VE320 – Summer 2021

Introduction to Semiconductor Devices

Instructor: Yaping Dan （但亚平）
yaping.dan@sjtu.edu.cn

Chapter 11 Metal-Oxide-Semiconductor Field Effect Transistors: More Concepts

Outline

Nonideal Effects:

11.1 Channel length modulation

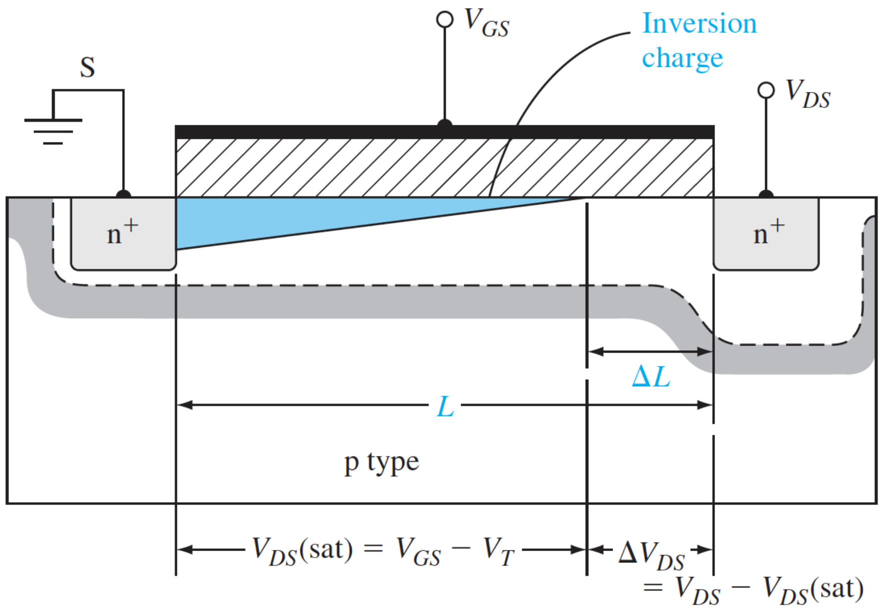
11.2 Conductance and transconductance

11.3 Subthreshold conduction

11.4 Velocity Saturation

11.5 Short Channel Effect

11.1 Channel length modulation



$$I_D' = \frac{k_n'}{2} \cdot \frac{W}{L} \cdot [(V_{GS} - V_T)^2 (1 + \lambda V_{DS})]$$

11.1 Channel length modulation

$$I_D = \begin{cases} 0 & V_{GS} - V_T < 0 \\ \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2 & 0 \le V_{GS} - V_T < V_{DS} \\ \mu_n C_{ox}\frac{W}{L}[(V_{GS} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2] & V_{GS} - V_T \ge V_{DS} \end{cases}$$

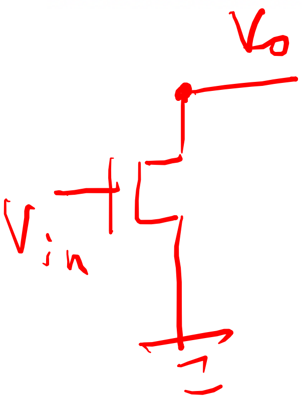
$$\Downarrow$$

$$I_D = \begin{cases} 0 & V_{GS} - V_T < 0 \\ \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS}) & 0 \le V_{GS} - V_T < V_{DS} \\ \mu_n C_{ox}\frac{W}{L}[(V_{GS} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2] & V_{GS} - V_T \ge V_{DS} \end{cases}$$

Check your understanding

Problem Example 1

Consider an n-channel silicon MOSFET. The parameters are $k_n' = 75\ \mu A/V^2$, $W/L = 10$, and $V_T = 0.35$ V. The applied drain-to-source voltage is $V_{DS} = 1.5$ V. (*a*) For $V_{GS} = 0.8$ V, find (*i*) the ideal drain current, (*ii*) the drain current if $\lambda = 0.02\ V^{-1}$, and (*iii*) the output resistance for $\lambda = 0.02\ V^{-1}$. (*b*) Repeat part (*a*) for $V_{GS} = 1.25$ V.



$$\frac{1}{r_o} = \frac{dI_D}{dV_{ds}}$$

$$r_o = \frac{dV_{ds}}{dI_D}$$

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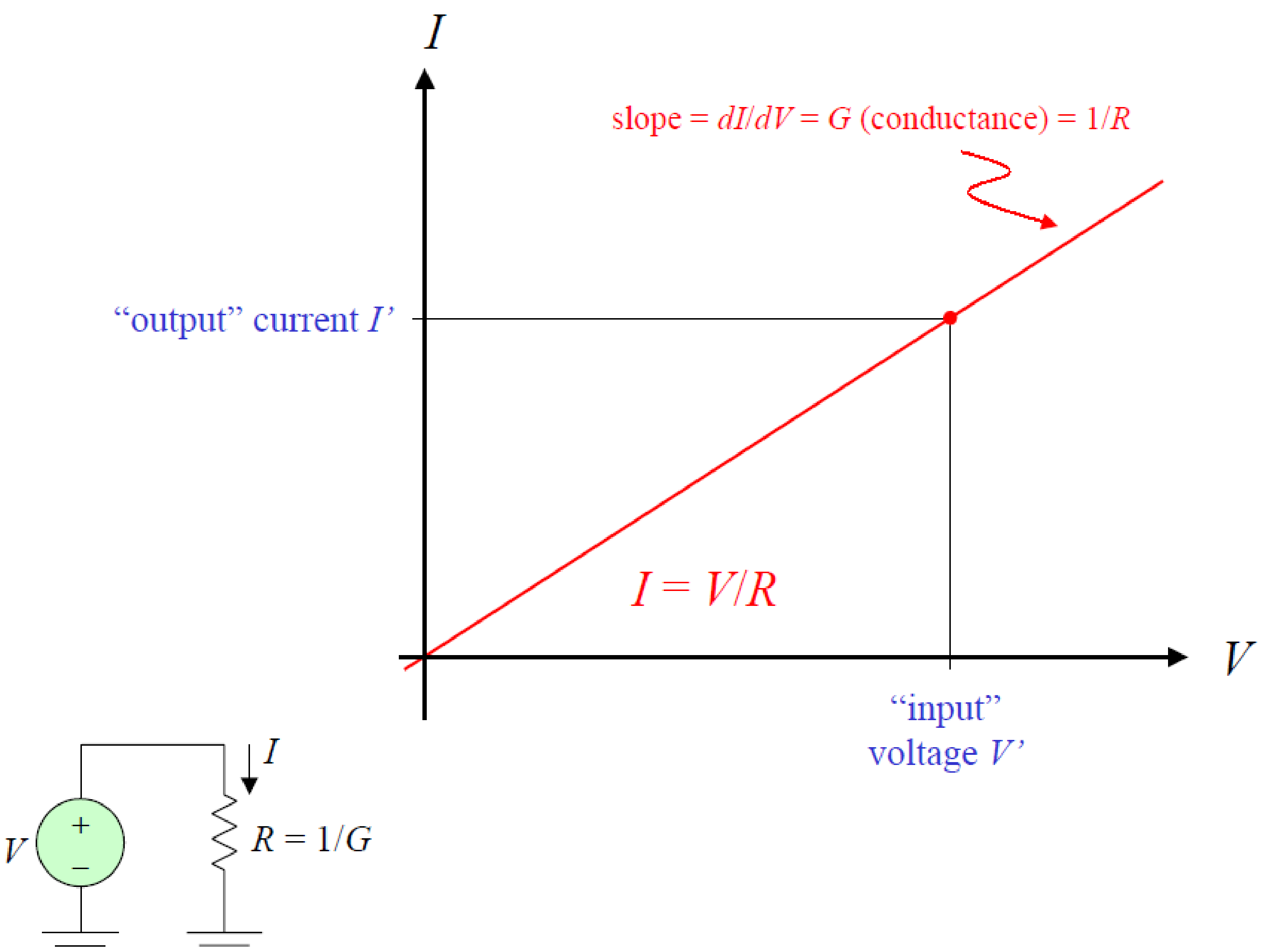
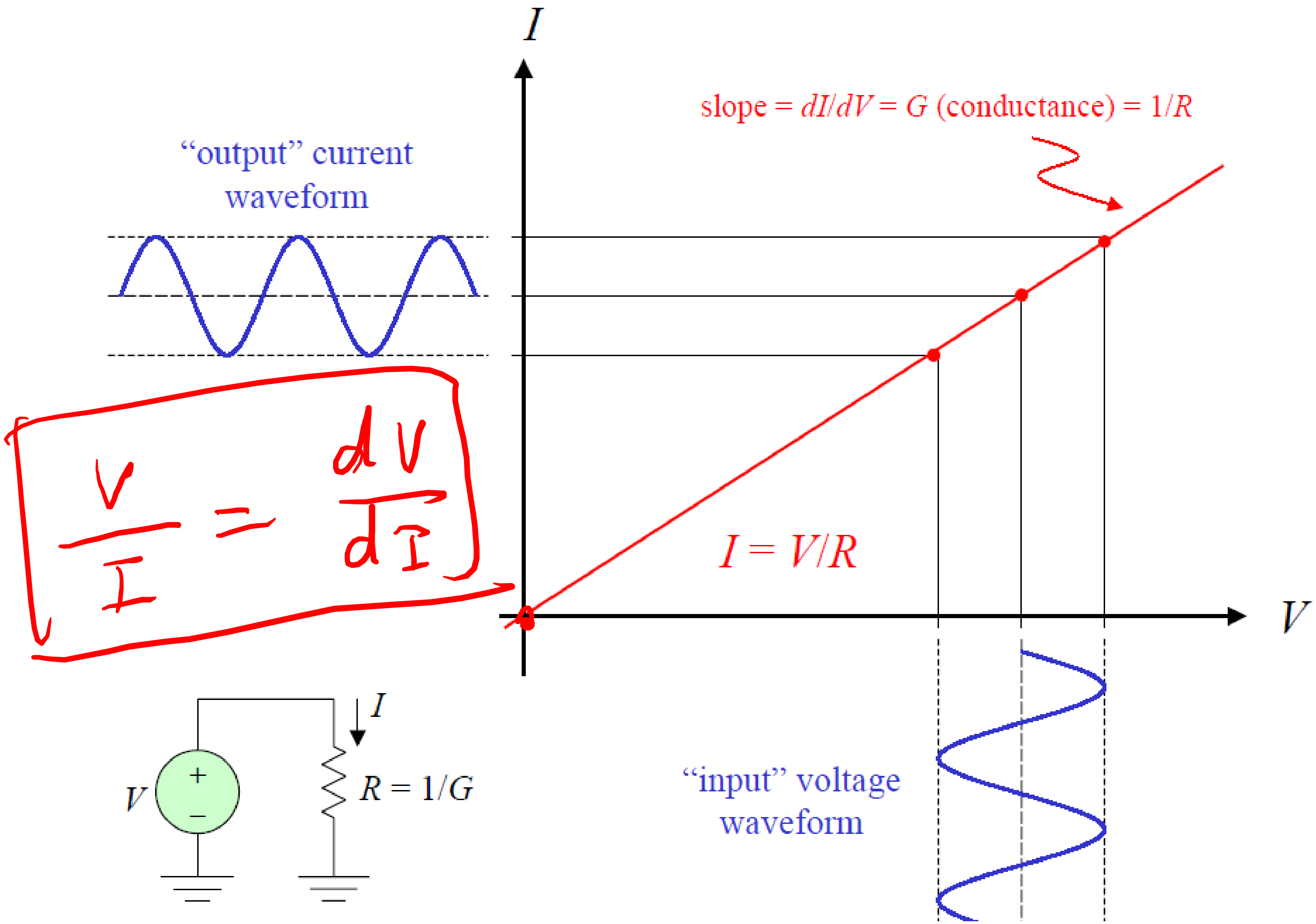
11.2 conductance and transconductance

