MOS Transistors

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Syllabus

- MOS Transistor Theory
- Advanced Features of MOS Transistors

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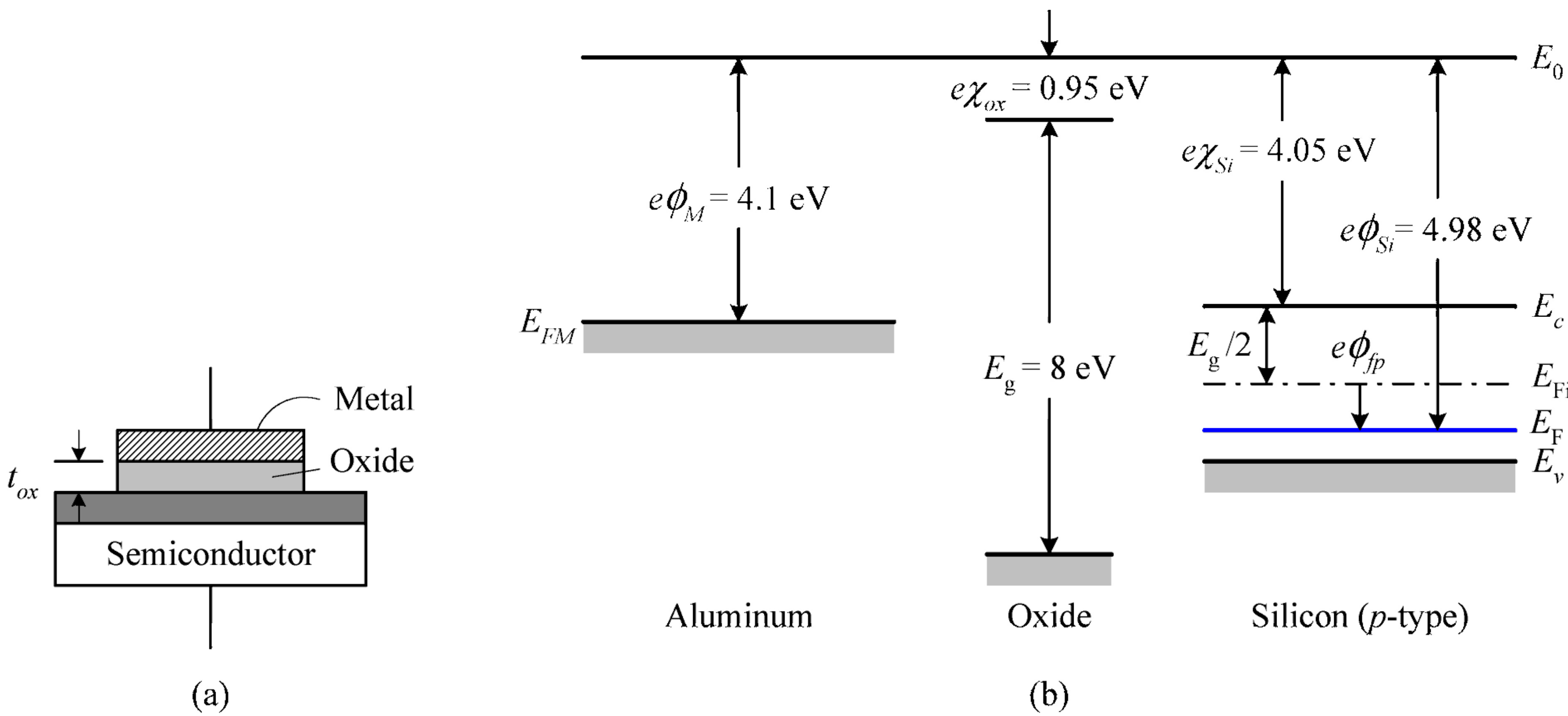
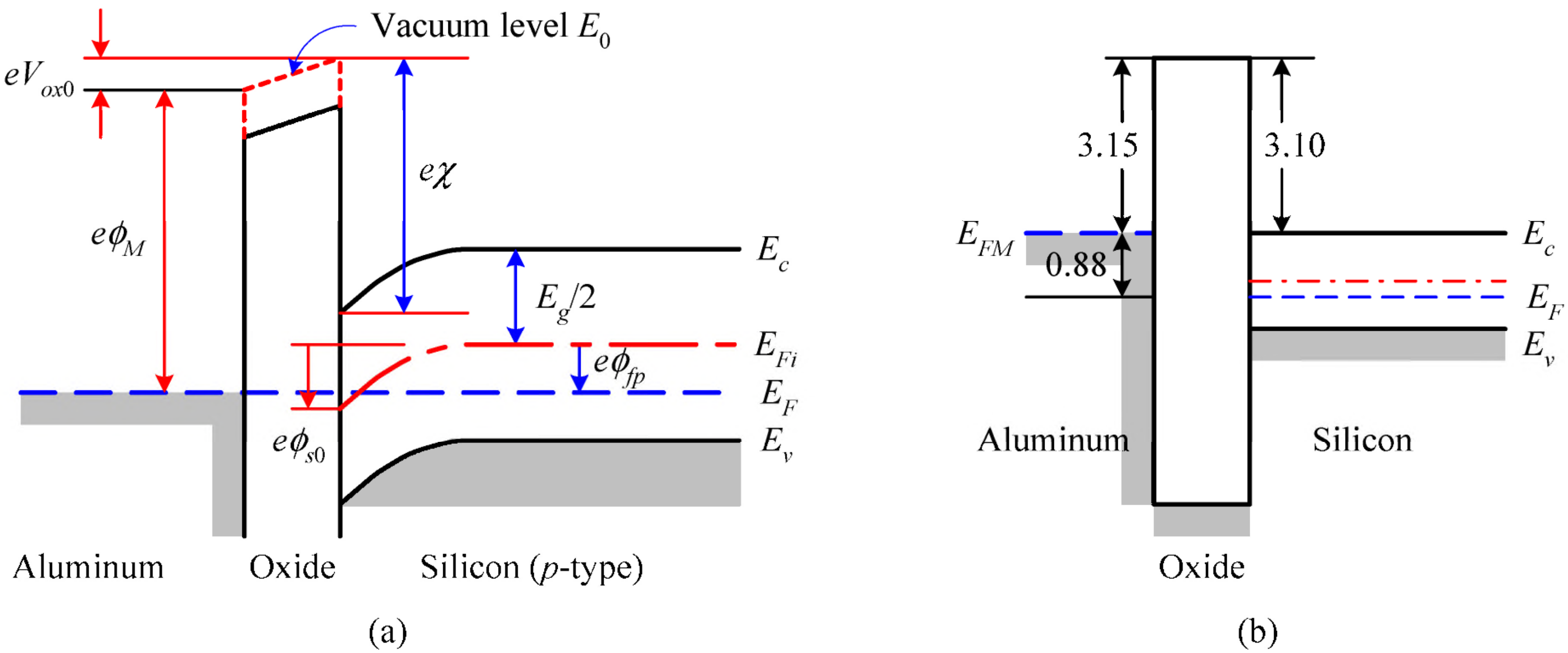
- MOS Transistor Theory
  - MOS systems
  - The operation of MOS transistors
  - The *I-V* characteristics of MOS transistors
  - Scaling theory
- Advanced Features of MOS Transistors

