VE320 – Summer 2021

Introduction to Semiconductor Devices

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

Outline

Nonideal Effects:

11.1 Channel length modulation

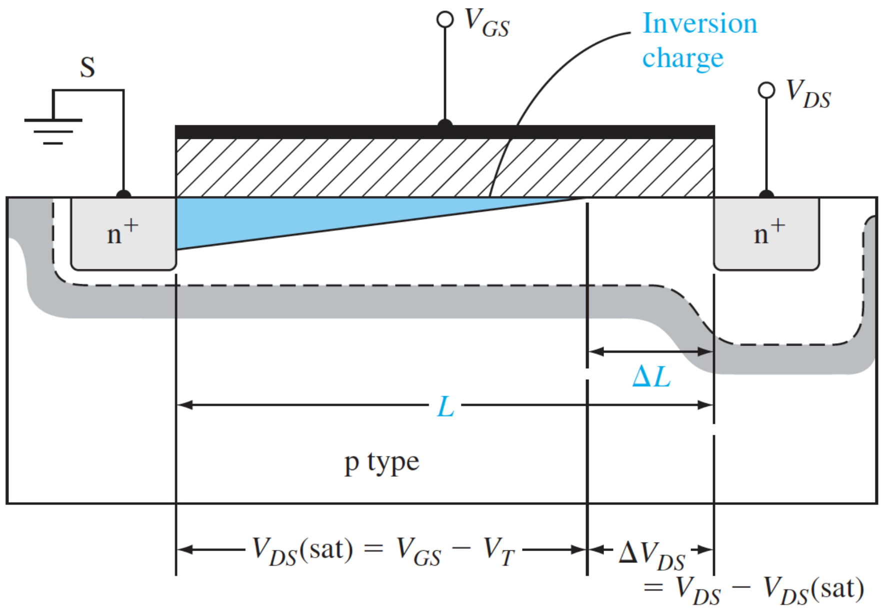
11.2 Conductance and transconductance

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.

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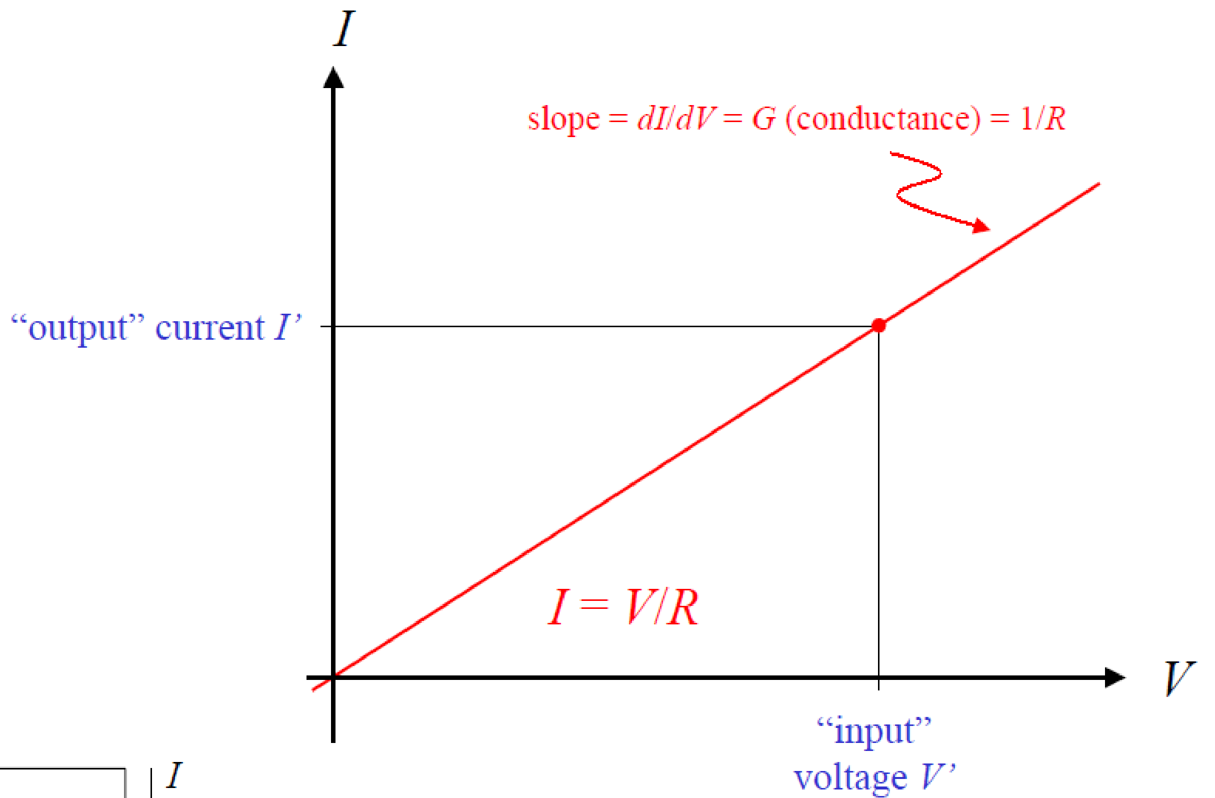
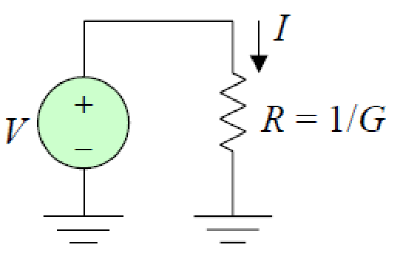
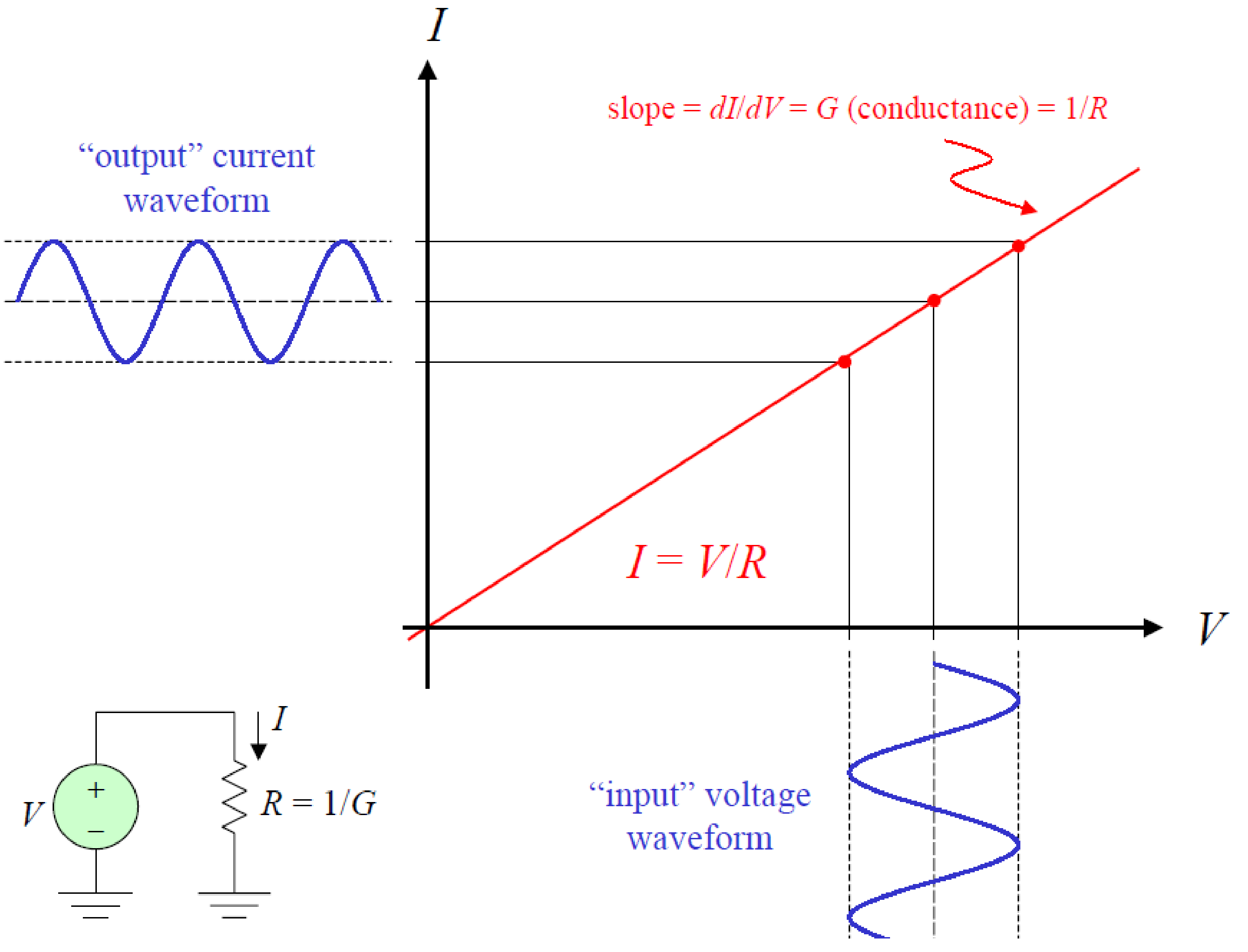
11.2 conductance and transconductance





11.2 conductance and transconductance



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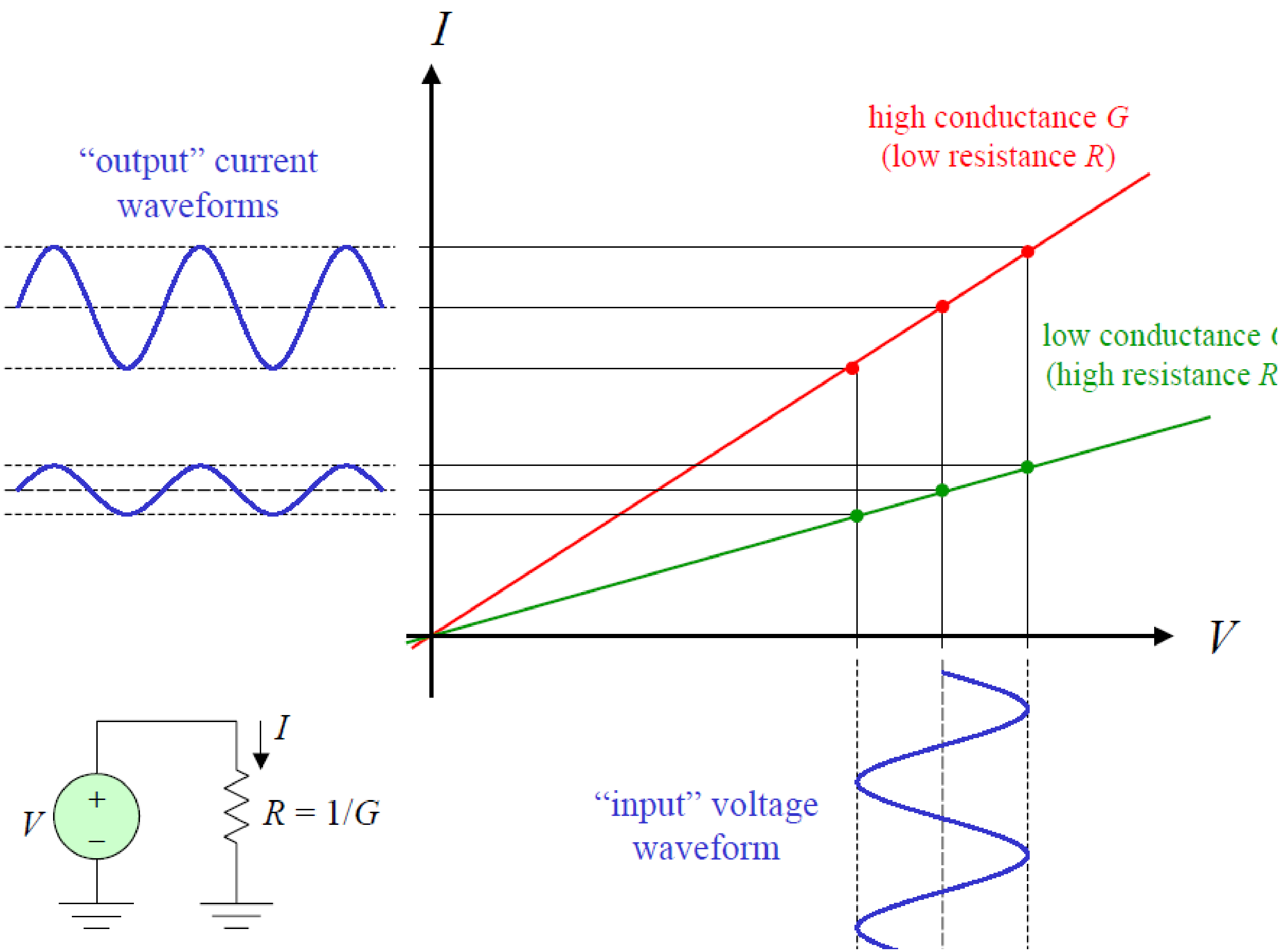