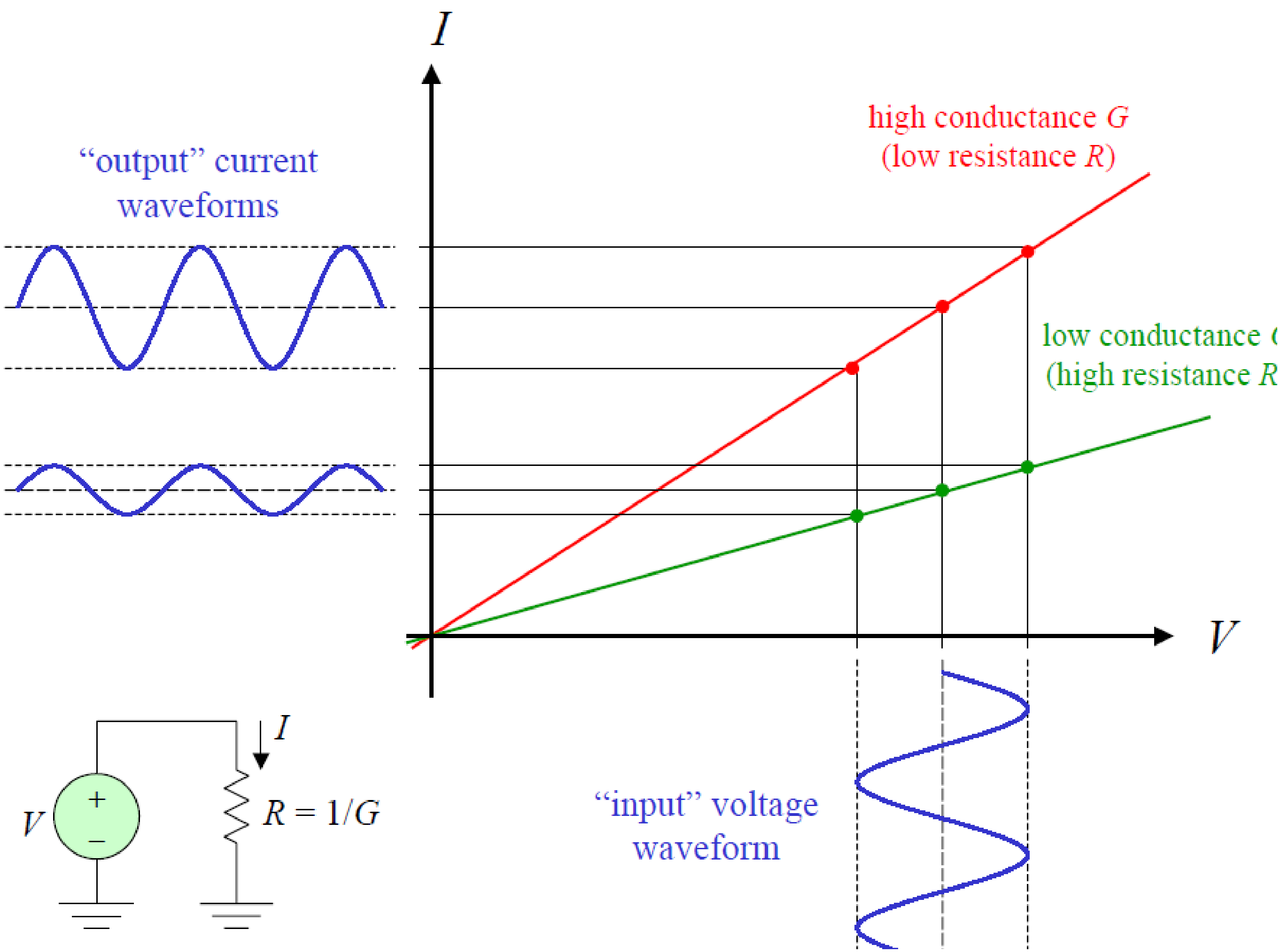


11.2 conductance and transconductance

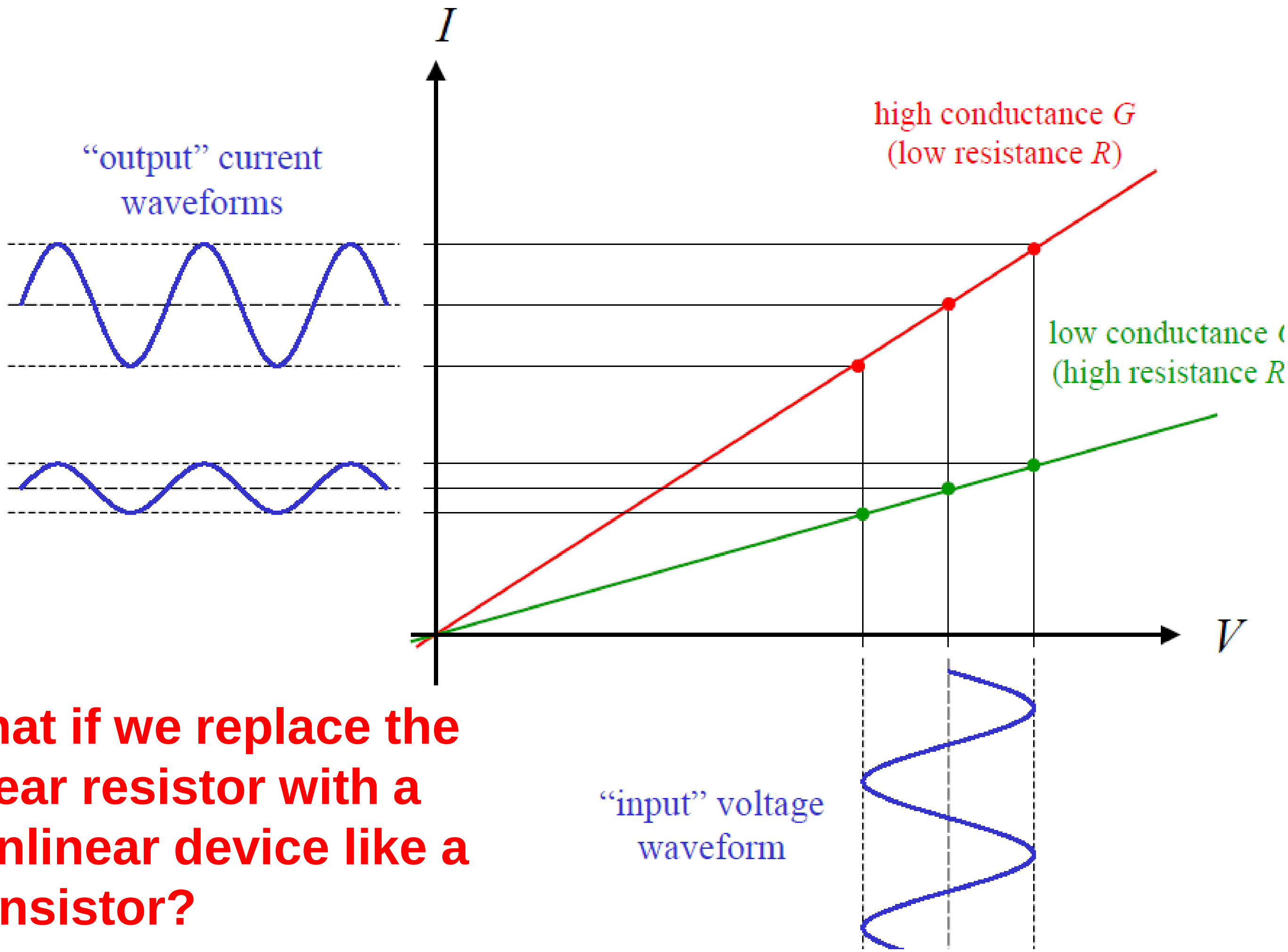


$$\boxed{\frac{V}{I} = \frac{dV}{dI}}$$

11.2 conductance and transconductance

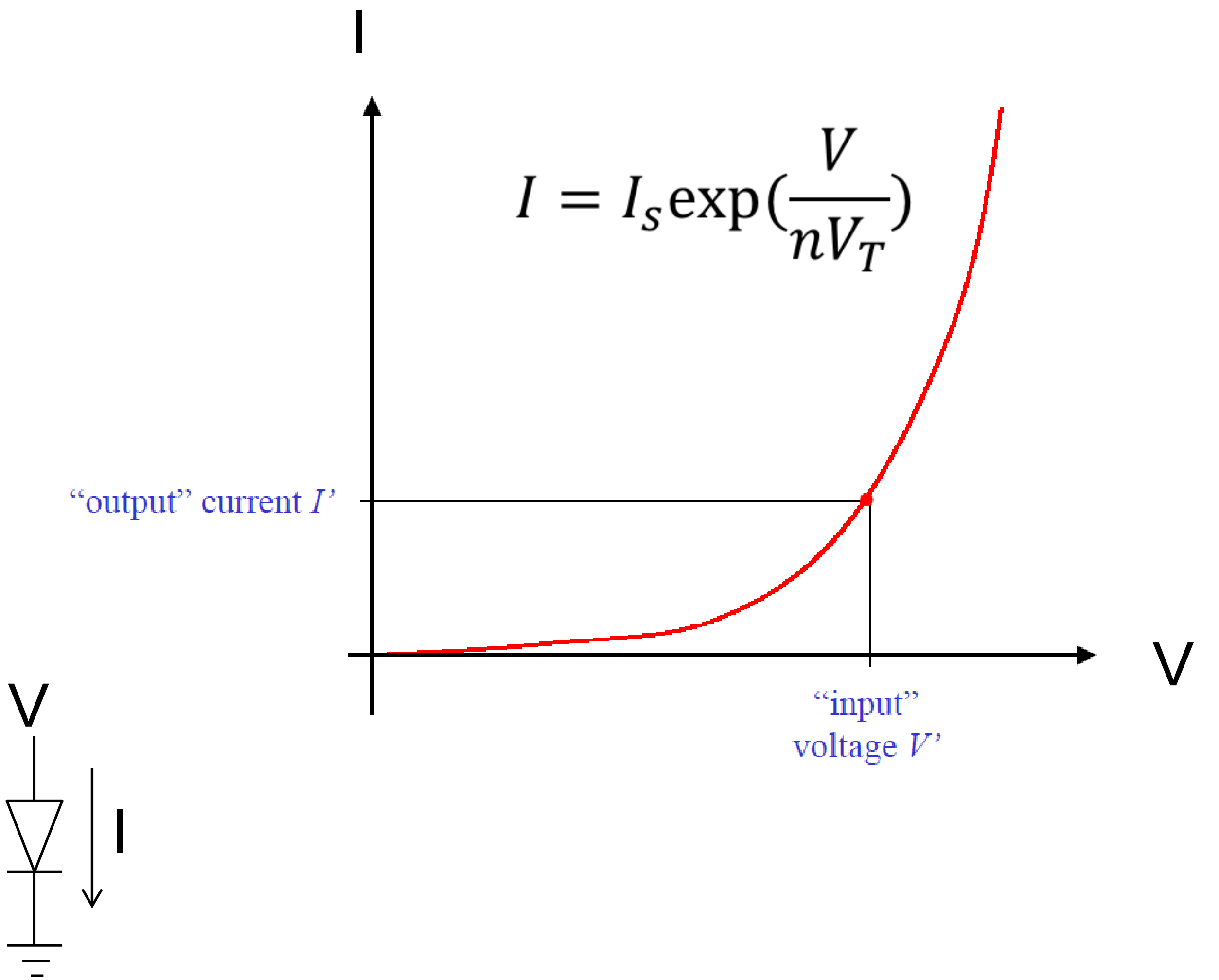


11.2 conductance and transconductance



What if we replace the linear resistor with a nonlinear device like a transistor?

11.2 conductance and transconductance



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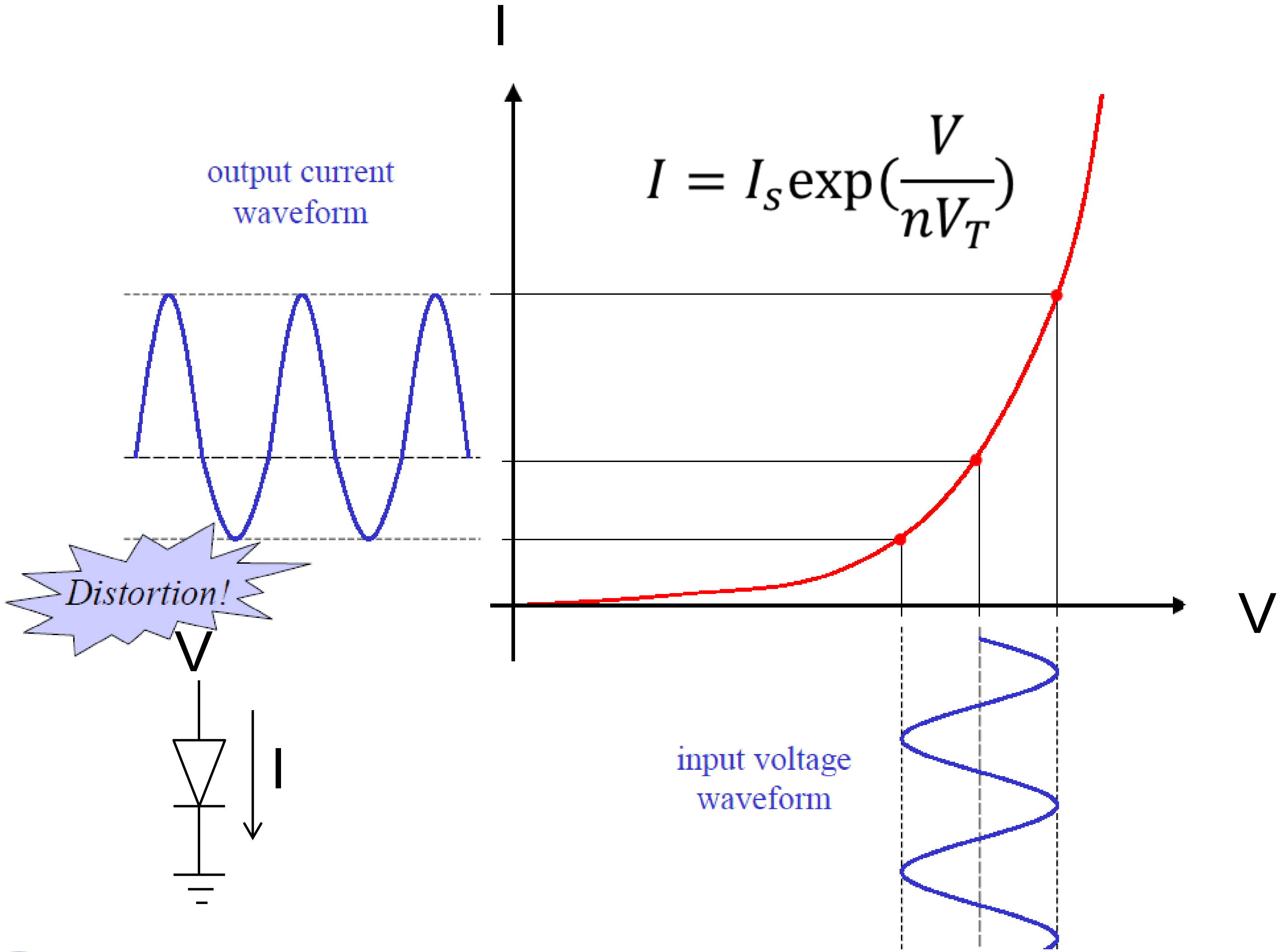