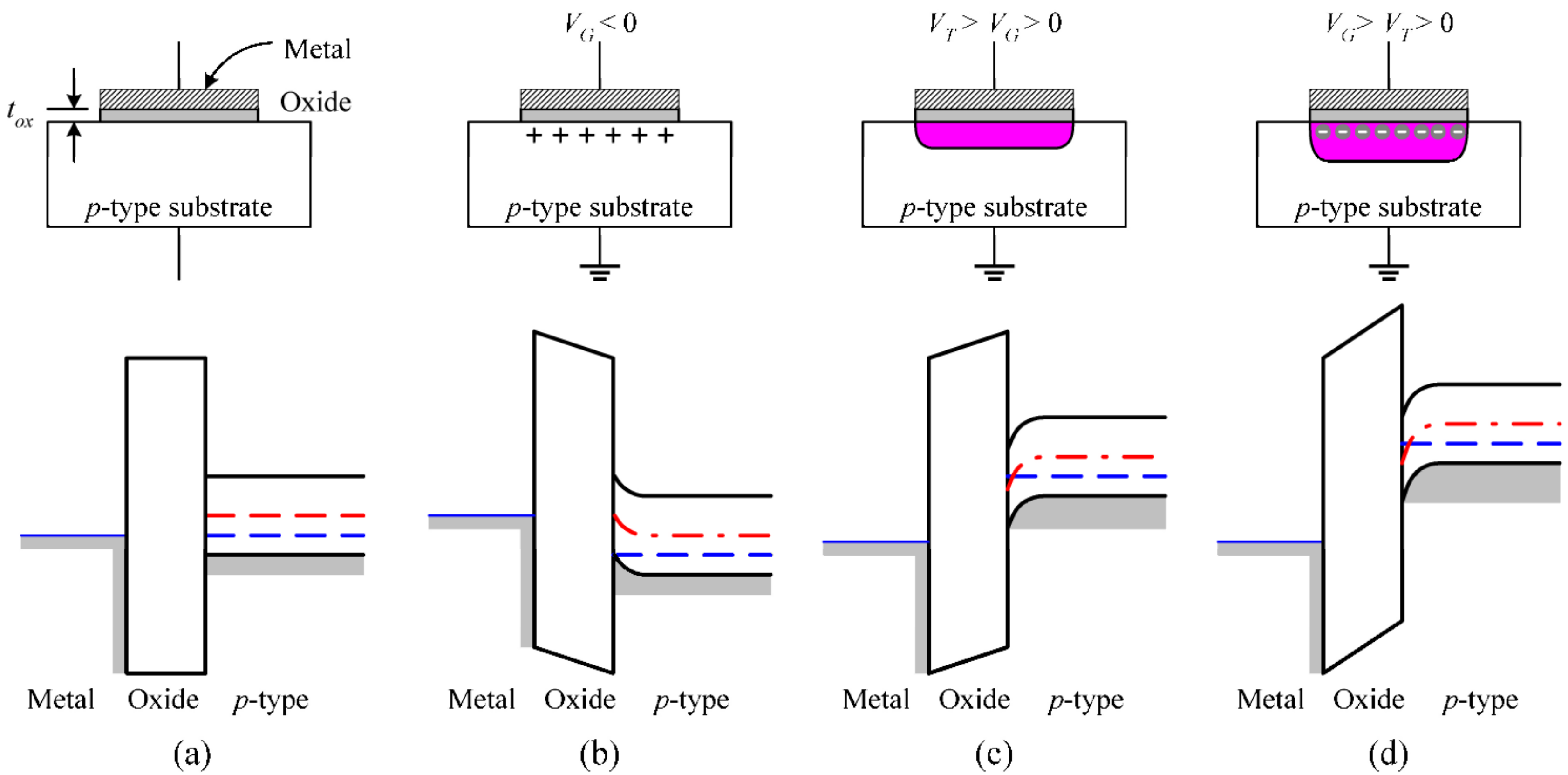
Energy-Band Diagram



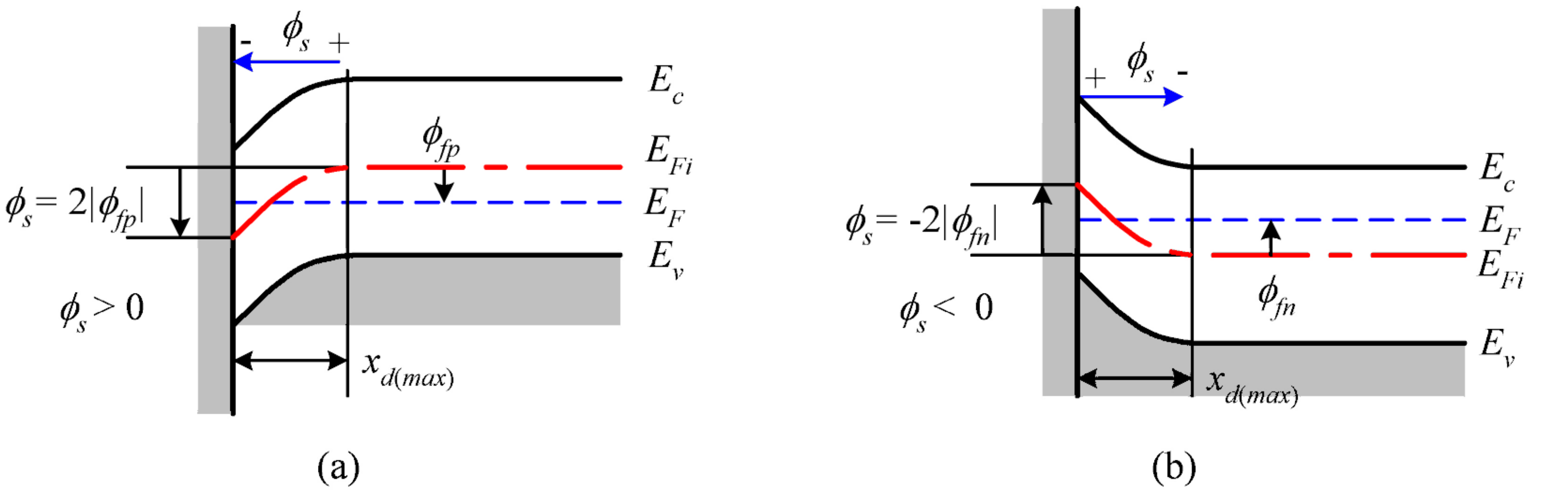
Flat-Band Voltage



MOS System


Metal
Oxide
t_{ox}
p-type substrate
$V_G < 0$
$V_T > V_G > 0$
$V_G > V_T > 0$
Metal Oxide p-type
(a)
(b)
(c)
(d)

Depletion Width



Maximum Depletion-Layer Thickness

- Maximum Depletion-Layer Thickness

$$x_{d(\max)} = \sqrt{\frac{4\varepsilon_{si}\left|\phi_{fp}\right|}{eN_a}}$$

  - ϕ_{fp} is the Fermi potential
  - N_a is the impurity concentration of p-type substrate

Maximum Depletion-Layer Thickness

- Find $x_{d(\max)}$
  - T = 300 K
  - $N_a = 2 \times 10^{16}$ cm-3
  - $n_i = 1.45 \times 10^{10}$ cm-3

$$|\phi_{fp}| = V_t \ln\left(\frac{N_a}{n_i}\right) = 0.0259 \ln\left(\frac{2 \times 10^{16}}{1.45 \times 10^{10}}\right) = 0.37 \text{ V}$$

$$x_{d(\max)} = \left(\frac{4\varepsilon_{Si}|\phi_{fp}|}{eN_a}\right)^{1/2} = \left(\frac{4 \times 11.7 \times 8.854 \times 10^{-14} \times 0.37}{1.6 \times 10^{-19} \times 2 \times 10^{16}}\right)^{1/2}$$

$$= 0.22 \ \mu\text{m}$$

Threshold Voltage

- Strong inversion condition $(2|\phi_{\mathrm{fp}}| + Q_{d(\max)} / C_{ox})$
- Work function difference (ϕ_{GS})
- Fixed-oxide charge (Q_{SS})
- Threshold voltage adjustment (eD_I / C_{ox})

$$V_{Tn} = 2\left|\phi_{fp}\right| + \frac{Q_{d(\max)}}{C_{ox}} + \phi_{GS} - \frac{Q_{SS}}{C_{ox}} + \frac{eD_I}{C_{ox}}$$

$$Q_{d(\max)} = eN_a x_{d(\max)} = \sqrt{4e\varepsilon_{si} N_a \left|\phi_{fp}\right|}$$

An Example

- An n^+ polysilicon gate MOS system
  - ϕ_{GS} = -0.88 V
  - $N_a = 2 \times 10^{16}$ cm^{-3}
  - $n_i = 1.45 \times 10^{10}$ cm^{-3}
  - $Q_{SS} = 5 \times 10^{10}$ cm^{-2}
  - T = 300 K
- We have
  - $|f_{\mathrm{fp}}|$ = 0.37 V
  - $x_{d(\max)}$ = 0.22 μm = 0.22×10^{-4} cm
- Find V_{Tn}

An Example

- Solution

$$Q_{d(\max)} = eN_a x_{d(\max)} = 1.6\times10^{-19}\times2\times10^{16}\times0.22\times10^{-4}$$

$$= 7.04\times10^{-8}\ \text{C/cm}^2$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9\times8.854\times10^{-14}}{5\times10^{-7}} = 6.9\times10^{-7}\ \text{F/cm}^2$$

$$V_{Tn} = 2\left|\phi_{fp}\right| + \frac{Q_{d(\max)}}{C_{ox}} + \phi_{GS} - \frac{Q_{SS}}{C_{ox}}$$

$$= 2\times0.37 + \frac{7.04\times10^{-8}}{6.9\times10^{-7}} + (-0.88) - \frac{5\times10^{10}\times1.6\times10^{-19}}{6.9\times10^{-7}}$$

$$= -0.05\ \text{V}$$

An Example

- Find D_I required
  - Adjust the threshold voltage to 0.45 V
- We have
  - V_{Tn} = -0.05 V
  - $C_{ox} = 6.9 \times 10^{-7}$ F/cm^2

$$\Delta V_{Tn} = 0.45 - (-0.05) = 0.5 \text{ V}$$

$$\Delta V_{Tn} = \frac{eD_I}{C_{ox}}$$

$$D_I = \frac{C_{ox}}{e} \Delta V_{Tn} = \frac{6.9 \times 10^{-7}}{1.6 \times 10^{-19}} \times 0.5 = 2.16 \times 10^{12} \text{ cm}^{-2}$$

