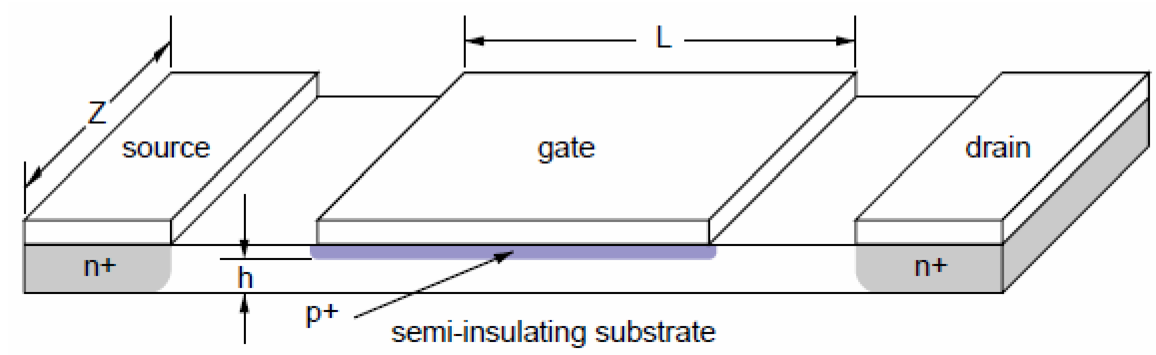
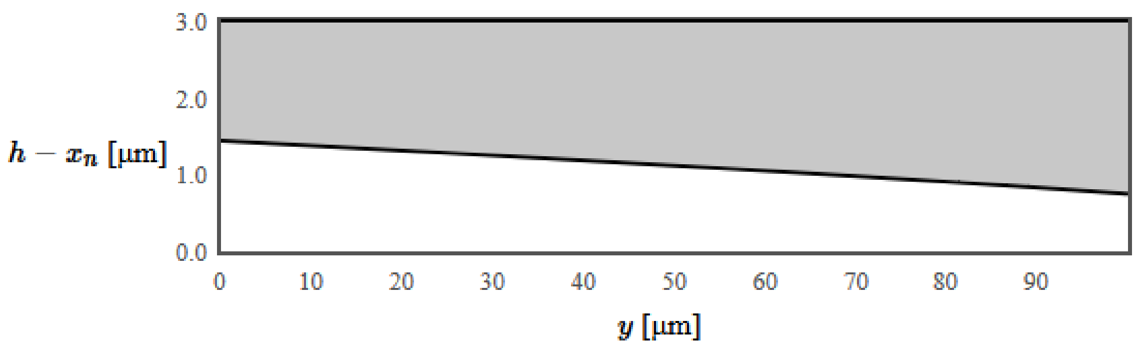
Technische Universität Graz