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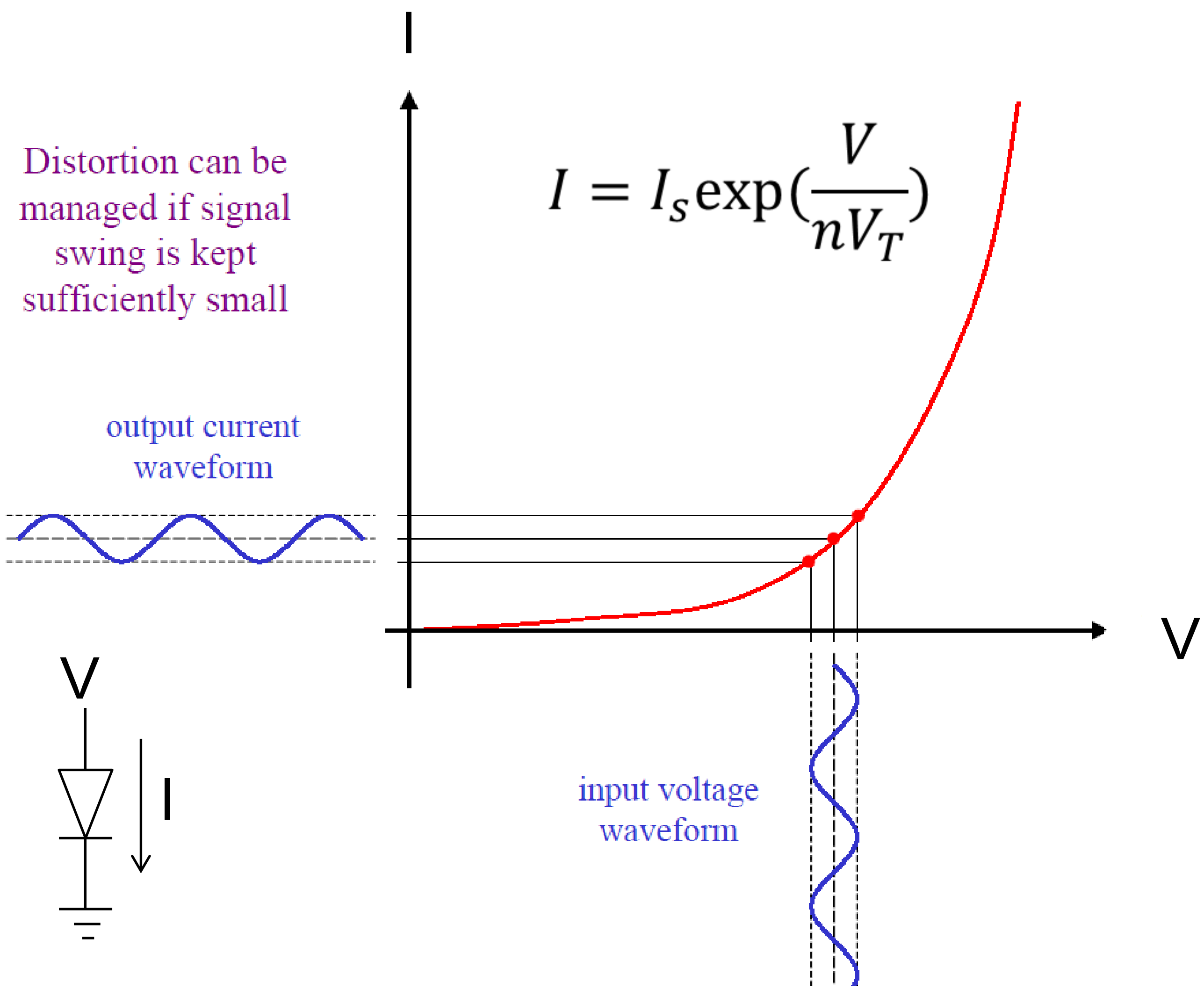

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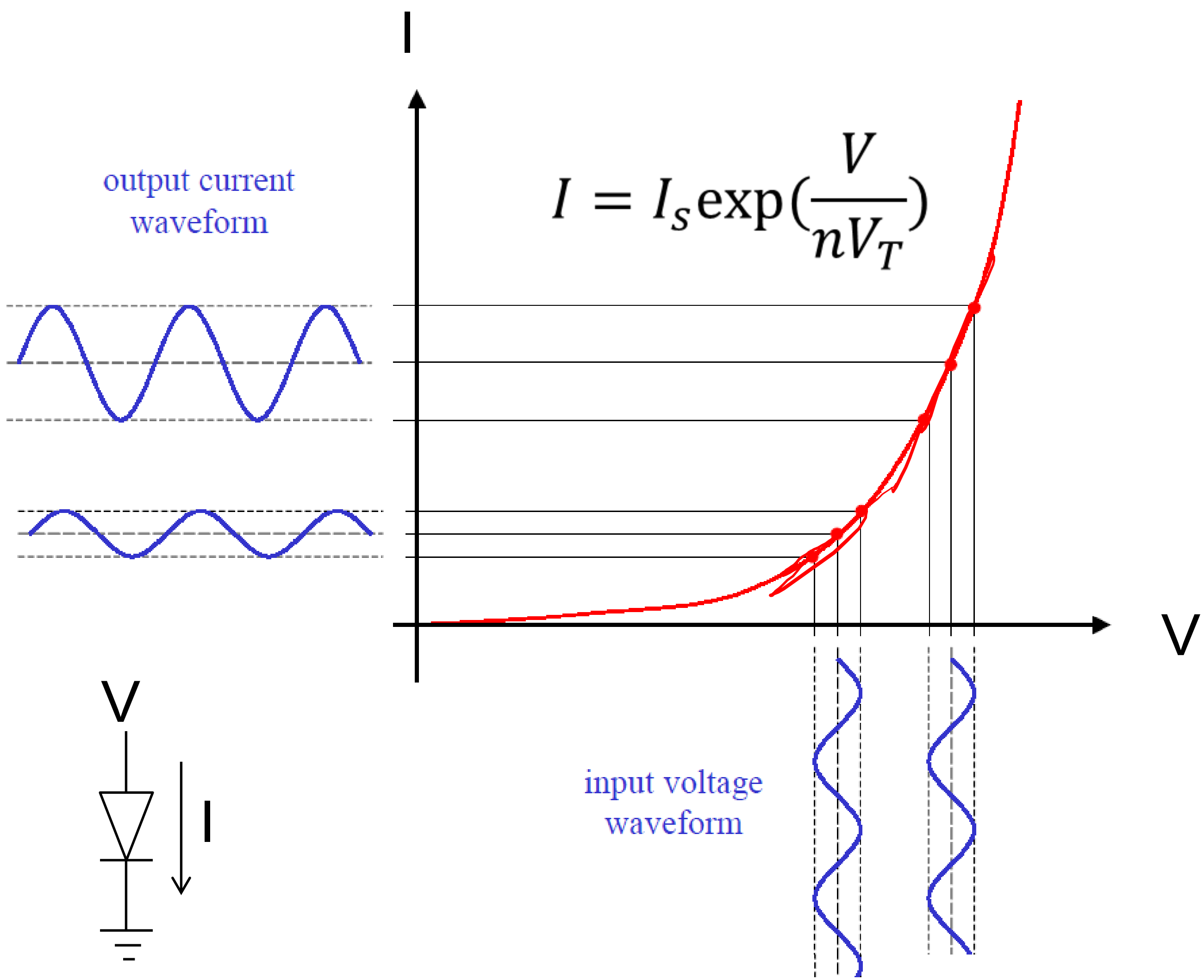

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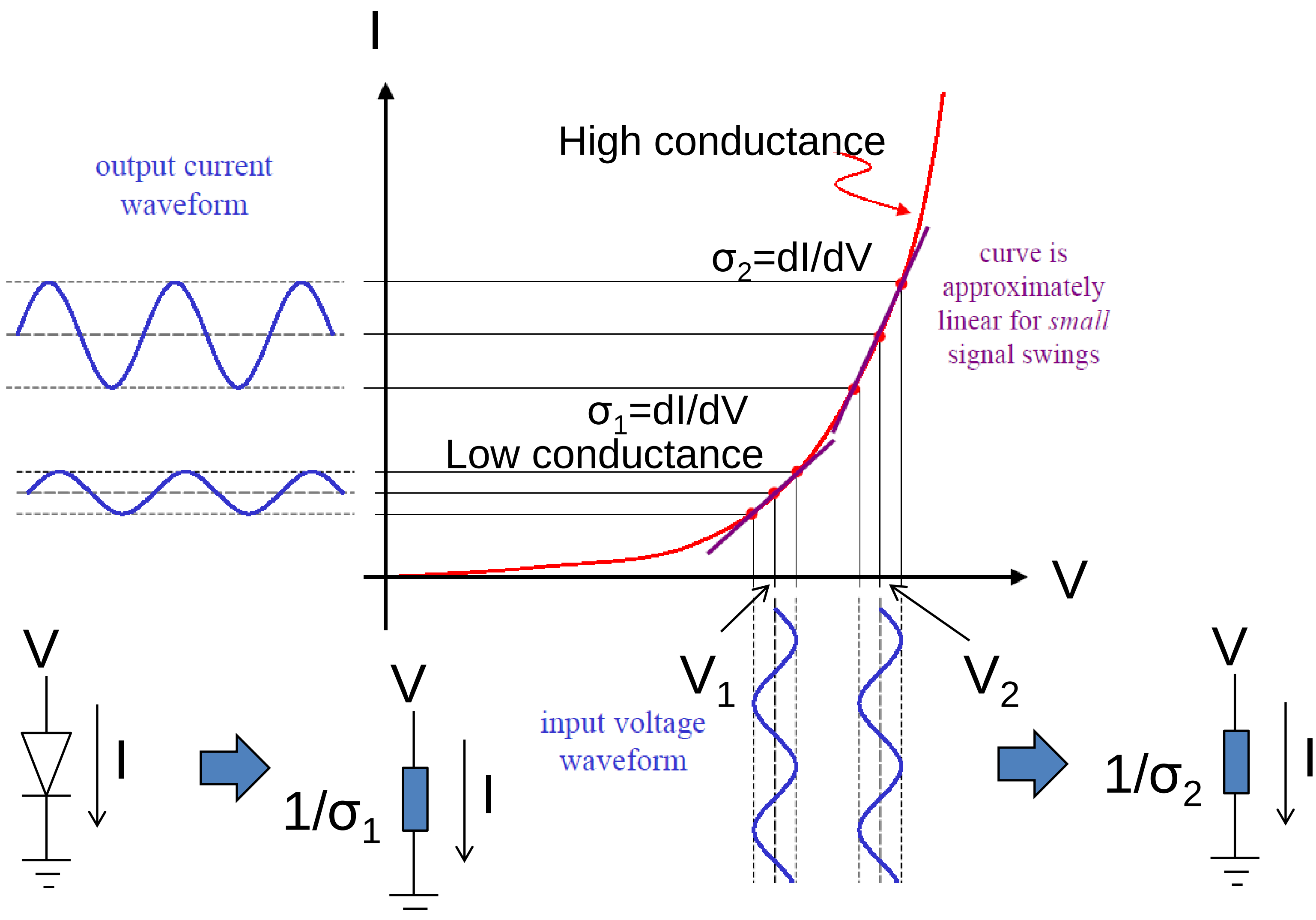
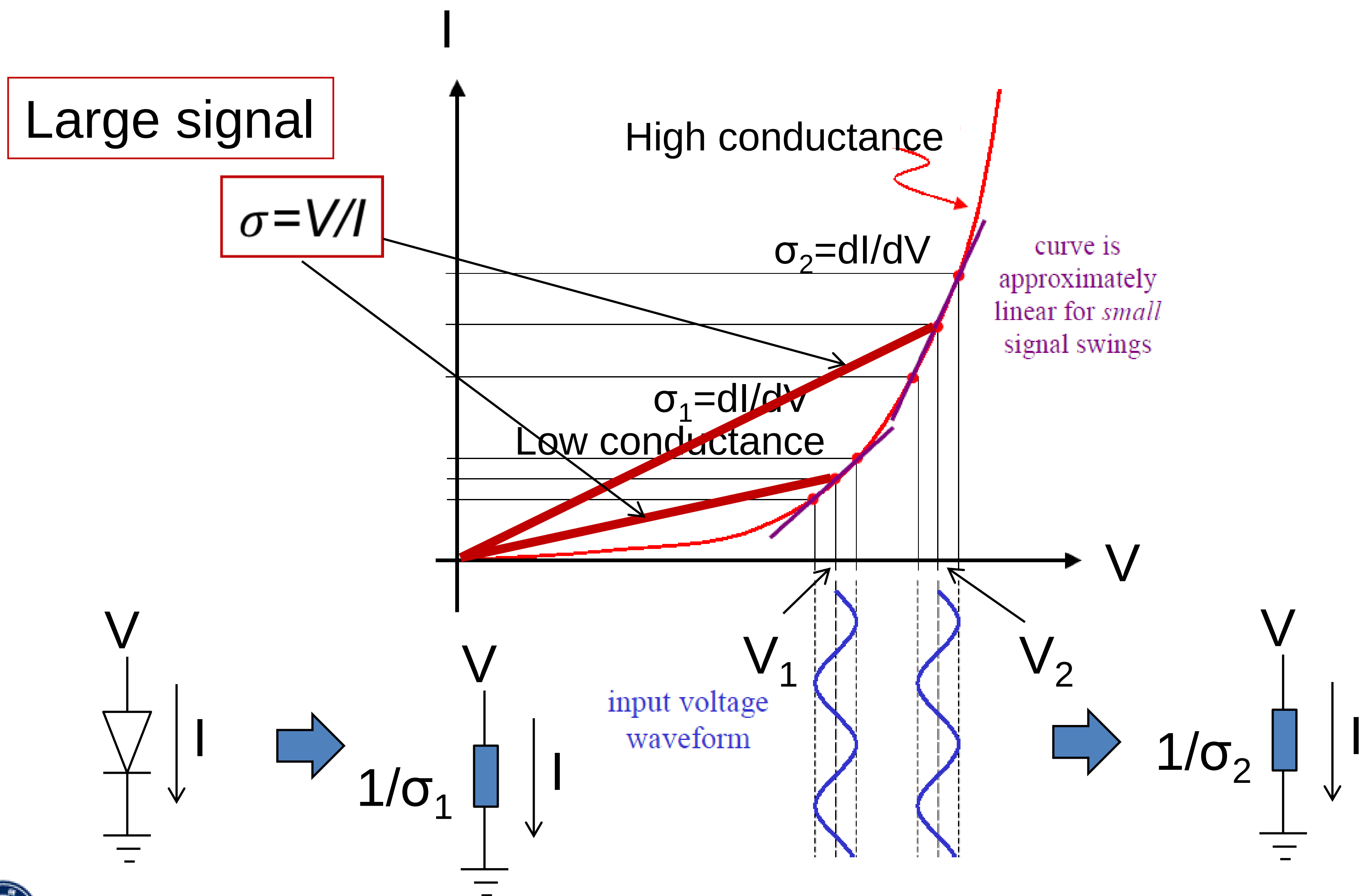