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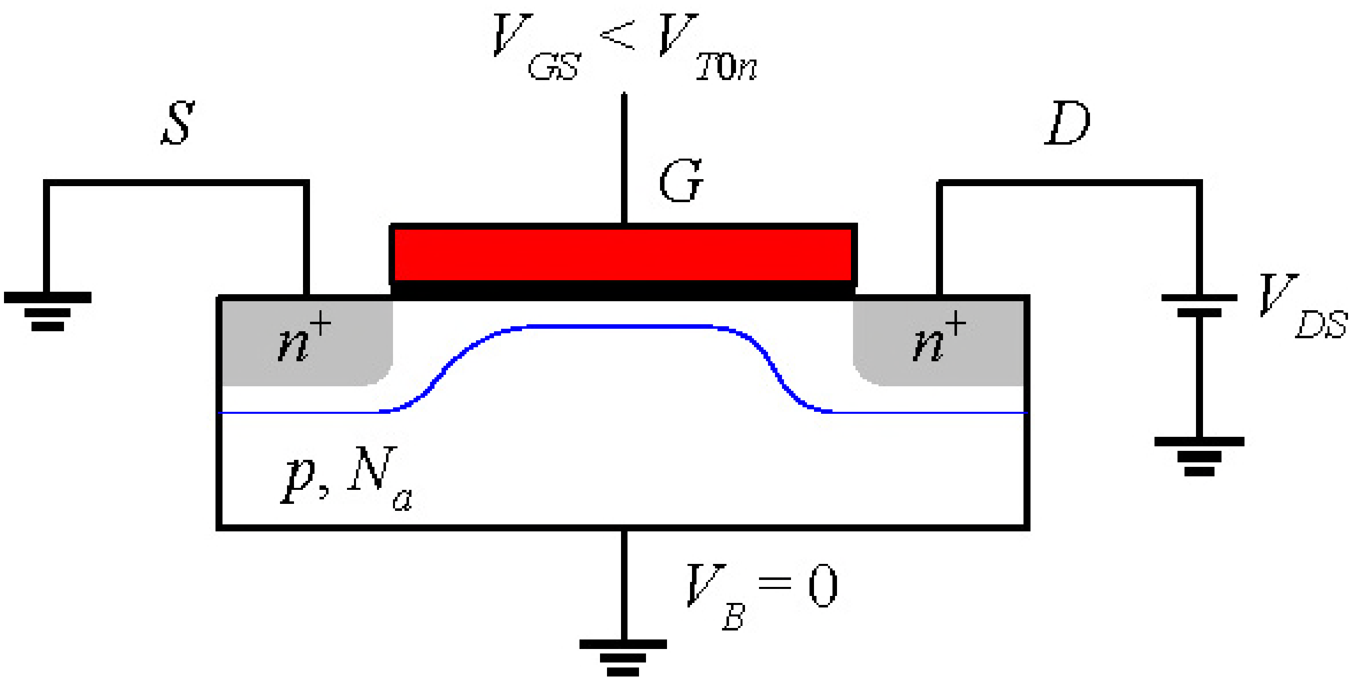
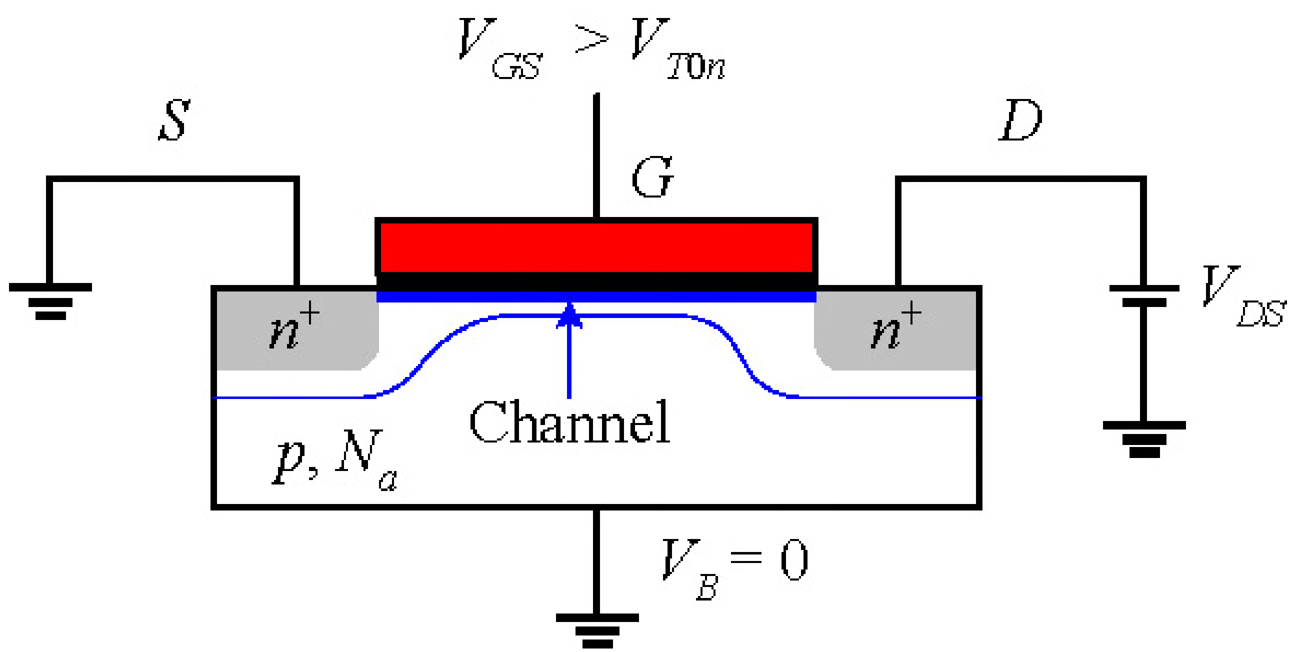
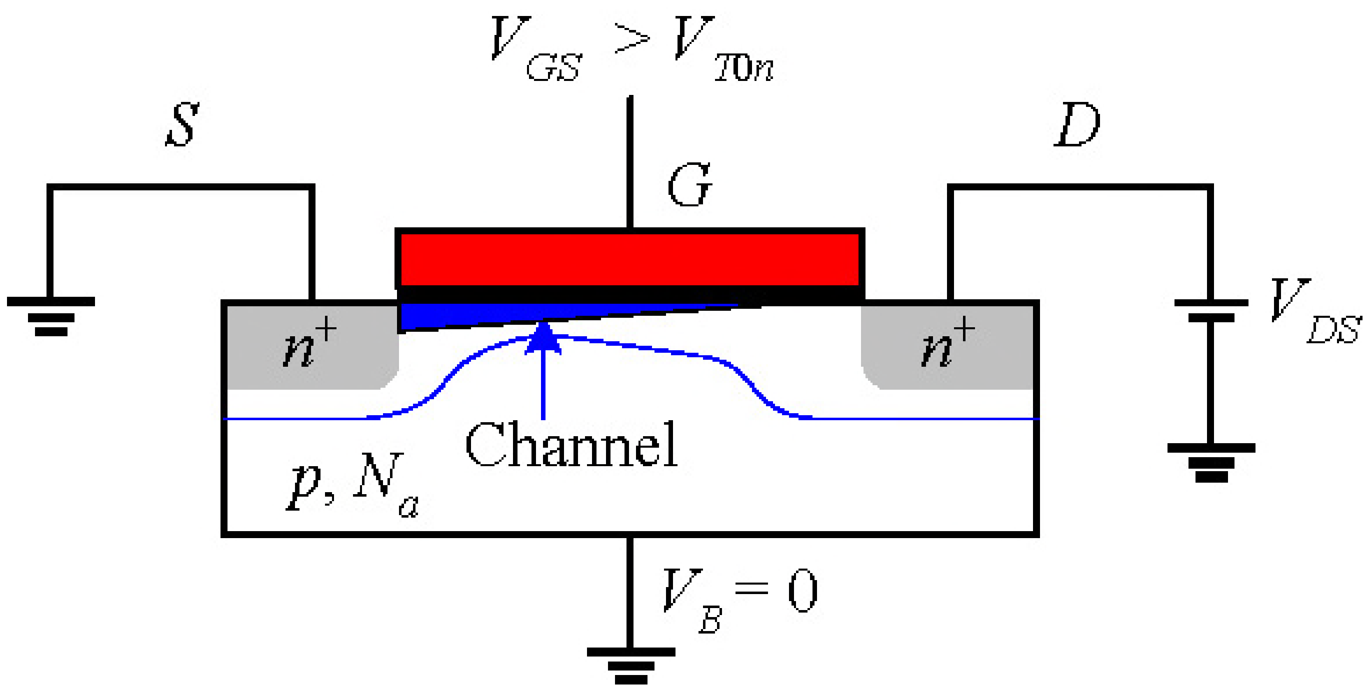
Cutoff Mode



Linear Mode



Saturation Mode



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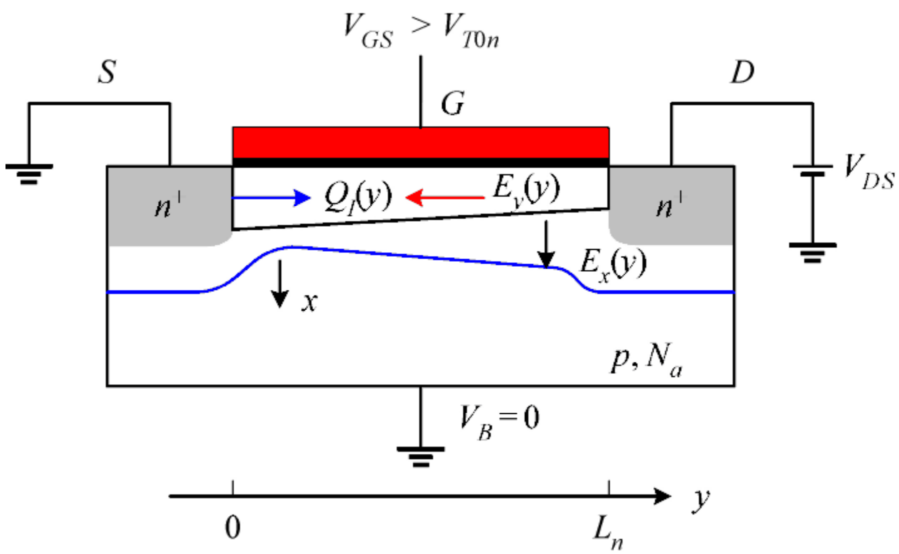
I-*V* Characteristics

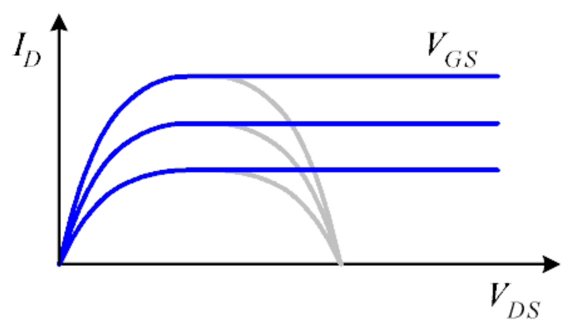
- Gradual channel approximation (GCA)

$$V(y=0) = V_S = 0$$
$$V(y=L) = V_{DS}$$

- $V_{GS} \geqq V_{T0n}$,
- $V_{GD} = V_{GS} - V_{DS} \geqq V_{T0n}$
- Mobility μ_n is constant



(a)



(b)

I-V Characteristics

- Drain current

$$I_D = WQ_I(y)\frac{dy}{dt} = WQ_I(y)v(y)$$

$$Q_I(y) = -C_{ox}[V_{GS} - V_T - V(y)]$$

$$\boxed{I_D = \mu_n C_{ox}\frac{W}{L}\left[\left(V_{GS} - V_T - \frac{1}{2}V_{DS}\right)V_{DS}\right]}$$