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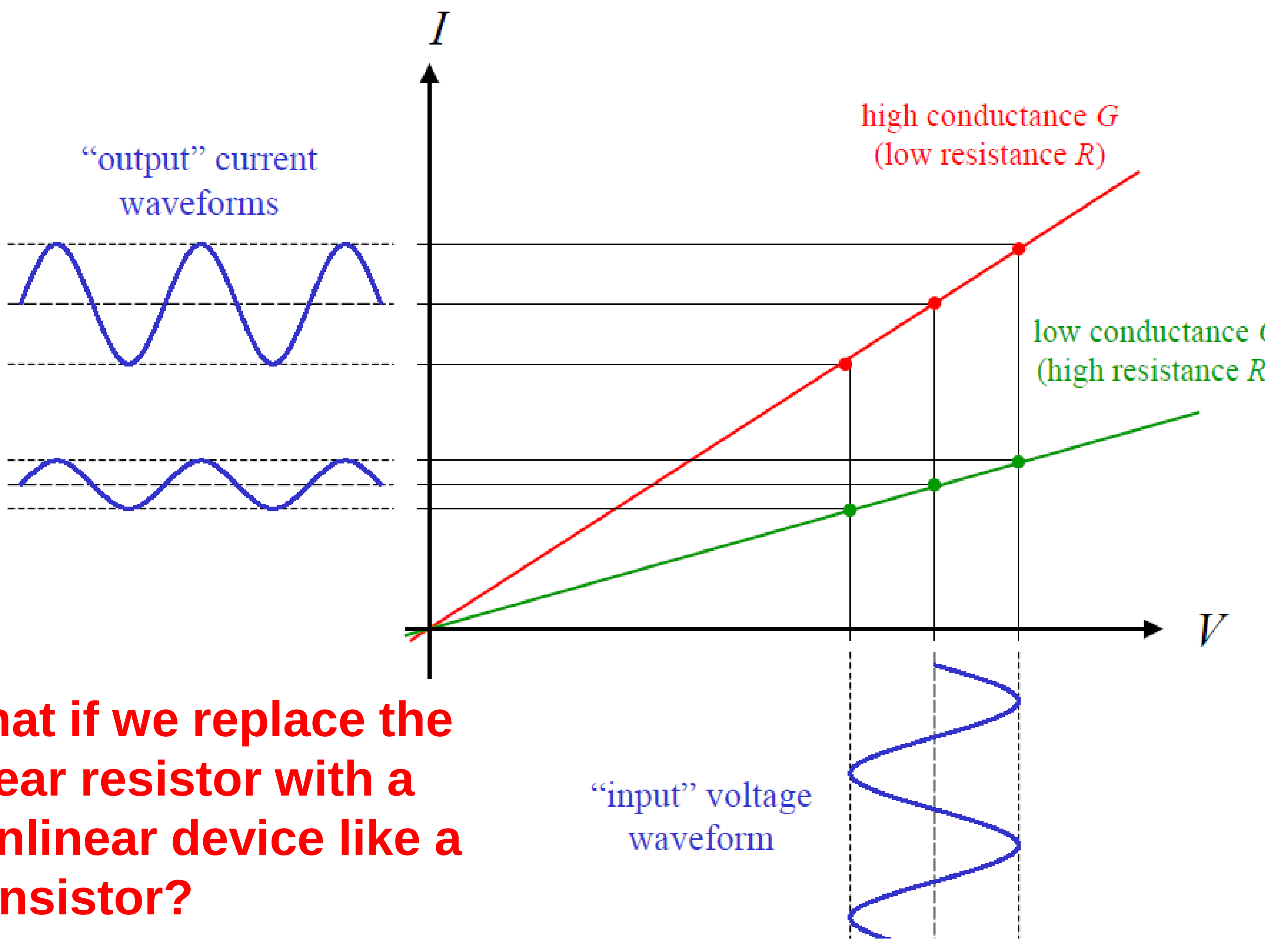
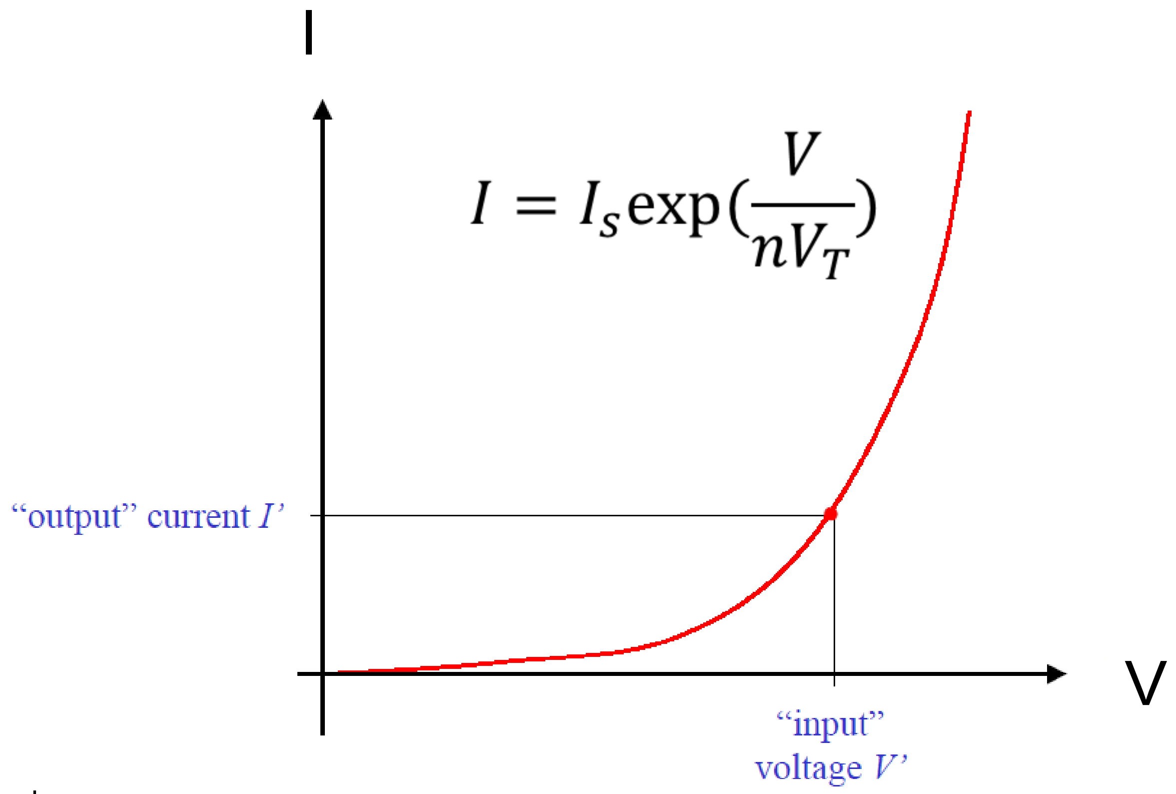
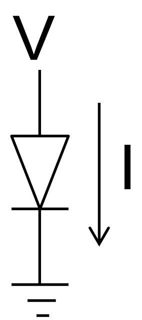


What if we replace the linear resistor with a nonlinear device like a transistor?

11.2 conductance and transconductance



$$I = I_s \exp\left(\frac{V}{nV_T}\right)$$



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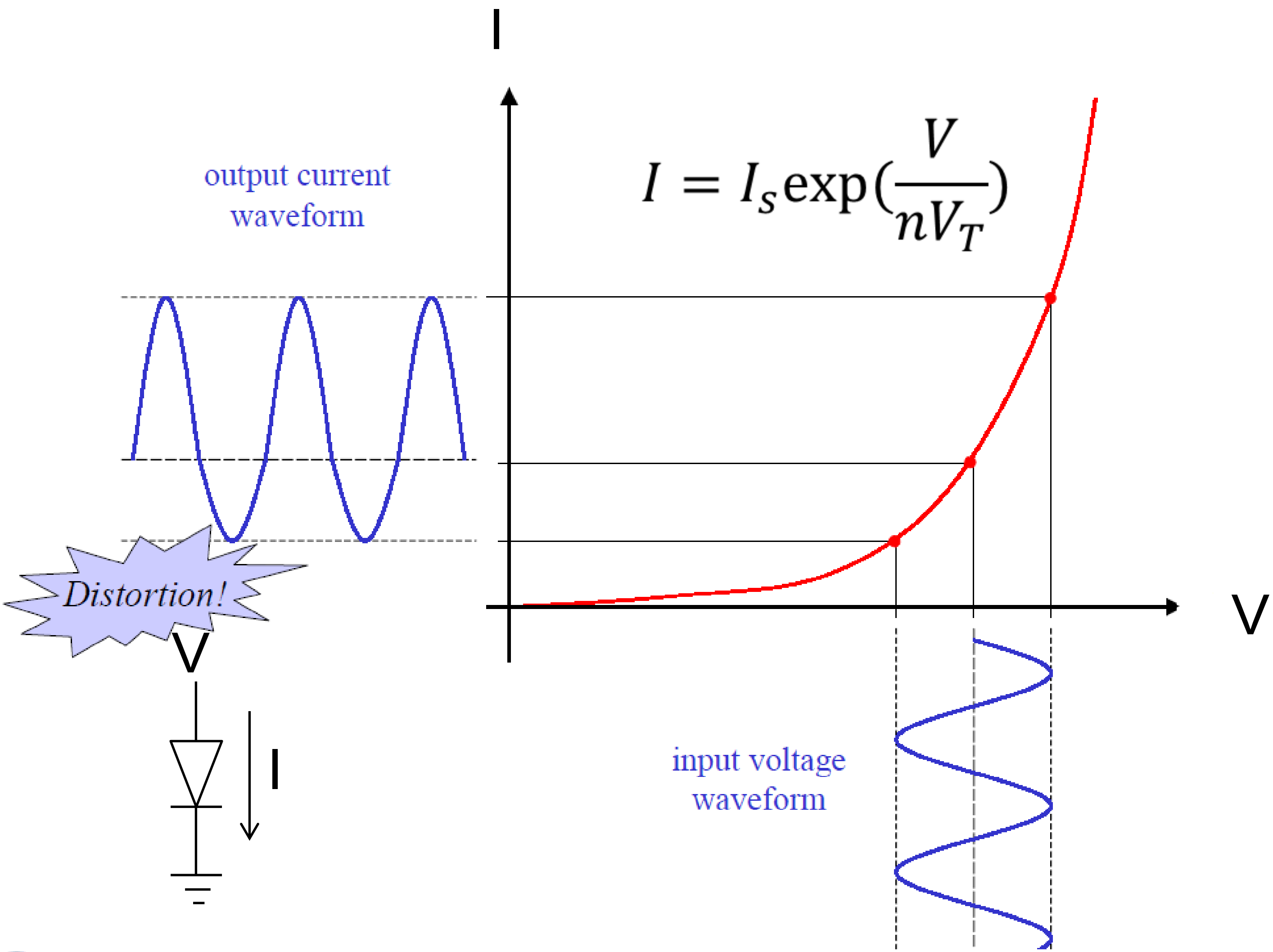