11.2 conductance and transconductance



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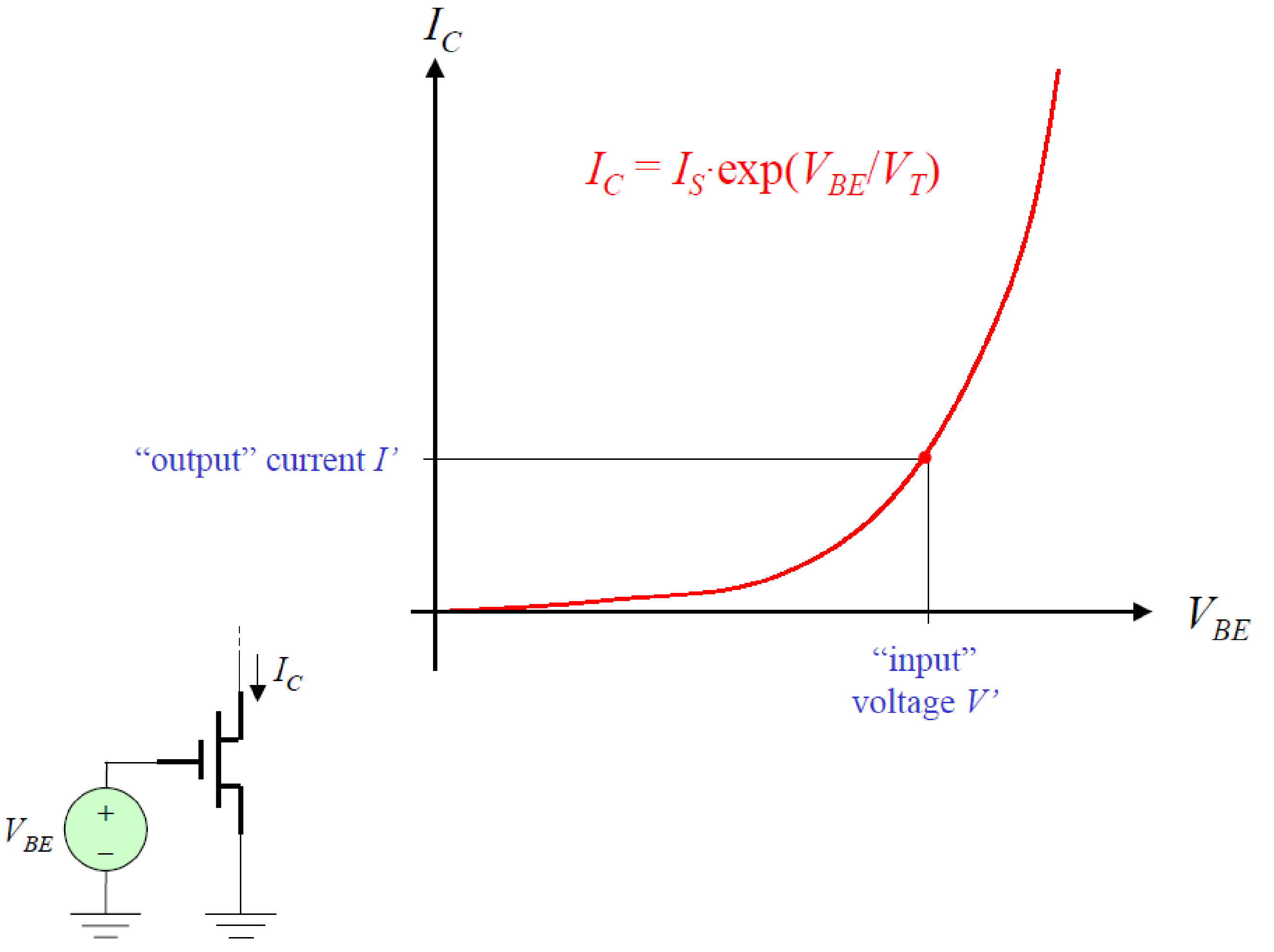
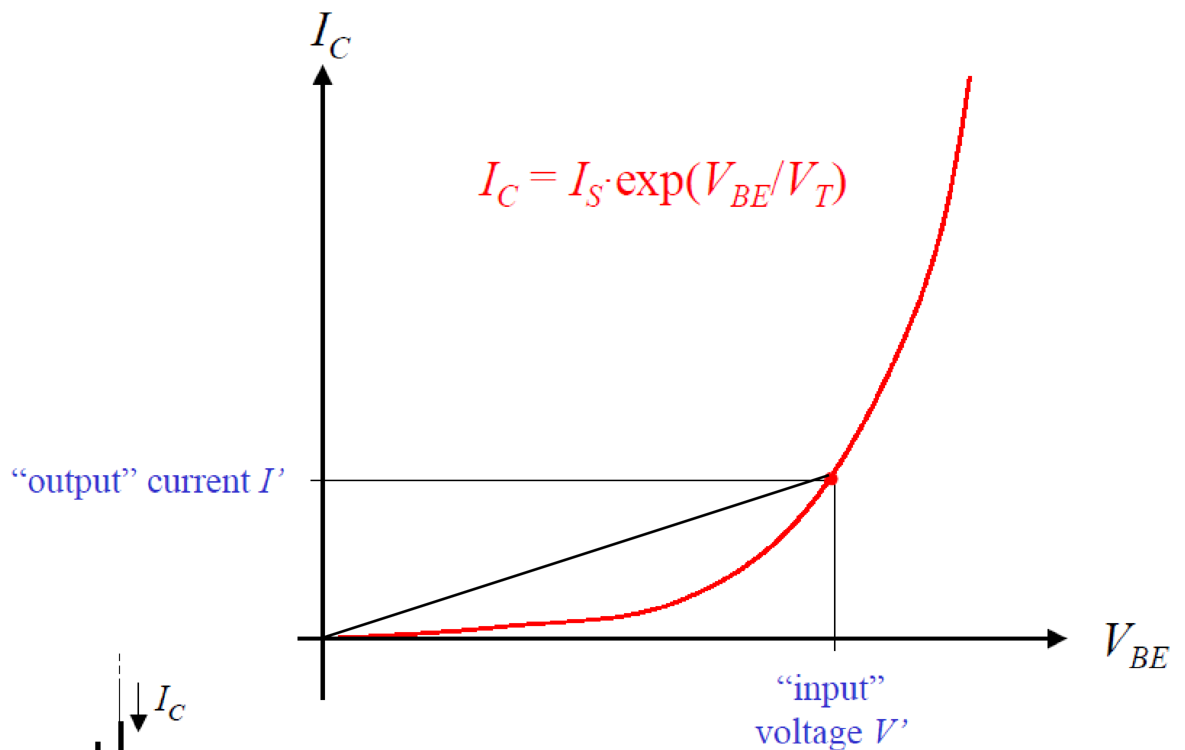
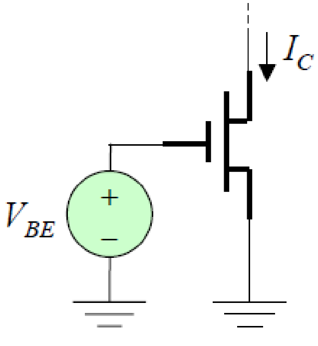
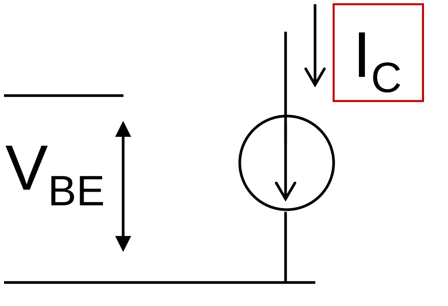


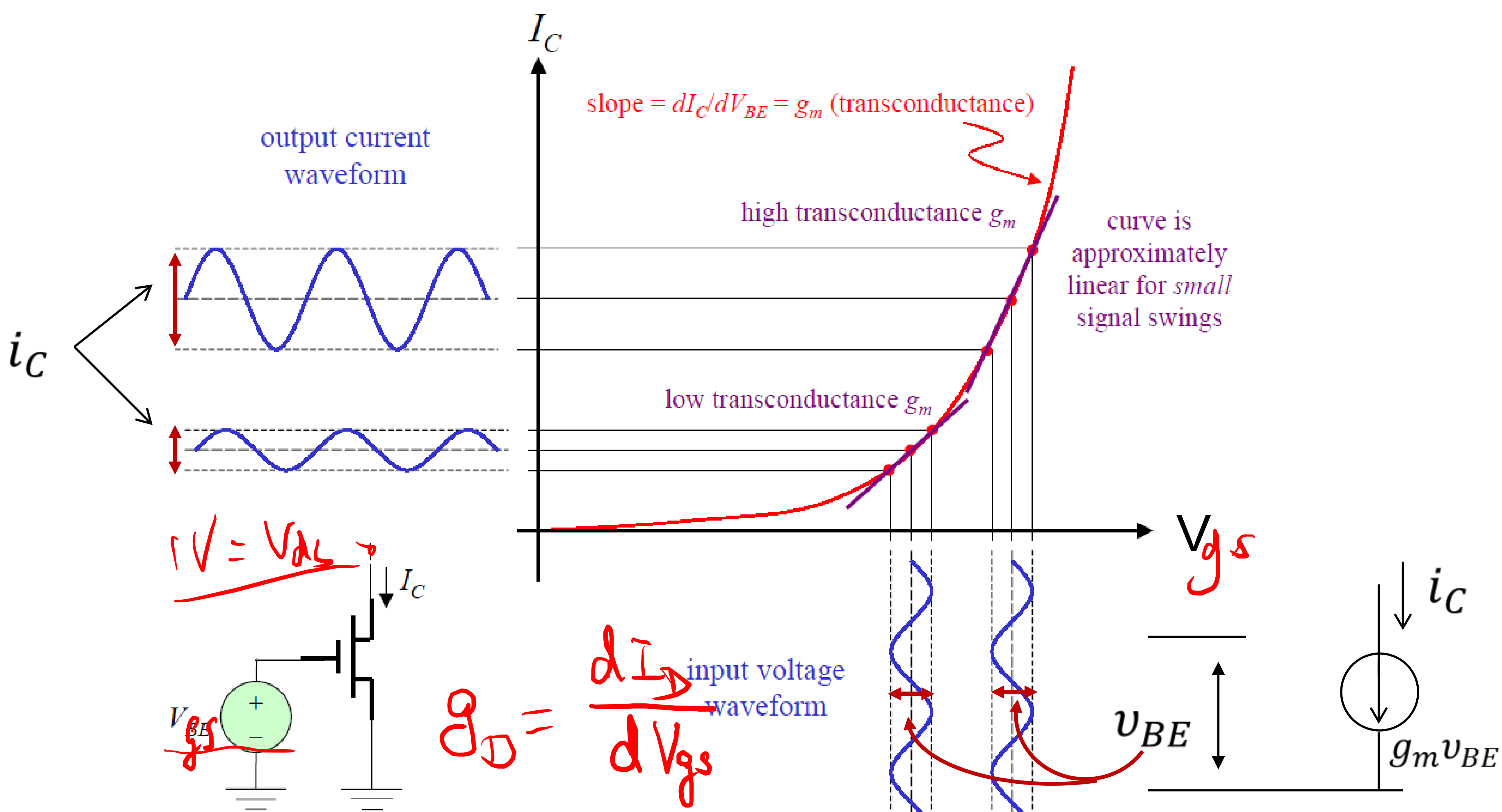
11.2 conductance and transconductance







11.2 conductance and transconductance



11.2 conductance and transconductance

$$I_d = \begin{cases} 0 & V_{gs} - V_T < 0 \\ \frac{1}{2} k_n (V_{gs} - V_T)^2 (1 + \lambda V_{ds}) & 0 \le V_{gs} - V_T < V_{ds} \\ k_n [(V_{gs} - V_T) V_{ds} - \frac{1}{2} V_{ds}^2] & V_{gs} - V_T \ge V_{ds} \end{cases}$$

output conductance $g_D = \frac{dI_D}{dV_{ds}} = \begin{cases} \frac{1}{2} k_n (V_{gs} - V_T)^2 \cdot \lambda V_{ds} \\ \\ k_n [V_{gs} - V_T - V_{ds}] \end{cases}$

transconductance $g_m = \frac{dI_D}{dV_{gs}} = \begin{cases} k_n (V_{gs} - V_T)(1 + \lambda V_{ds}) = \frac{2 I_d}{1 + \lambda V_{ds}} \\ \\ k_n \cdot V_{ds} \end{cases}$

