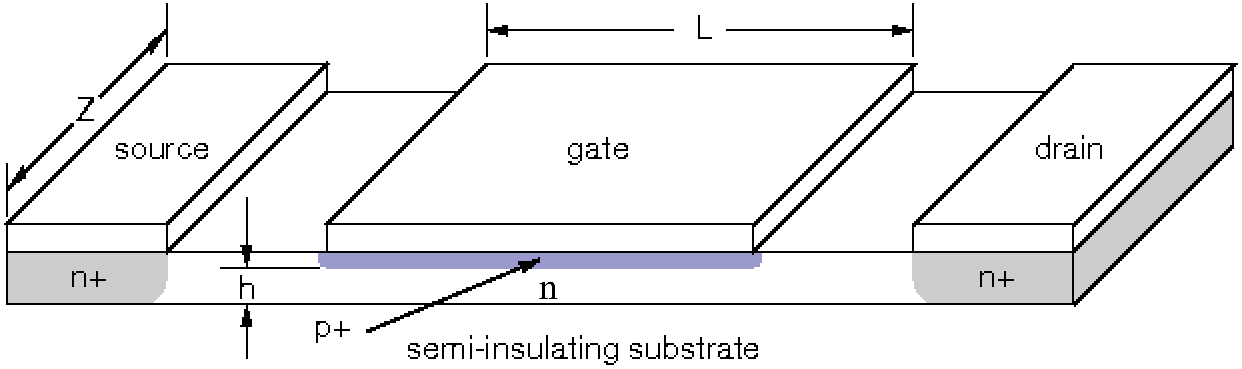
Junction Field Effect Transistors (JFETs)

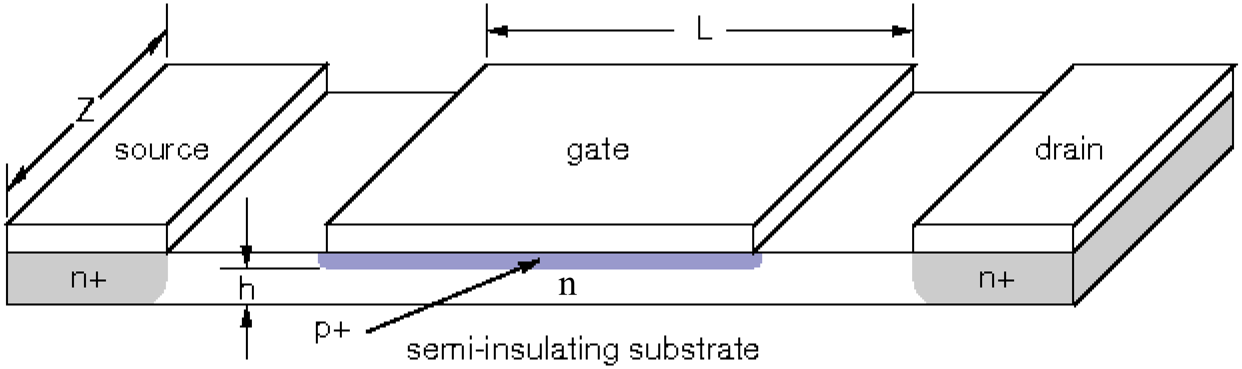
JFETs - MESFETs - MODFETs

Junction Field Effect Transistors (JFET)
Metal-Semiconductor Field Effect Transistors (MESFET)
Modulation Doped Field Effect Transistors (MODFET)