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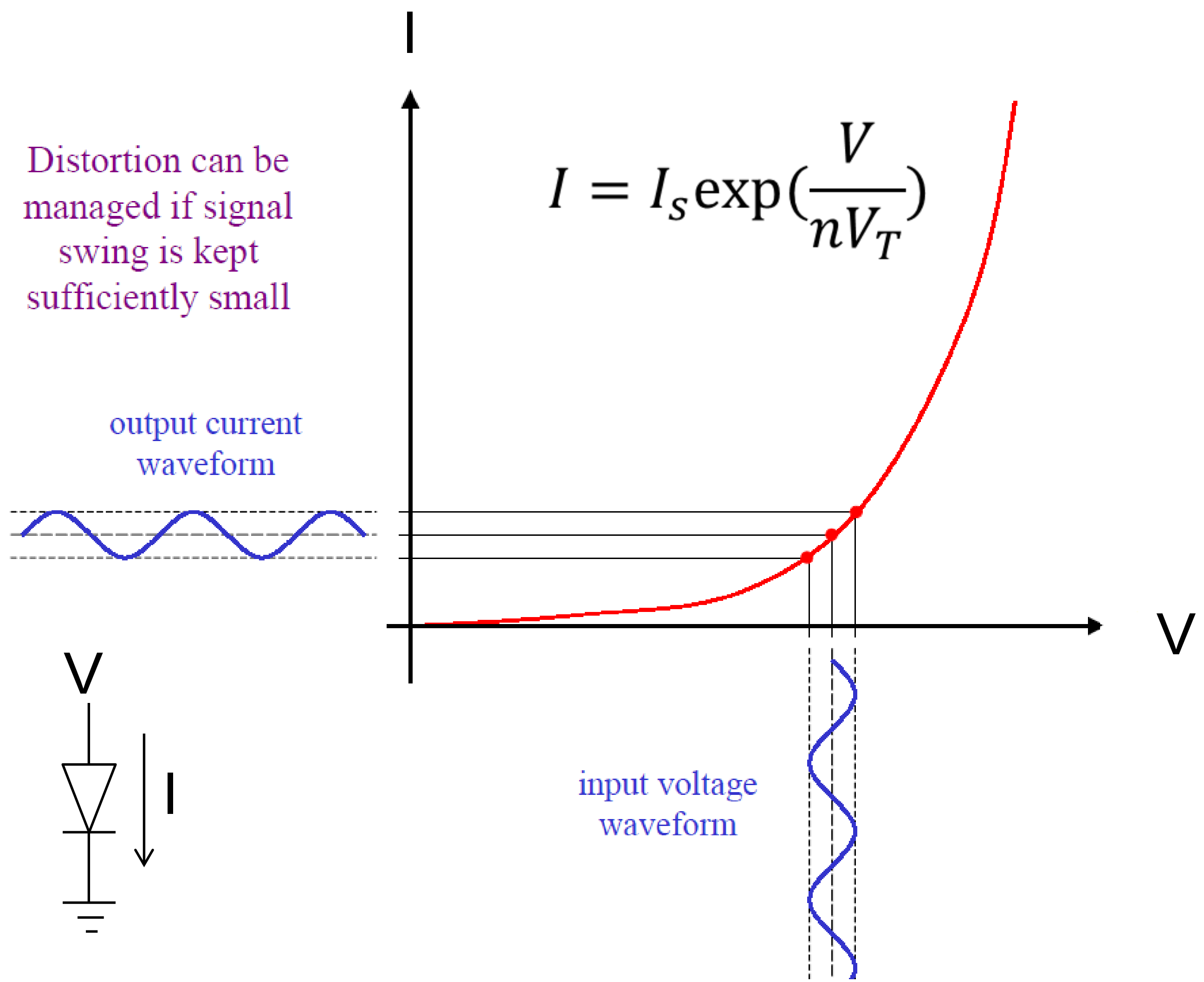

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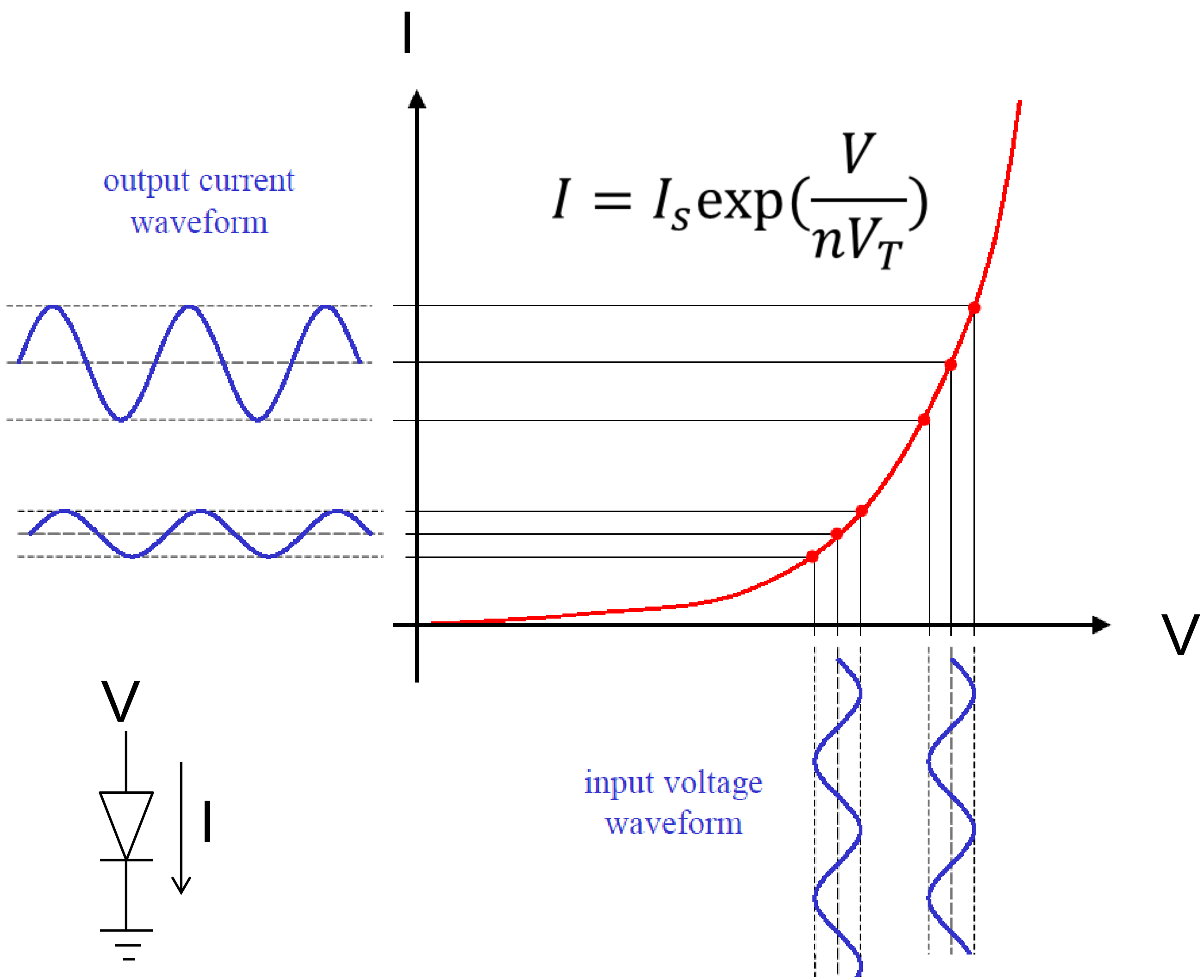

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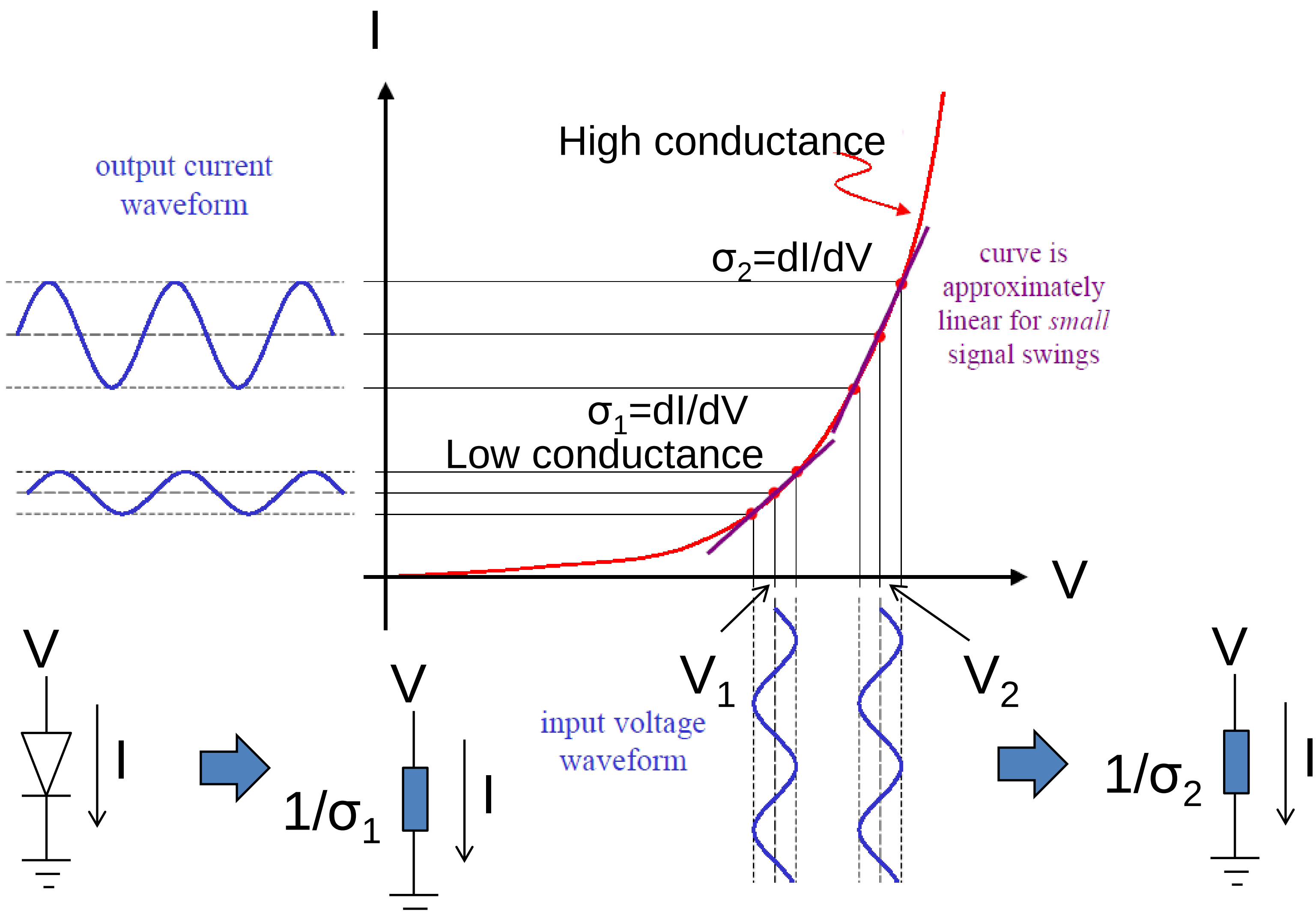