11.2 conductance and transconductance

Transconductance

$$I_d = \begin{cases} 0 & V_{gs} - V_T < 0 \\ \frac{1}{2} k_n \left(V_{gs} - V_T\right)^2 (1 + \lambda V_{ds}) & 0 \le V_{gs} - V_T < V_{ds} \\ k_n [\left(V_{gs} - V_T\right) V_{ds} - \frac{1}{2} V_{ds}^2] & V_{gs} - V_T \ge V_{ds} \end{cases}$$

11.2 conductance and transconductance

Output Impedance

$$I_d = \begin{cases} 0 & V_{gs} - V_T < 0 \\ \frac{1}{2} k_n \left(V_{gs} - V_T\right)^2 (1 + \lambda V_{ds}) & 0 \le V_{gs} - V_T < V_{ds} \\ k_n\left[\left(V_{gs} - V_T\right) V_{ds} - \frac{1}{2} V_{ds}^2\right] & V_{gs} - V_T \ge V_{ds} \end{cases}$$

How the knowledge used by engineers and scientists

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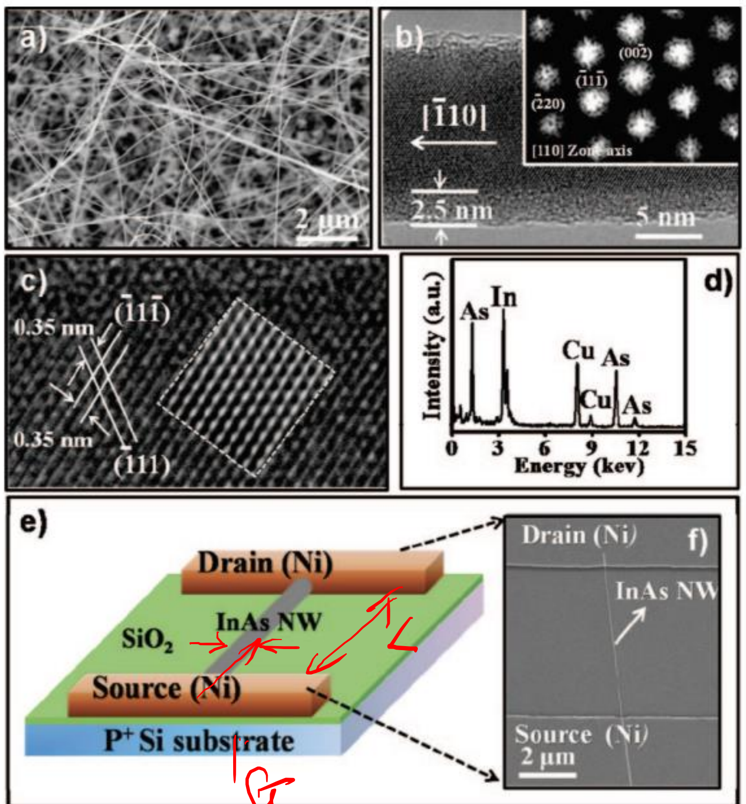
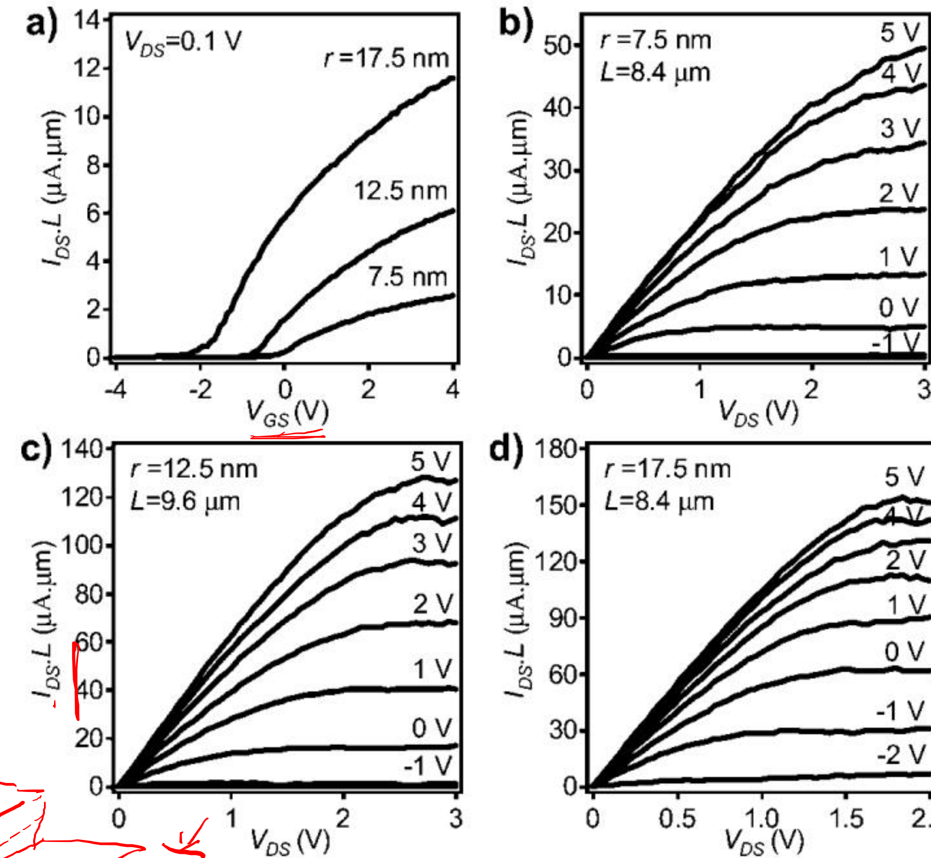
Diameter-Dependent Electron Mobility of InAs Nanowires

Alexandra C. Ford,[†,‡,§,||] Johnny C. Ho,[†,‡,§,||] Yu-Lun Chueh,[†,‡,§,||] Yu-Chih Tseng,[‡] Zhiyong Fan,[‡,§,||] Jing Guo,[⊥] Jeffrey Bokor,[‡,§] and Ali Javey*[,‡,§,||]

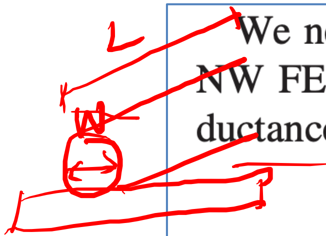
Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley, California 94720, Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, Berkeley Sensor and Actuator Center, University of California at Berkeley, Berkeley, California 94720, and Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611

How the knowledge used by engineers and scientists





How the knowledge used by engineers and scientists



We next assess the field-effect electron mobility of InAs NW FETs by using the low-bias ($V_{DS} = 0.1$ V) transconductance

$$g_m = \frac{dI_{DS}}{dV_{GS}}\Big|_{V_{DS}}$$

and the analytical expression

$$\mu_n = g_m \frac{L^2}{C_{ox}} \frac{1}{V_{DS}}$$

V_{gs} large

linear

total

$$g_m = k_n V_{ds} = \mu_n C_{ox} \frac{W}{L} V_{ds}$$

$$= \mu_n \cdot \frac{C_{ox}^t}{W \cdot L} \cdot \frac{W}{L} V_{ds}$$

$$= \mu_n C_{ox}^t \frac{1}{L^2} \cdot V_{ds}$$

$$\mu_n = \frac{g_m}{C_{ox}^t \cdot \frac{1}{L^2} \cdot V_{ds}}$$

$$= g_m \cdot \frac{L^2}{C_{ox}^t} \frac{1}{V_{ds}}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$C_{ox}^t = \frac{\varepsilon_{ox}}{t_{ox}} \cdot W \cdot L = C_{ox} \cdot WL$$

$$C_{ox} = \frac{C_{ox}^t}{W \cdot L}$$

MOSFETs. The field-effect and effective mobilities are, however, deduced from the $I-V$ characteristics by using different analytical models. Specifically, the effective mobility is deduced from the drain conductance

$$g_D = \frac{dI_{DS}}{dV_{DS}}\Big|_{V_{GS}}$$

with

$$g_D = \mu_n \cdot C_{ox} \cdot \frac{W}{L} (V_{gs} - V_T)$$

$$\mu_{n,\mathrm{eff}} = g_D \frac{L^2}{C_{ox}} \frac{1}{(V_{GS} - V_t)}$$

Check your understanding

Problem example 2

The transconductance of an n-channel MOSFET is found to be $g_m = \partial I_D/\partial V_{GS} = 1.25$ mA/V when measured at $V_{DS} = 50$ mV. The threshold voltage is $V_T = 0.3$ V. (a) Determine the conductance parameter K_n. (b) What is the current at $V_{GS} = 0.8$ V and $V_{DS} = 50$ mV? (c) Determine the current at $V_{GS} = 0.8$ V and $V_{DS} = 1.5$ V.

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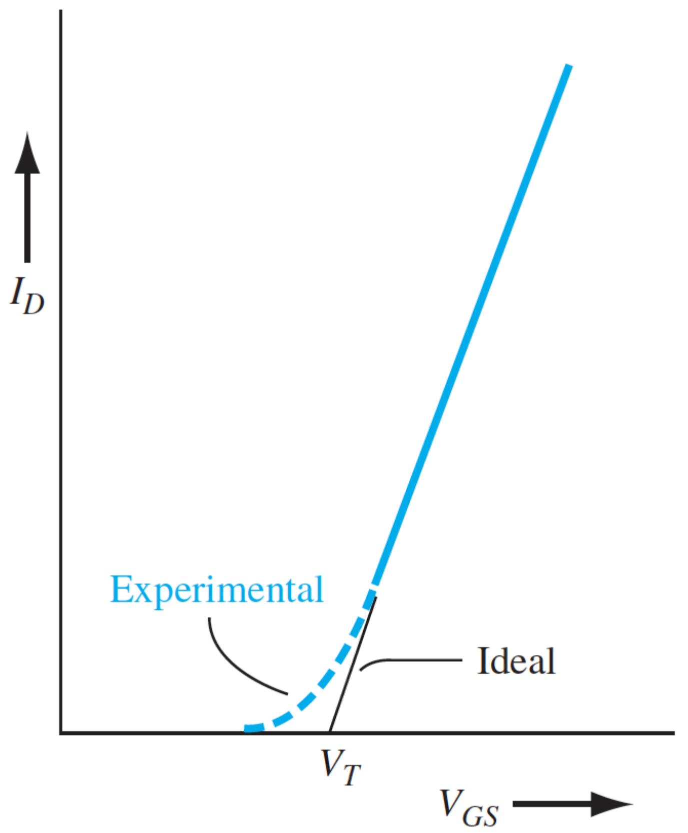
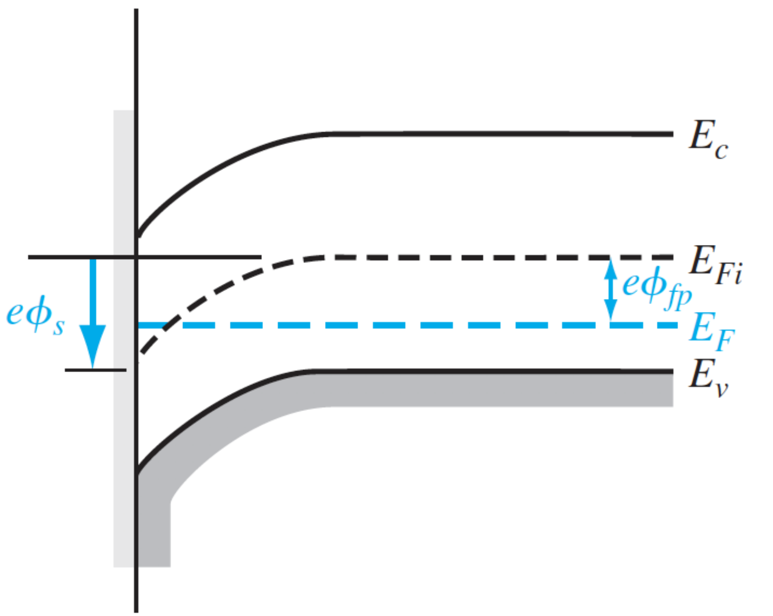
11.3 Subthreshold conduction