JFET

n-channel JFET



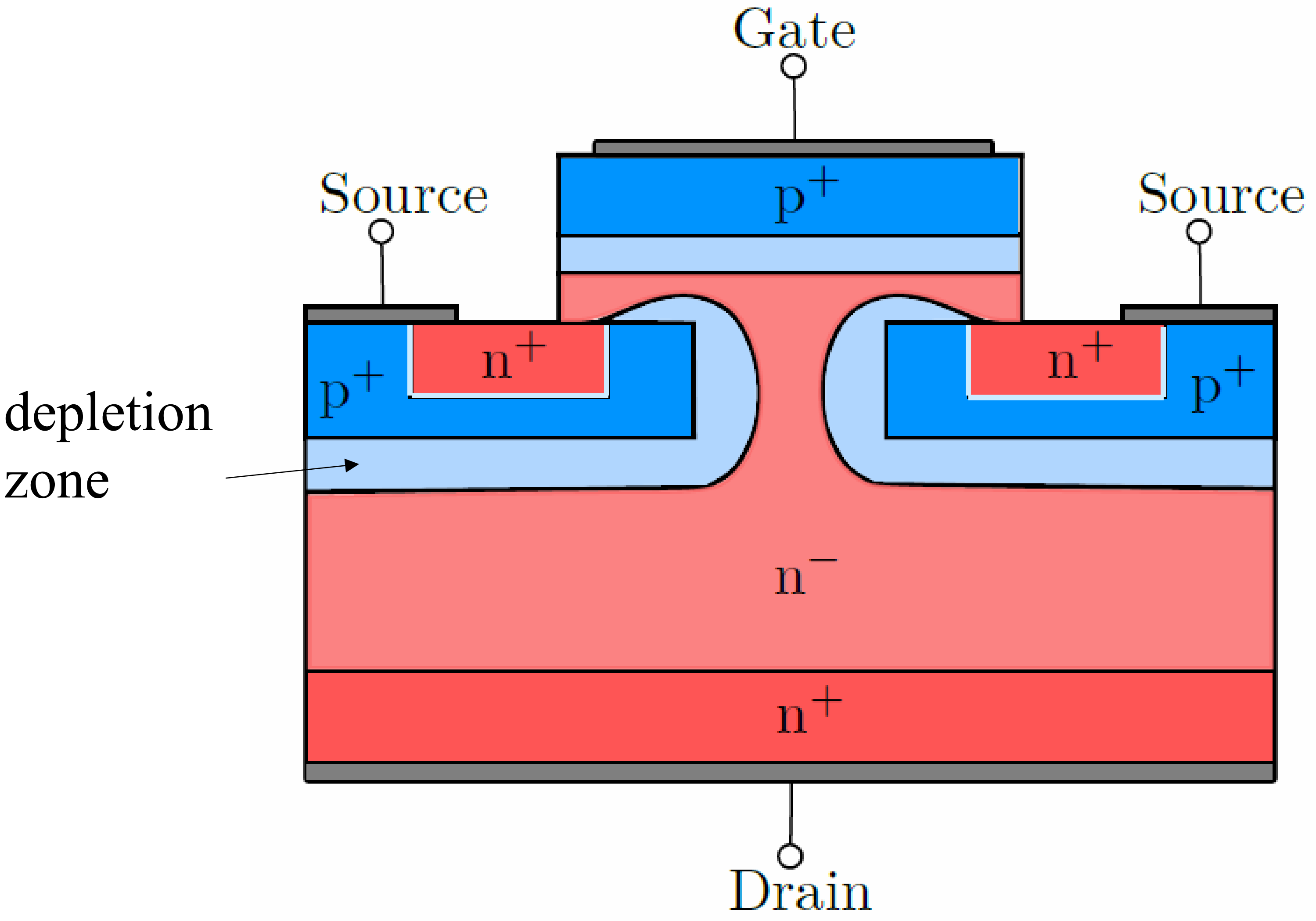
For $N_A >> N_D$

$$x_n = \sqrt{\frac{2\varepsilon(V_{bi} - V)}{eN_D}}$$

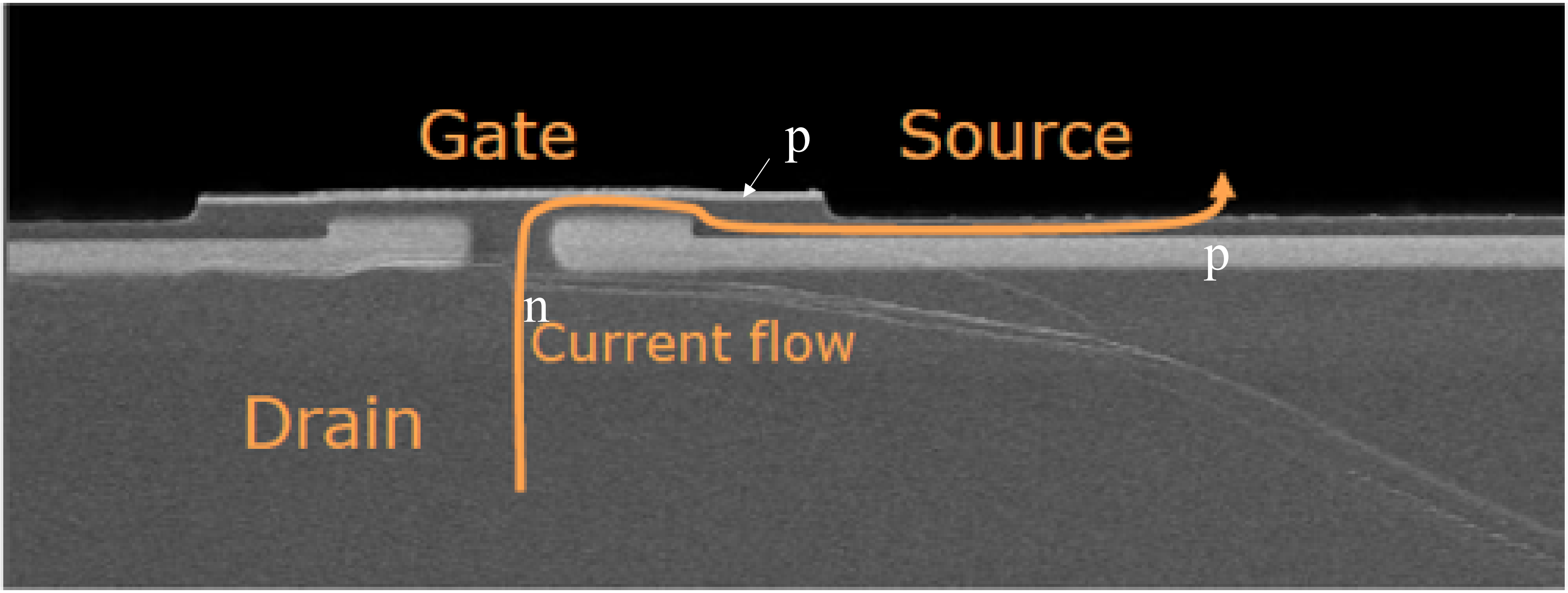
Depletion mode $h > x_n = \sqrt{\frac{2\varepsilon V_{bi}}{eN_D}}$ conducting at $V_g = 0$

Enhancement mode $h < x_n = \sqrt{\frac{2\varepsilon V_{bi}}{eN_D}}$ nonconducting at $V_g = 0$

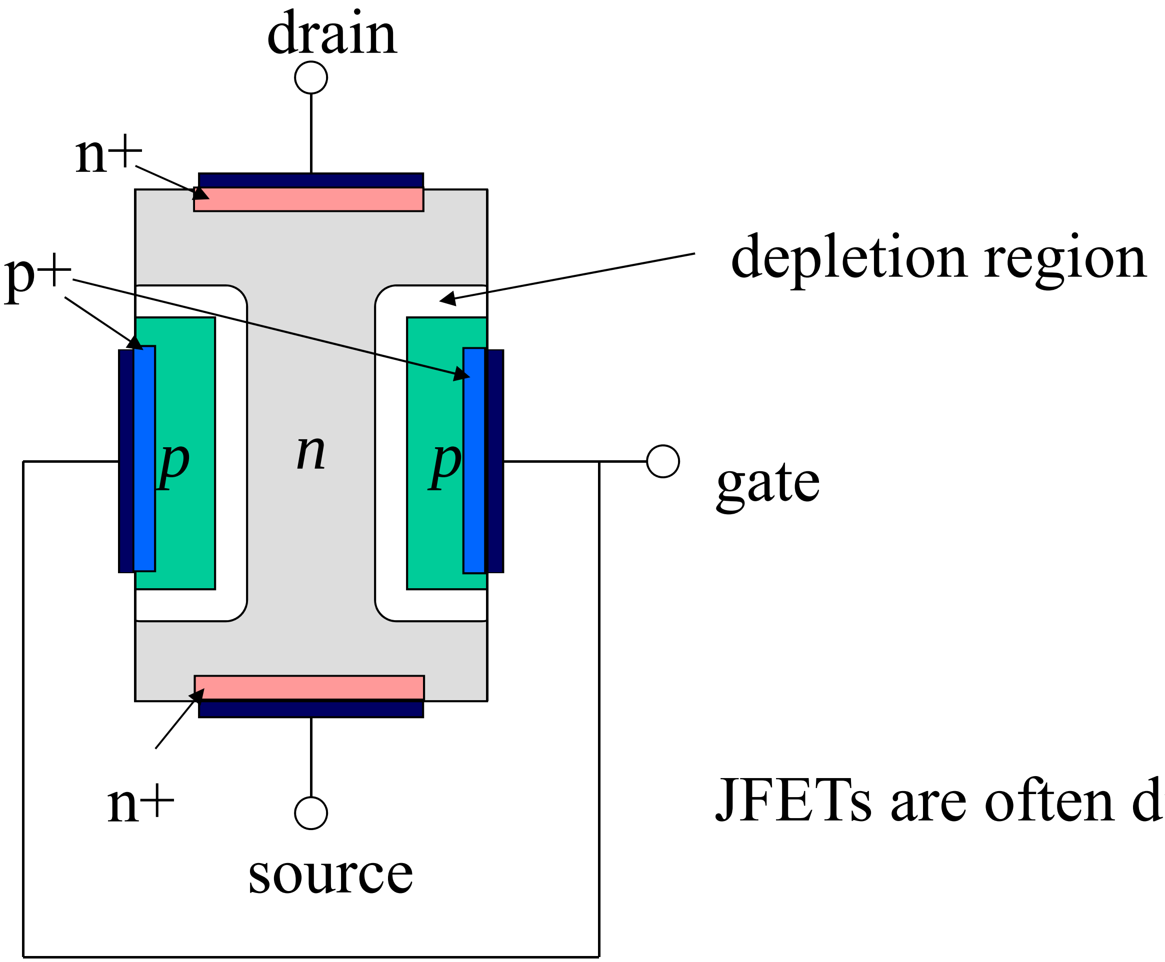
n-channel (power) JFET



Power SiC JFET



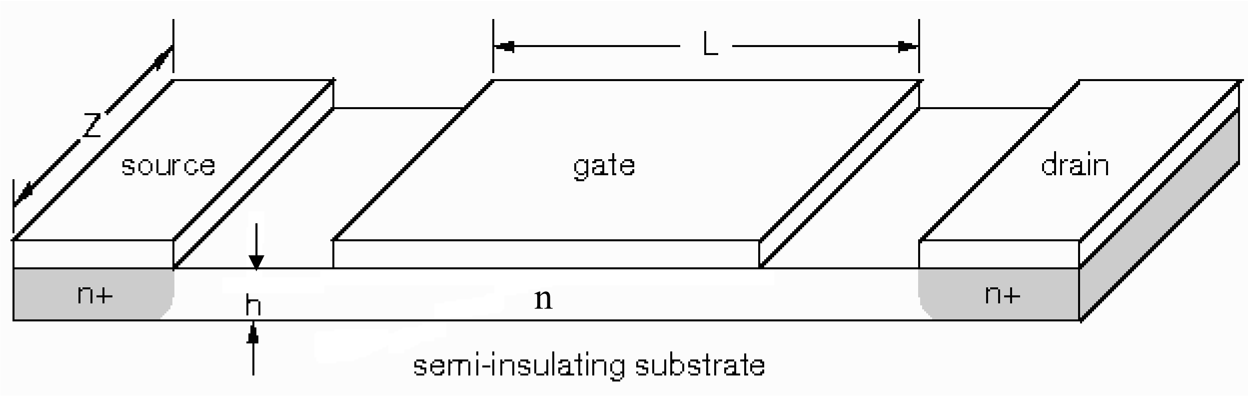
n-channel JFET



JFETs are often discrete devices

MESFET

Metal-Semiconductor Field Effect Transistors

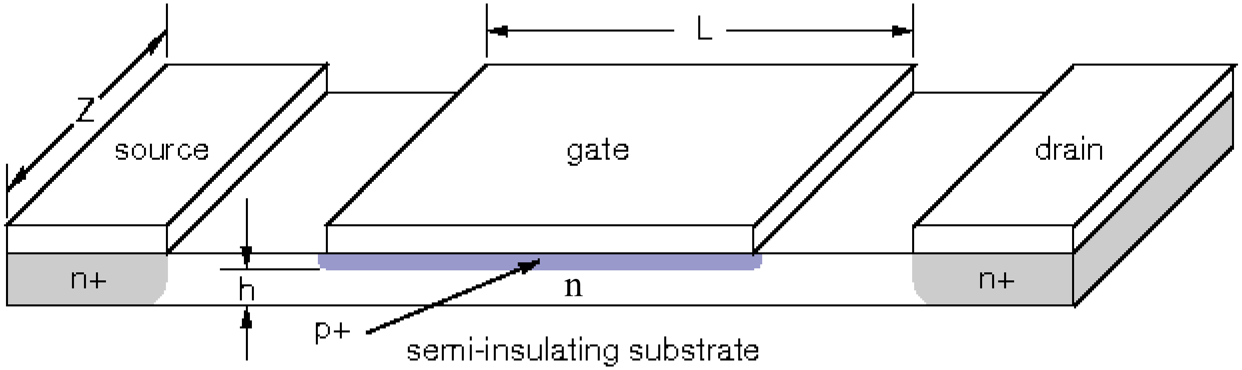


Depletion layer created by Schottky barrier

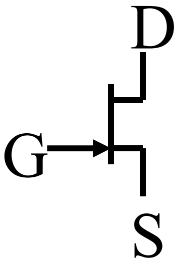
$$x_n = \sqrt{\frac{2\varepsilon(V_{bi} - V)}{eN_D}}$$

Fast transistors can be realized in n-channel GaAs, however GaAs has a low hole mobility making p-channel devices slower.

