
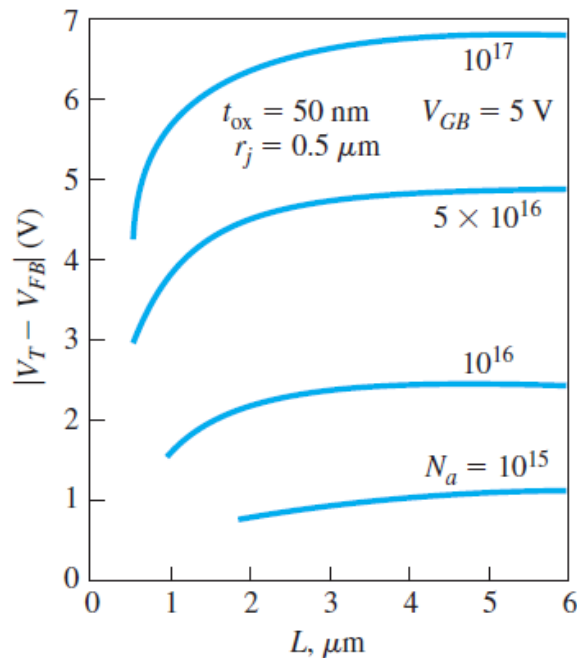
$$\Delta V_T = -\frac{eN_a x_{dT}}{C_{ox}} \left[\frac{r_j}{L} \left(\sqrt{1 + \frac{2x_{dT}}{r_j}} - 1 \right) \right]$$



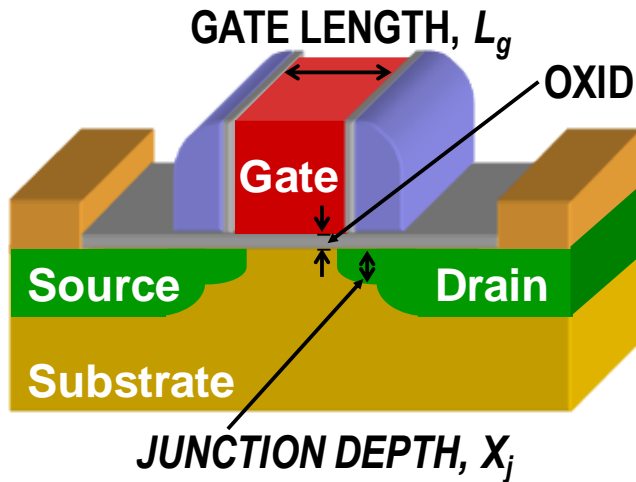
MOSFET: threshold voltage

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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

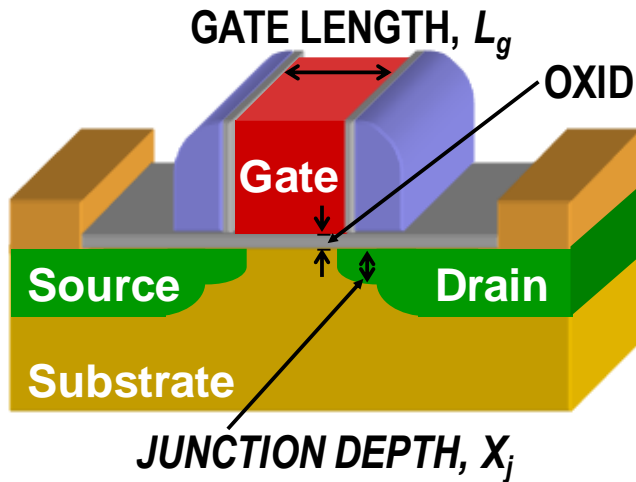
$$|Q_{B0}| = eN_a W L x_{dT}$$

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

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

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

$$\begin{aligned} |Q_B| &= |Q_{B0}| + |\Delta Q_B| = eN_a WL x_{dT} + eN_a L x_{dT} (\xi x_{dT}) \\ &= eN_a WL x_{dT} \left(1 + \frac{\xi x_{dT}}{W} \right) \end{aligned}$$

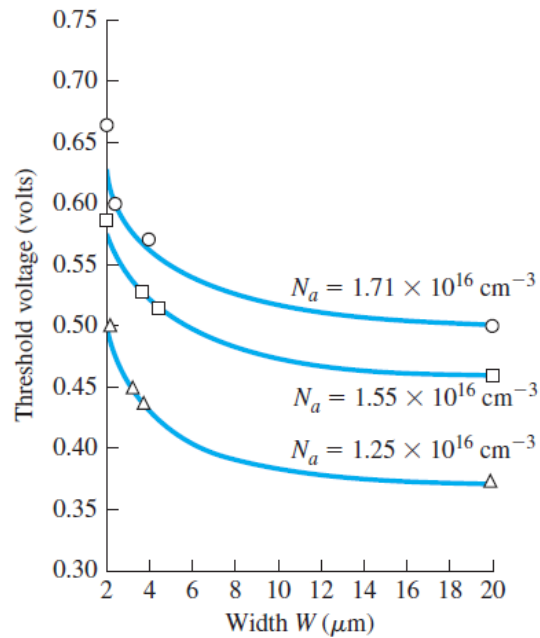
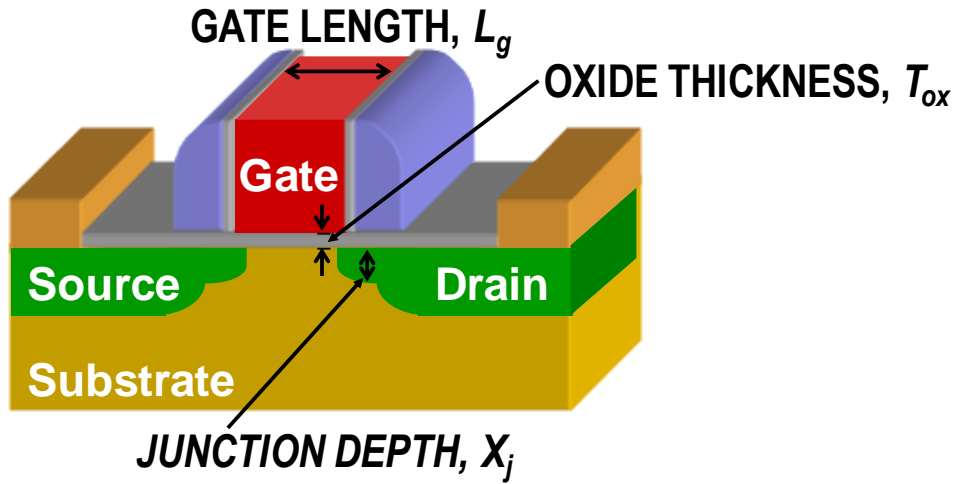
The effect of the end space charge regions becomes significant as the width W decreases and the factor (ξx_{dT}) becomes a significant fraction of the width W .

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

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