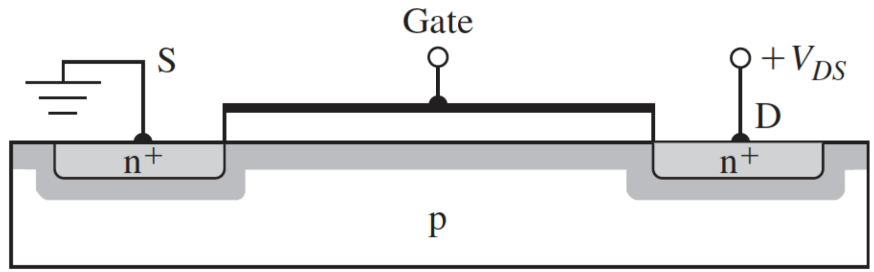
$V_{GS} < V_T$



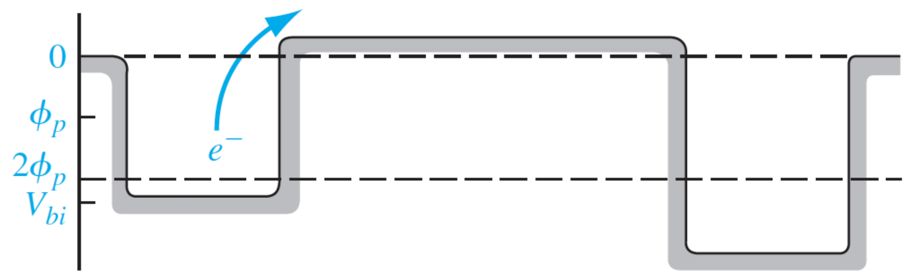


$$\phi_{fp} < \phi_s < 2\phi_{fp}.$$

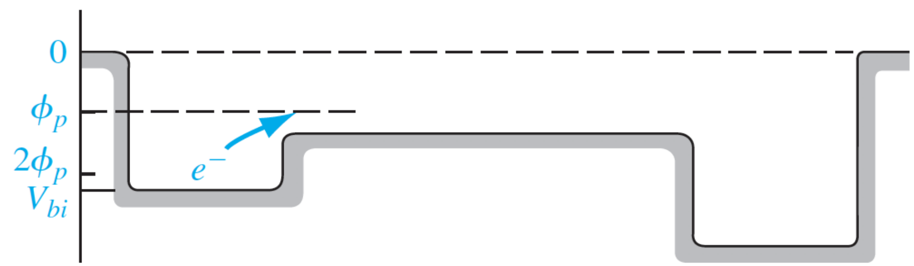
11.3 Subthreshold conduction



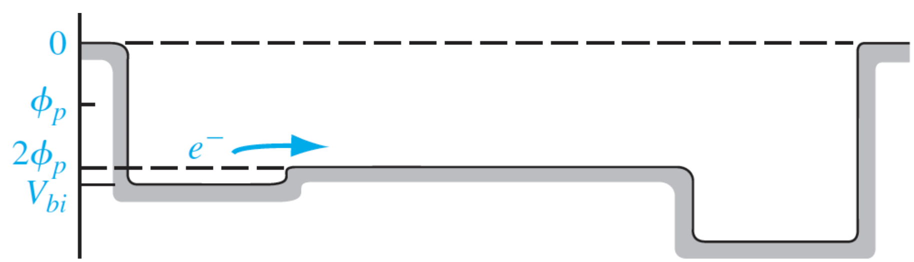
Accumulation



Weak inversion



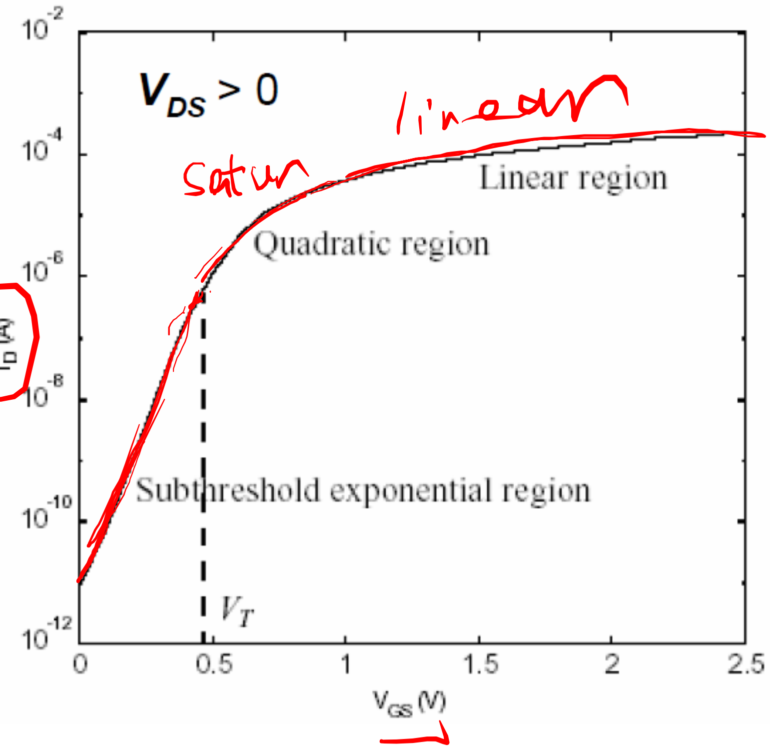
Inversion



11.3 Subthreshold conduction

Subthreshold Conduction (Leakage Current)

- The transition from the ON state to the OFF state is gradual. This can be seen more clearly when I_D is plotted on a logarithmic scale:



- In the subthreshold ($V_{GS} < V_T$) region,

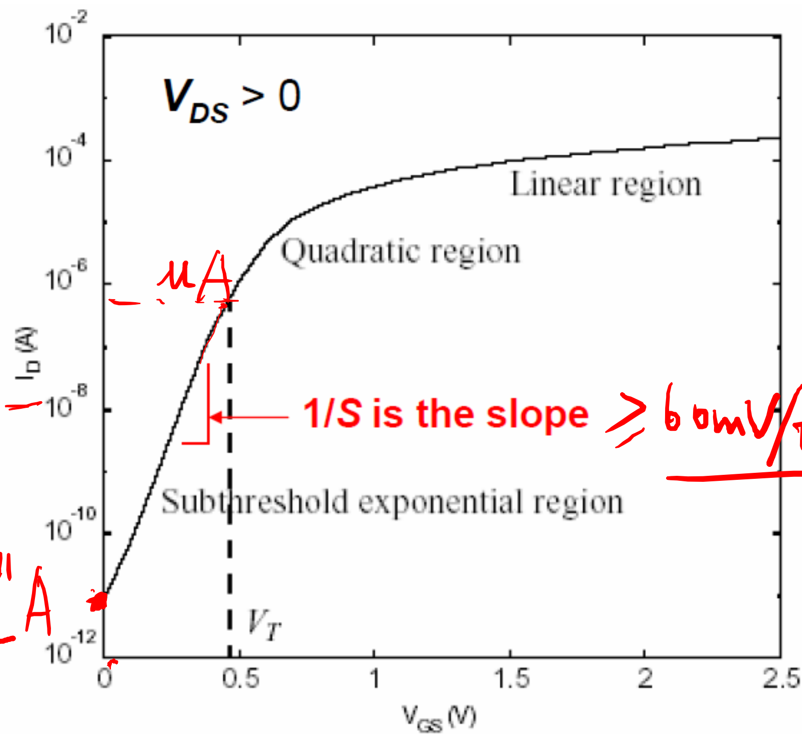
$$I_D \propto \exp\left(\frac{qV_{GS}}{nkT}\right)$$

$C_{ox} > C_s$

This is essentially the channel-source pn junction current.
(Some electrons diffuse from the source into the channel, if this pn junction is forward biased.)

Slope Factor (or Subthreshold Swing) *S*

- ***S*** is defined to be the inverse slope of the log (I_D) *vs.* V_{GS} characteristic in the subthreshold region:



60mV/Dec

$$\boxed{S \equiv n\left(\frac{kT}{q}\right)\ln(10)}$$

n > 1

Units: Volts per decade

> 60mV/Dec

Note that ***S*** ≥ 60 mV/dec at room temperature:

$$\left(\frac{kT}{q}\right)\ln(10) = 60\,\text{mV}$$

300k

uA

V

10^{-11} A

1 billion

10^9

$10^{-11} \times 10^9 = 10^{-2}$ A × 2.5V = 25mW

11.3 Subthreshold conduction

V_T Design Trade-Off

(Important consideration for digital-circuit applications)

- Low V_T is desirable for high ON current

$$I_{DSAT} \propto (V_{DD} - V_T)^{\eta} \qquad 1 < \eta < 2$$

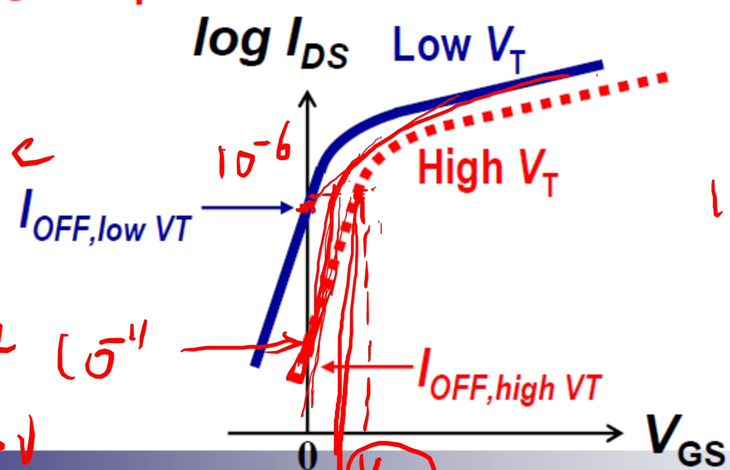
where V_{DD} is the power-supply voltage

…but high V_T is needed for low OFF current

60mV/dec

40mV/de 10^{-11}

100mV/dev



$10^{-6} \times 10^{9} = 10^{3}$ A

10^{3} A × 2.5 V

= 2.5 kW

$V_{DD} < 2 \times V_T < 1.5$ V

10 V

Check your understanding

Problem example 3

Assume that the subthreshold current of a MOSFET is given by

$$I_D = 10^{-15} \exp\left(\frac{V_{GS}}{(2.1)V_t}\right)$$

over the range $0 \le V_{GS} \le 1$ volt and where the factor n 2.1 takes into account the effect of interface states. Assume that 10^6 identical transistors on a chip are all biased at the same V_{GS} and at $V_{DD} = 5$ V. (*a*) Calculate the total current that must be supplied to the chip at $V_{GS} = 0.5$, 0.7, and 0.9 V. (*b*) Calculate the total power dissipated in the chip for the same V_{GS} values.

$V_{GS} = 0.5V$

$$I_D^t = 10^6 I_D = 10^6 \times 10^{-15} \exp\left(\frac{0.5}{2.1 \times 0.0259}\right) = 9.8 \times 10^{-6} A$$

$P = 50 \mu W$

$V_{GS} = 0.7V$ $\quad I_D^t = 3.88 \times 10^{-4} A$ $\quad P = 1.9 mW$

$V_{GS} = 0.9V$ $\quad I_D^t = 1.54 \times 10^{-2} A$ $\quad P = 75 mW$

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11.4 Velocity Saturation

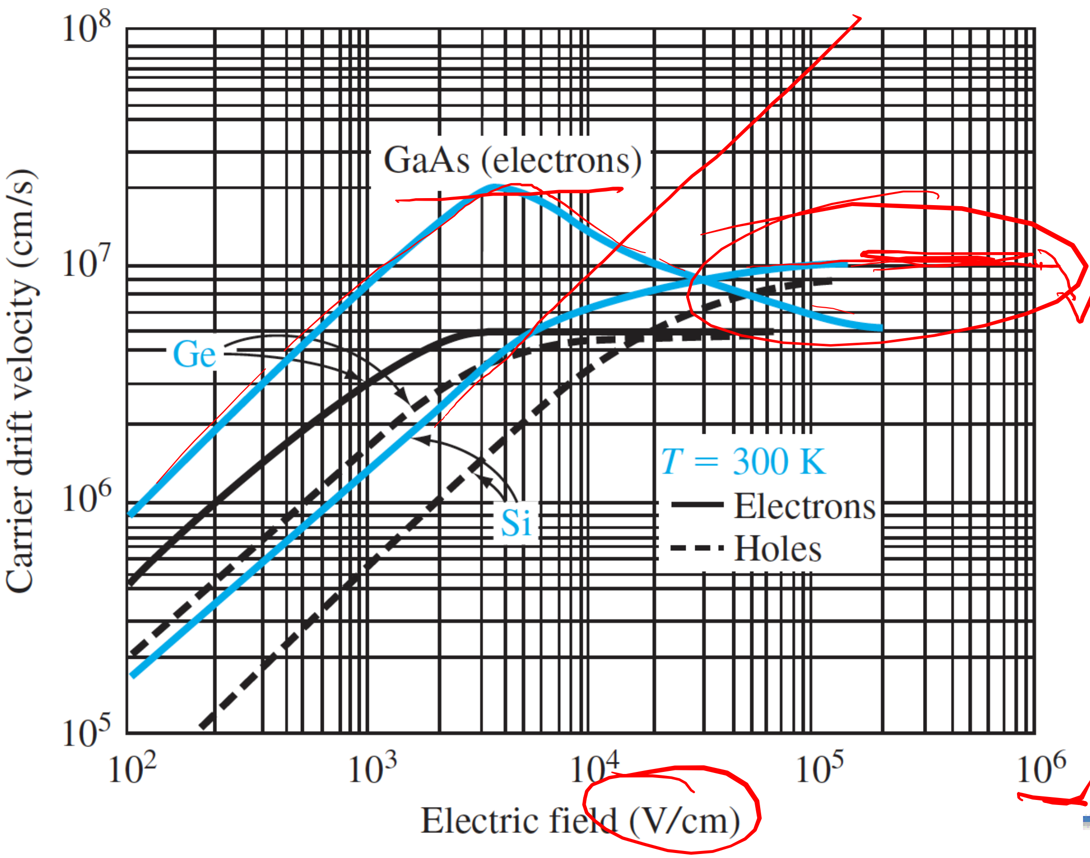
$\frac{3}{2}kT = \frac{1}{2}m_e v_{th}^2$