JFET

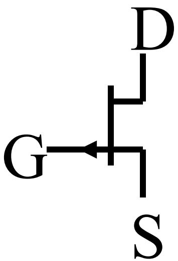


n-channel JFET



n-channel JFET

$$x_n = \sqrt{\frac{2\varepsilon(V_{bi} - V)}{eN_D}}$$



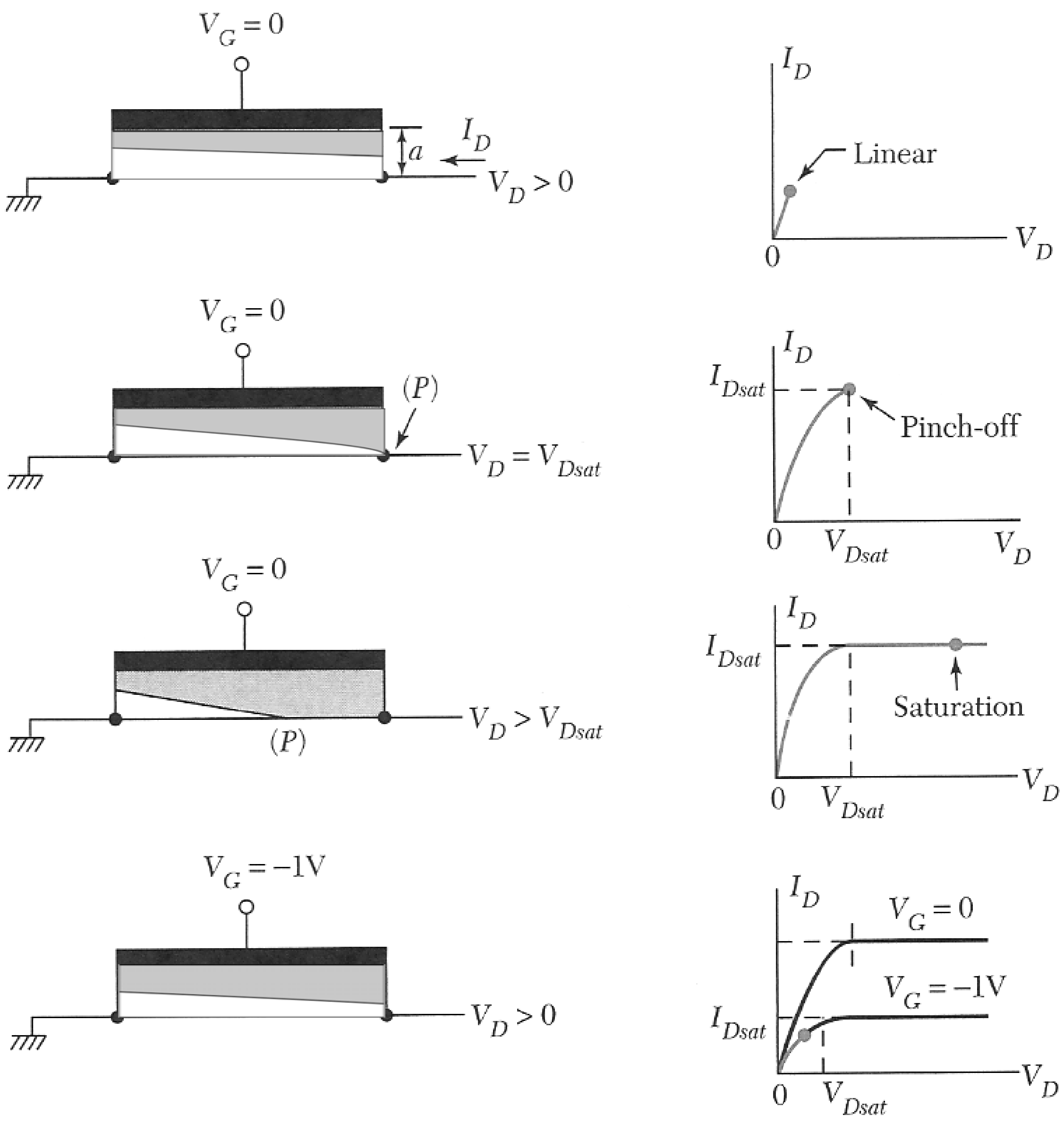
p-channel JFET

Pinch-off at $h = x_n$

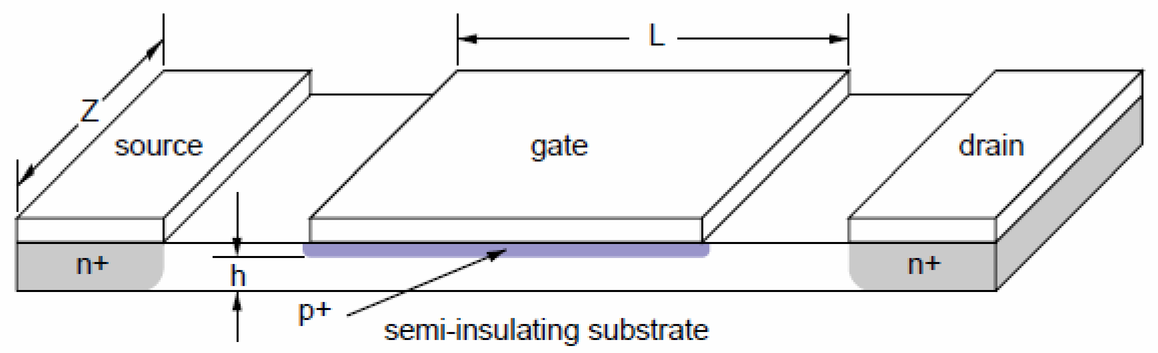
At Pinch-off, $V = V_{bi} - \dfrac{eN_D h^2}{2\varepsilon}$

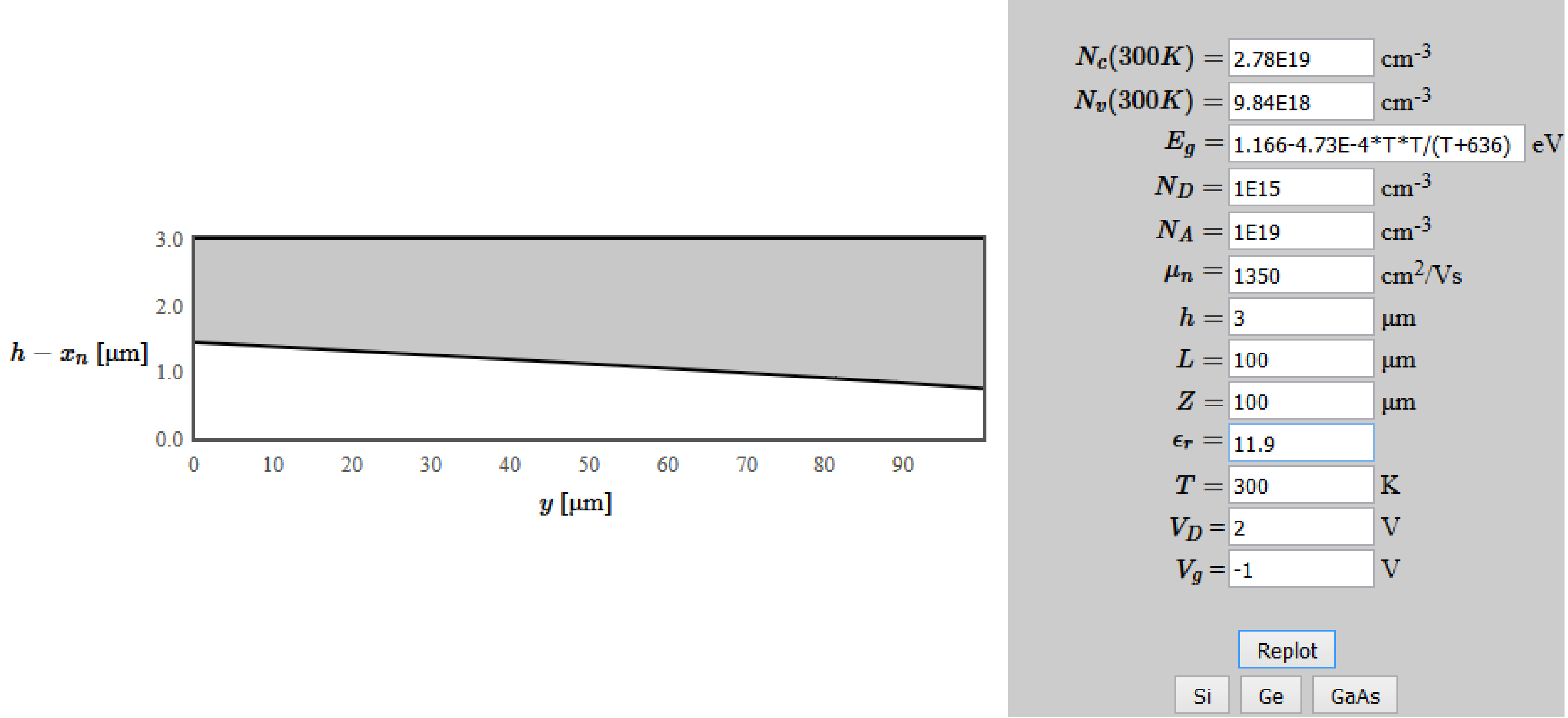
JFET

The drain is the side of the transistor that gets pinched off.