9. JFETs / MESFETS /MODFETs

Nov. 27, 2019

JFET Gradual Channel Approximation





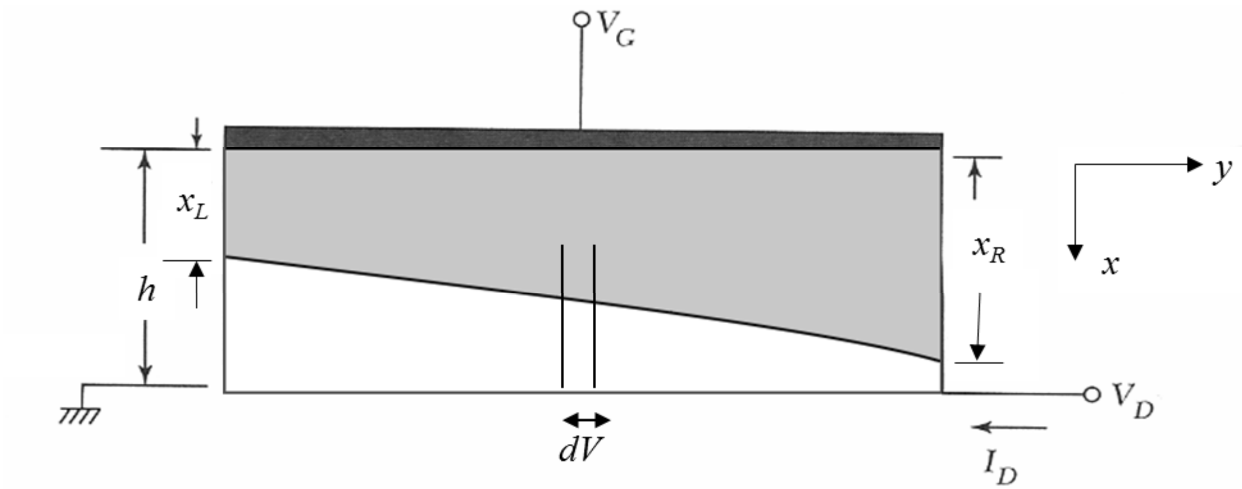
$N_c(300K) =$	2.78E19	cm^{-3}
$N_v(300K) =$	9.84E18	cm^{-3}
$E_g =$	1.166-4.73E-4*T*T/(T+636)	eV
$N_D =$	1E15	cm^{-3}
$N_A =$	1E19	cm^{-3}
$\mu_n =$	1350	cm^2/Vs
$h =$	3	µm
$L =$	100	µm
$Z =$	100	µm
$\epsilon_r =$	11.9	
$T =$	300	K
$V_D =$	2	V
$V_g =$	-1	V

Replot

Si Ge GaAs

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

JFET

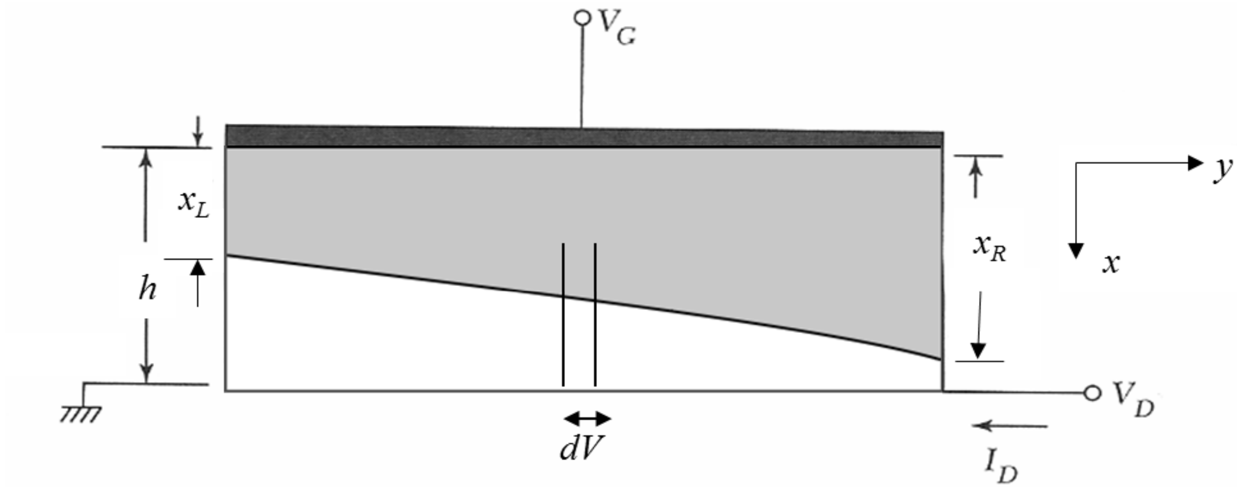


There is a long derivation to determine how the current depends on V_G and V_D.

