

SEMICONDUCTOR DEVICES

Junction Field-Effect Transistors: Part 2



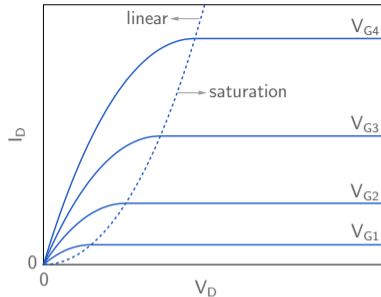
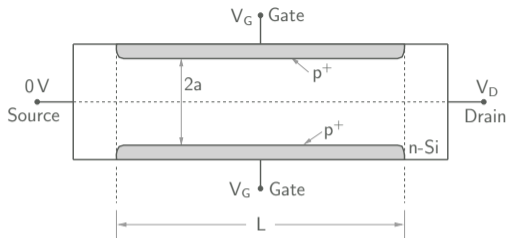
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Indian Institute of Technology Bombay

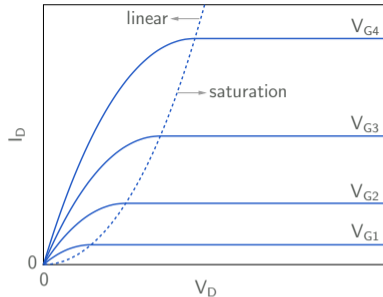
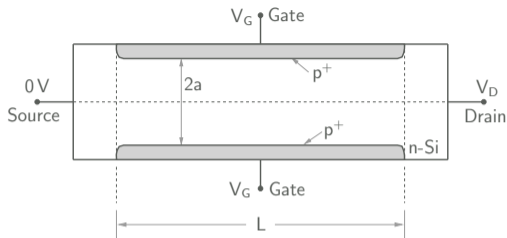
JFET I-V relationship



In the linear region, i.e., $V_D < V_D^{\text{sat}}$,

$$I_D = G_0 \left\{ V_D - \frac{2}{3} (V_{\text{bi}} - V_P) \left[\left(\frac{V_D + V_{\text{bi}} - V_G}{V_{\text{bi}} - V_P} \right)^{3/2} - \left(\frac{V_{\text{bi}} - V_G}{V_{\text{bi}} - V_P} \right)^{3/2} \right] \right\}, \quad G_0 = \frac{(2aZ)}{L} \times (q\mu_n N_d).$$

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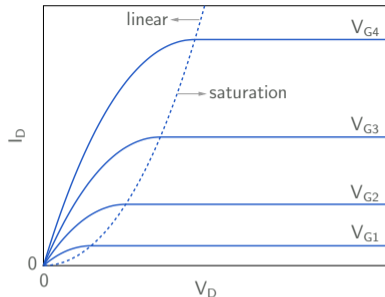
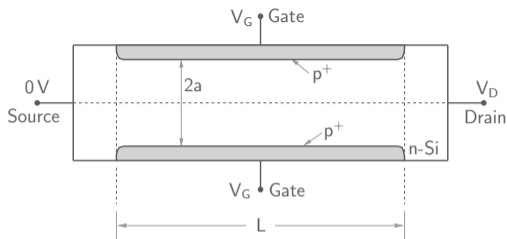


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Pinch-off (saturation): $V_G - V_D = V_P \rightarrow V_D^{\text{sat}} = V_G - V_P$.

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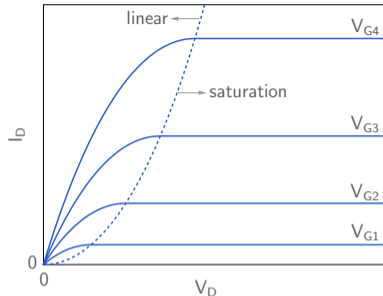
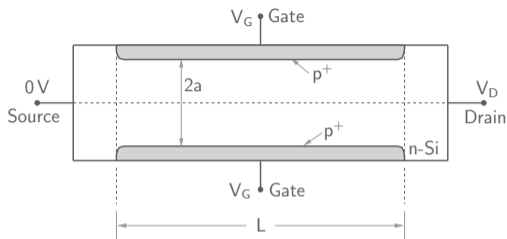
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Substituting in the I_D equation, we get

$$I_D^{\text{sat}}(V_G) = G_0 \left\{ (V_G - V_P) - \frac{2}{3} (V_{\text{bi}} - V_P) \left[1 - \left(\frac{V_{\text{bi}} - V_G}{V_{\text{bi}} - V_P} \right)^{3/2} \right] \right\}.$$

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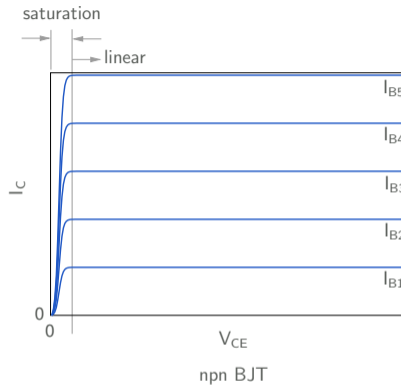
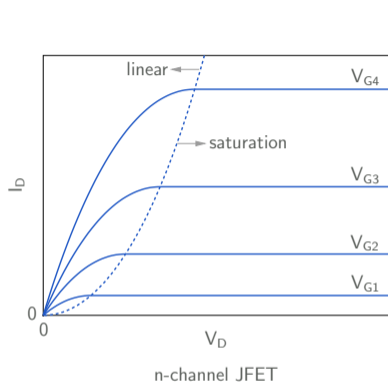
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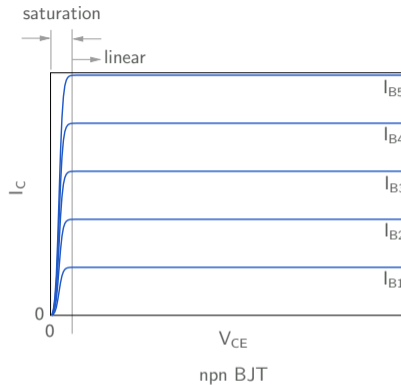
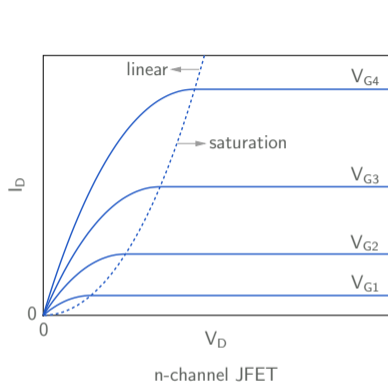
$$I_D^{\text{sat}}(V_G) = G_0 \left\{ (V_G - V_P) - \frac{2}{3} (V_{\text{bi}} - V_P) \left[1 - \left(\frac{V_{\text{bi}} - V_G}{V_{\text{bi}} - V_P} \right)^{3/2} \right] \right\}.$$

Note that I_D^{sat} depends on V_G . For an n -channel JFET, $I_D^{\text{sat}} \downarrow$ as $V_G \downarrow$

Comparison of JFET and BJT I - V relationships

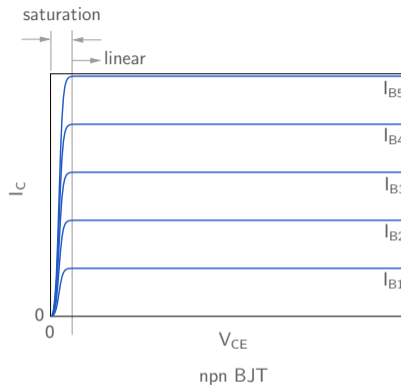
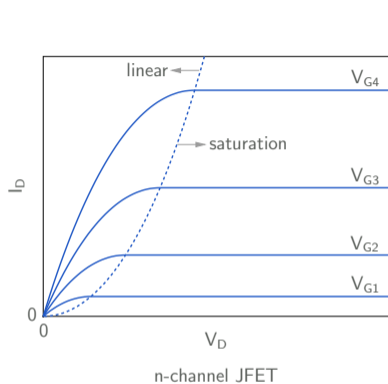


Comparison of JFET and BJT I - V relationships



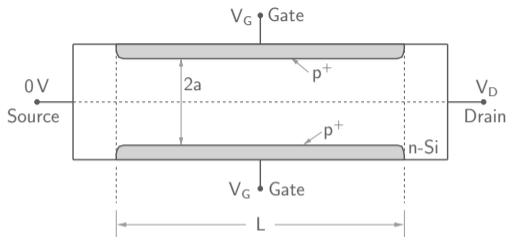
* Note the different nomenclature for linear and saturation regions.

Comparison of JFET and BJT I - V relationships



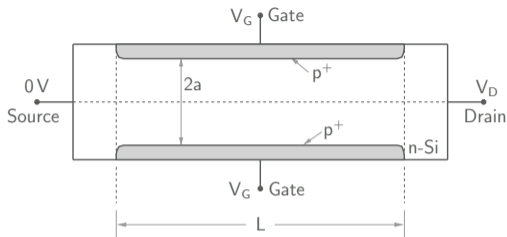
- * Note the different nomenclature for linear and saturation regions.
- * In a BJT, $V_{CE}^{\text{sat}} \approx 0.2 \text{ V}$ irrespective of I_B .
In a JFET, $V_D^{\text{sat}} (= V_G - V_P)$ depends on V_G .

Example



For an n -channel Si JFET with $N_d = 1 \times 10^{17} \text{ cm}^{-3}$, $\mu_n = 300 \text{ cm}^2/\text{V-s}$, $a = 0.2 \text{ } \mu\text{m}$, $L = 5 \text{ } \mu\text{m}$, $Z = 10 \text{ } \mu\text{m}$, $V_{bi} = 0.9 \text{ V}$ for the p^+n gate-to-channel junction,

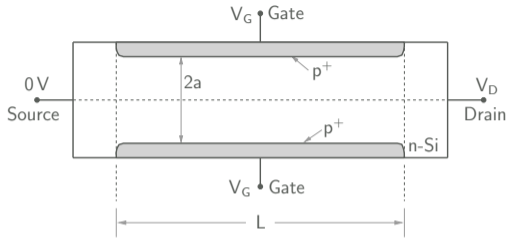
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(a) What is the pinch-off voltage V_P ?