JFET Gradual Channel Approximation





$N_c(300K) =$ 2.78E19 cm^{-3}

$N_v(300K) =$ 9.84E18 cm^{-3}

$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$N_D =$ 1E15 cm^{-3}

$N_A =$ 1E19 cm^{-3}

$\mu_n =$ 1350 cm^2/Vs

$h =$ 3 μm

$L =$ 100 μm

$Z =$ 100 μm

$\epsilon_r =$ 11.9

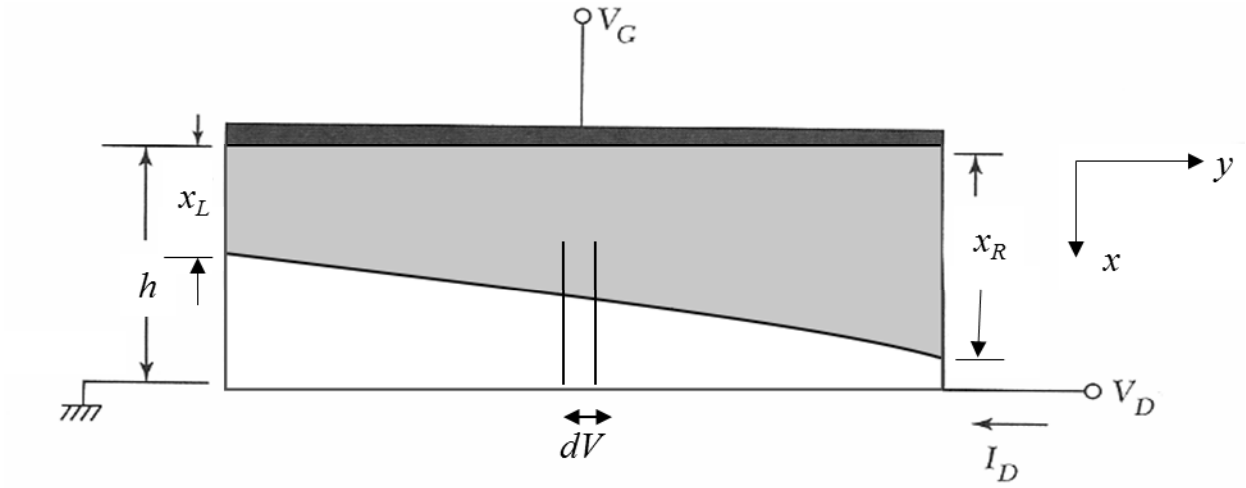
$T =$ 300 K

$V_D =$ 2 V

$V_g =$ -1 V

http://lampx.tugraz.at/~hadley/psd/L9/gradual.php

JFET

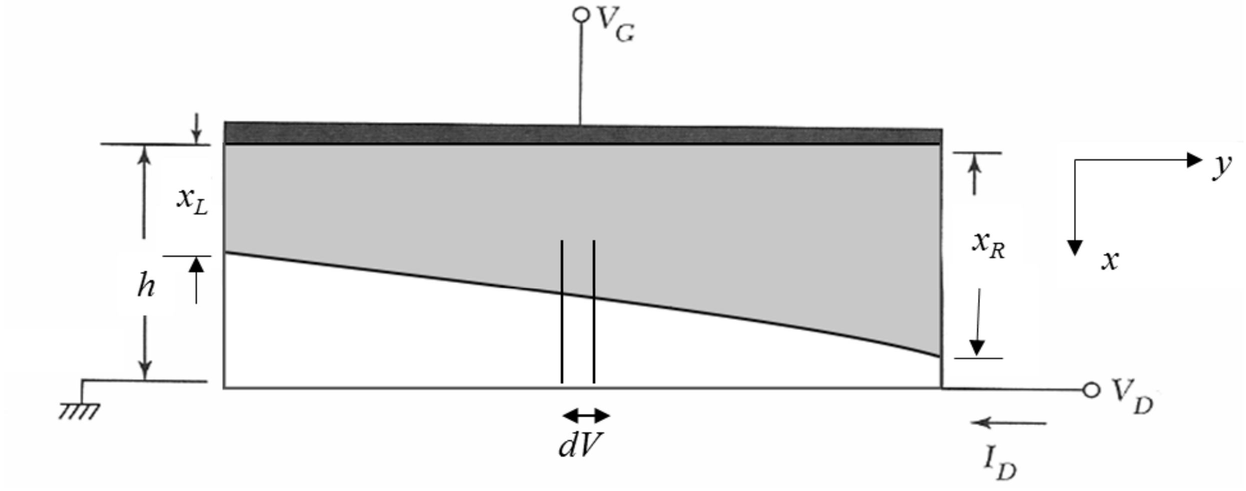


There is a long derivation to determine how the current depends on V_G and V_D.

We will find a relatively simple formula (probably familiar to electrical engineers).

Understanding the derivation is important for knowing when this formula is valid.

JFET



$$dV = I_D dR = I_D \frac{\rho dy}{Z(h - x_n(y))}$$

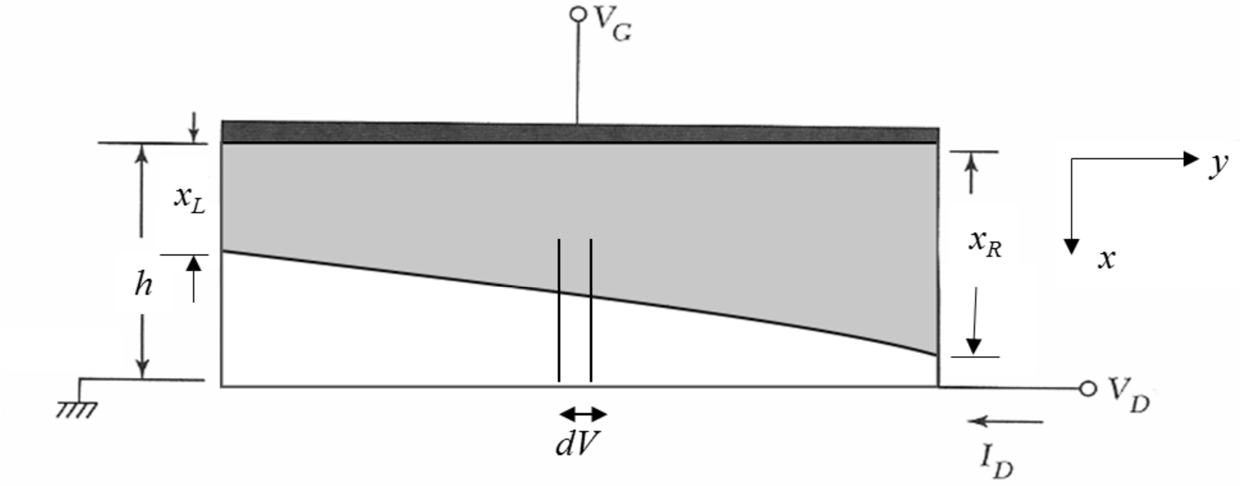
$$\rho = \frac{1}{\sigma} = \frac{1}{ne\mu_n} = \frac{1}{N_D e\mu_n}$$

$$dV = I_D \frac{dy}{e\mu_n N_D Z(h - x_n(y))}$$

I_D is constant throughout the transistor ⟶ $I_D dy = e\mu_n N_D Z(h - x_n(y))dV$