- Process transconductance

$$k_n^{'} = \mu_n C_{ox}$$

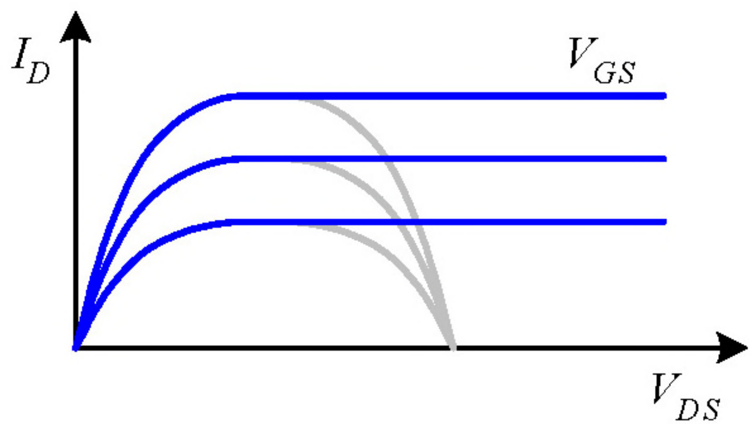
- Device transconductance

$$k_n = \mu_n C_{ox}(W/L)$$

I-V Characteristics

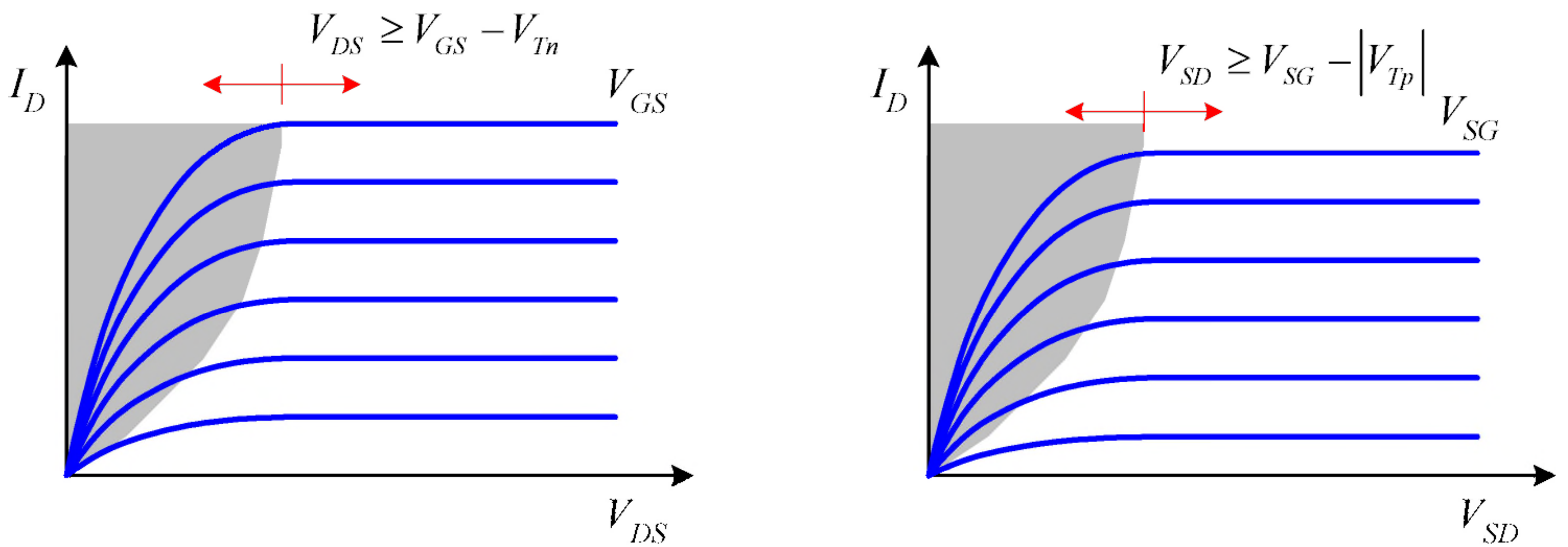
- Drain current

$$I_{Dsat} = I_D(V_{DS} = V_{DSsat}) = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_{Tn}\right)^2$$



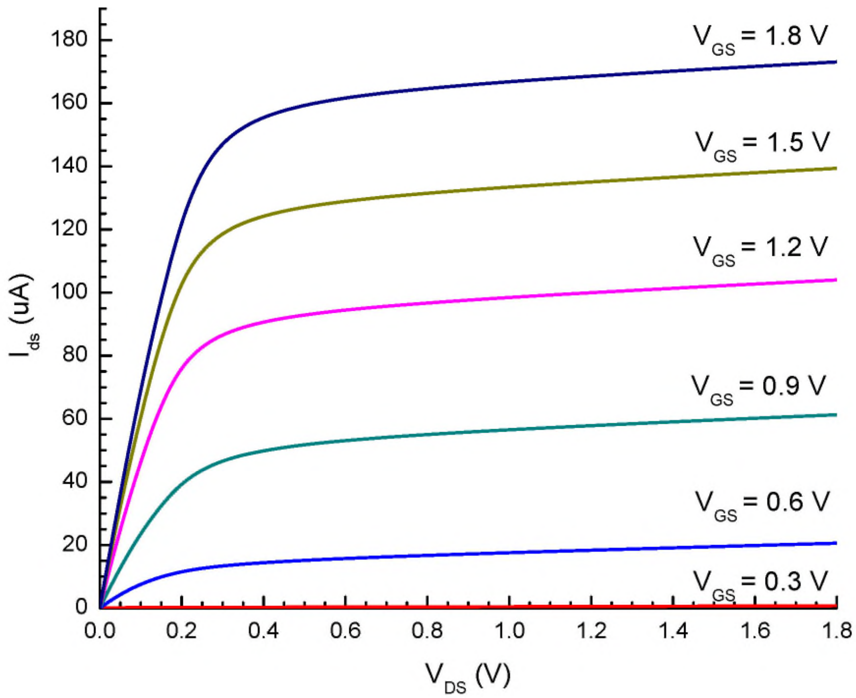
(b) *I-V* characteristics

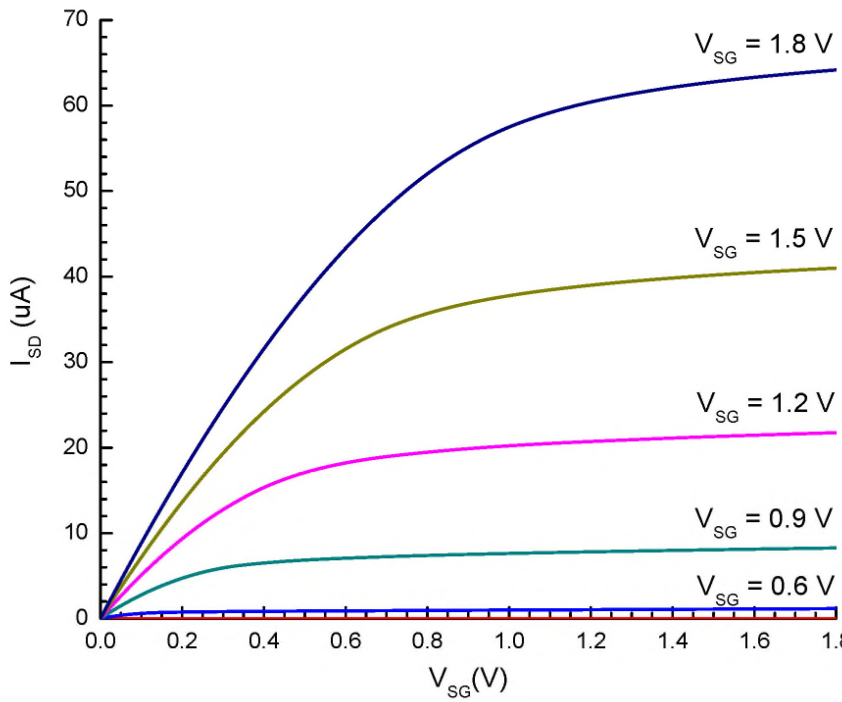
I-*V* Characteristics



(a) (b)

I-V Characteristics





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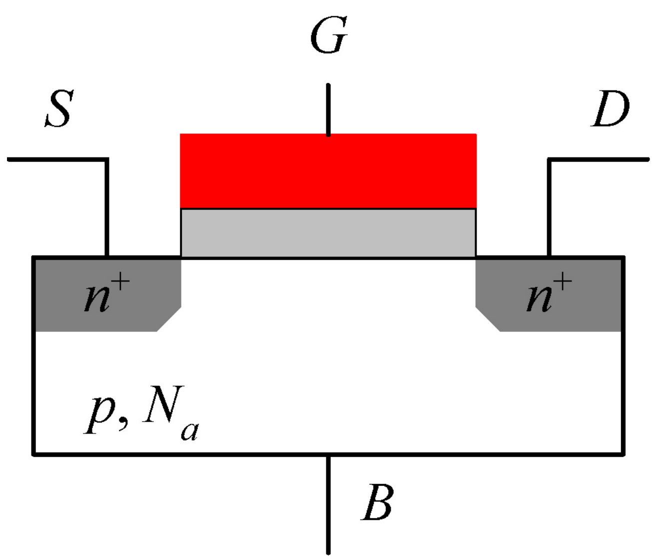
Scaling Theory

- Constant-field scaling
  - Full scaling
- Constant-voltage scaling

Scaling Theory

- Concepts of scaling
  - k = 0.7 for each generation



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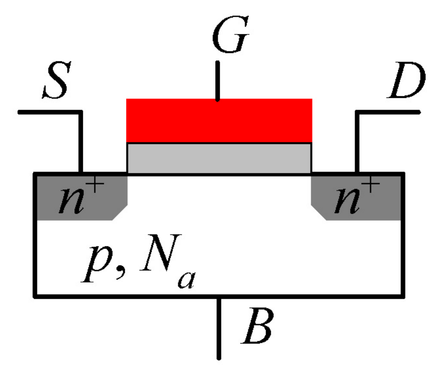

(b)

Constant Field Scaling

- Poisson's equation

$$\nabla^2 \phi(x, y, z) = -\frac{\rho(x, y, z)}{\varepsilon} \qquad \text{(Poisson's equation)}$$

- Let $x' = kx$, $y' = ky$, $z' = kz$

$$\frac{\partial^2 \phi'}{\partial (kx)^2} + \frac{\partial^2 \phi'}{\partial (ky)^2} + \frac{\partial^2 \phi'}{\partial (kz)^2} = -\frac{\rho'}{\varepsilon}$$

$\phi' = k\phi$ and $\rho' = \rho / k$

$N'_a = N_a / k$ and $N'_d = N_d / k$

Constant Field Scaling

- Gate oxide capacitance

$$C_{ox}^{'} = \frac{\varepsilon_{ox}}{t_{ox}^{'}} = \frac{1}{k} C_{ox}$$

- Drain current

$$I_D^{'} = kI_D$$

$$I_{Dsat}^{'} = kI_{Dsat}$$

- Power dissipation

$$P' = I_D^{'} V_{DS}^{'} = k^2 I_D V_{DS} = k^2 P$$

Constant Voltage Scaling

- All dimensions are scaled down
- All voltages are kept unchanged

Constant Voltage Scaling

- Gate oxide capacitance

$$C_{ox}^{'} = \frac{\varepsilon_{ox}}{t_{ox}^{'}} = \frac{1}{k} C_{ox}$$

- Drain current

$$I_D^{'} = \frac{1}{k} I_D \qquad\qquad I_{Dsat}^{'} = \frac{1}{k} I_{Dsat}$$

- Power dissipation

$$P' = I_D^{'} V_{DS}^{'} = \frac{1}{k} I_D V_{DS} = \frac{1}{k} P$$

Summary of Scaling

Table 2.3: Effects of constant-field and constant-voltage scaling ($0 < k < 1$).