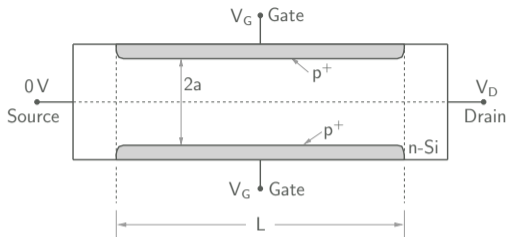
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- (a) What is the pinch-off voltage V_P ?
- (b) Plot I_D versus V_G for $-2.5 \text{ V} < V_G < 0 \text{ V}$ and with (i) $V_D = 0.1 \text{ V}$ and (ii) $V_D = 5 \text{ V}$.

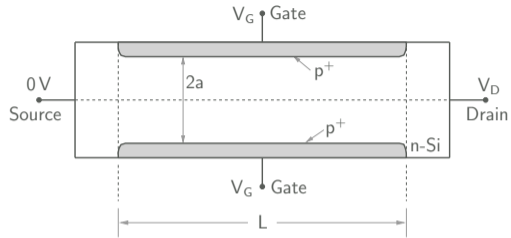
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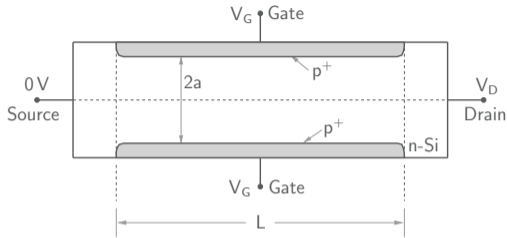
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- (c) Plot I_D versus V_D for $0 \text{ V} < V_D < 5 \text{ V}$ and $V_G = -1.5, -1, -0.5, 0 \text{ V}$. Mark the boundary between the linear and saturation regions.

Example



(a) $V_P = V_{bi} - \frac{qN_d}{2\epsilon} a^2 = -2.2 V.$

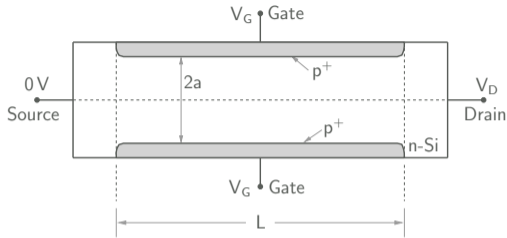
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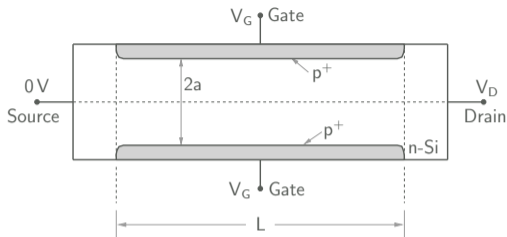


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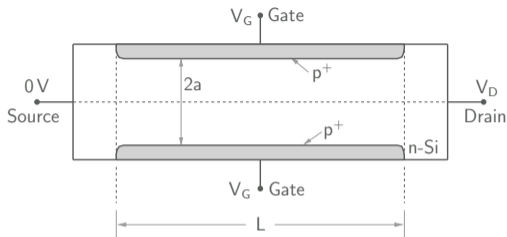
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$$G_0 = \frac{2aZ}{L} q\mu_n N_d = \frac{2 \times 0.2 \times 10^{-4} \times 10 \times 10^{-4}}{5 \times 10^{-4}} \times 1.6 \times 10^{-19} \times 300 \times 10^{17} = 3.84 \times 10^{-4} \text{ V} = 0.384 \text{ mV}.$$

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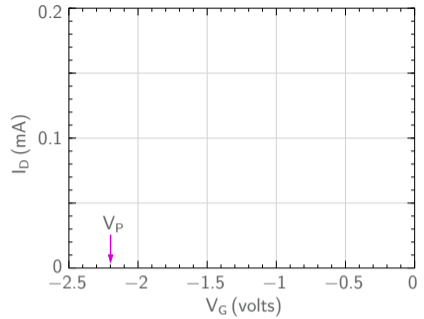
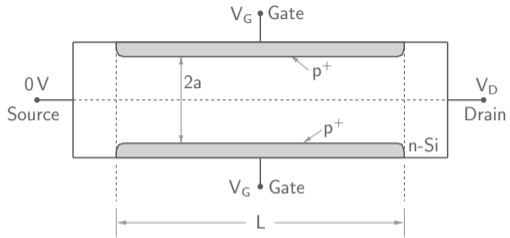
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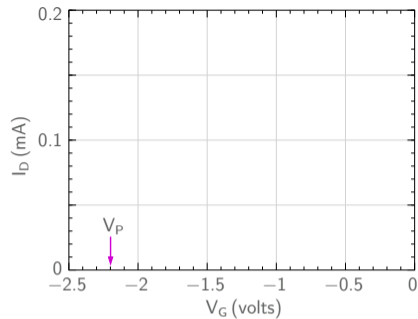
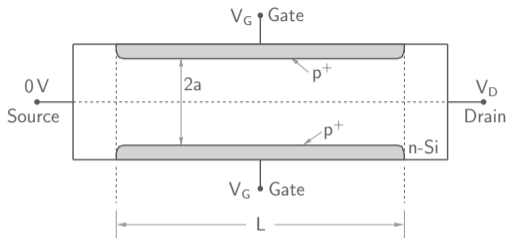
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$$\text{Units: } \frac{\text{cm} \times \text{cm}}{\text{cm}} \times \text{Coul} \times \frac{\text{cm}^2}{\text{V-sec}} \times \frac{1}{\text{cm}^3} = \frac{\text{A}}{\text{V}} = \mathcal{U}.$$

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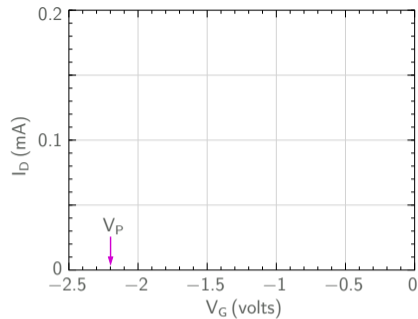
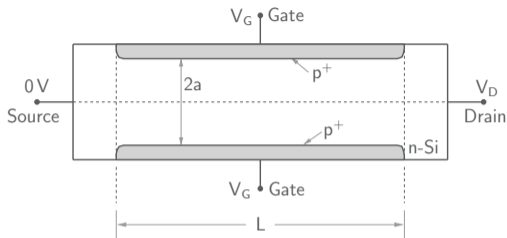


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(b) For the transistor to be in the linear region, we need $V_G - V_D > V_P$, i.e., $V_G > V_P + V_D$.

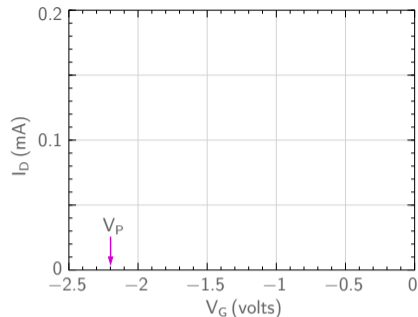
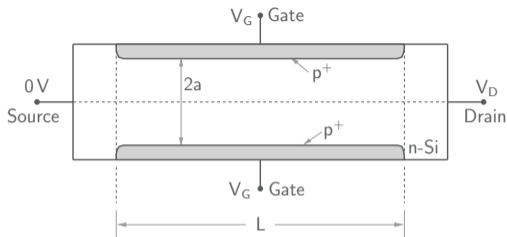
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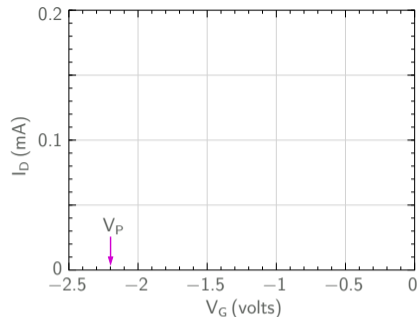
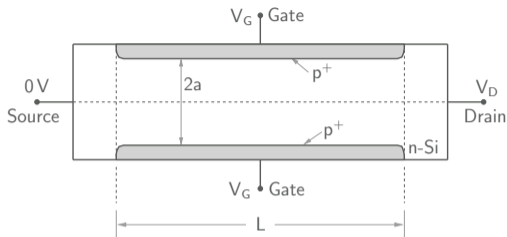
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(Note: such a large V_G is not realistic.)

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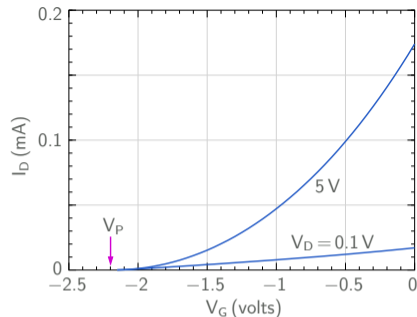
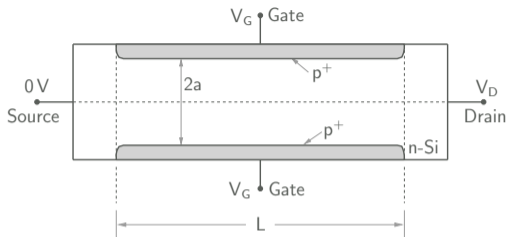
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The I_D - V_G plot can now be obtained using the appropriate I_D expression.