JFET

$$I_D dy = e\mu_n N_D Z(h - x_n(y))dV$$



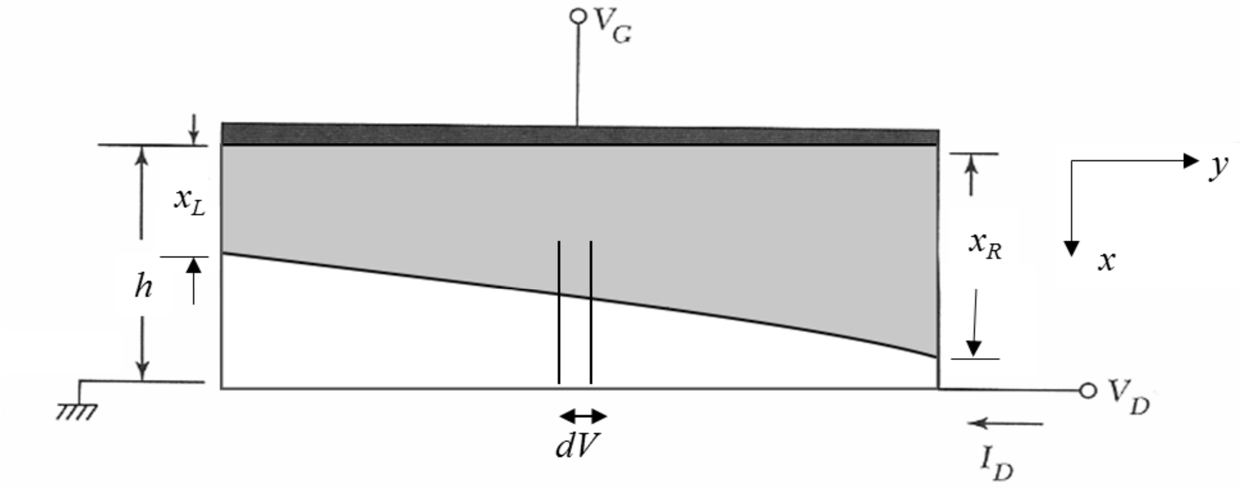
V_G is a forward bias
$V(y)$ is a reverse bias.

depletion width is a function of position $x_n(y) = \sqrt{\dfrac{2\varepsilon(V_{bi} + V(y) - V_G)}{eN_D}}$

differentiate $\dfrac{dx_n(y)}{dV} =$

JFET

$$I_D dy = e\mu_n N_D Z(h - x_n(y))dV$$



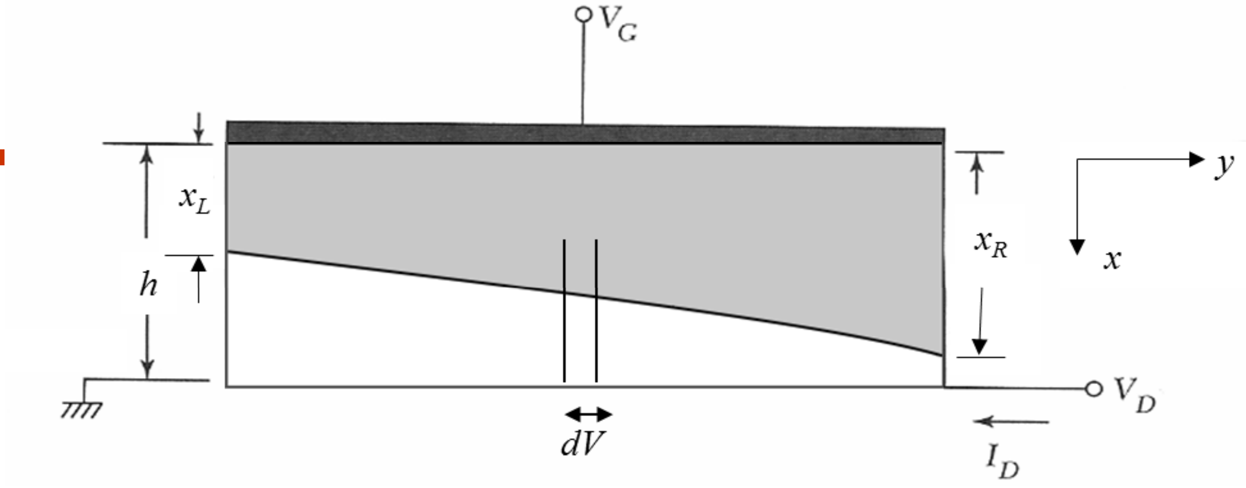
V_G is a forward bias
$V(y)$ is a reverse bias.

depletion width is a function of position $x_n(y) = \sqrt{\dfrac{2\varepsilon(V_{bi} + V(y) - V_G)}{eN_D}}$

differentiate $$\frac{dx_n(y)}{dV} = \tfrac{1}{2}\left(\frac{2\varepsilon(V_{bi} + V(y) - V_G)}{eN_D}\right)^{-1/2} \frac{2\varepsilon}{eN_D} = \frac{\varepsilon}{eN_D x_n(y)}$$

$$dV = \frac{eN_D x_n}{\varepsilon} dx_n$$

JFET



$$I_D dy = e\mu_n N_D Z(h - x_n(y))dV$$

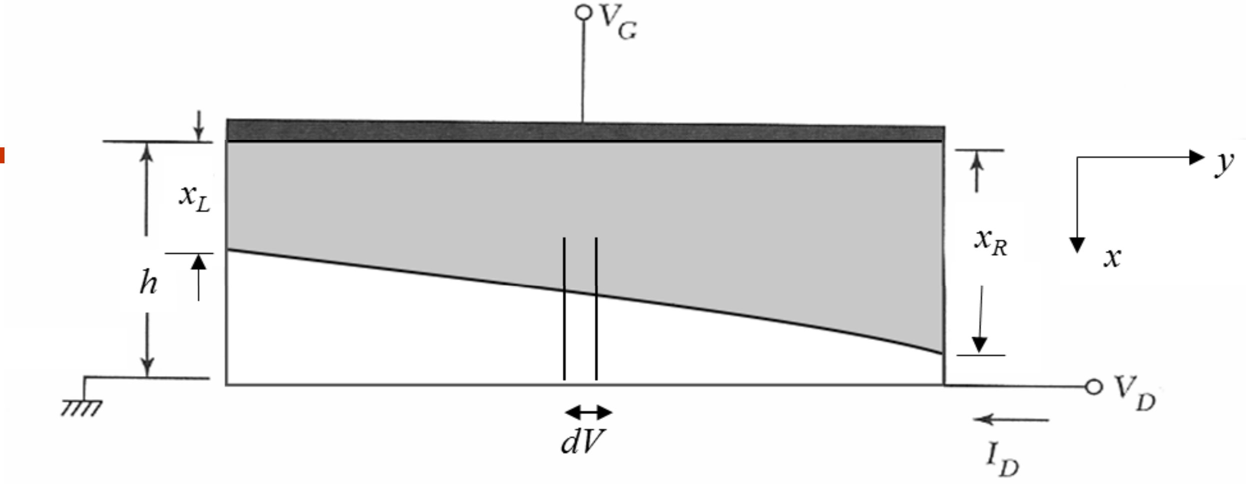
from last slide

$$dV = \frac{eN_D x_n}{\varepsilon} dx_n$$

$$\frac{dx_n(y)}{dy} = \frac{I_D}{e\mu_n N_D Z(h - x_n(y))\frac{eN_D}{\varepsilon} x_n(y)}$$

If I_D is known, this can be solved for $x_n(y)$.

JFET



$$I_D dy = e\mu_n N_D Z(h - x_n(y))dV$$

$$dV = \frac{eN_D x_n}{\varepsilon} dx_n$$

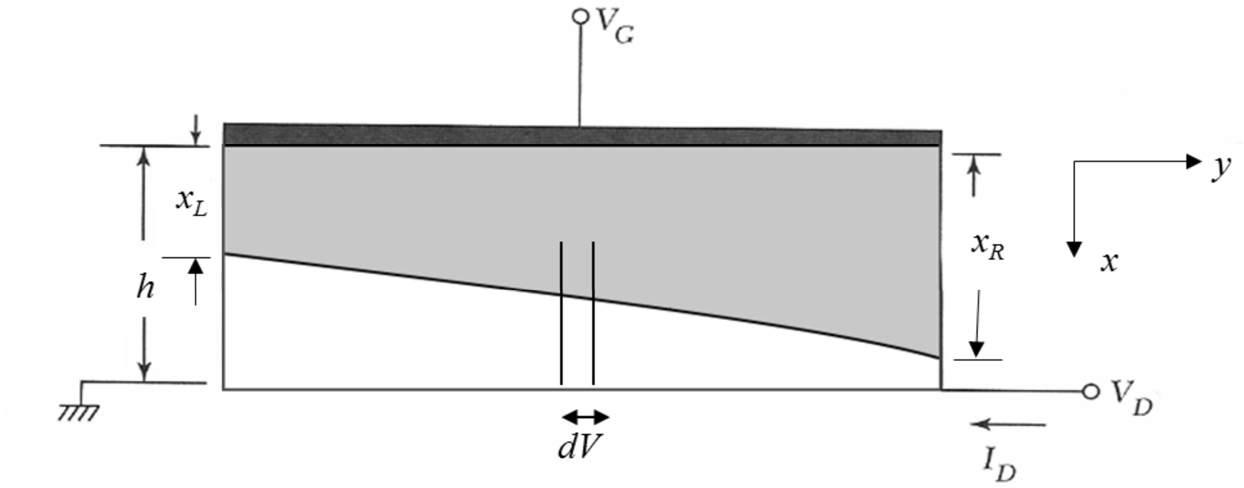
from a previous slide

$$I_D dy = e\mu_n N_D Z(h - x_n(y))\frac{eN_D}{\varepsilon} x_n dx_n$$

$$I_D \int_0^L dy = e\mu_n N_D Z \frac{eN_D}{\varepsilon} \int_{x_L}^{x_R} (h - x_n(y))x_n dx_n$$

$$I_D = \frac{\mu_n N_D^2 Z e^2}{2L\varepsilon}\left[h\left(x_R^2 - x_L^2\right) - \tfrac{2}{3}\left(x_R^3 - x_L^3\right)\right]$$