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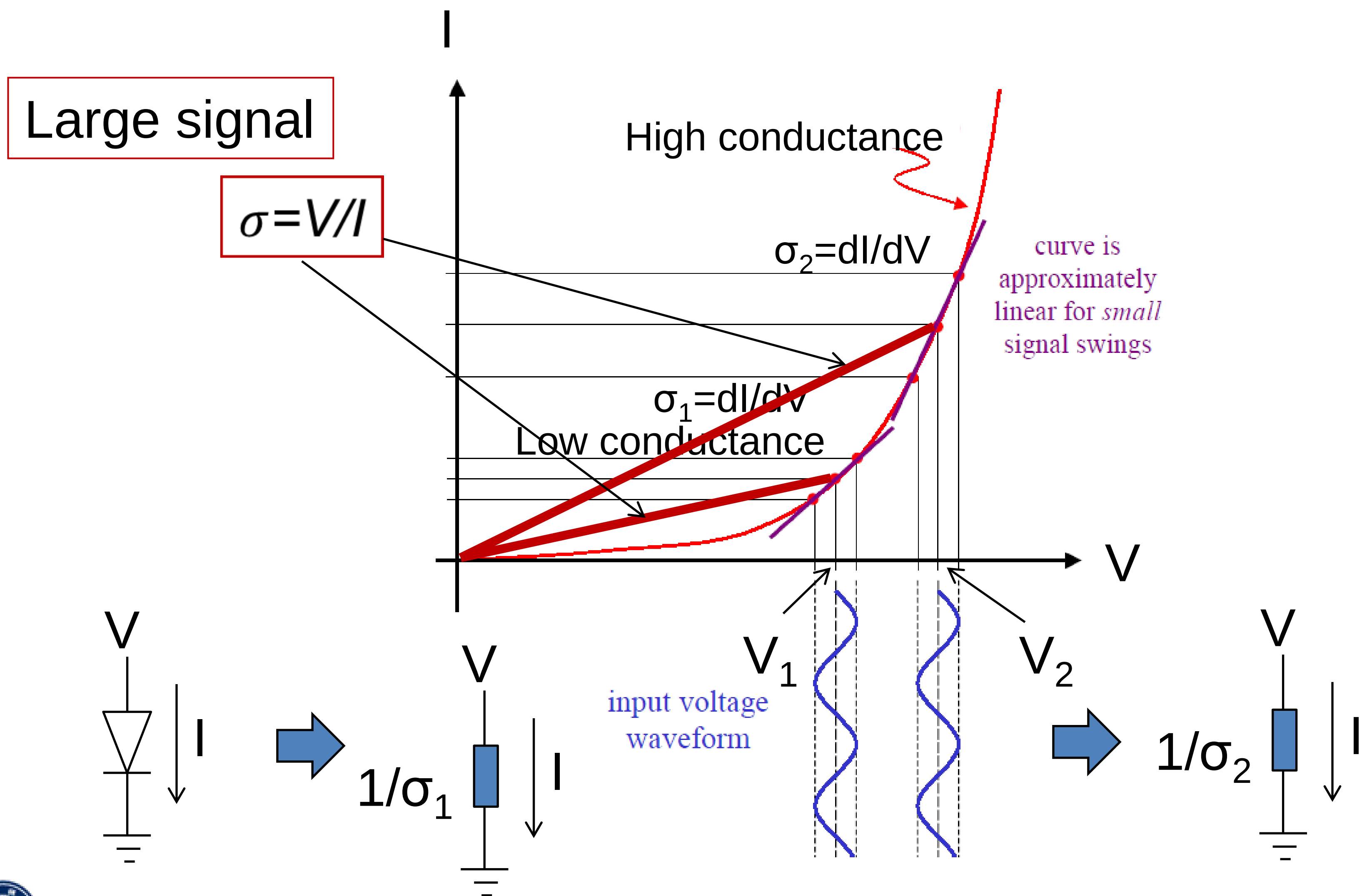

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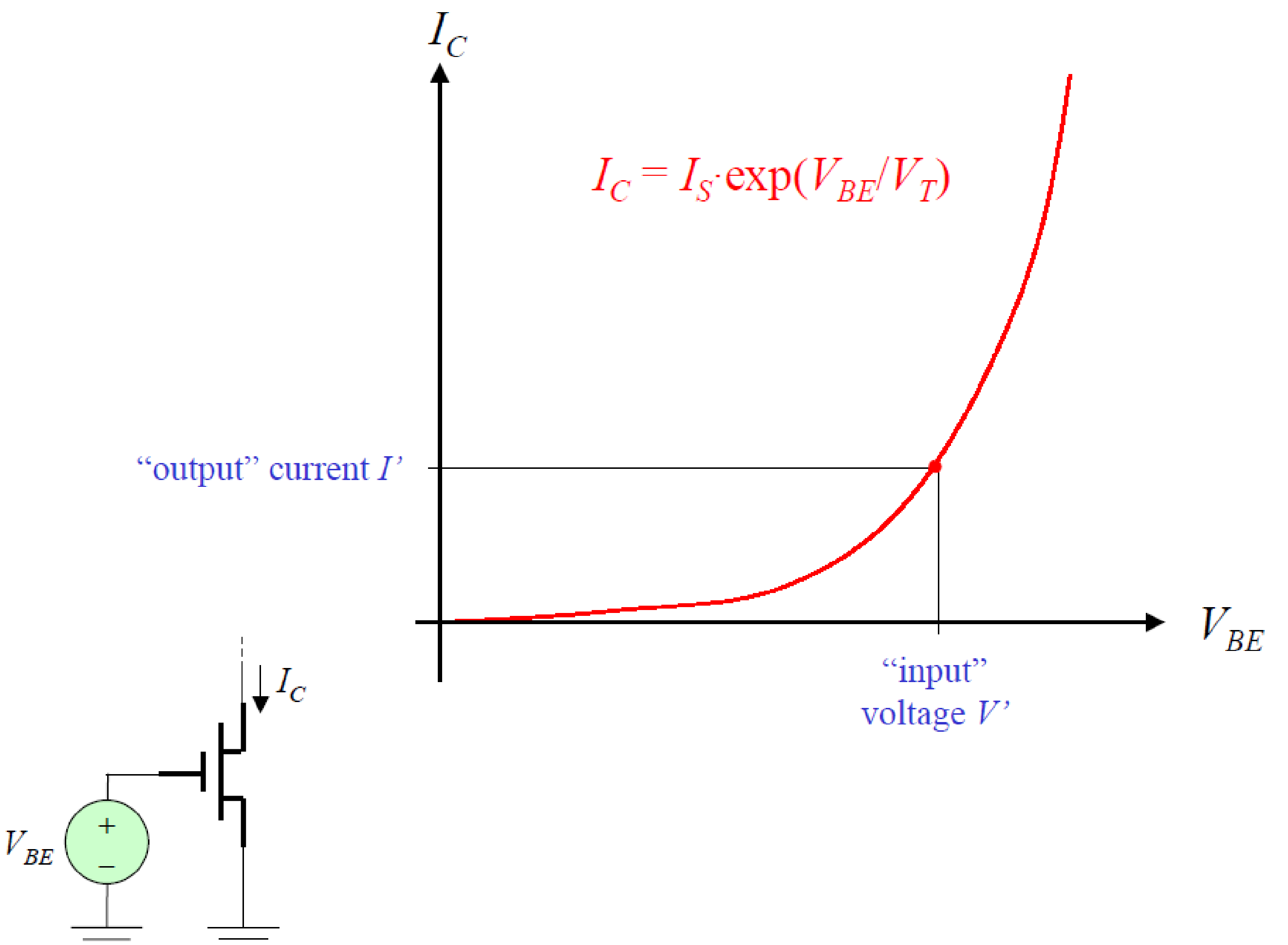

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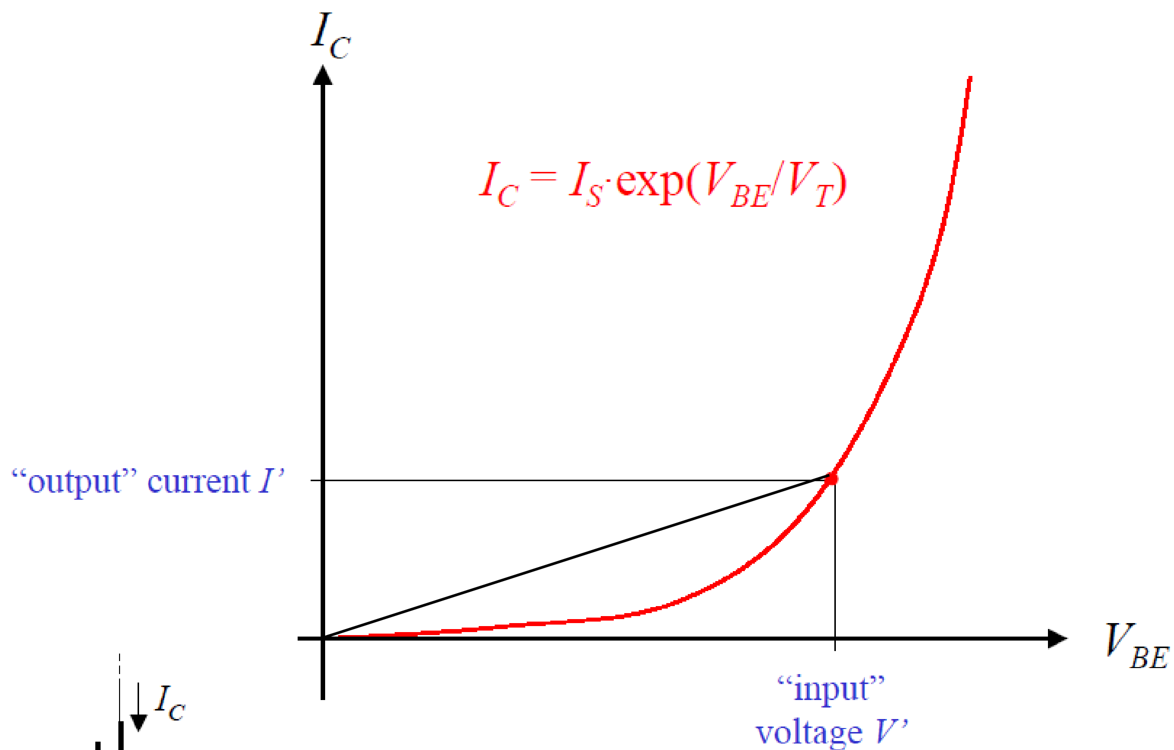
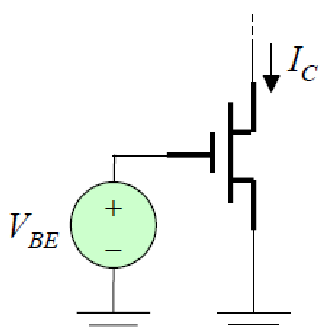
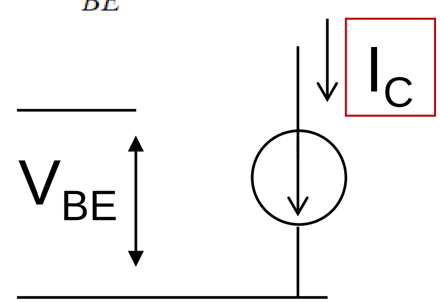
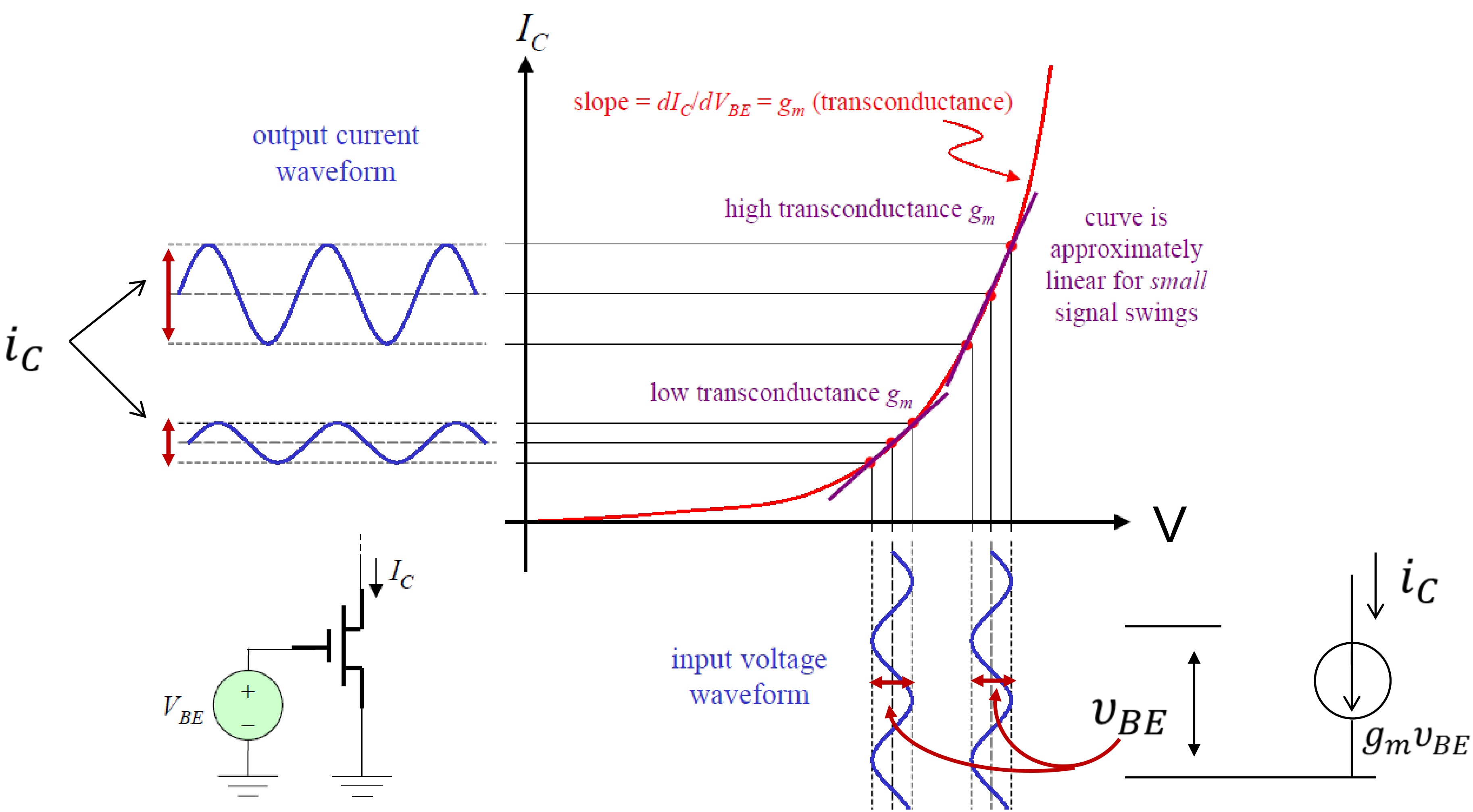