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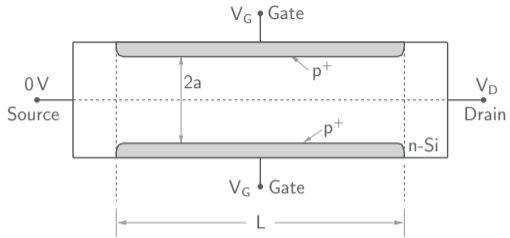
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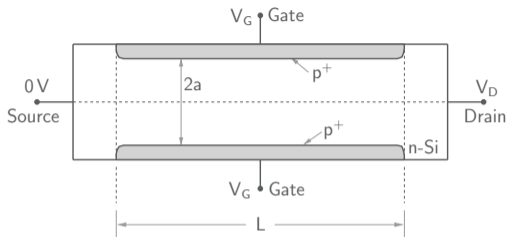
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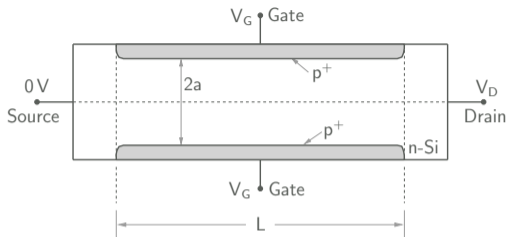


Example



$$\begin{aligned} \text{(c) } I_D &= G_0 \left\{ V_D - \frac{2}{3} (V_{bi} - V_P) \left[\left(\frac{V_D + V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} - \left(\frac{V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} \right] \right\}, & V_D < V_D^{\text{sat}} \\ &= G_0 \left\{ (V_G - V_P) - \frac{2}{3} (V_{bi} - V_P) \left[1 - \left(\frac{V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} \right] \right\}, & V_D > V_D^{\text{sat}} \end{aligned}$$

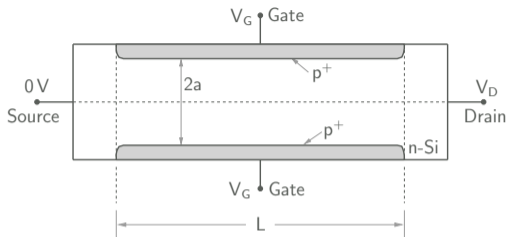
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For each V_G , we first find V_D^{sat} . For example, with $V_G = -1.5\text{V}$, $V_D^{\text{sat}} = V_G - V_P = -1.5 - (-2.2) = 0.7\text{V}$.

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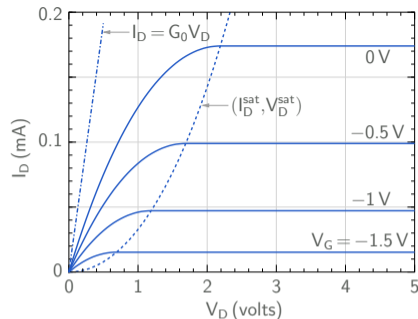
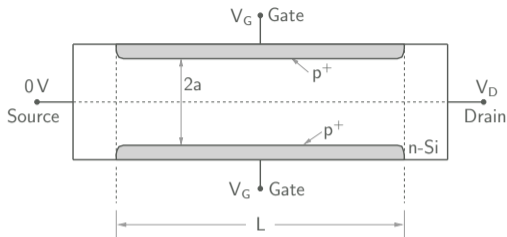


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We then use the appropriate I_D expression to obtain the I_D - V_D plot for that particular V_G .

Example

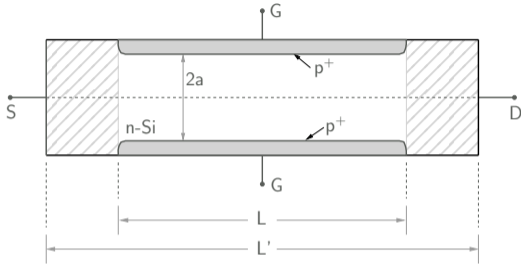


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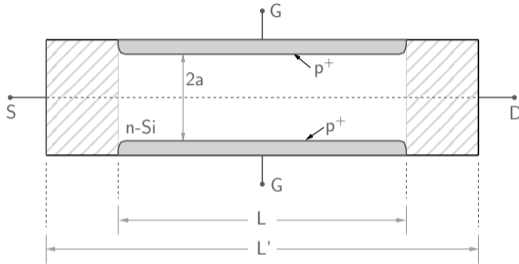
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JFET source/drain resistances

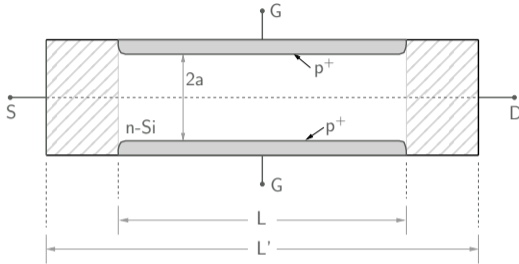


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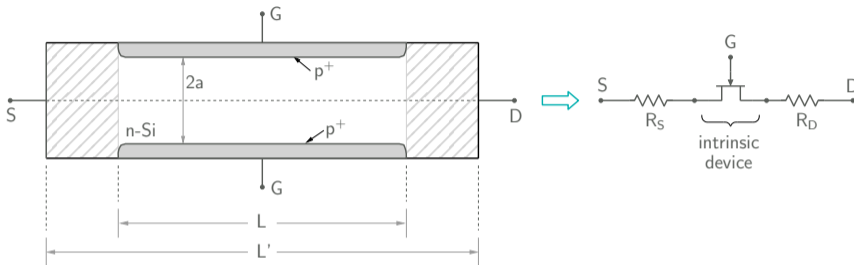


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JFET source/drain resistances

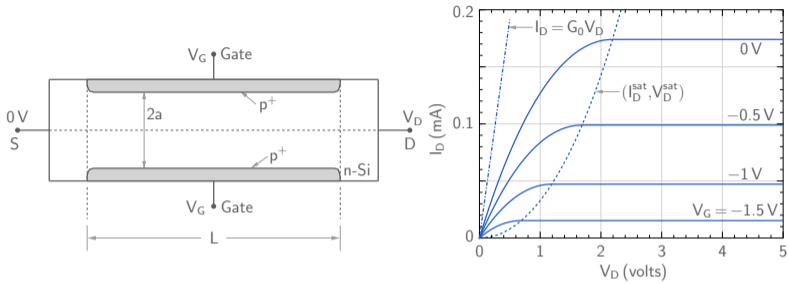


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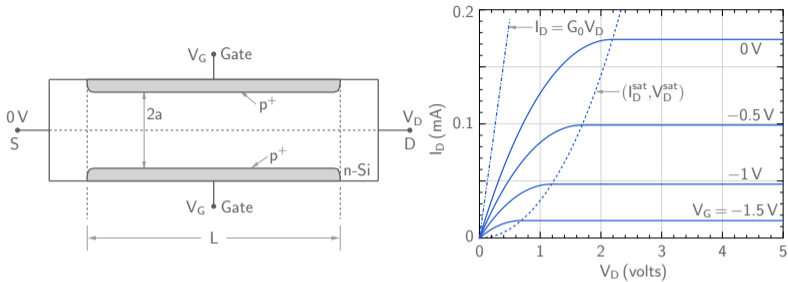


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Simplified JFET model for circuit analysis

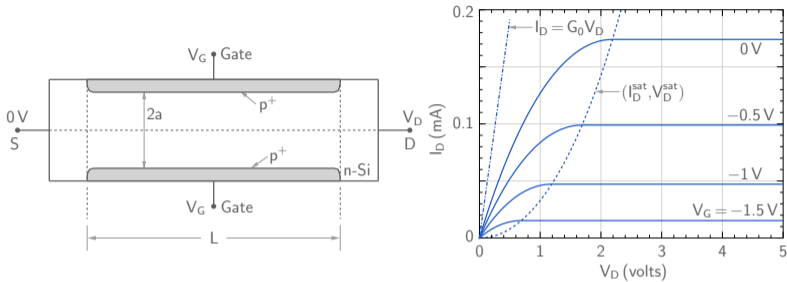


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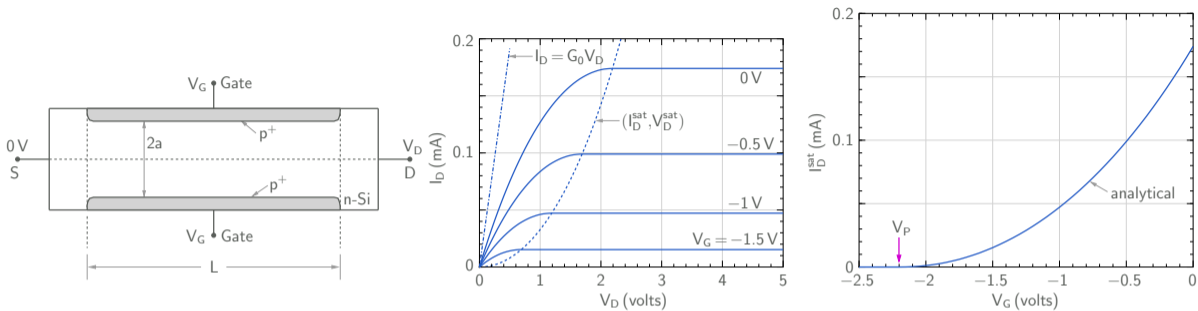
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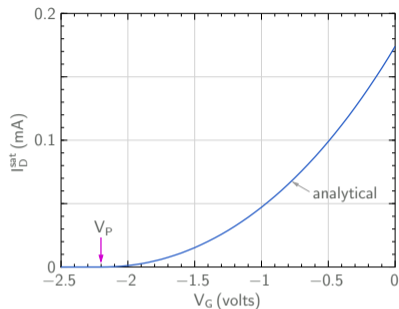
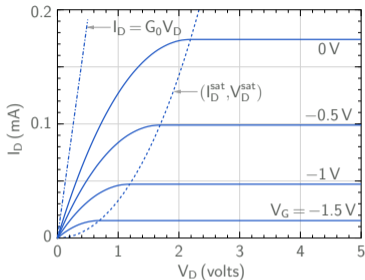
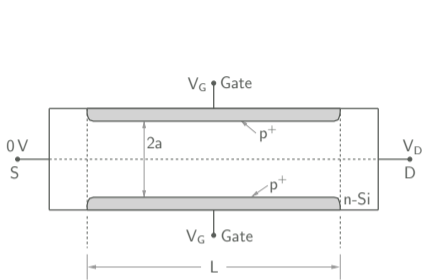
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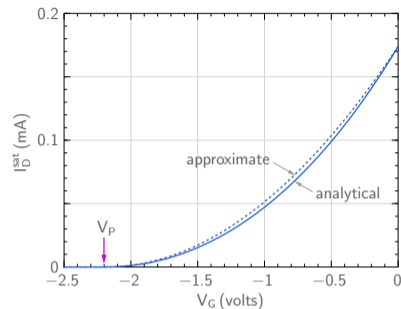
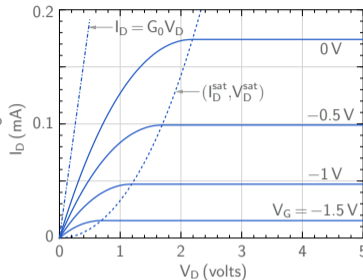
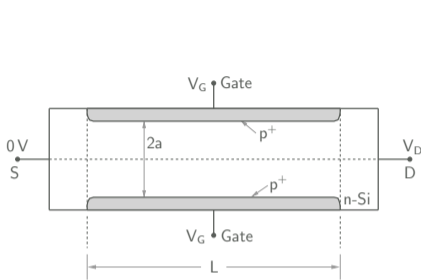
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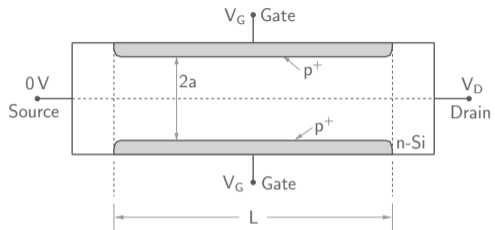
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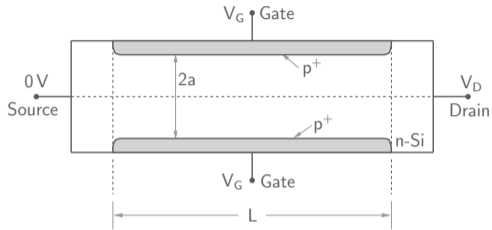
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JFET small-signal model