JFET



$$I_D = \frac{\mu_n N_D^2 Z e^2}{2L\varepsilon}\left[h\left(x_R^2 - x_L^2\right) - \tfrac{2}{3}\left(x_R^3 - x_L^3\right)\right]$$

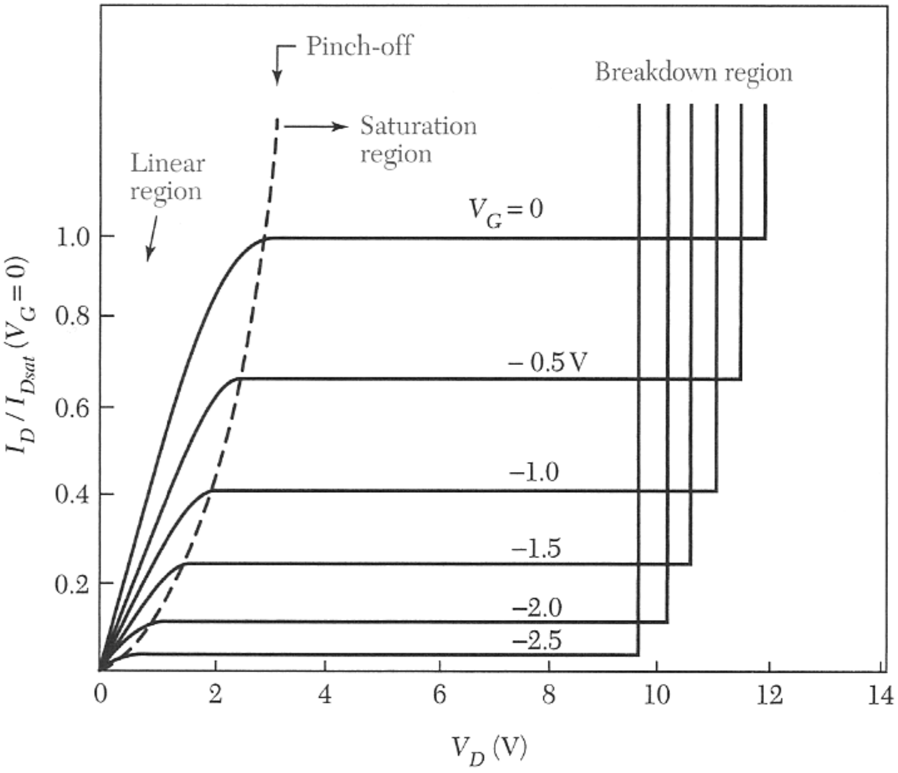
$$h = \sqrt{\frac{2\varepsilon V_p}{eN_D}} \qquad x_L = \sqrt{\frac{2\varepsilon(V_{bi} - V_G)}{eN_D}} \qquad x_R = \sqrt{\frac{2\varepsilon(V_{bi} - V_G + V_D)}{eN_D}}$$

JFET - drain current

$$\boxed{I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]}$$

$$I_p = \frac{\mu_n N_D^2 Z e^2 h^3}{2L\varepsilon}$$

valid in the linear regime
(until pinch-off)



JFET - Linear regime

$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

In the linear regime $V_D << V_{sat}$.

$$\frac{dI_D}{dV_D} =$$

JFET - Linear regime

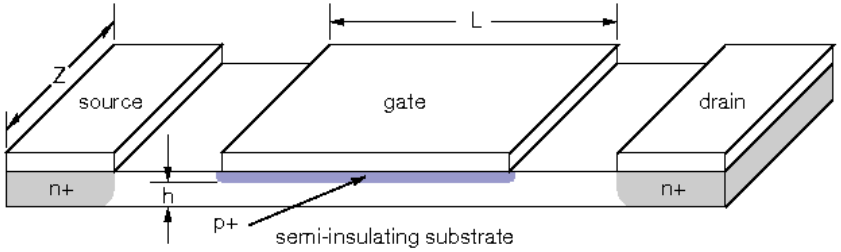
$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

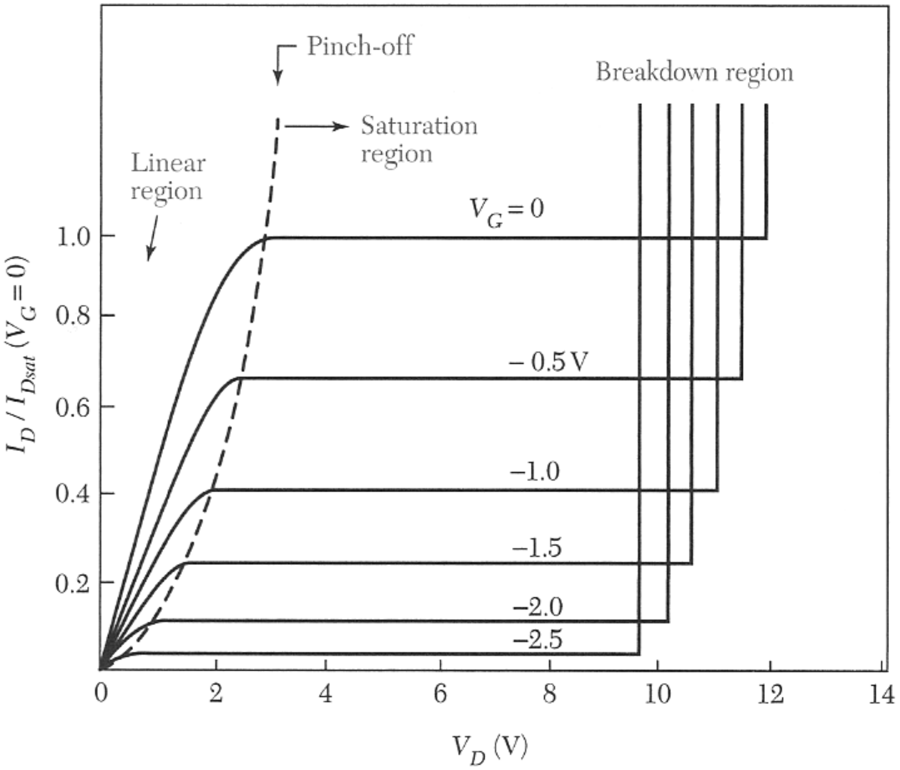
In the linear regime $V_D << V_{sat}$.