11.2 conductance and transconductance



11.2 conductance and transconductance

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

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

transconductance

$$\boxed{g_n = \frac{dI_d}{dV_g} = k_n\left(V_{gs} - V_T\right)(1 + \lambda V_{ds}) = \frac{2I_d}{\left(V_{gs} - V_T\right)}}$$

$$g_m = k_n(V_{gs} - V_T)(1 + \lambda V_{ds})$$

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 Impedance

$$\boxed{\frac{1}{r_{on}} = \frac{dI_d}{dV_{ds}} = \lambda k_n (V_{gs} - V_T)^2 = \frac{\lambda I_d}{1 + \lambda V_{ds}}}$$

$$g_m = k_n (V_{gs} - V_T)(1 + \lambda V_{ds})$$

How the knowledge used by engineers and scientists

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Diameter-Dependent Electron Mobility of InAs Nanowires

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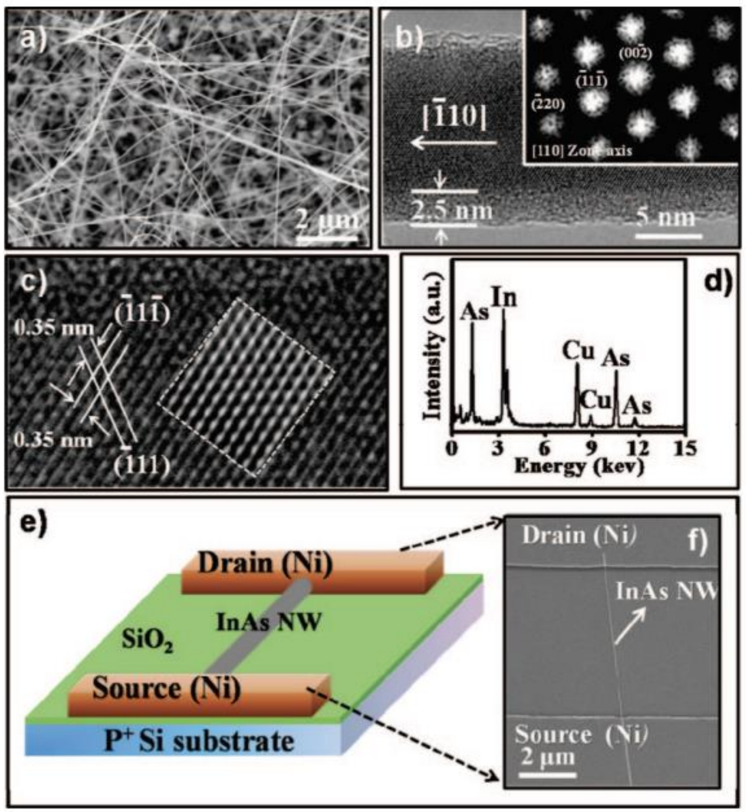
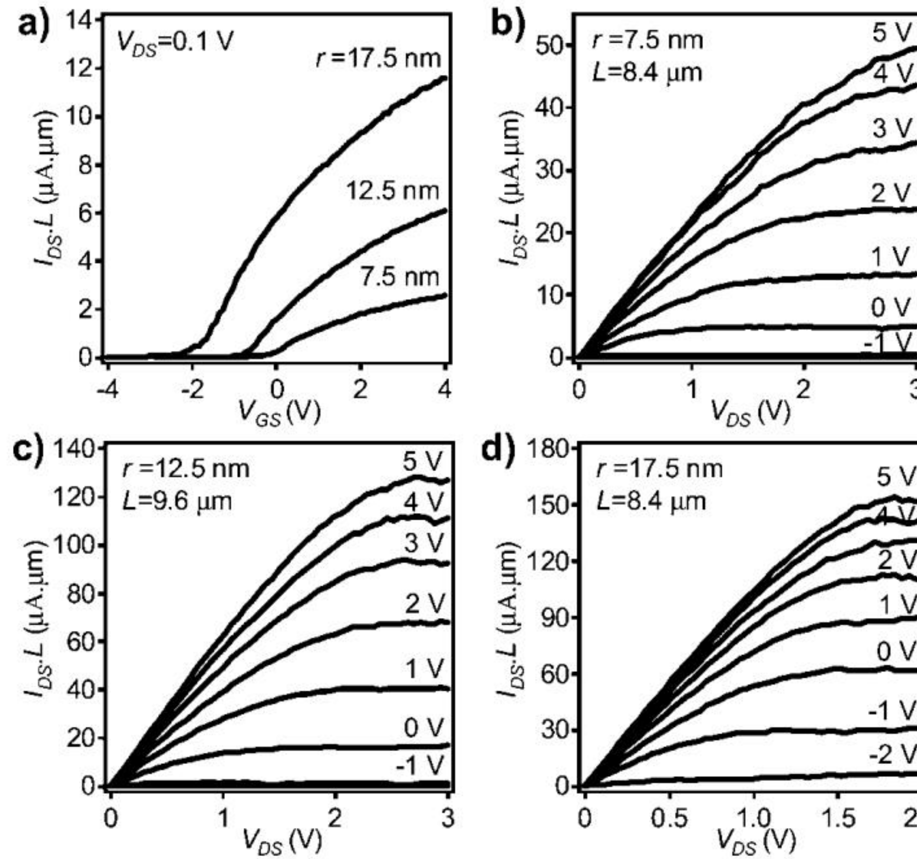
How the knowledge used by engineers and scientists





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

$$g_m = \left.\frac{dI_{DS}}{dV_{GS}}\right|_{V_{DS}}$$

and the analytical expression

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

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

$$g_D = \left.\frac{dI_{DS}}{dV_{DS}}\right|_{V_{GS}}$$

with

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

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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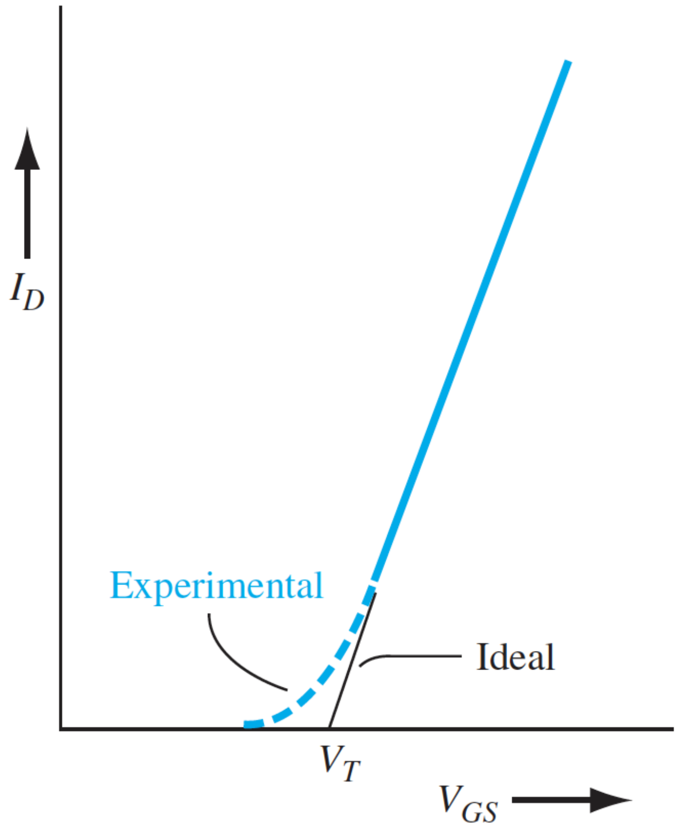
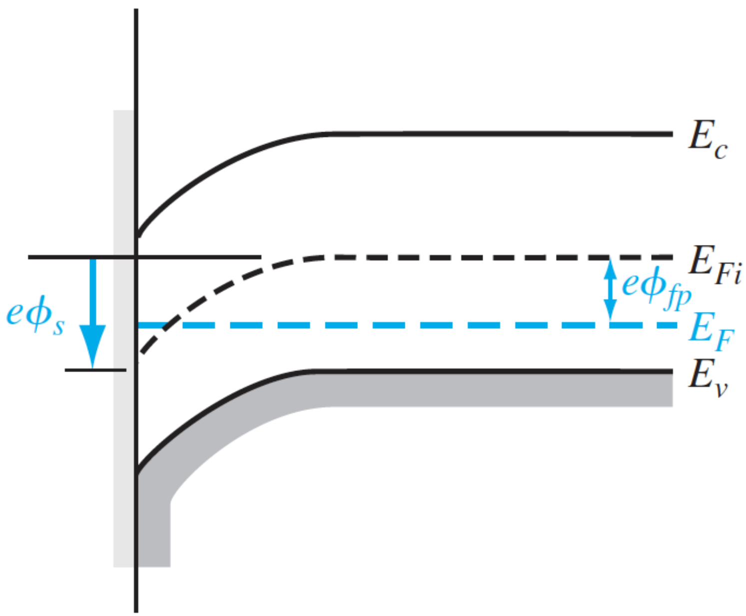
11.3 Subthreshold conduction