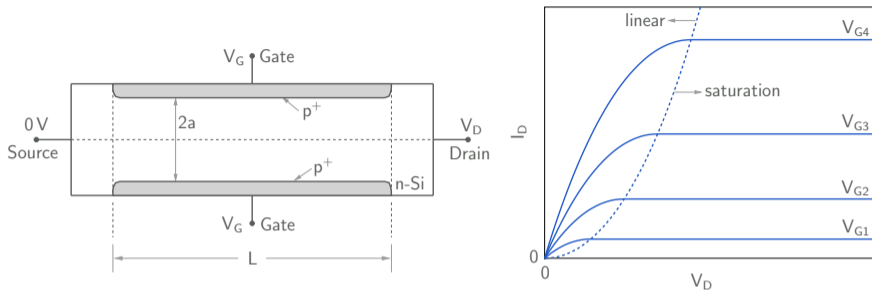
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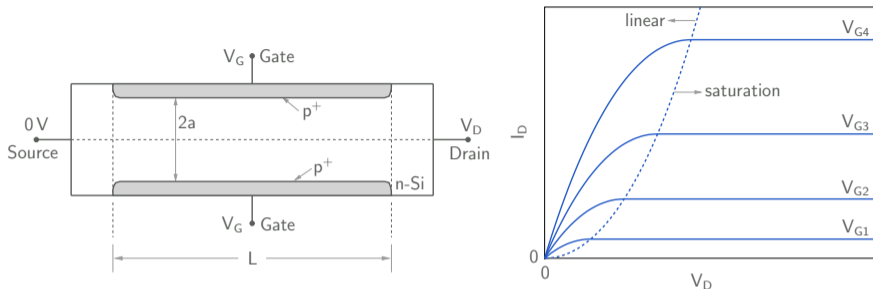
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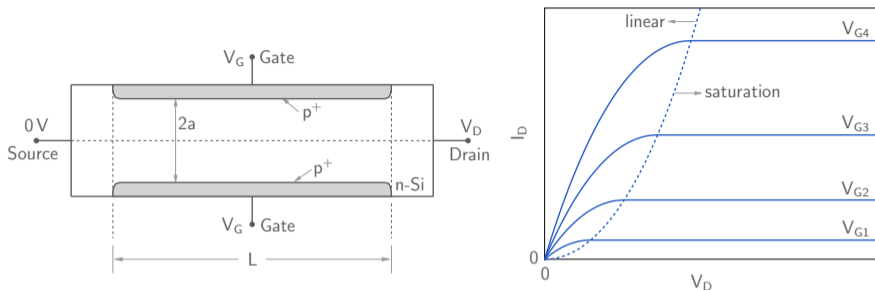
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$$\Delta I_D = \frac{\partial I_D}{\partial V_G} \Delta V_G + \frac{\partial I_D}{\partial V_D} \Delta V_D.$$

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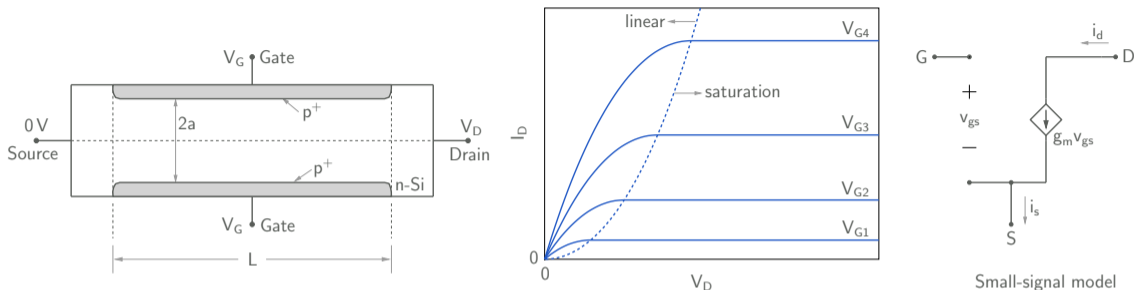
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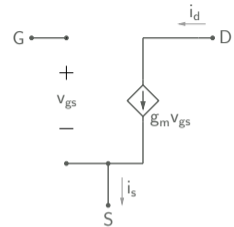
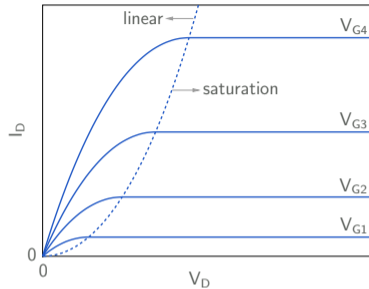
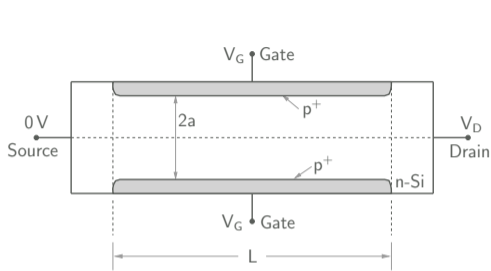
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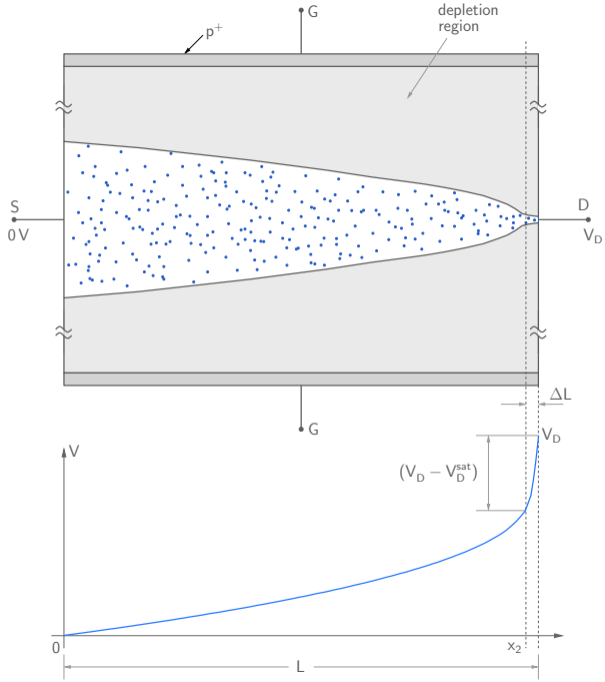
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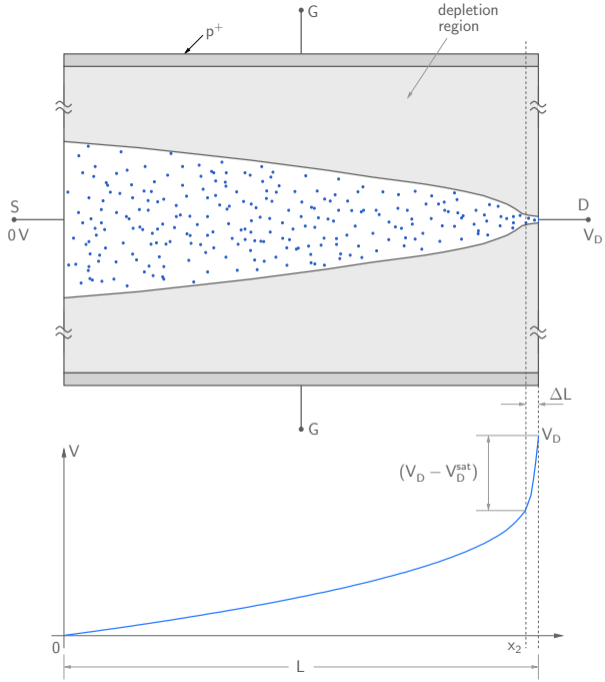
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(Note that there is a reverse biased *pn* junction between G and S and between G and D. $\rightarrow i_g = 0$.)

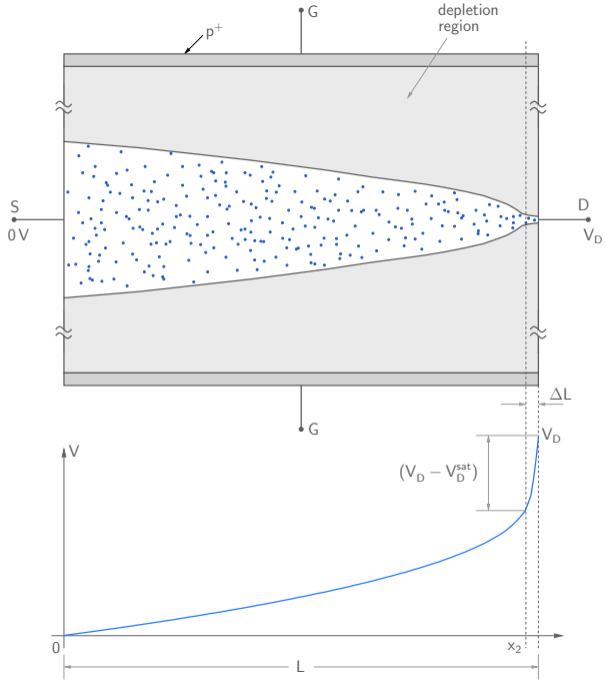


Channel length modulation:



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- * In saturation, the actual channel length is $L_{\text{eff}} = L - \Delta L$.