$$\frac{dI_D}{dV_D} = I_p\left[\frac{1}{V_p} - \frac{1}{V_p}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{1/2}\right]$$

$$I_D = \frac{I_p}{V_p}\left[1-\sqrt{\frac{V_{bi}-V_G}{V_p}}\right]V_D \text{ for } V_D \ << \ V_{sat}$$

variable resistor





JFET - Saturation regime

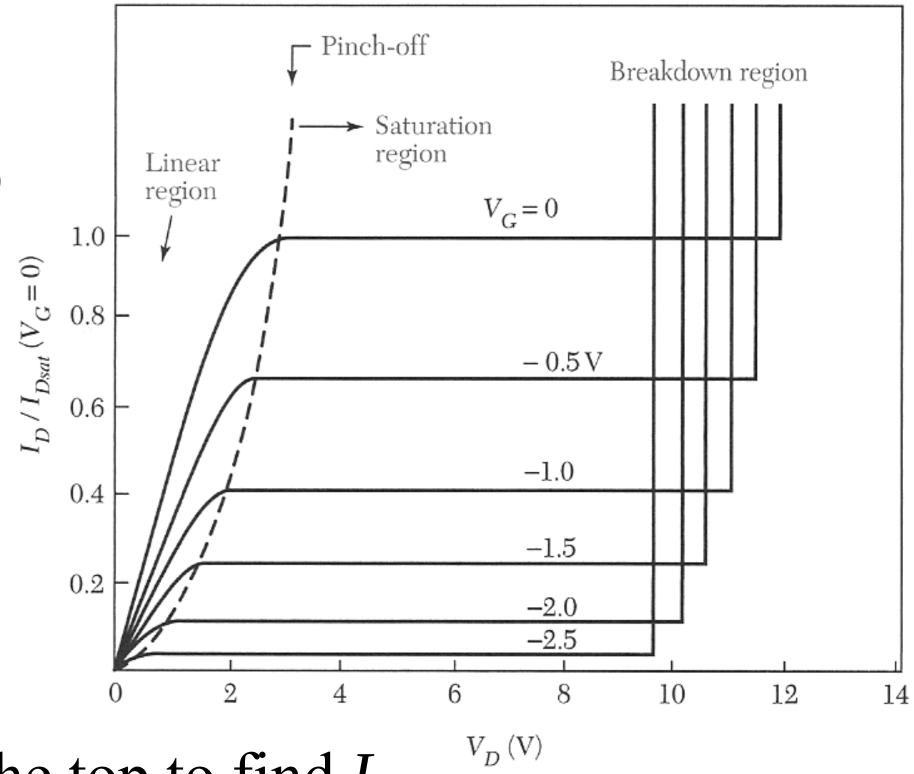
$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

set $dI_D/dV_D = 0$ to find V_{sat}

$$\frac{dI_D}{dV_D} = I_p\left[\frac{1}{V_p} - \frac{1}{V_p}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{1/2}\right] = 0$$

$dI_D/dV_D = 0$ when $\dfrac{V_{bi}+V_D-V_G}{V_p} = 1$

$$V_{sat} = V_p - V_{bi} + V_G$$



Substitute V_{sat} into the equation at the top to find I_{sat}

JFET - Saturation regime

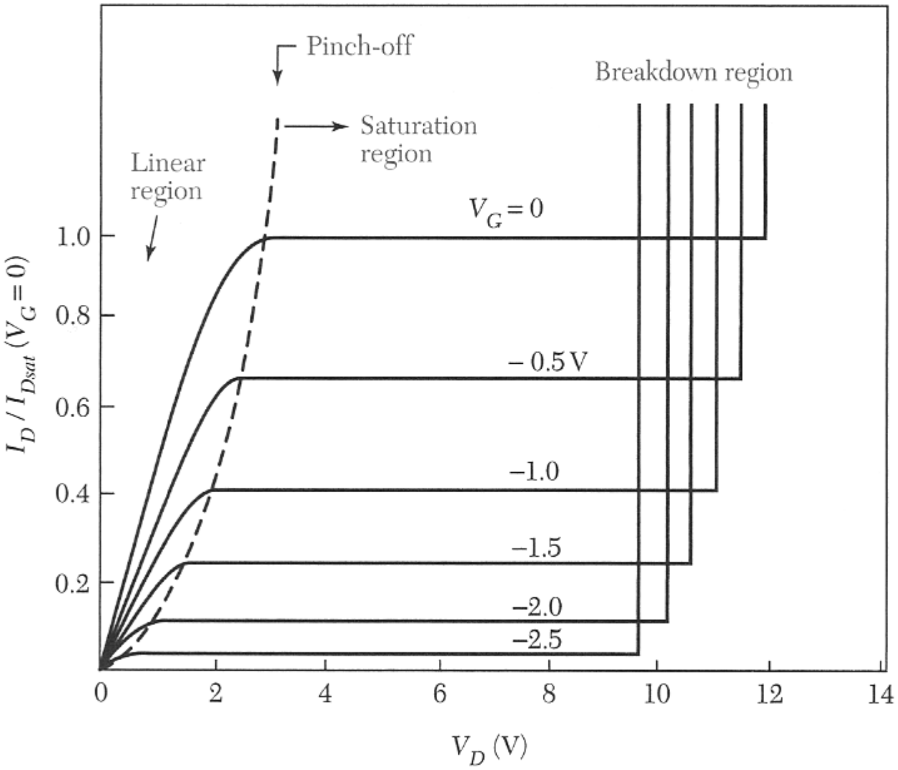
$$V_{sat} = V_p - V_{bi} + V_G$$

$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

$$I_{sat} = I_p\left[\frac{1}{3} - \frac{V_{bi}-V_G}{V_p} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

No V_D dependence

Voltage controlled current source



JFET - transconductance

In the saturation regime,

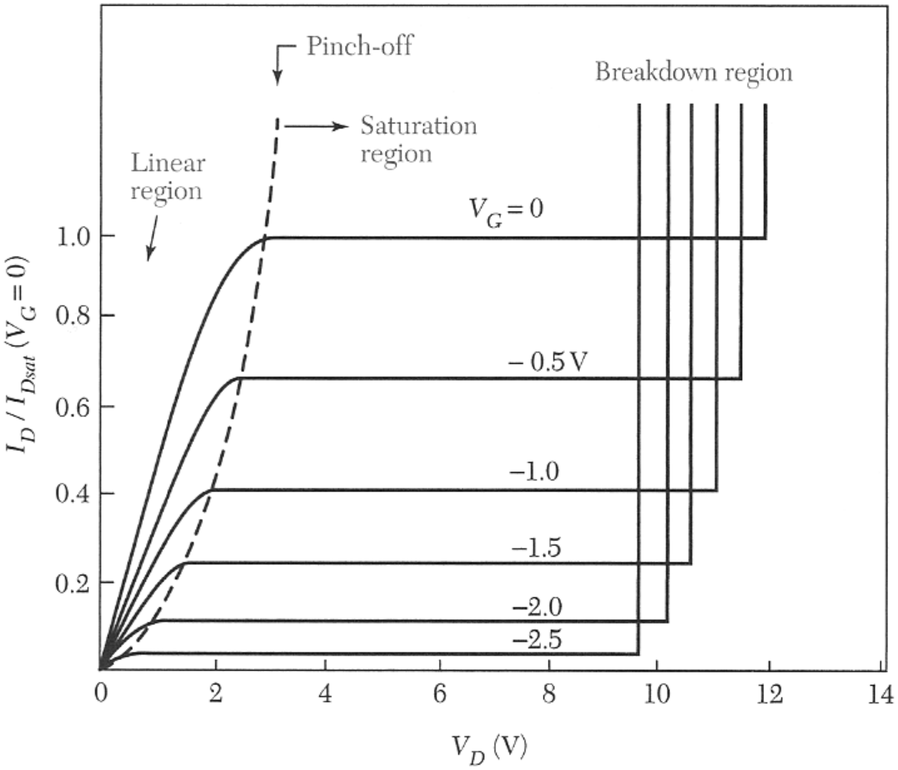
$$I_{sat} = I_p \left[\frac{1}{3} - \frac{V_{bi} - V_G}{V_p} + \frac{2}{3} \left(\frac{V_{bi} - V_G}{V_p} \right)^{3/2} \right]$$

transconductance (describes how good the voltage controlled current source is)