Device and circuit parameters	Scaled factor: Constant field	Scaled factor: Constant voltage
Device parameters (L, t_{ox}, W, x_j)	k	k
Impurity concentrations (N_a, N_d)	$1/k$	$1/k^2$
Voltages (V_{DD}, V_{DS}, and V_{GS})	k	1
Depletion-layer thickness ($x_{d(max)}$)	k	k
Capacitance ($C = \varepsilon A/d$)	k	k
Drain current (I_{DS})	k	$1/k$
Device density	$1/k^2$	$1/k^2$
Power density (P/A)	1	$1/k^3$
Power dissipation per device ($P_D = I_{DS}V_{DS}$)	k^2	$1/k$
Circuit propagation delay ($t_{pd} = R_{on}C_{load}$)	k	k^2
Power-delay product ($E = P_D t_{pd}$)	k^3	$1/k$

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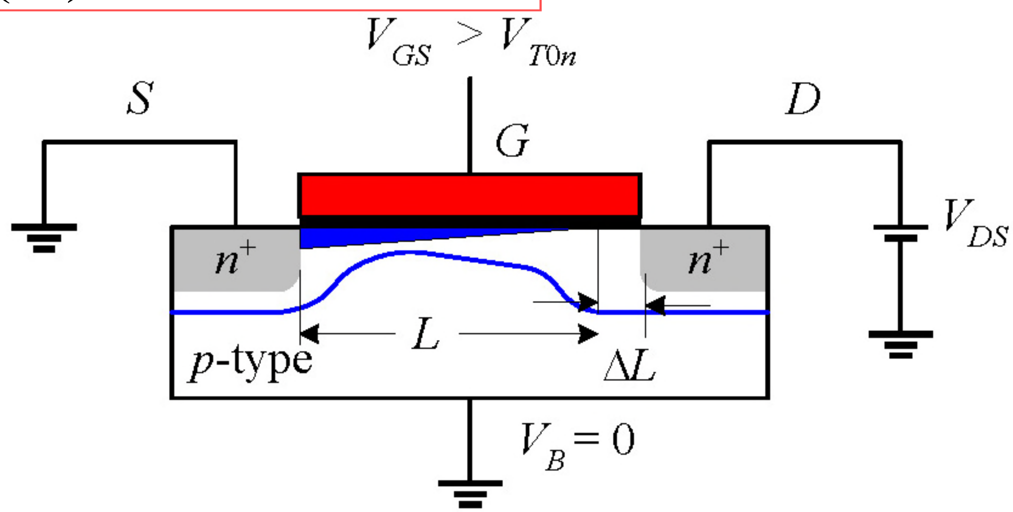
Channel-Length Modulation

- An empirical relation

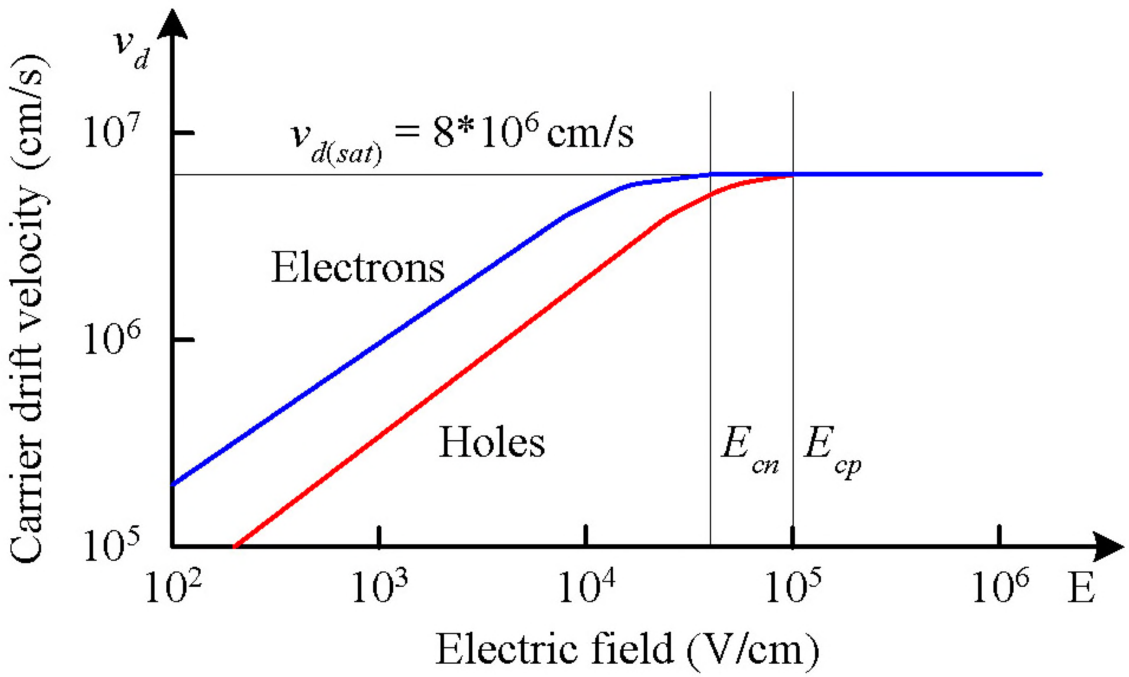
$$I'_D = \left(\frac{L}{L-\Delta L}\right) I_D = \frac{1}{1-\lambda V_{DS}} I_D$$

$$\boxed{I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)(V_{GS}-V_T)^2(1+\lambda V_{DS})}$$



Velocity Saturation

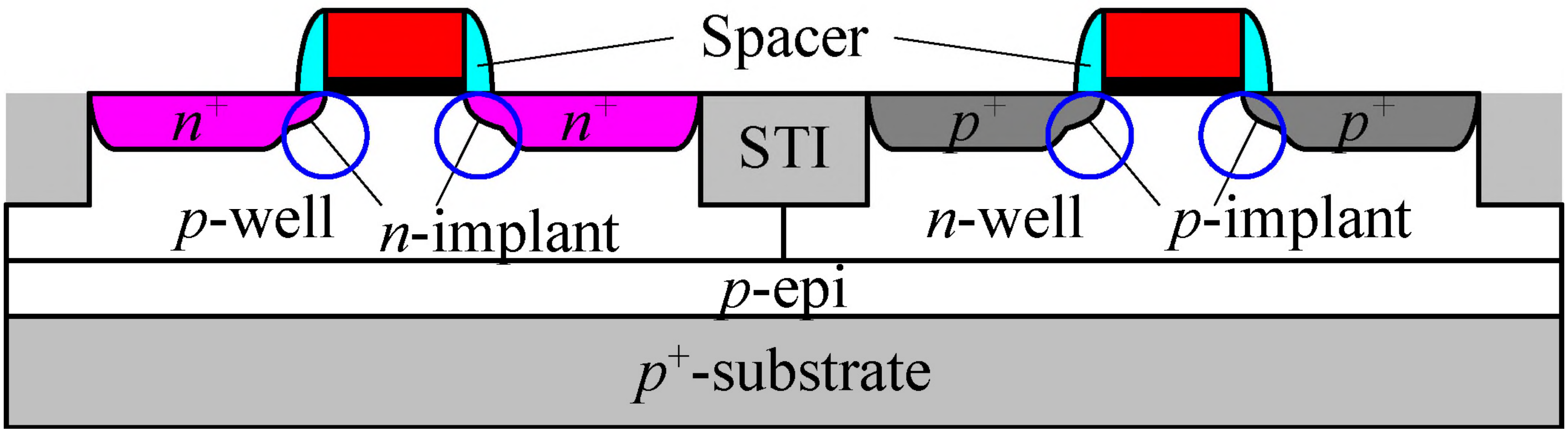
- The total velocity is the sum of
  - the random thermal velocity
  - drift velocity due to an electric field



Hot Carriers

- What are hot carriers?
- Hot-electron injection (HEI)
- Hot carrier effects
  - Substrate current
  - Device degradation
  - Gate leakage current

Lightly-Doped Drain (LDD) Structure



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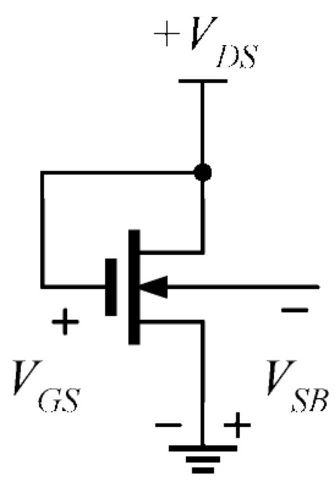
Body Effect

- Threshold voltage

$$V_{Tn} = V_{T0n} + \gamma\left(\sqrt{2|\phi_{fp}| + V_{SB}} - \sqrt{2|\phi_{fp}|}\right)$$