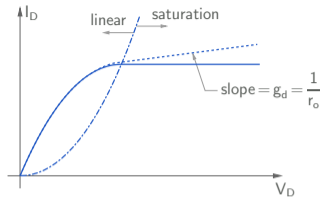
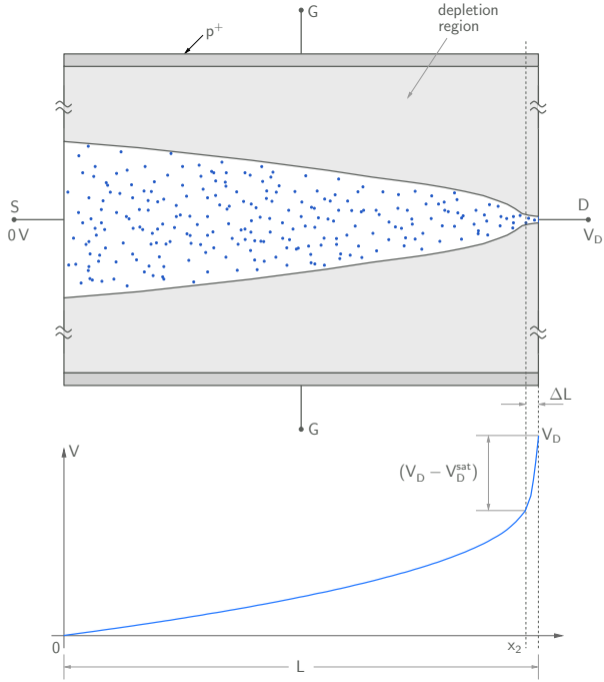
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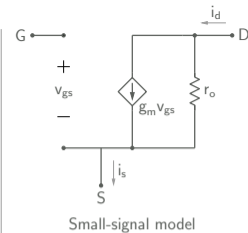
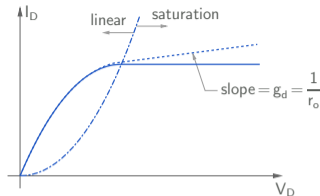
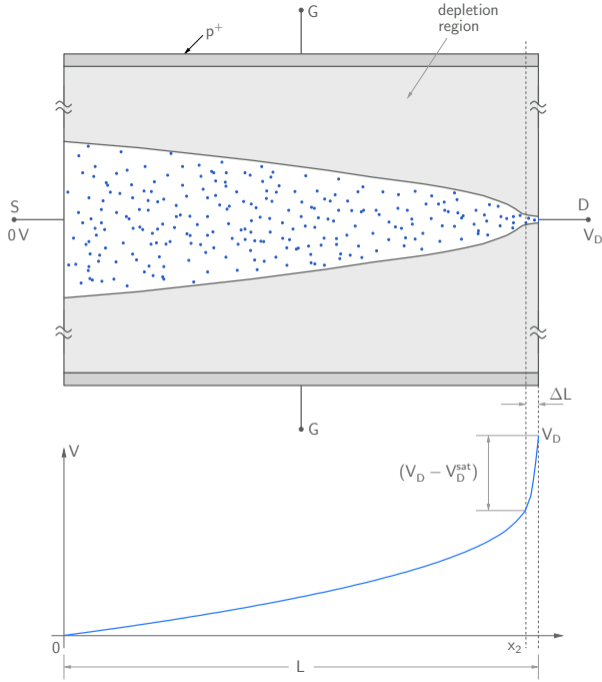
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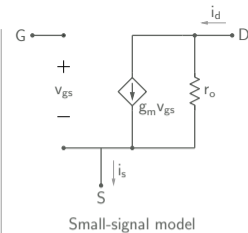
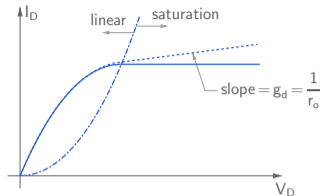
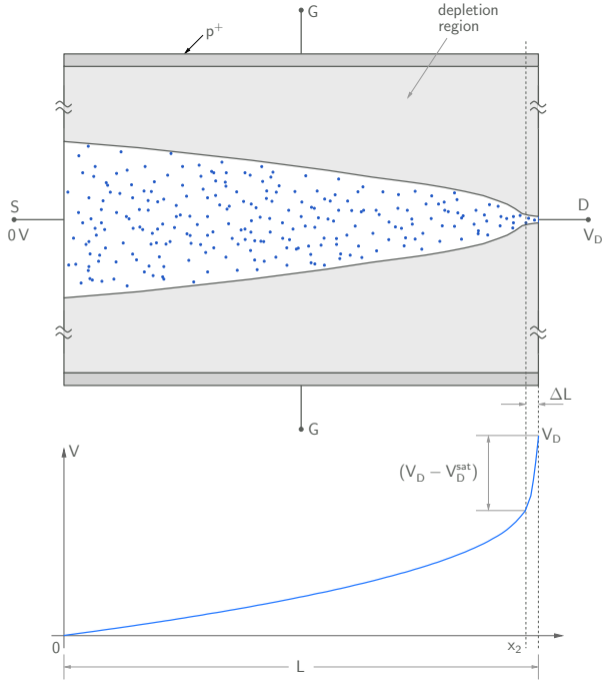
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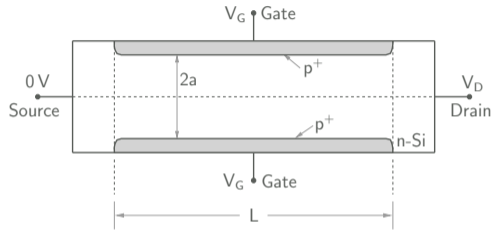
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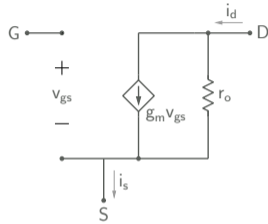
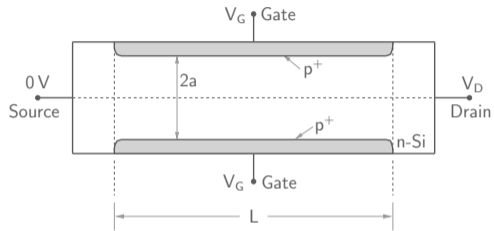
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- * This "channel length modulation" is significant in short-channel devices ($L \sim 1 \mu\text{m}$).

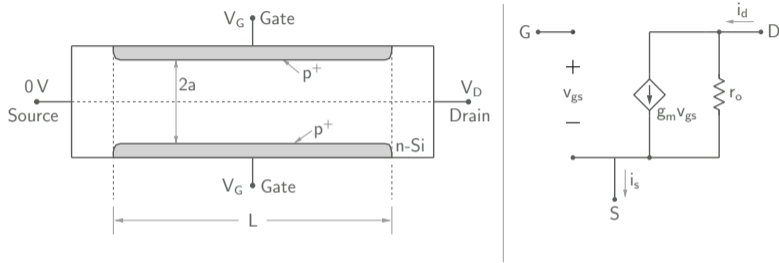
JFET: small-signal model



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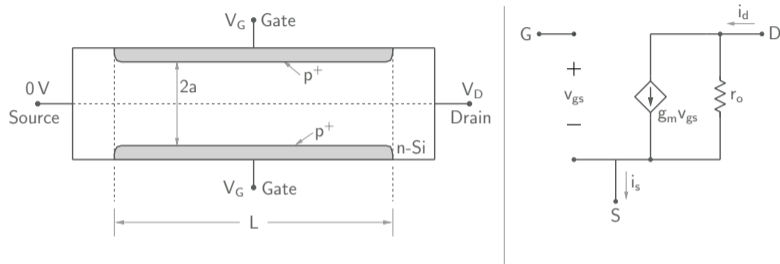


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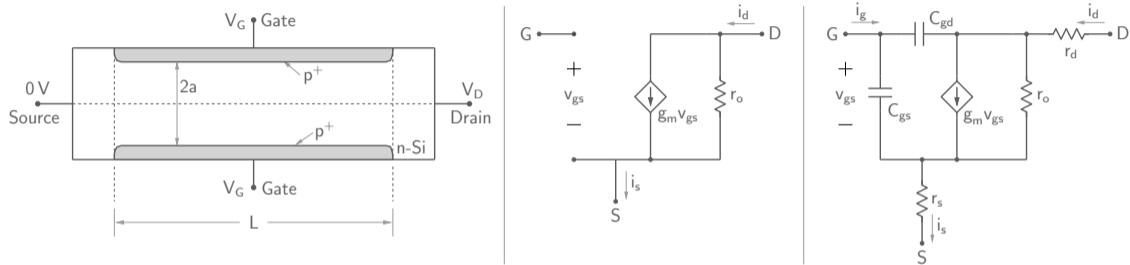
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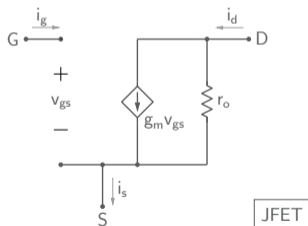
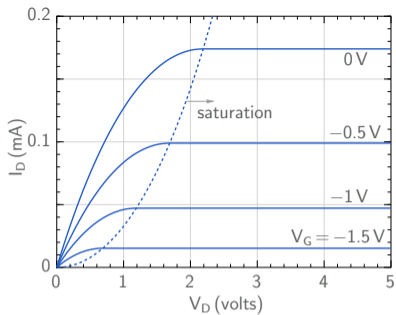
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JFET: small-signal model

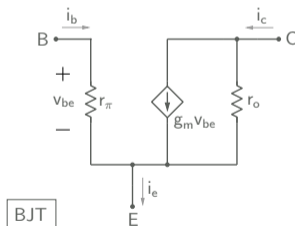
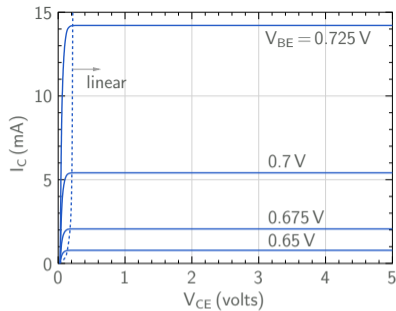