$$V_{GS} < V_T$$





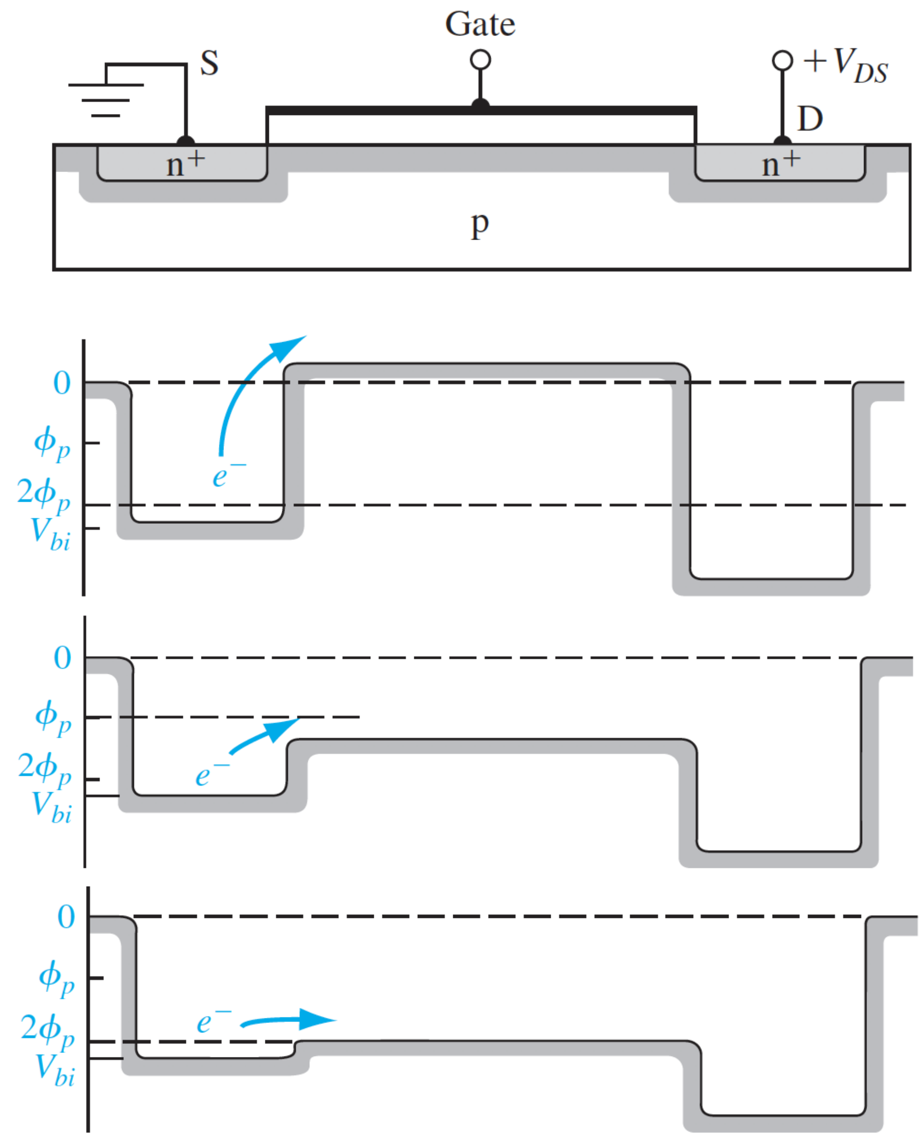
$$\phi_{fp} < \phi_s < 2\phi_{fp}.$$

11.3 Subthreshold conduction

Accumulation

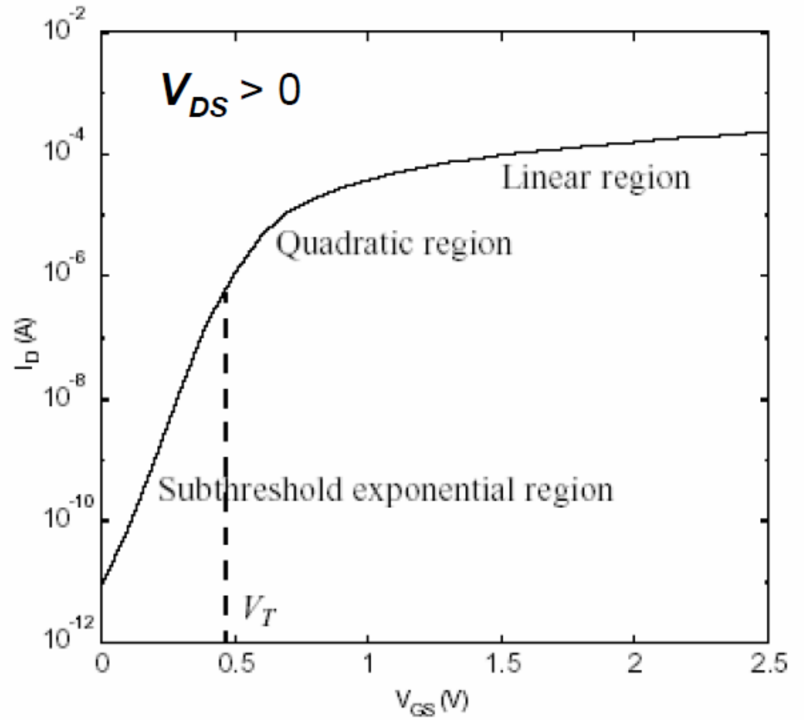
Weak inversion

Inversion



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,

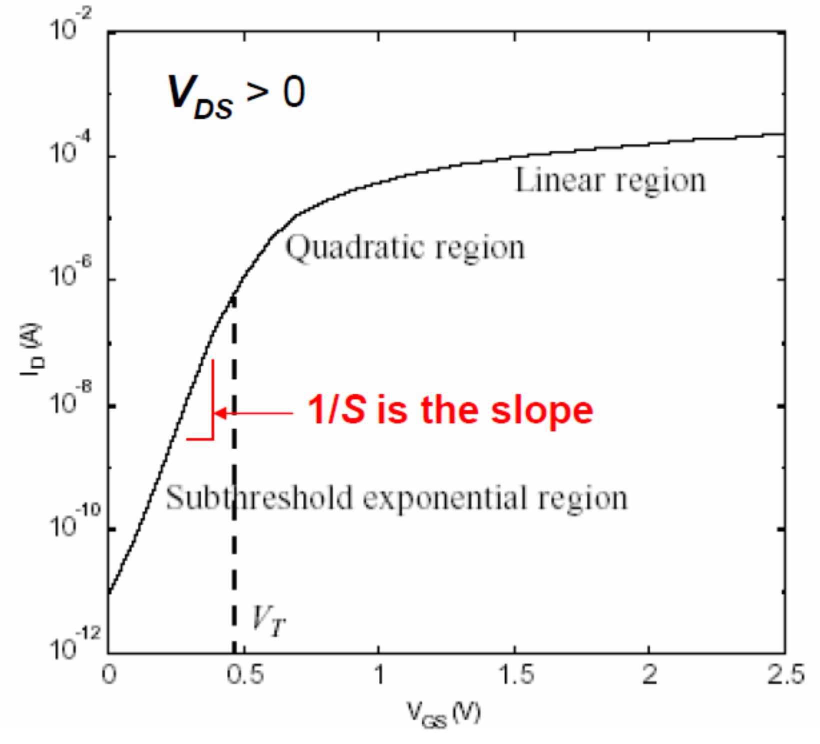
$$I_D \propto \exp\left(\frac{qV_{GS}}{nkT}\right)$$

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.)

11.3 Subthreshold conduction

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:



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

Units: Volts per decade

Note that ***S*** $\geq$ 60 mV/dec at room temperature:

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

11.3 Subthreshold conduction

V_T Design Trade-Off

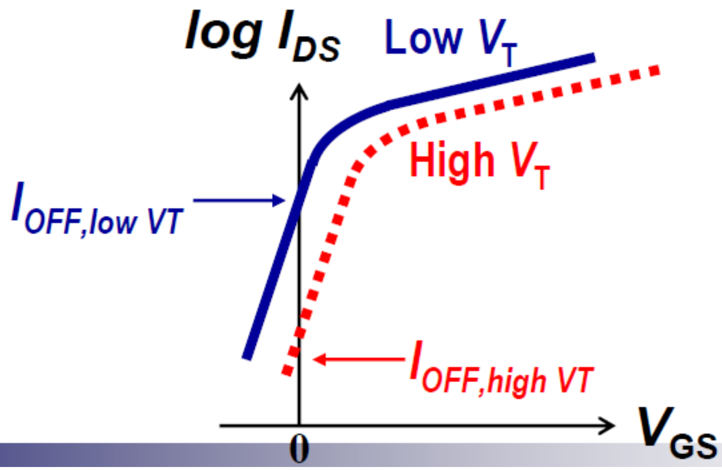
(Important consideration for digital-circuit applications)

- 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



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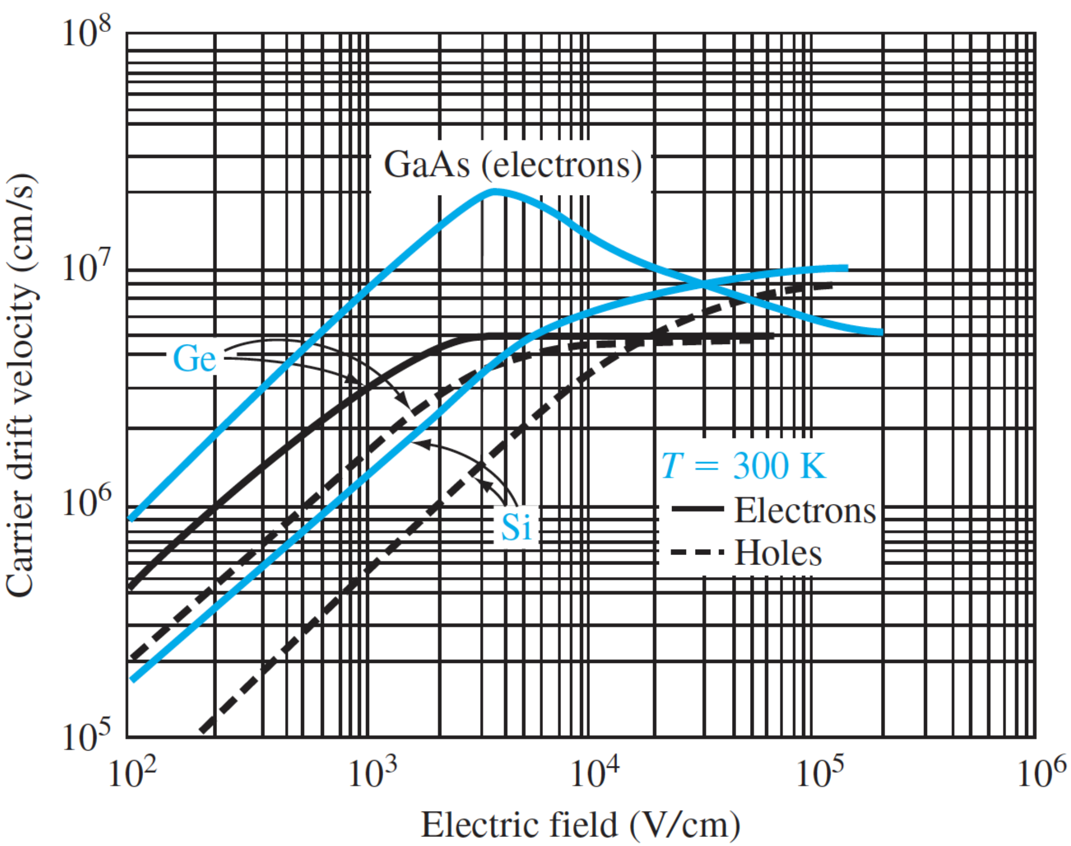
11.4 Velocity Saturation