$$v_d \rightarrow v_{th}$$

$\delta v \sim v_{th}$

$E_e \rightarrow E_{th}$

- Electric field is heating up electrons
- Electrons transfer energy to lattice to reach thermal equilibrium



$$v_n = \frac{v_s}{\left[1 + \left(\frac{E_{on}}{E}\right)^2\right]^{1/2}}$$

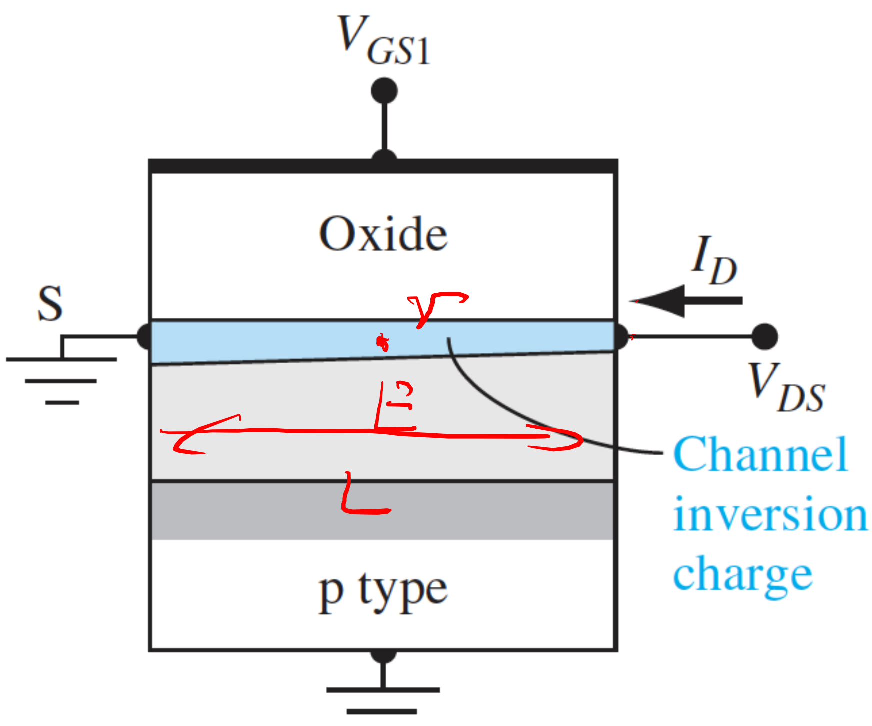
$$v_p = \frac{v_s}{\left[1 + \left(\frac{E_{op}}{E}\right)^2\right]^{1/2}}$$

Probably a typo in textbook

11.4 Velocity Saturation

$$\boxed{v_d \to v_{th}}$$

- Electric field is heating up electrons
- Electrons transfer energy to lattice to reach thermal equilibrium



$$E_{DS} = \frac{V_{DS}}{L}$$

As the transistor size scales down, the electric field intensity E increases.

$$E_{on} = \frac{V_{DSAT}}{L}$$

11.4 Velocity Saturation

$$v_d \rightarrow v_{th}$$

As the transistor size scales down, the electric field intensity E increases.

- Electric field is heating up electrons
- Electrons transfer energy to lattice to reach thermal equilibrium

$$I_{DSAT} = \mu_n C_{ox} \frac{W}{L}\left(V_{GS} - VT - \frac{1}{2}V_{DS}\right)V_{DS}$$

linear

$$= C_{ox}W\left(V_{GS} - VT - \frac{1}{2}V_{DSAT}\right)\frac{V_{DSAT}}{L}\mu_n$$

$= E_{on}$

v

$$I_{DSAT} = WC_{ox}\left[V_{GS} - V_T - \frac{V_{DSAT}}{2}\right]v_{sat}$$

where $V_{DSAT} = \dfrac{L}{\mu_n} v_{sat}$

$\mu E_{on} = v$

11.4 Velocity Saturation

Unified model

$k_n' = \mu_n C_{ox}$

μC_{ox} $k_p' = \mu_p C_{ox}$

$$I_D = 0 \quad \text{for} \quad V_{GT} \le 0$$

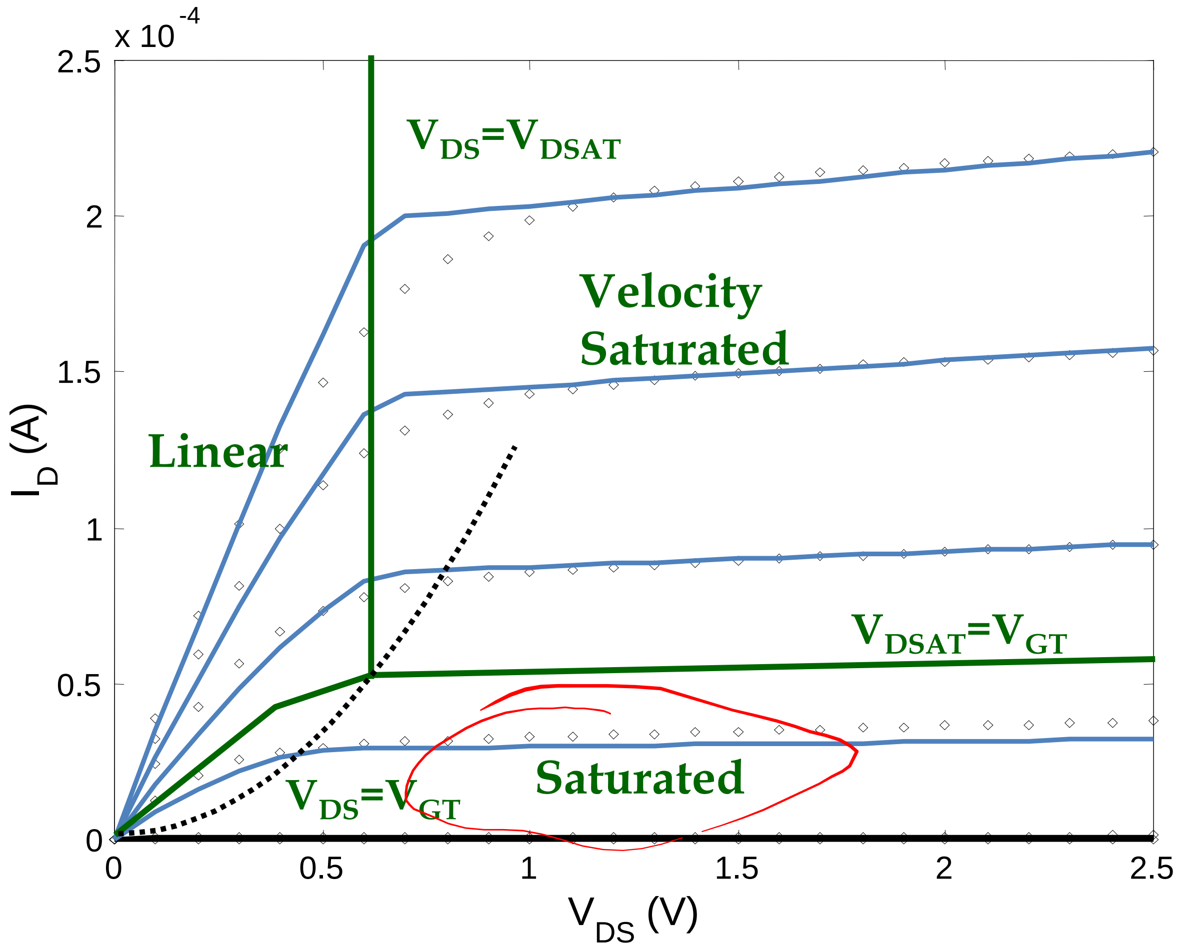
$$I_D = k' \frac{W}{L}\left(V_{GT}V_{min} - \frac{V_{min}^2}{2}\right) \qquad \text{for } V_{GT} \ge 0$$

with $V_{min} = \min(V_{GT}, V_{DS}, V_{DSAT})$,

$V_{GT} = V_{GS} - V_T$,

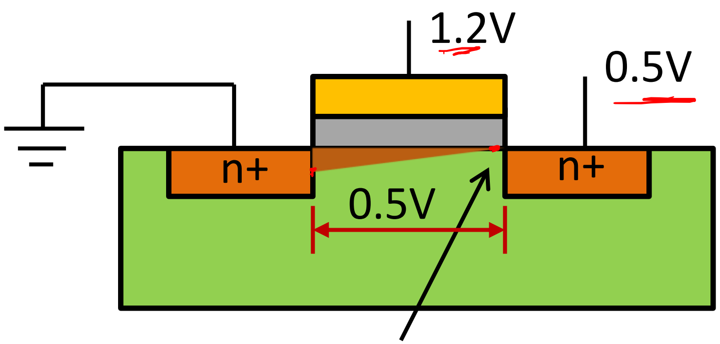
and $V_T = V_{T0} + \gamma\left(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|}\right)$