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JFET amplifiers

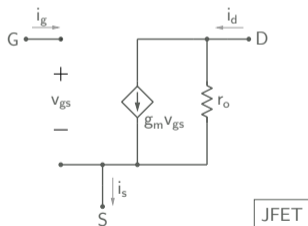
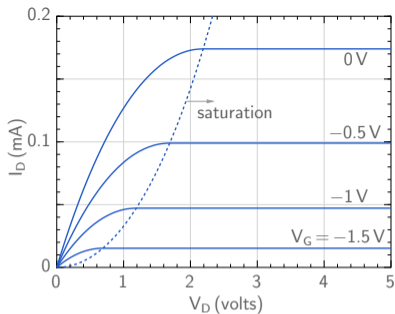


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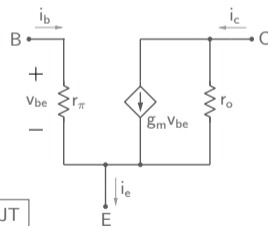
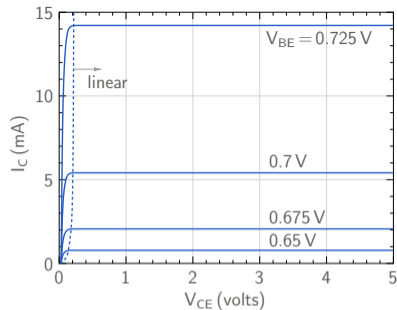


BJT

JFET amplifiers



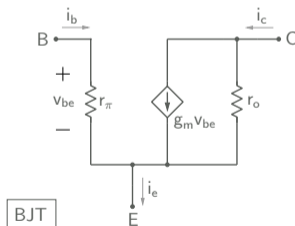
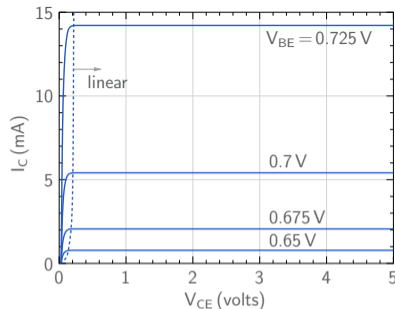
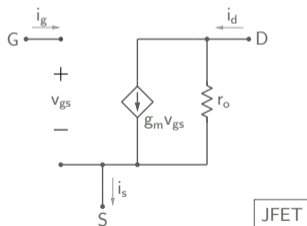
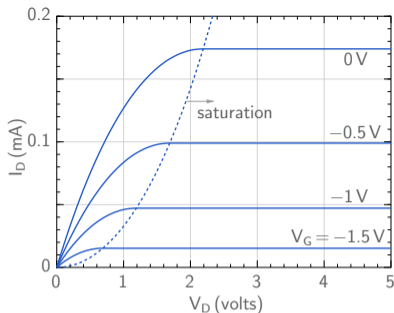
JFET



BJT

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JFET amplifiers



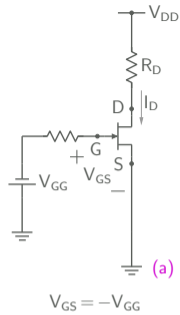
- * Qualitatively, the I_D - V_{DS} relationship of a JFET is similar to the I_C - V_{CE} relationship of a BJT.
- * A JFET can be used for amplification, e.g., we can have a “common-source” amplifier which is similar to the “common-emitter” amplifier.

JFET amplifiers

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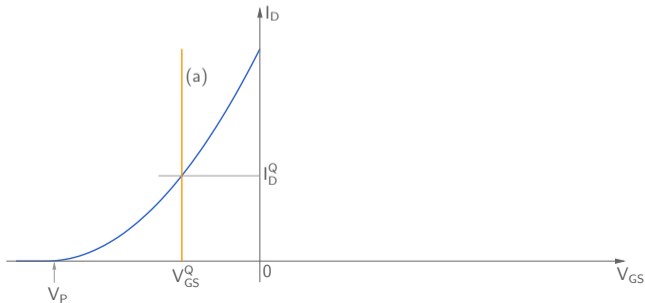
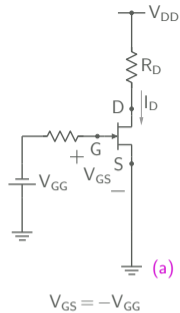
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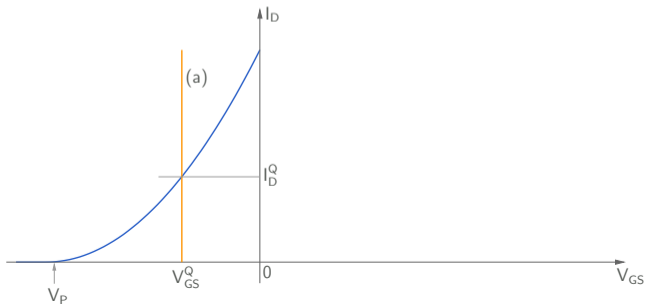
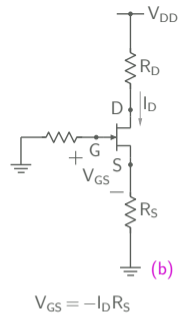
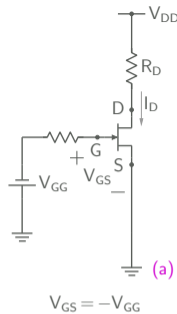
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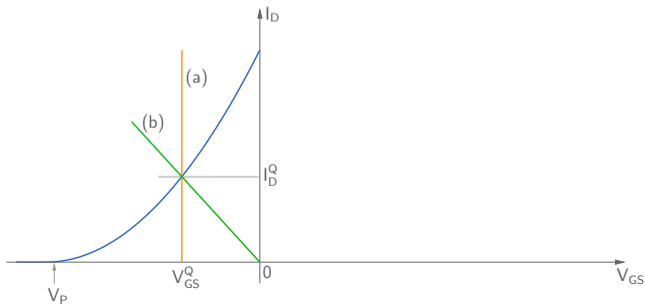
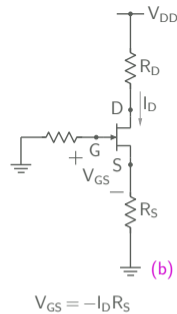
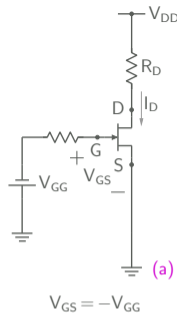
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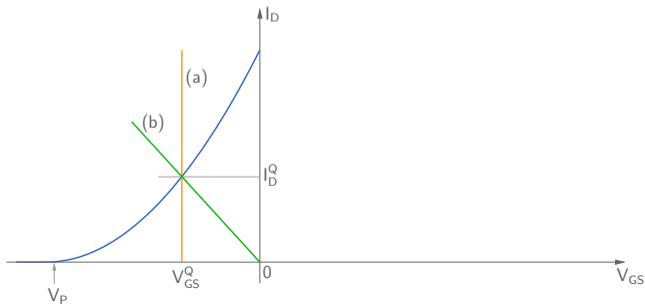
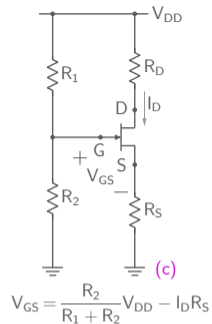
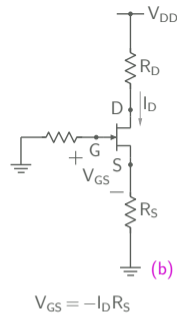
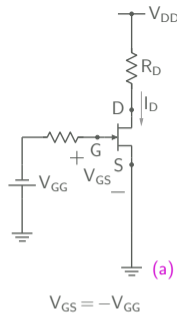
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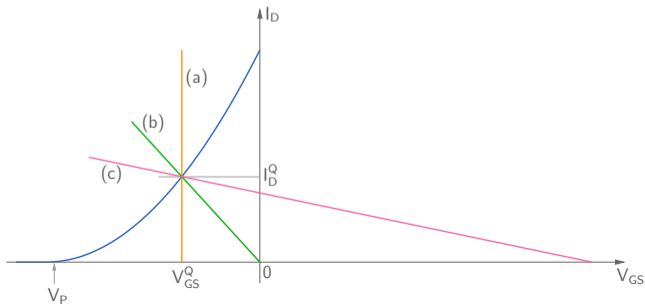
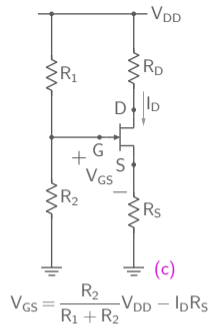
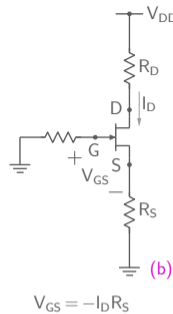
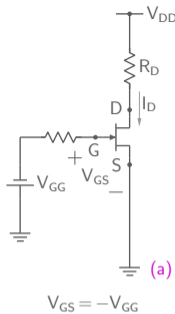
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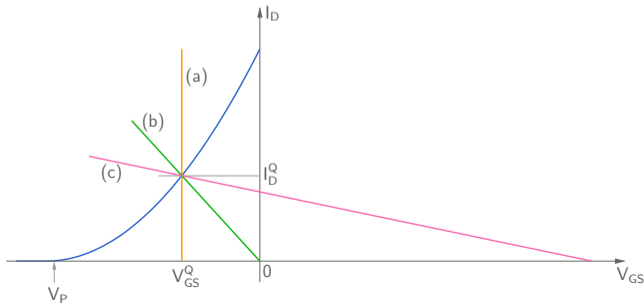
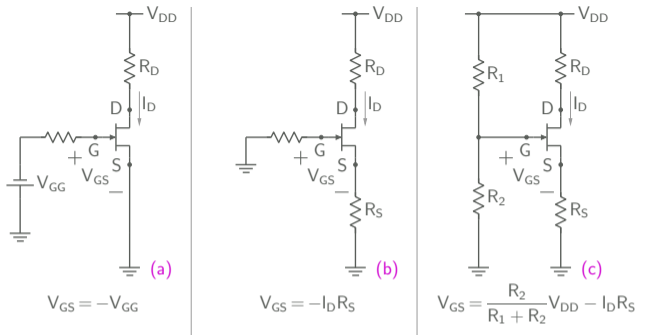
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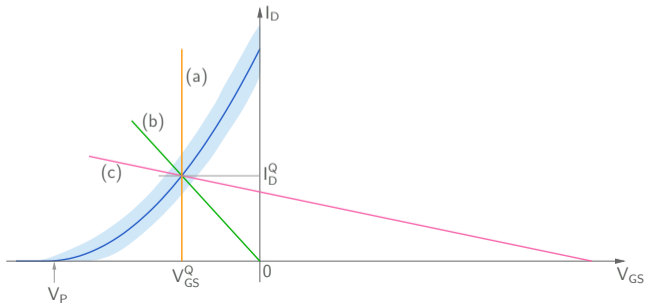
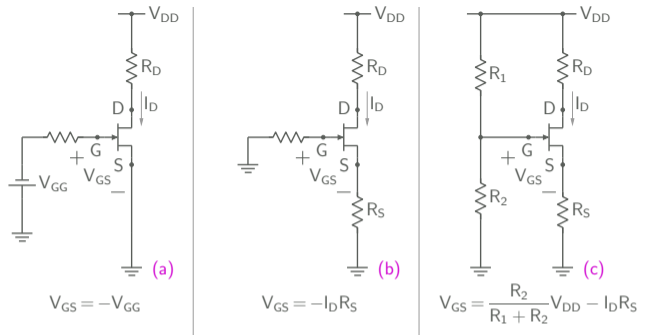
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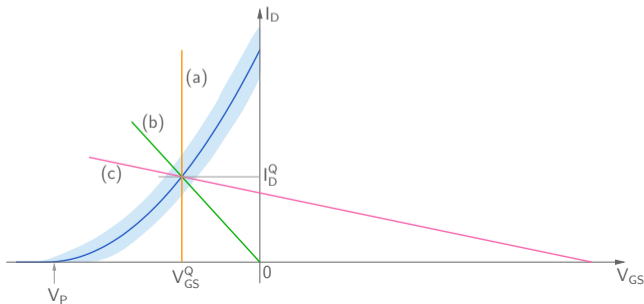
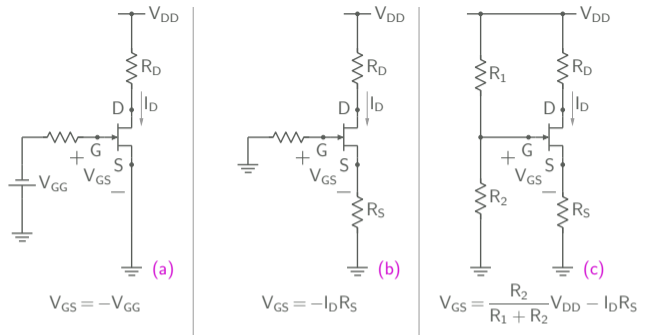
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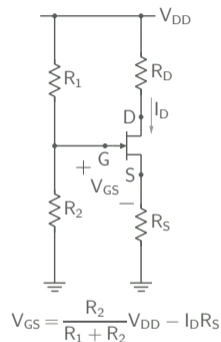
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- * The voltage divider scheme (c) is superior since it is least sensitive, i.e., the deviation in I_D is small compared to the other schemes.