↓

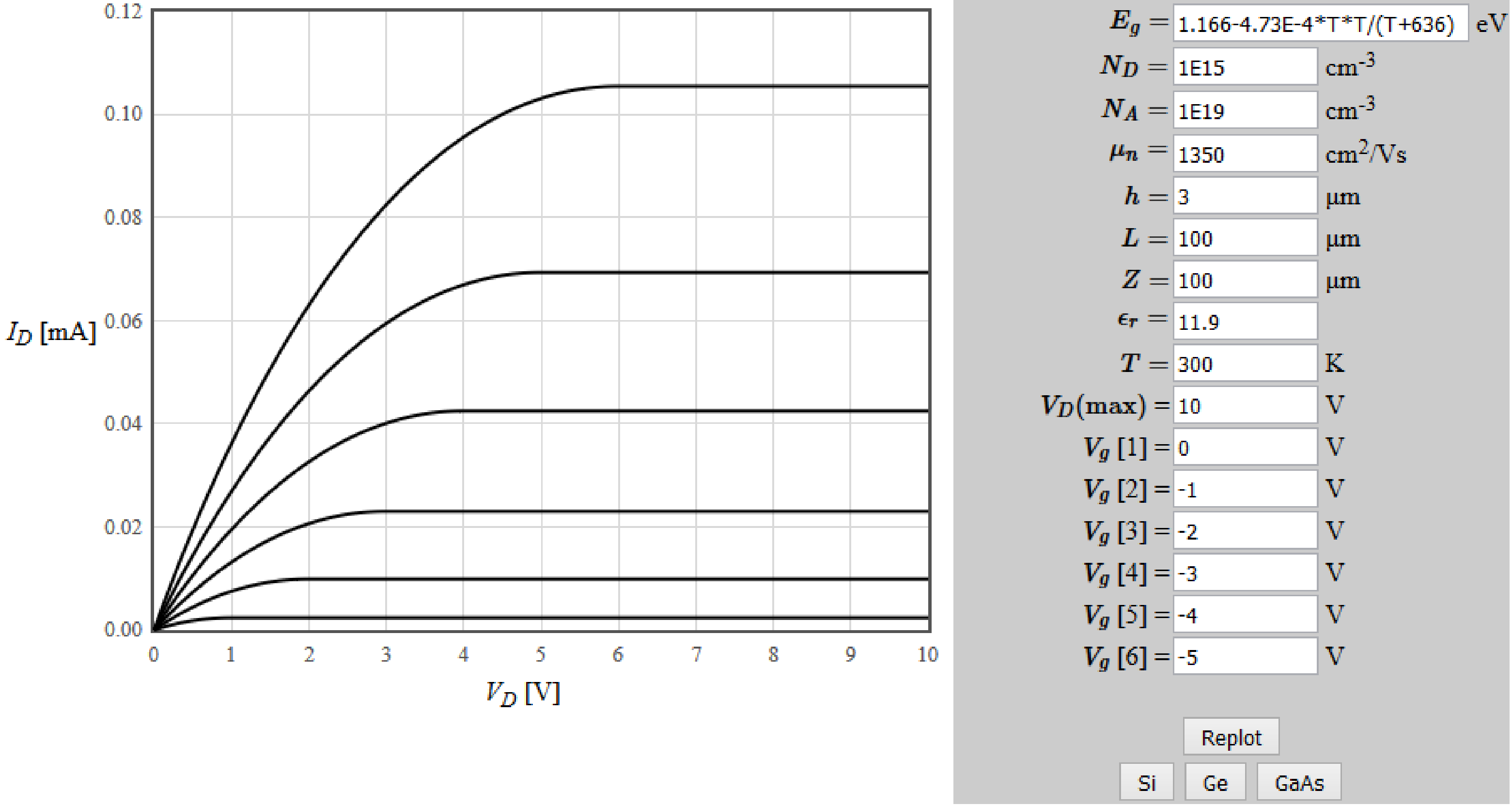
$$g_m = \frac{dI_{sat}}{dV_G} = \frac{I_p}{V_p} \left(1 - \sqrt{\frac{V_{bi} - V_G}{V_p}} \right)$$

$$g_m = \frac{dI_{sat}}{dV_G} = \frac{2Z\mu_n e N_D h}{L} \left(1 - \sqrt{\frac{V_{bi} - V_G}{V_p}} \right)$$



JFET

$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$



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$N_v(300K) =$ 9.84E18 cm^{-3}

$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$N_D =$ 1E15 cm^{-3}

$N_A =$ 1E19 cm^{-3}

$\mu_n =$ 1350 cm^2/Vs

$h =$ 3 μm

$L =$ 100 μm

$Z =$ 100 μm

$\epsilon_r =$ 11.9

$T =$ 300 K

$V_D(\max) =$ 10 V

V_g [1] = 0 V

V_g [2] = -1 V

V_g [3] = -2 V

V_g [4] = -3 V

V_g [5] = -4 V

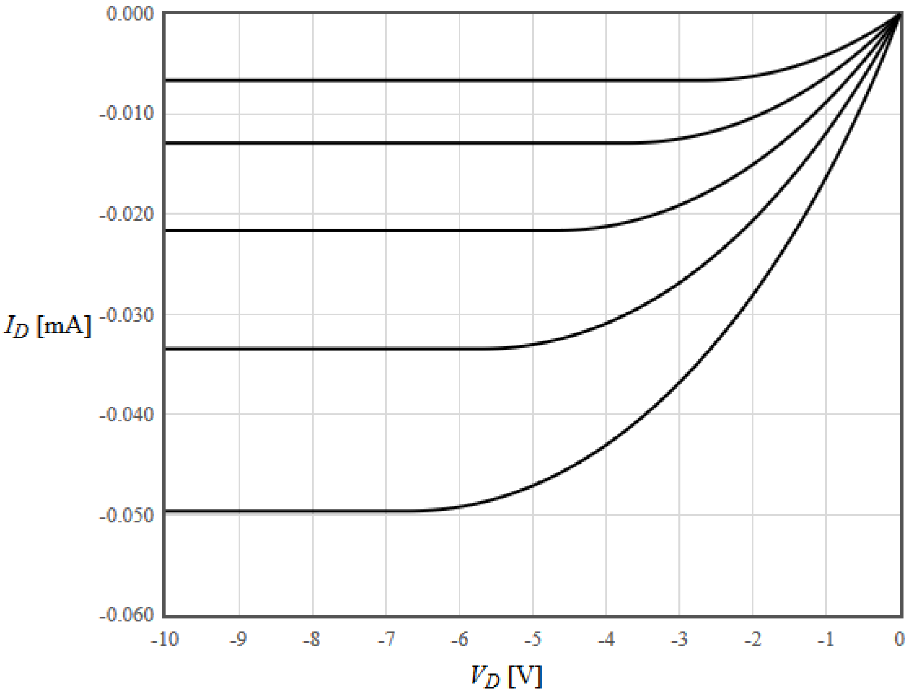
V_g [6] = -5 V

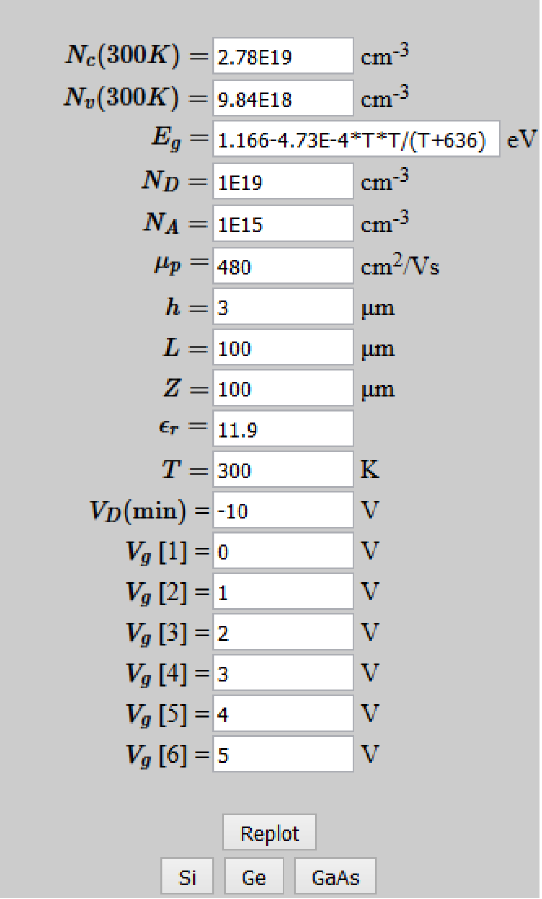
$E_g = 1.12$ eV; $n_i = 6.41\text{e+9}$ cm^{-3}; $V_{bi} = 0.856$ V; $I_p = 0.000444$ A; $V_p = 6.84$ V.

p-channel JFET

The expression for the drain current of a p-channel JFET in the linear regime is,

$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$





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$N_v(300K) =$ 9.84E18 cm^{-3}

$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$N_D =$ 1E19 cm^{-3}

$N_A =$ 1E15 cm^{-3}

$\mu_p =$ 480 cm^2/Vs

$h =$ 3 μm

$L =$ 100 μm

$Z =$ 100 μm

$\epsilon_r =$ 11.9

$T =$ 300 K

$V_D(\min) =$ -10 V

V_g [1] = 0 V

V_g [2] = 1 V

V_g [3] = 2 V

V_g [4] = 3 V

V_g [5] = 4 V

V_g [6] = 5 V

$E_g = 1.12$ eV; $n_i = 6.41\text{e+}9$ cm^{-3}; $V_{bi} = 0.856$ V; $I_p = -0.000158$ A; $V_p = -6.84$ V.

High frequencies

$$\tilde{i}_{in} = 2\pi f C_G \tilde{v}_G \qquad \tilde{i}_{out} = g_m \tilde{v}_G$$

for gain: $\tilde{i}_{in} < \tilde{i}_{out}$

$$f < \frac{g_m}{2\pi C_G} = f_T$$

f_T is the frequency where the gain drops below 1

average capacitance: $C_G = ZL\dfrac{\varepsilon}{\bar{x}_n}$

$$\boxed{f_T = \frac{\mu_n e N_D h^2}{2\pi\varepsilon L^2}}$$

For velocity saturation, the approximation $dV = I_D \frac{\rho dy}{Z(h - x_n(y))}$ is not valid

Ohm's law assumes $v_d = \mu E$

$$\boxed{f_T \approx \frac{v_s}{L}}$$