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

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



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

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

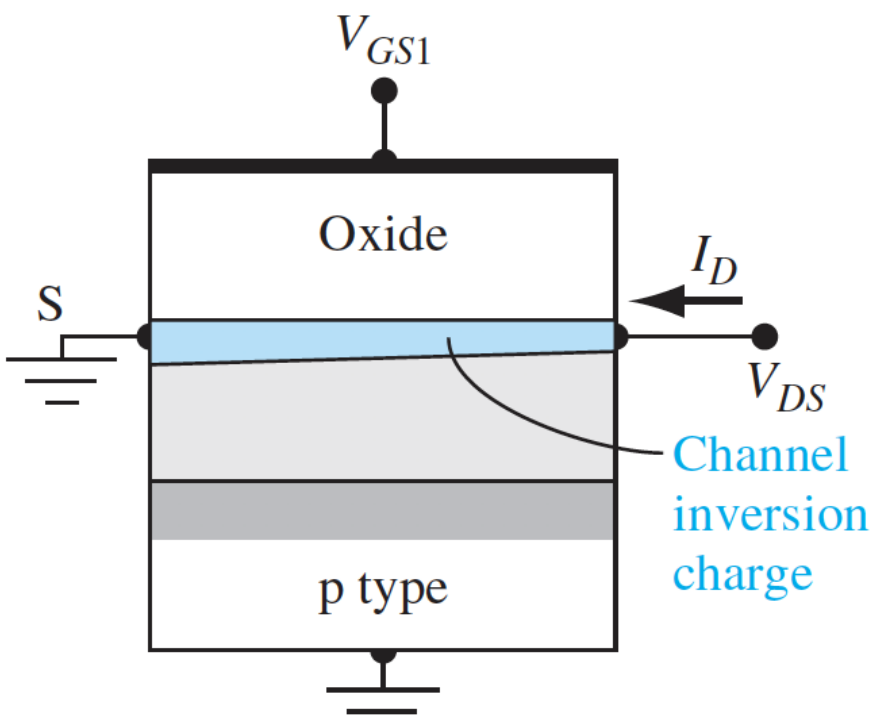
2 1/2

Probably a typo in textbook

11.4 Velocity Saturation

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

- 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

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

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

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

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

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

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

11.4 Velocity Saturation

Unified model

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

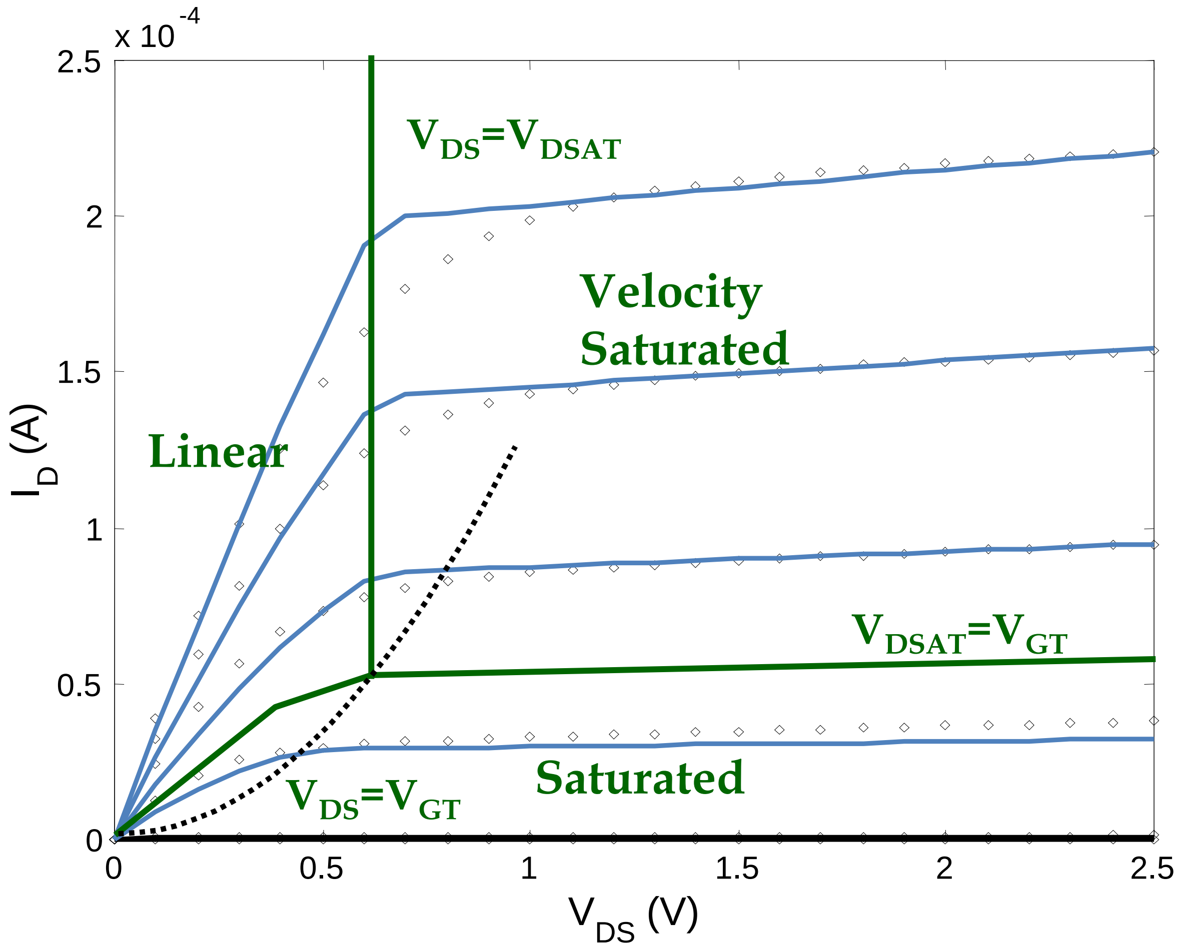
$$I_D = k'\frac{W}{L}\left(V_{GT}V_{min} - \frac{V_{min}^2}{2}\right) \qquad \text{for } V_{GT} \ge 0$$

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

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

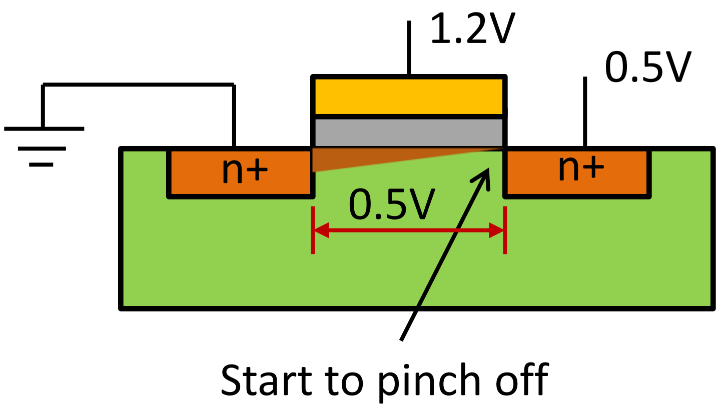
and $V_T = V_{T0} + \gamma(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|})$

11.4 Velocity Saturation



Example

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



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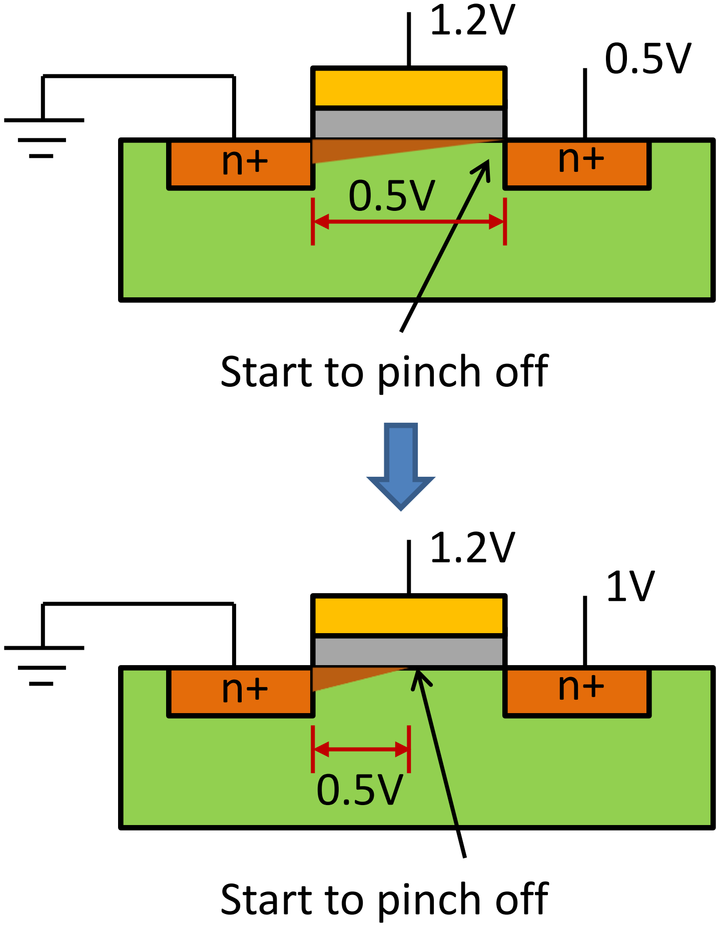