Example

The JFET parameters are $I_{DSS} = 1 \text{ mA}$, $V_P = -2 \text{ V}$. For $V_{DD} = 12 \text{ V}$ and $R_D = 15 \text{ k}\Omega$, find suitable values of R_1 , R_2 , R_S to get a bias point of $I_D^Q = 0.4 \text{ mA}$ and $V_{DS}^Q = 4 \text{ V}$.

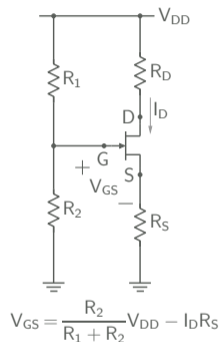


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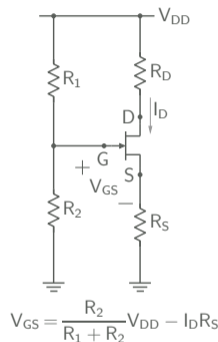
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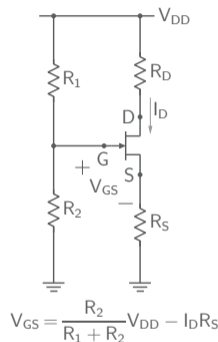
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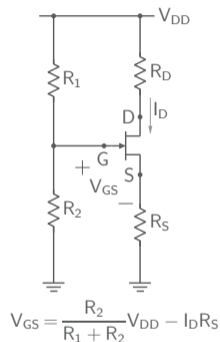
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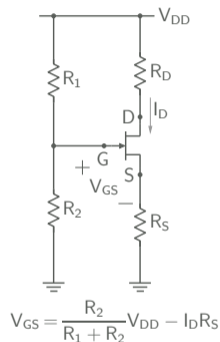
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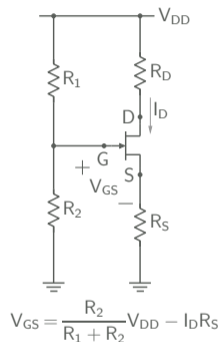
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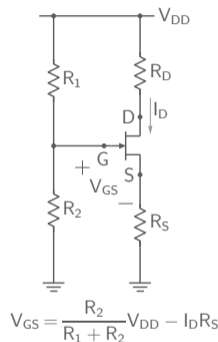
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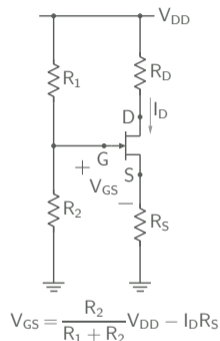
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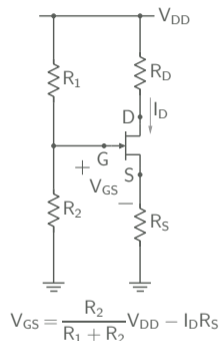
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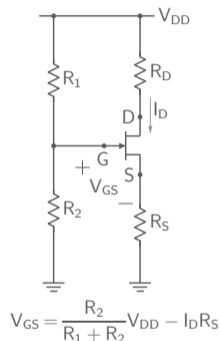
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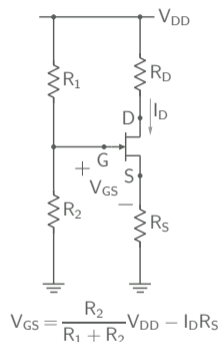
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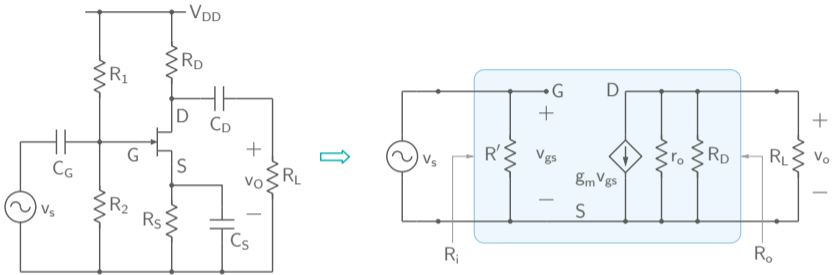
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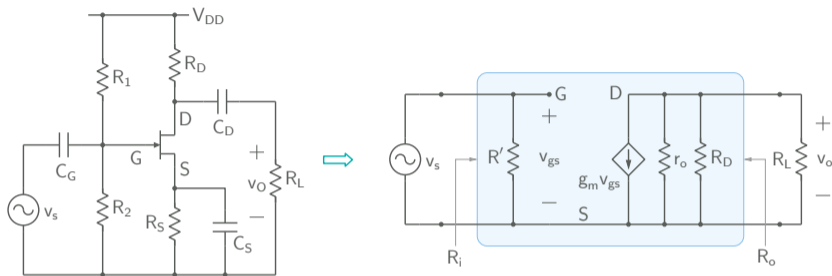
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Common-source amplifier

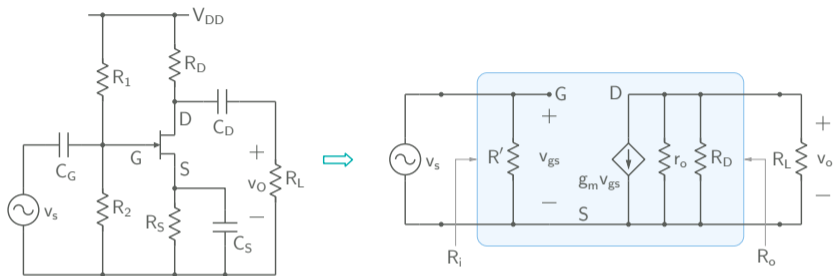


Common-source amplifier



* $A_V \equiv \frac{v_o}{v_s} = -g_m(R'_D \parallel R_L)$, where $R'_D = R_D \parallel r_o \approx R_D$ if r_o is large.