(Body effect coefficient)

$$\gamma = \frac{\sqrt{2\varepsilon_{si} e N_a}}{C_{ox}}$$



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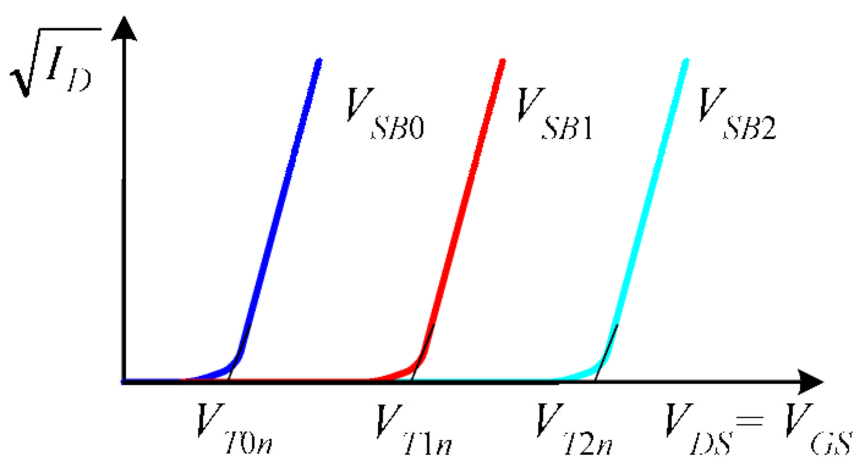

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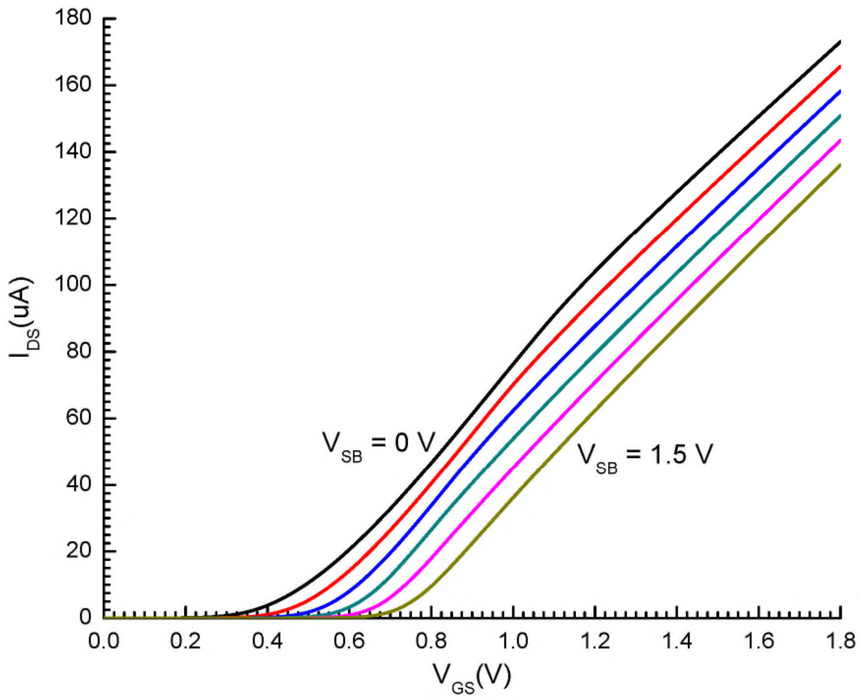
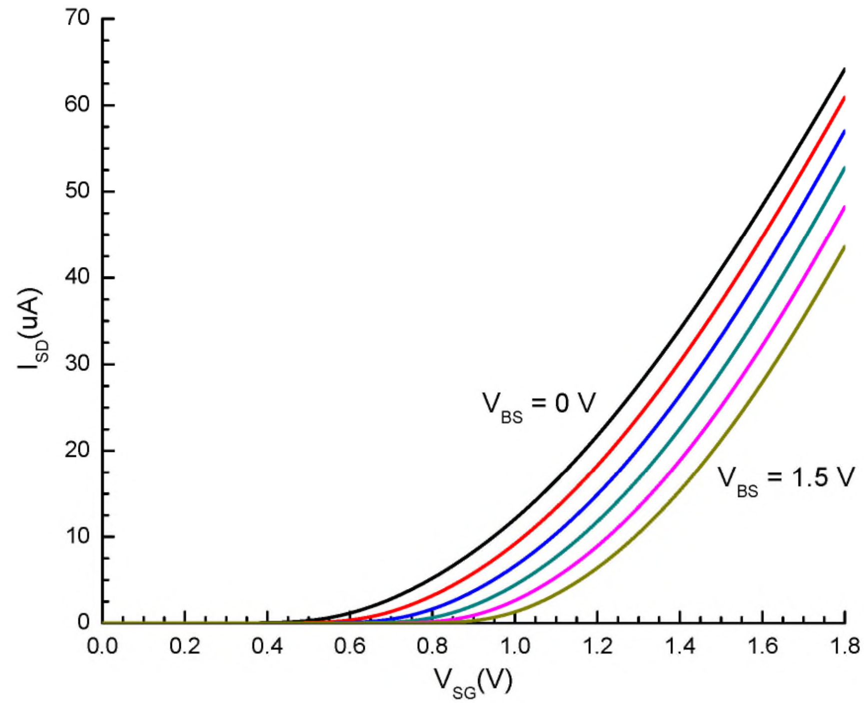
Body Effect



180
160
140
120
100
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
I_DS(uA)
V_GS(V)
V_SB = 0 V
V_SB = 1.5 V



70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
I_SD(uA)
V_SG(V)
V_BS = 0 V
V_BS = 1.5 V

Short-Channel Effects

- What is the short-channel effect?
- Short-channel effect
    - Charge sharing
    - Substrate punchthrough
    - Drain-induced barrier lowering (DIBL)

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Leakage Currents

- Junction leakage current
- Subthreshold current
- Gate leakage current

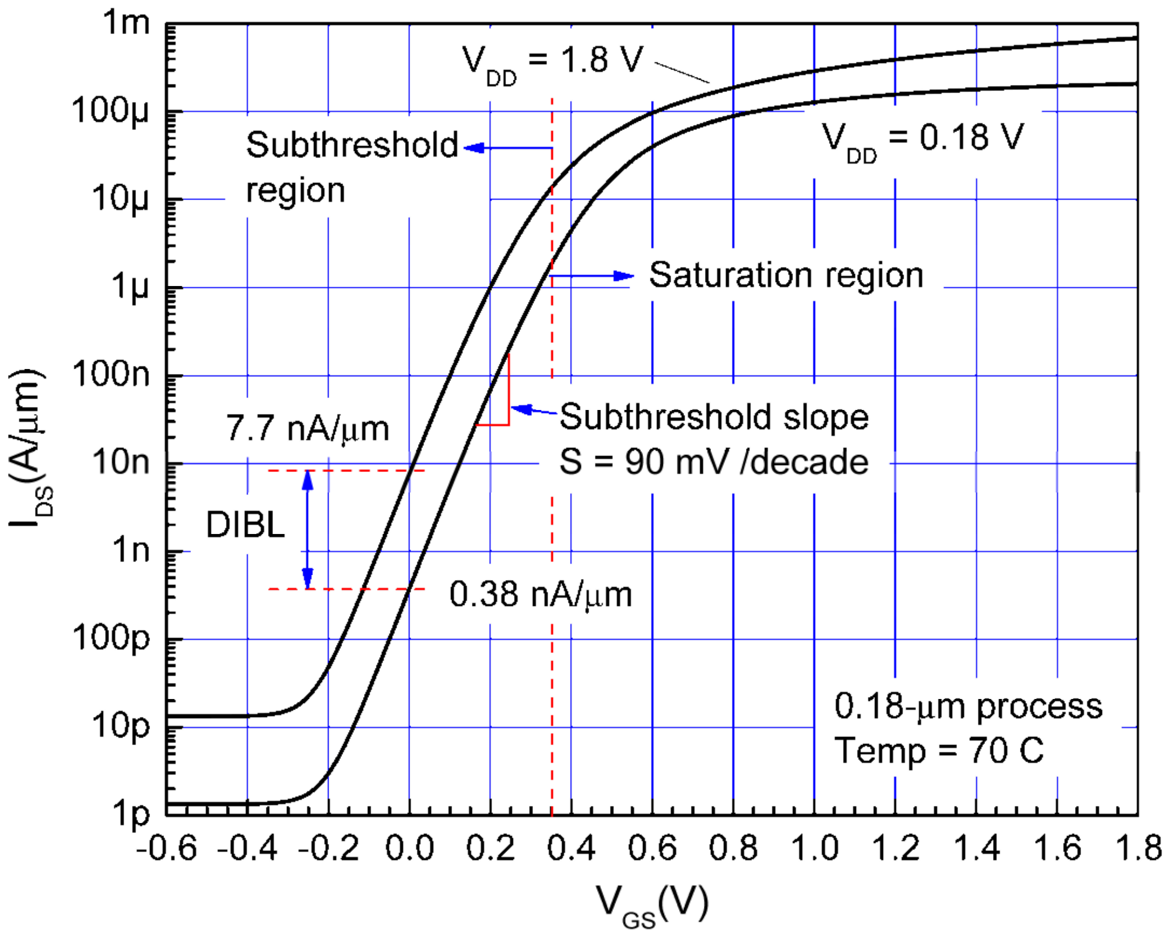
Junction Leakage Current

- Reverse saturation current
- Band-to-band tunneling (BTBT)
  - High electric field (> 10^6 cm/V)