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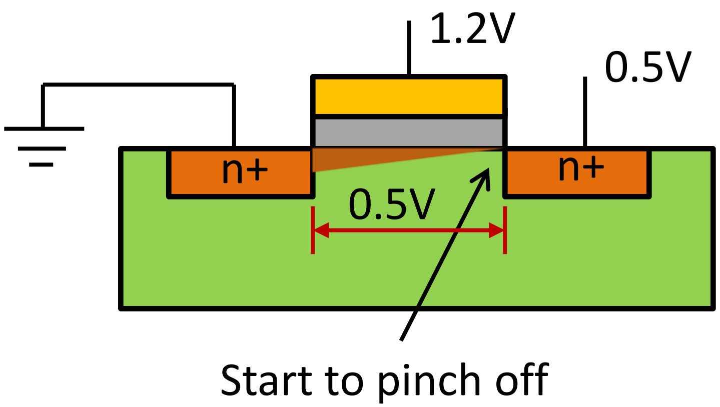
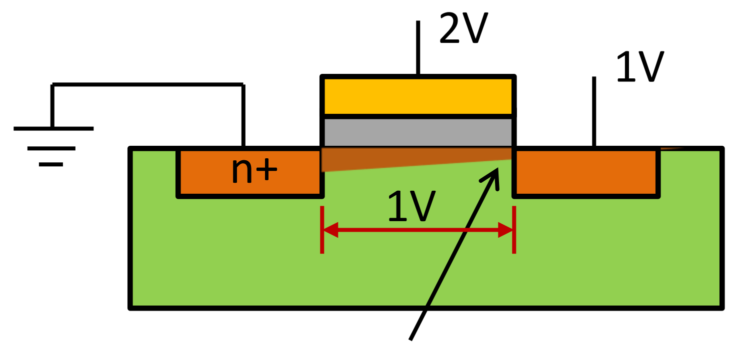
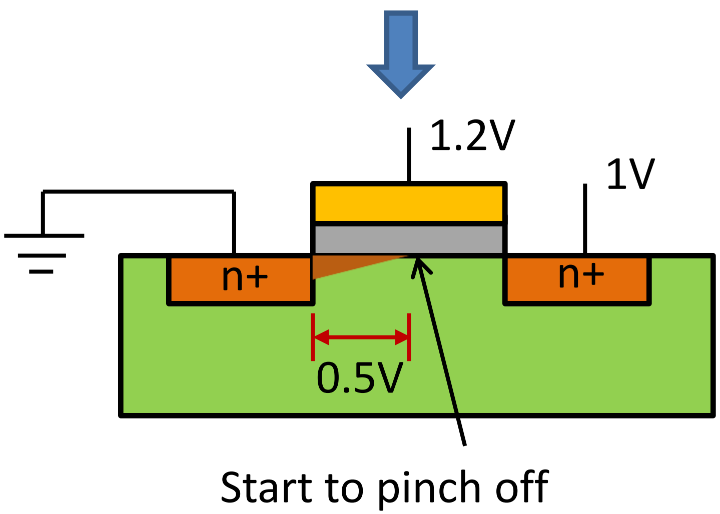




- NO pinch off
- Velocity saturation starts



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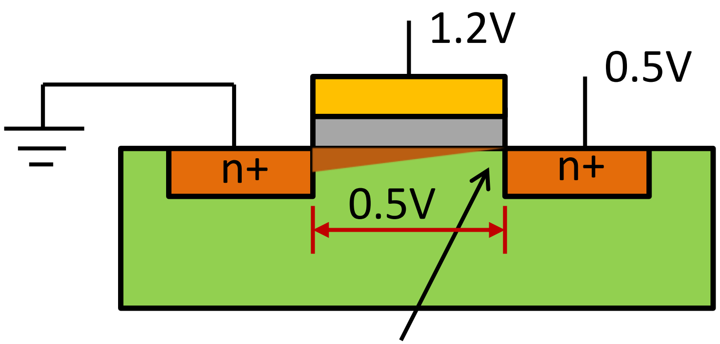
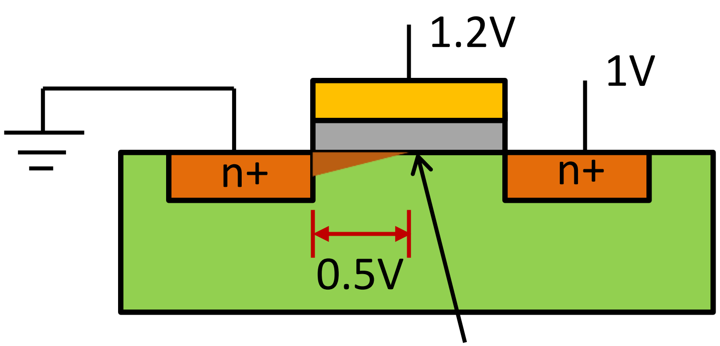
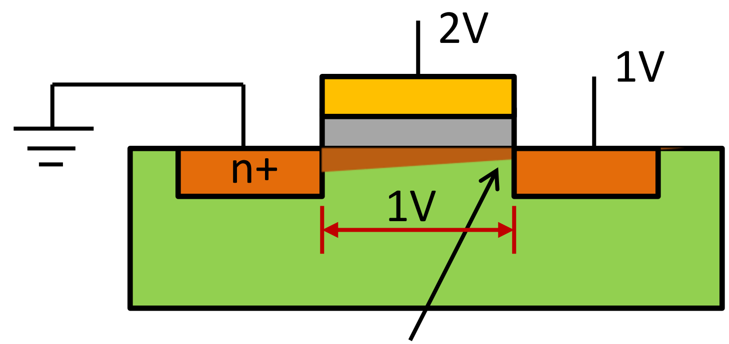


Start to pinch off



Start to pinch off



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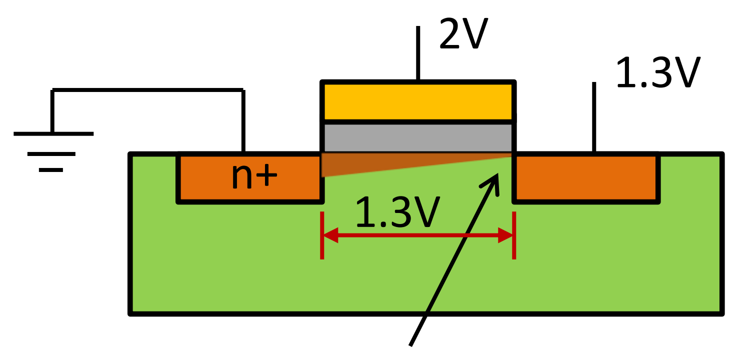

- Starts to pinch off
- Velocity saturation

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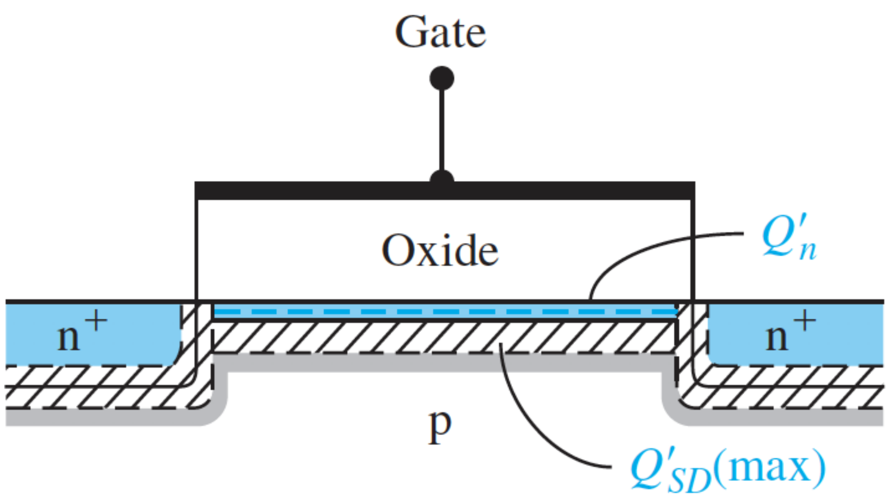
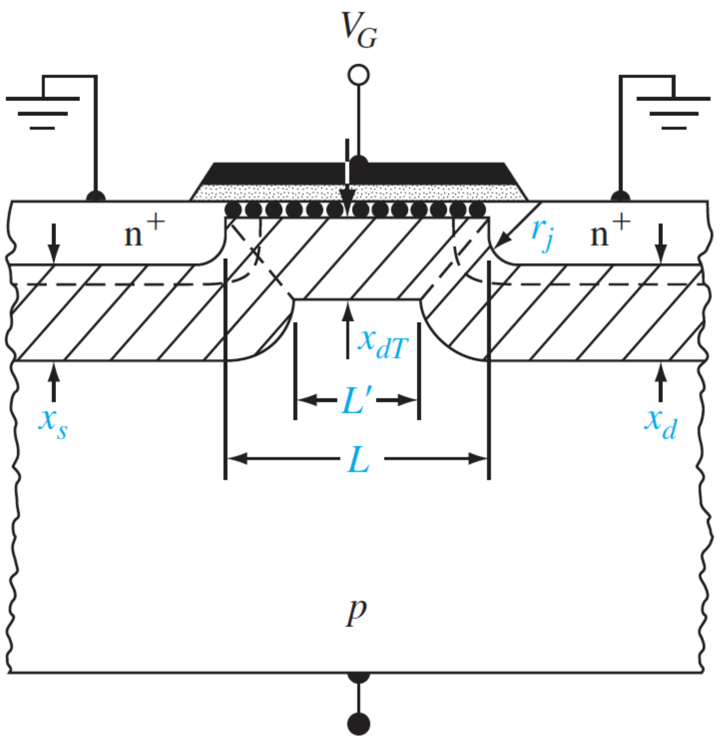


A long channel device



A short channel device

11.5 Short Channel Effect

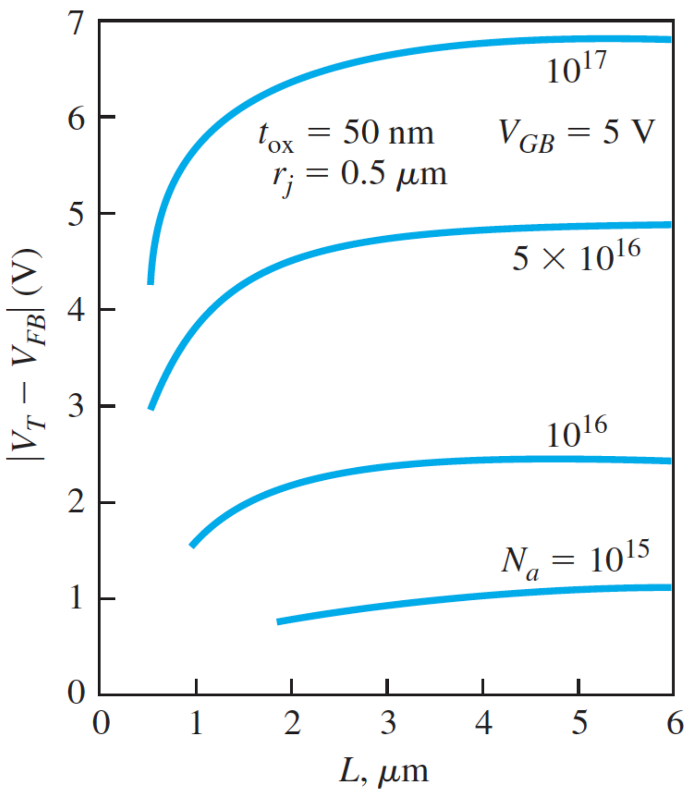


Figure 11.16 | Threshold voltage versus channel length for various substrate dopings. (*From Yau [26].*)

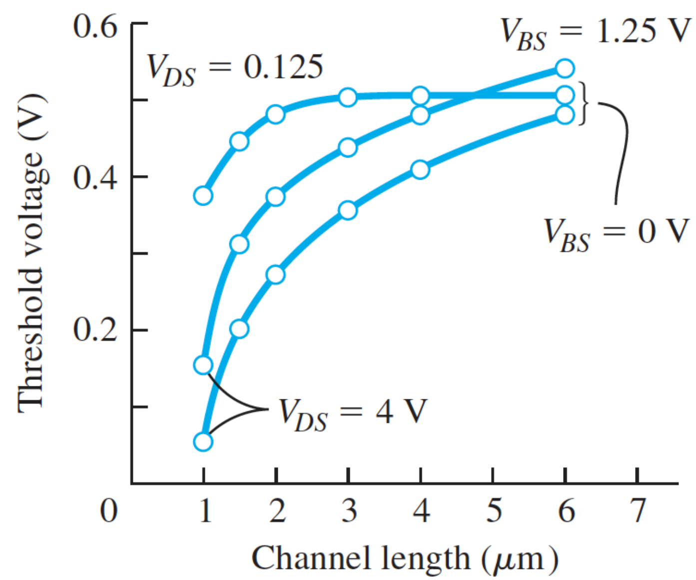


Figure 11.17 | Threshold voltage versus channel length for two values of drain-to-source and body-to-source voltage. (*From Yang [25].*)