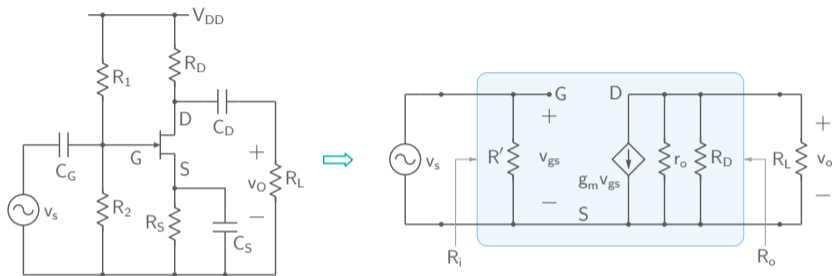
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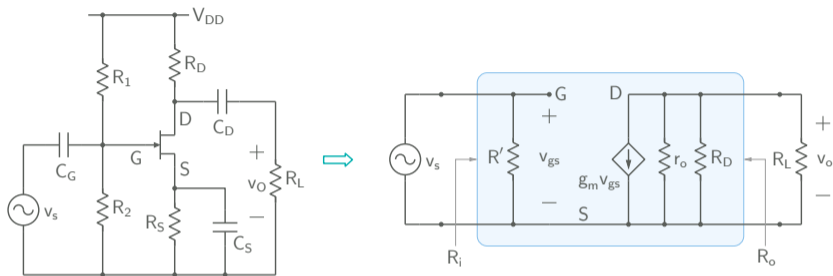


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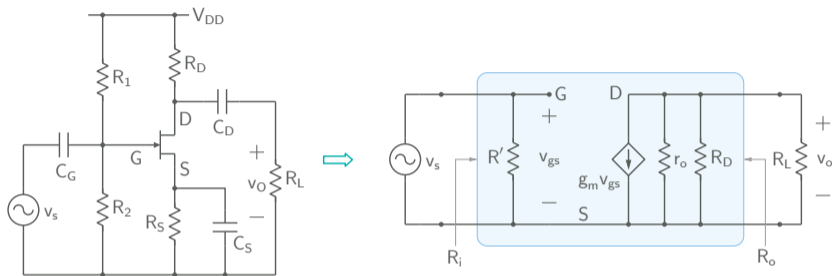
* $R_i = R' = R_1 \parallel R_2$, $R_o = R'_D.$

Common-source amplifier: Example



For the common-source amplifier of the last example, find (a) gain with $R_L \rightarrow \infty$ and (b) input resistance R_i .

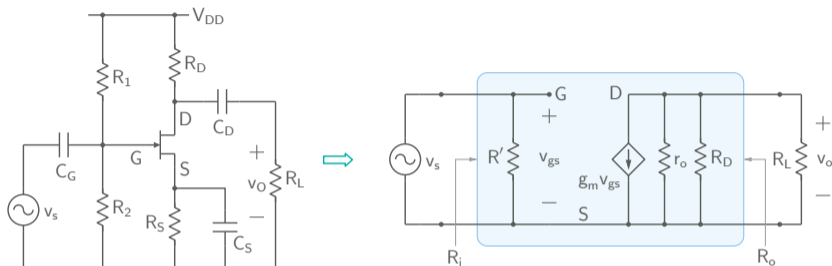
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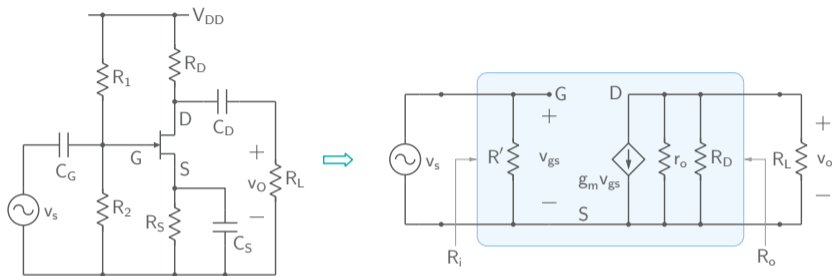


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Solution:

$$g_m = 2 I_{DSS} \left(1 - \frac{V_{GS}^Q}{V_P} \right) \times \left(-\frac{1}{V_P} \right) = 2 (1 \text{ mA}) \left(1 - \frac{-0.735 \text{ V}}{-2 \text{ V}} \right) \times \left(-\frac{1}{-2 \text{ V}} \right) = 0.63 \text{ mS}.$$

Common-source amplifier: Example



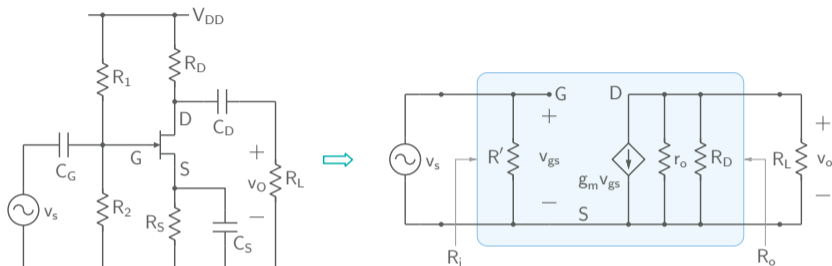
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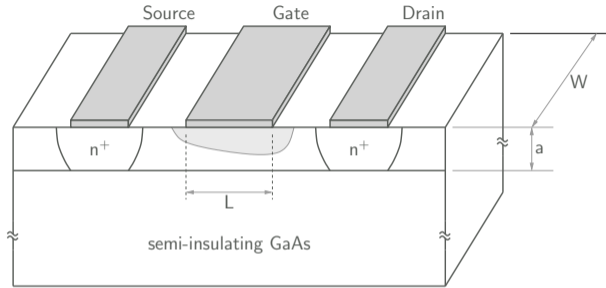
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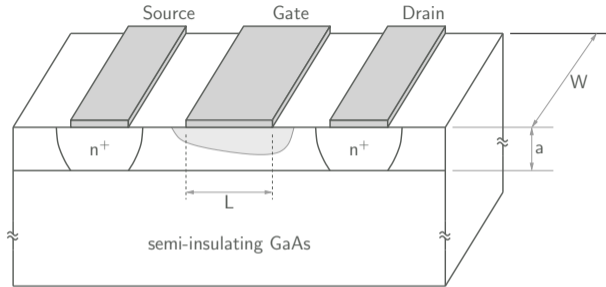
(a) $A_{VO} = -g_m R_D = -0.63 \text{ mS} \times 15 \text{ k}\Omega = -9.5$, assuming r_o to be large.

(b) $R_i = R_1 \parallel R_2 = 200 \text{ k}\Omega \parallel 23.5 \text{ k}\Omega = 21 \text{ k}\Omega$.

n -channel Metal-Semiconductor Field-Effect Transistor (MESFET)

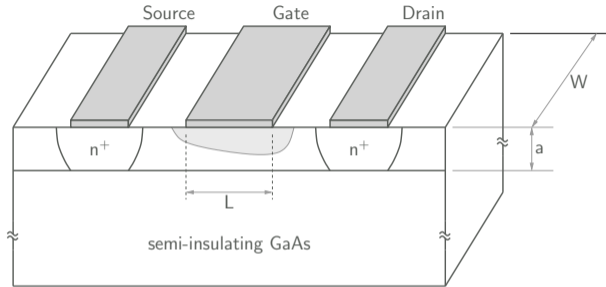


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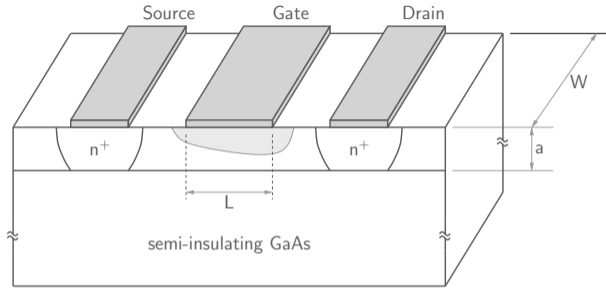
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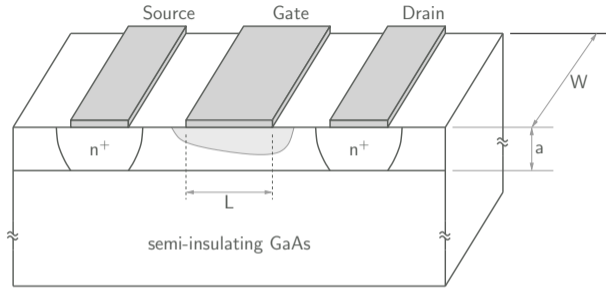
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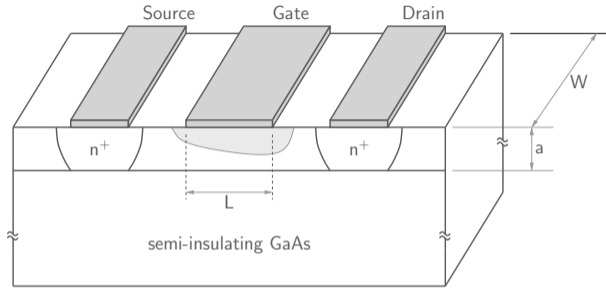
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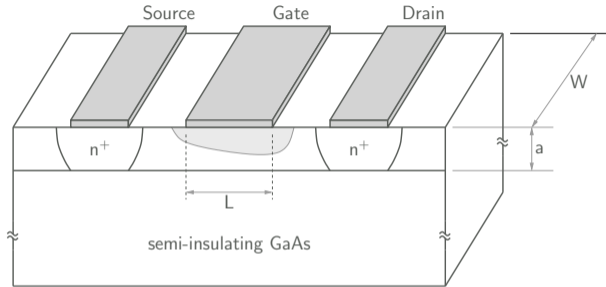


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- * The S/D contacts are ohmic; gate contact is rectifying.

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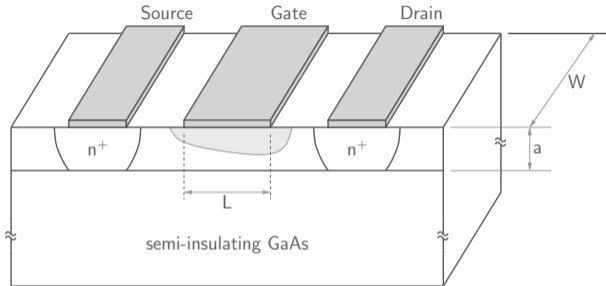


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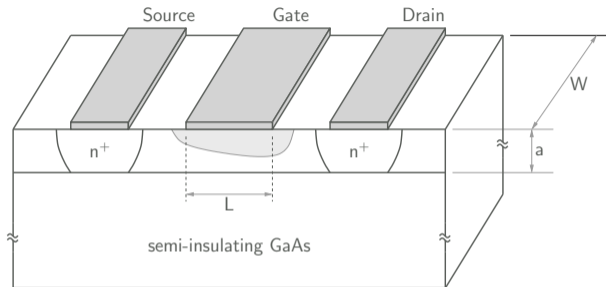
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- * GaAs MESFETs are commonly used in high-frequency (a few GHz) applications.