11.4 Velocity Saturation



Example

V_T=0.7V, V_{gs} = 1.2 V, V_{sat} = 1V

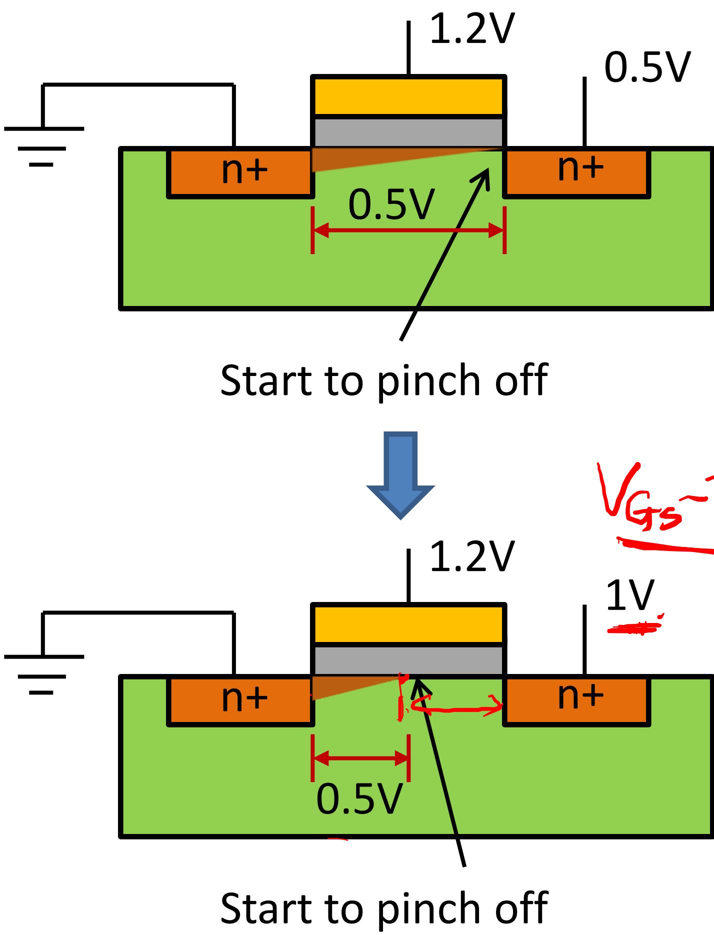


Start to pinch off

$V_{GS} - V_T = V_{DS}$

Example

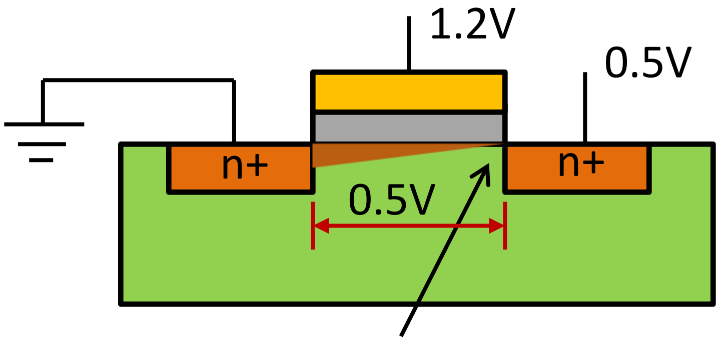
V_T=0.7 , V_{gs} = 1.2 V, V_{sat} = 1V



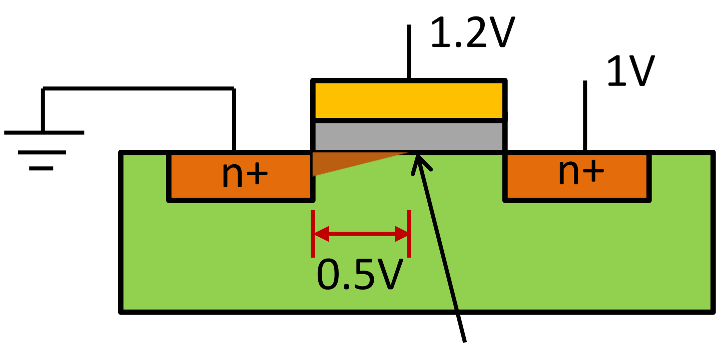
$V_{GS} - V_T = V_{GT}$

Example

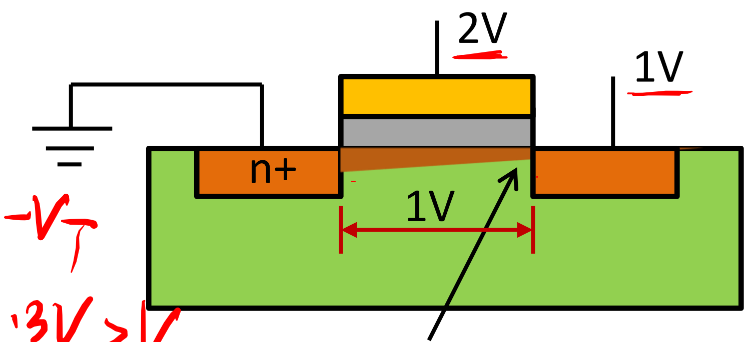
V_T=0.7 , V_{gs} = 1.2 V, V_{sat} = 1V



Start to pinch off



Start to pinch off

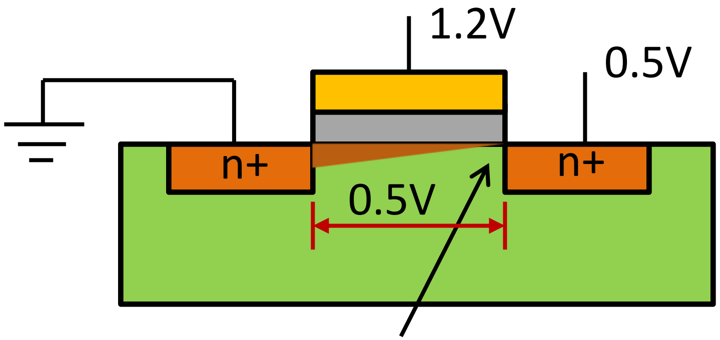


$V_{GS}-V_T = 1.3V > V_{DS}$

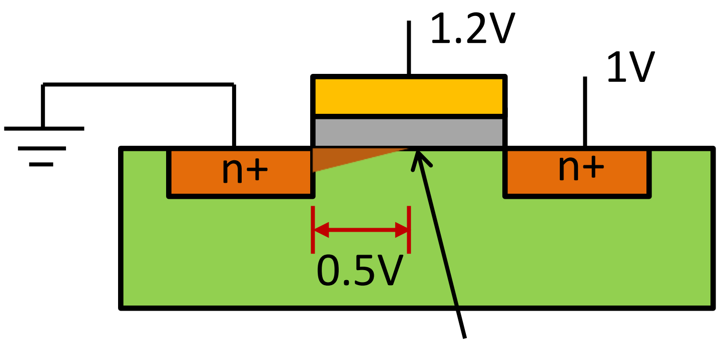
- NO pinch off
- Velocity saturation starts

Example

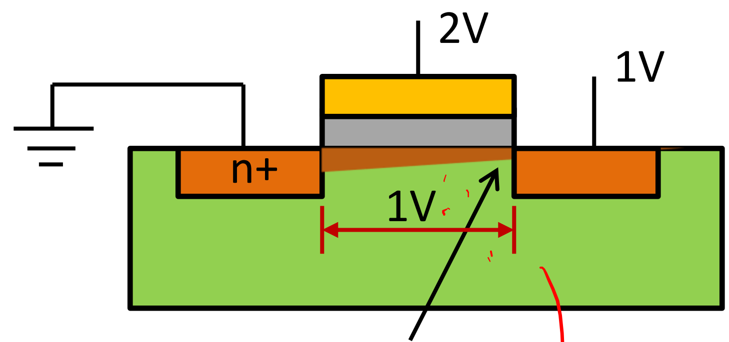
V_T=0.7 , V_{gs} = 1.2 V, V_{sat} = 1V



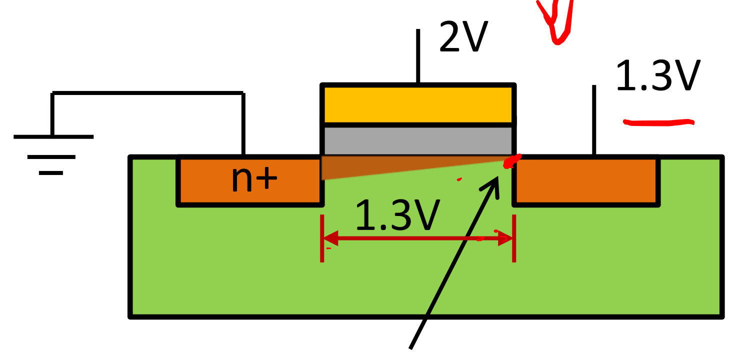
Start to pinch off



Start to pinch off



- NO pinch off
- Velocity saturation starts



- Starts to pinch off
- Velocity saturation

Outline

Nonideal Effects:

11.1 Channel length modulation

11.2 Conductance and transconductance

11.3 Subthreshold conduction

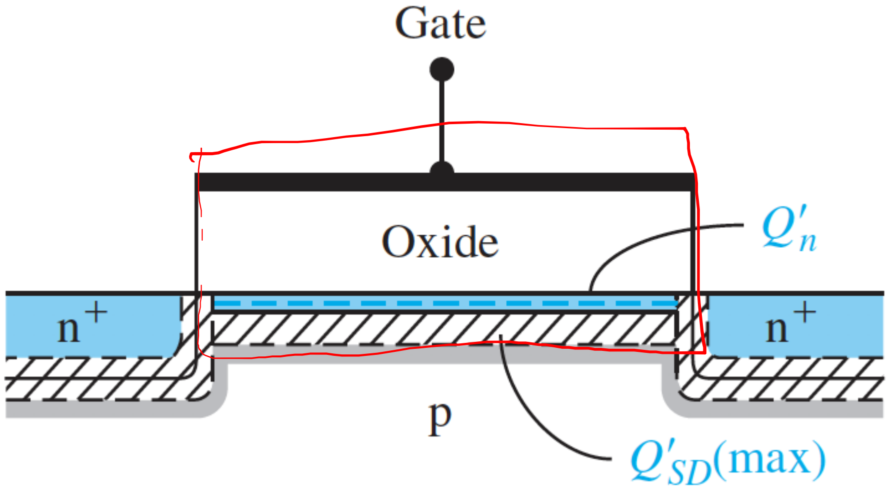
11.4 Velocity Saturation

11.5 Short Channel Effect

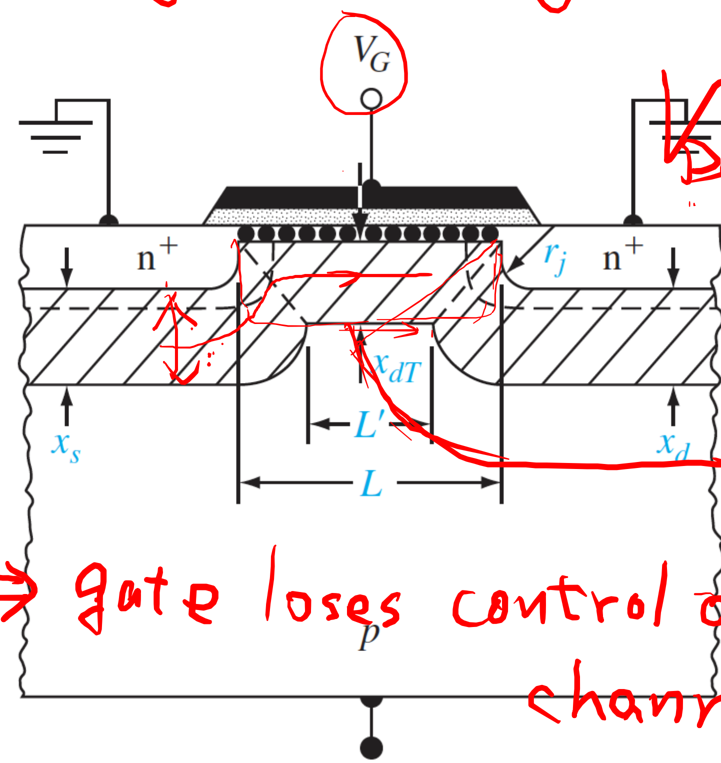
11.5 Short Channel Effect

MOSFET

charge sharing effect



A long channel device



⇒ gate loses control over channel

A short channel device

11.5 Short Channel Effect

W, L

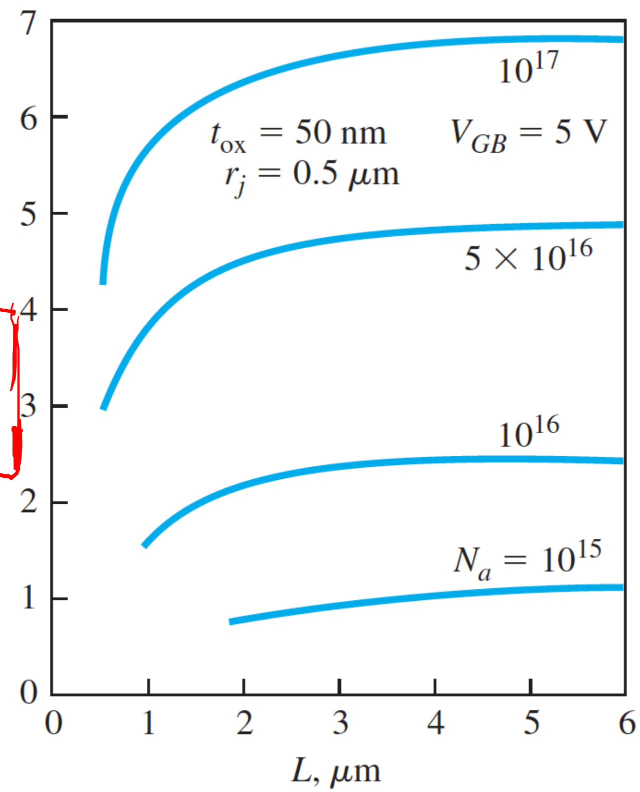


Figure 11.16 | Threshold voltage versus channel length for various substrate dopings. (*From Yau [26].*)

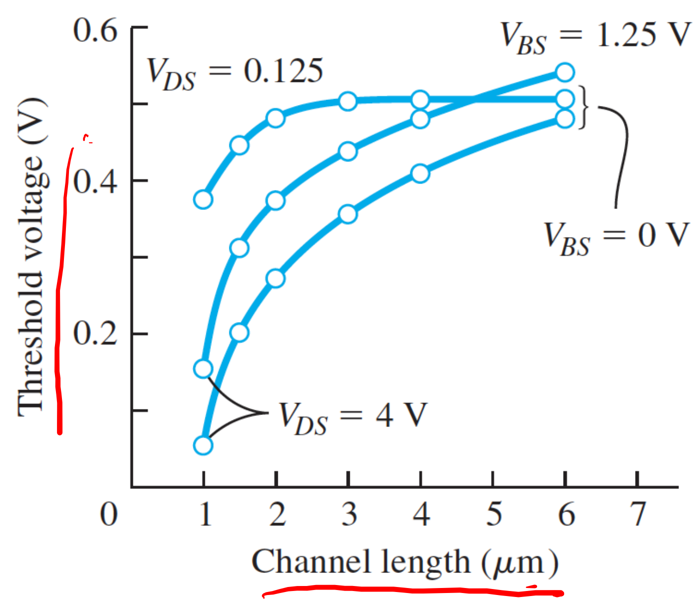
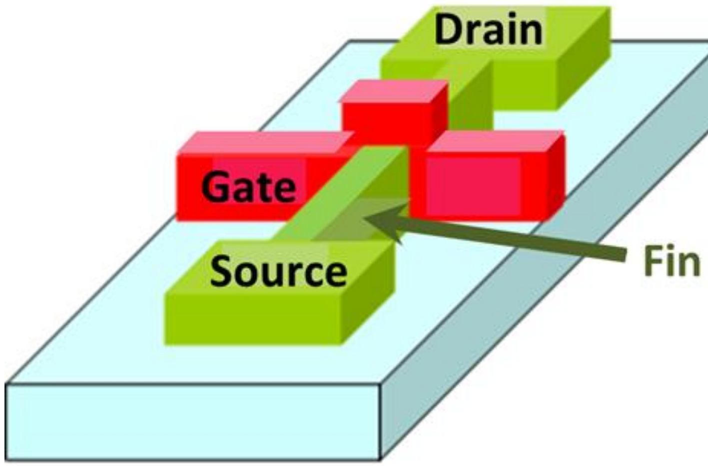


Figure 11.17 | Threshold voltage versus channel length for two values of drain-to-source and body-to-source voltage. (*From Yang [25].*)

11.5 Short Channel Effect



Chengming Hu

Fin Gate to suppress short channel effect