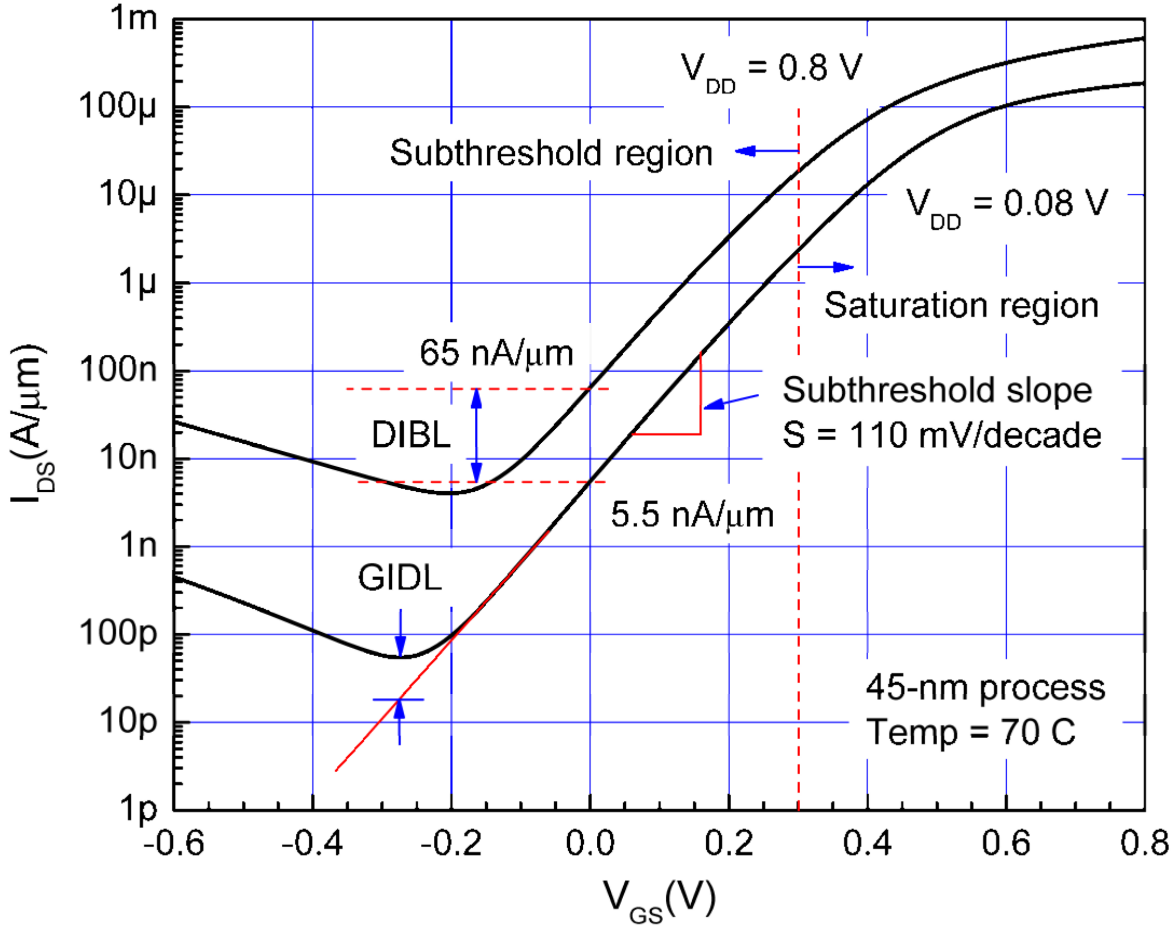
$$I_{BTBT} = A\alpha \frac{EV}{E_g^{1/2}} \exp\left(-\beta \frac{E_g^{3/2}}{E}\right)$$

- Gate-induced drain leakage (GIDL)
  - Gate at low voltage while drain at high voltage

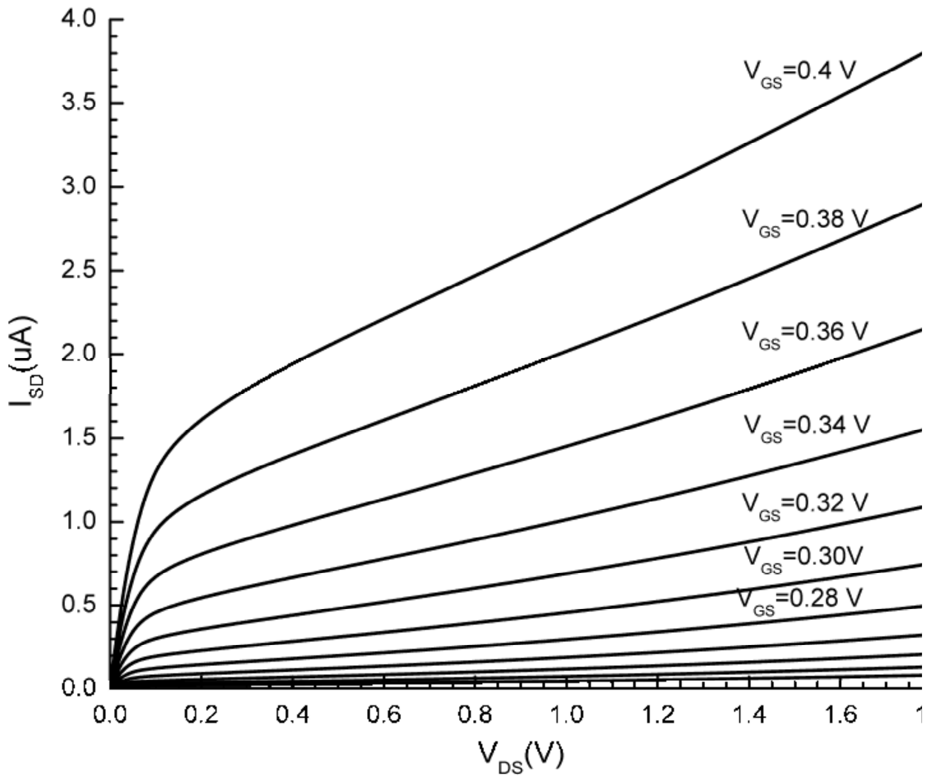
Subthreshold Current

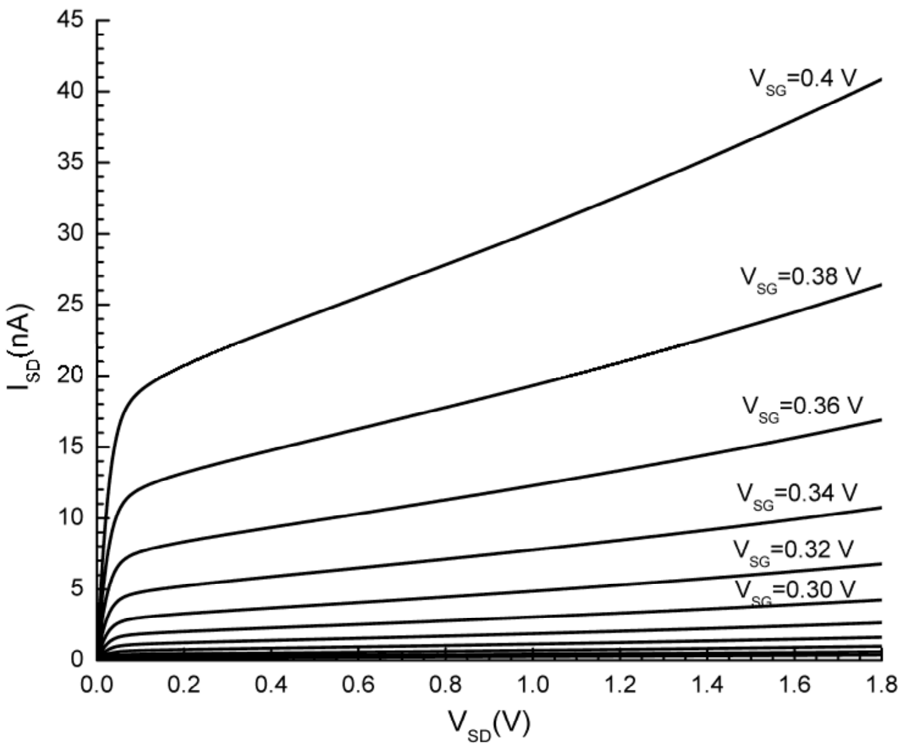


Subthreshold Current



Subthreshold Current





Gate Leakage Current

- Hot carrier injection
- Gate tunneling
  - FN tunneling
  - Direct tunneling

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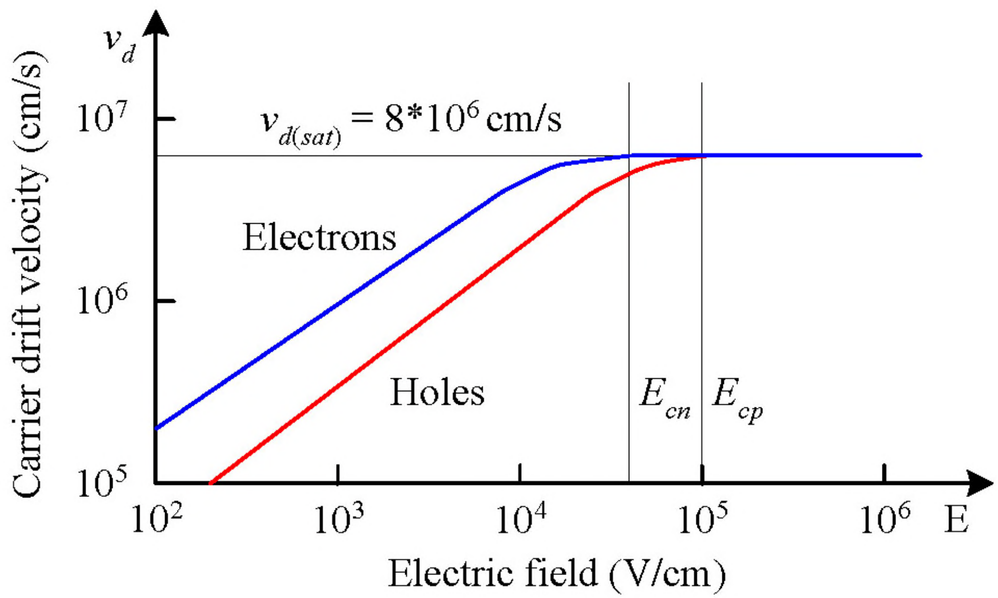
Short-Channel I-V Characteristics

- Electron velocity

$$v = \frac{\mu_{eff} E}{(1 + E / E_{sat})} \qquad E < E_{sat}$$

$$= v_{sat} \qquad E \geq E_{sat}$$

$$E_{sat} = \frac{2 v_{sat}}{\mu_{eff}}$$



Short-Channel *I-V* Characteristics

- Effective mobility

$$\mu_{eff} = \frac{A}{1+\left(\frac{E_{norm}}{B}\right)} \qquad E_{norm} = \frac{V_{GS}+V_T}{6t_{ox}}$$

  - For electron

    A = 670 cm^2/V-s and B = 6.6 $\times$ 10^5 V/cm
  - For holes

    A = 160 cm^2/V-s and B = 7 $\times$ 10^5 V/cm

Short-Channel I-V Characteristics

- Drain current

$$I_D = WC_{ox}[V_{GS} - V_T - V(y)]\frac{\mu_{eff}E(y)}{\left(1 + E(y)/E_{sat}\right)}$$

$$I_D = \mu_{eff}C_{ox}\left(\frac{W}{L}\right)\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}\frac{1}{\left(1 + V_{DS}/E_{sat}L\right)}$$

$$= \mu_n C_{ox}\left(\frac{W}{L}\right)\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} \quad \text{for } E_{sat} >> V_{DS}/L \text{ and } \mu_{eff} = \mu_n$$

Short-Channel I-V Characteristics

- Drain current

$$I_{Dsat} = WC_{ox}\left(V_{GS} - V_T - V_{DSsat}\right)v_{sat}$$

$$= WC_{ox}v_{sat}\frac{(V_{GS} - V_T)^2}{(V_{GS} - V_T) - E_{sat}L}$$

$$= \frac{W}{2L}\mu_{eff}C_{ox}(V_{GS} - V_T)^2 \quad \text{if } E_{sat}L \;>>\; (V_{GS} - V_T)$$

$$= Wv_{sat}C_{ox}(V_{GS} - V_T) \quad \text{if } E_{sat}L \;<<\; (V_{GS} - V_T)$$

- Saturation voltage

$$V_{DSsat} = \frac{(V_{GS} - V_T)E_{sat}L}{(V_{GS} - V_T) + E_{sat}L}$$

  - Converges to $V_{GS} - V_T$ when $E_{sat}L >> V_{GS} - V_T$.

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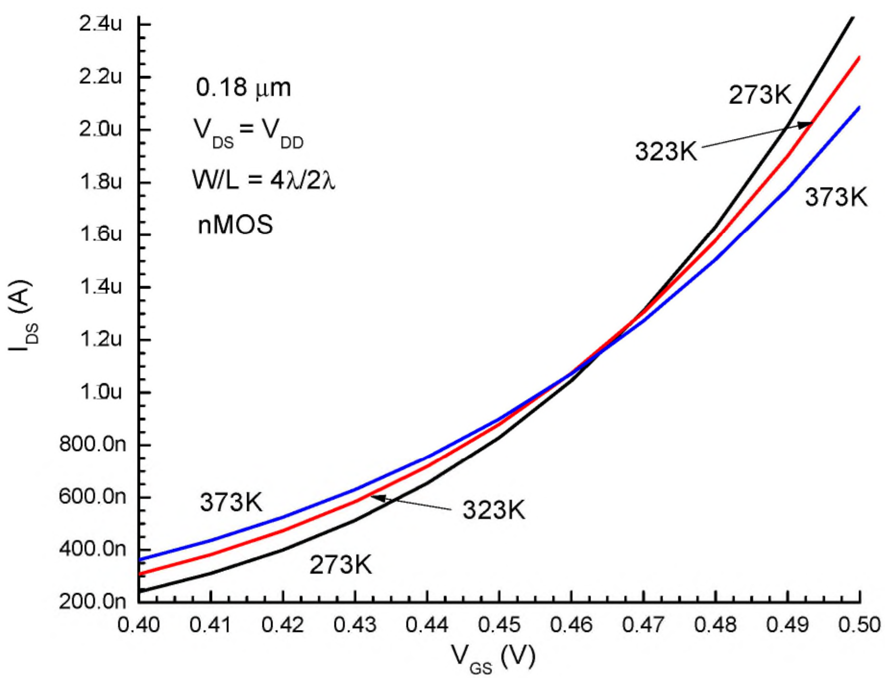
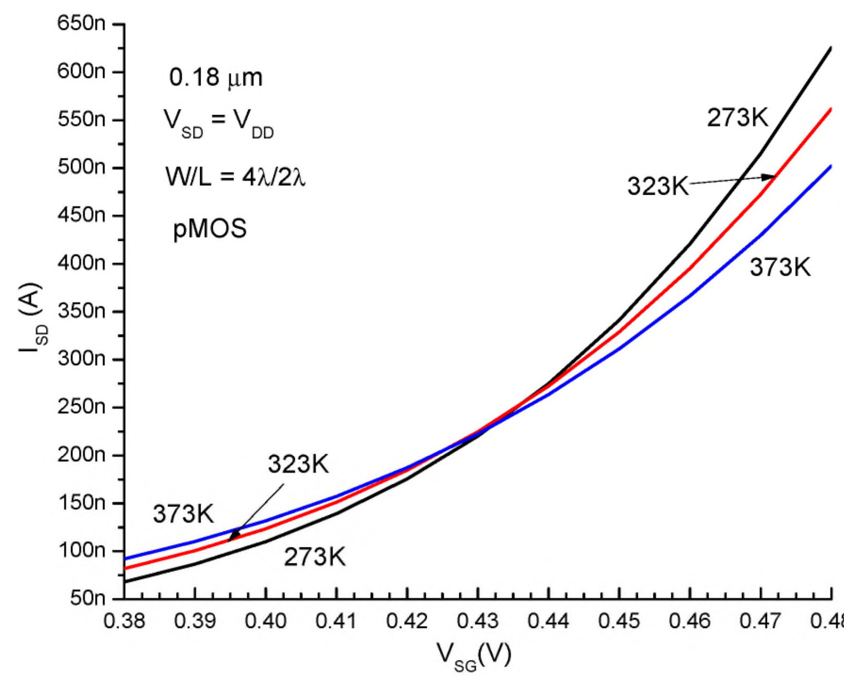
Temperature Effects

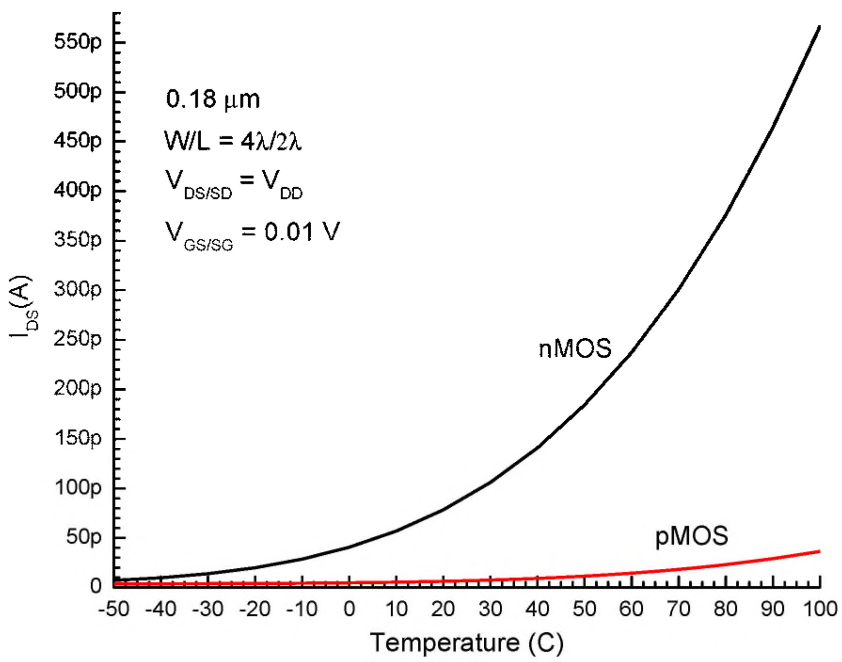
- Below/above threshold voltage

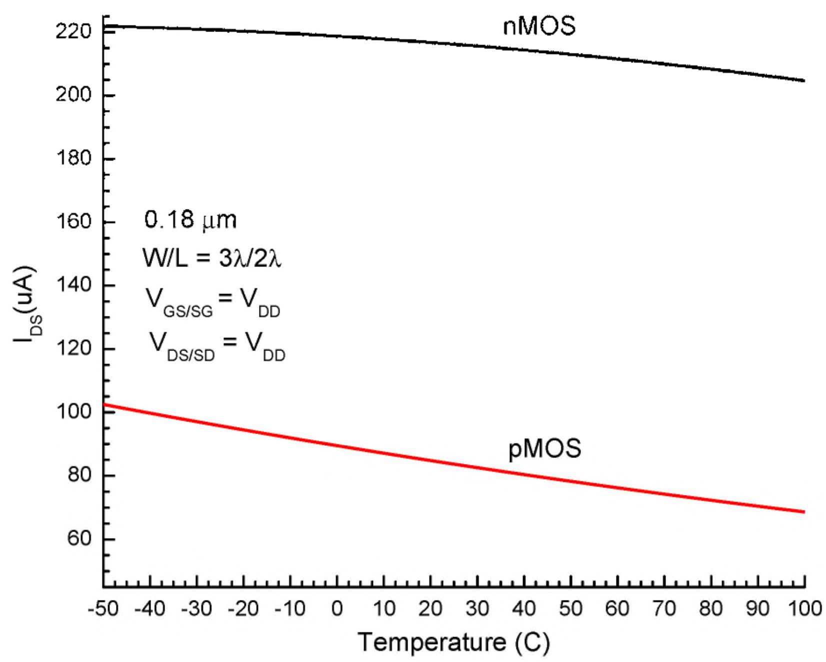




Temperature Effects

- Below/above threshold voltage





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Limitations of MOS Transistors

- Thin-oxide breakdown
- Avalanche breakdown
- Snapback breakdown
- Punch-through effects