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



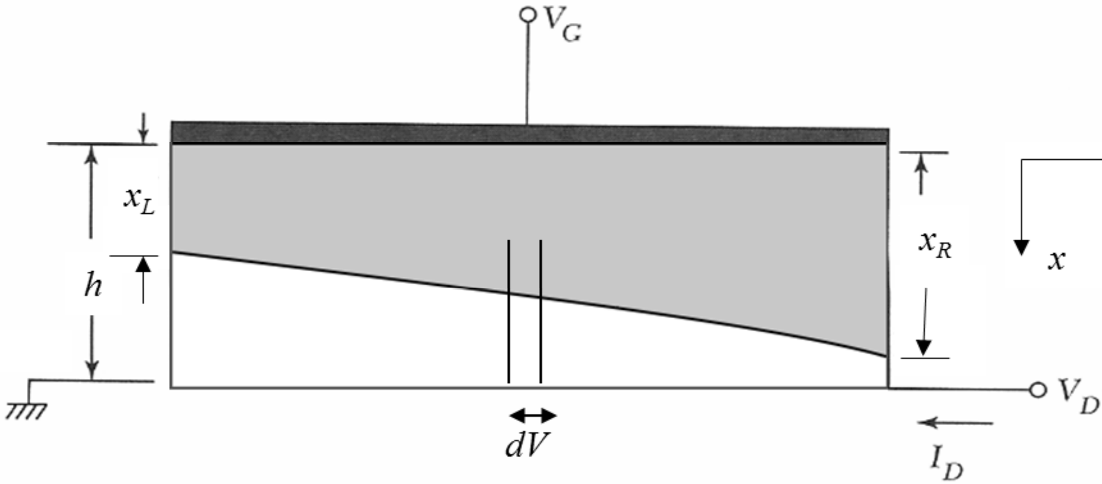
$$dV = I_D dR = I_D \frac{\rho dy}{Z(h - x_n(y))}$$

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

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

JFET

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



V_G is a forward bias

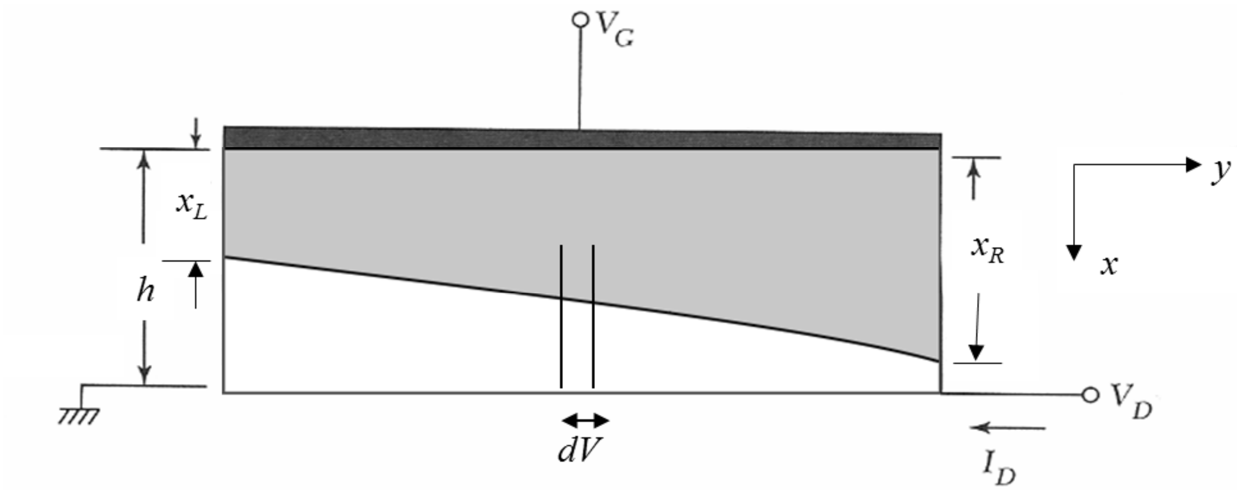
$V(y)$ is a reverse bias.

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.

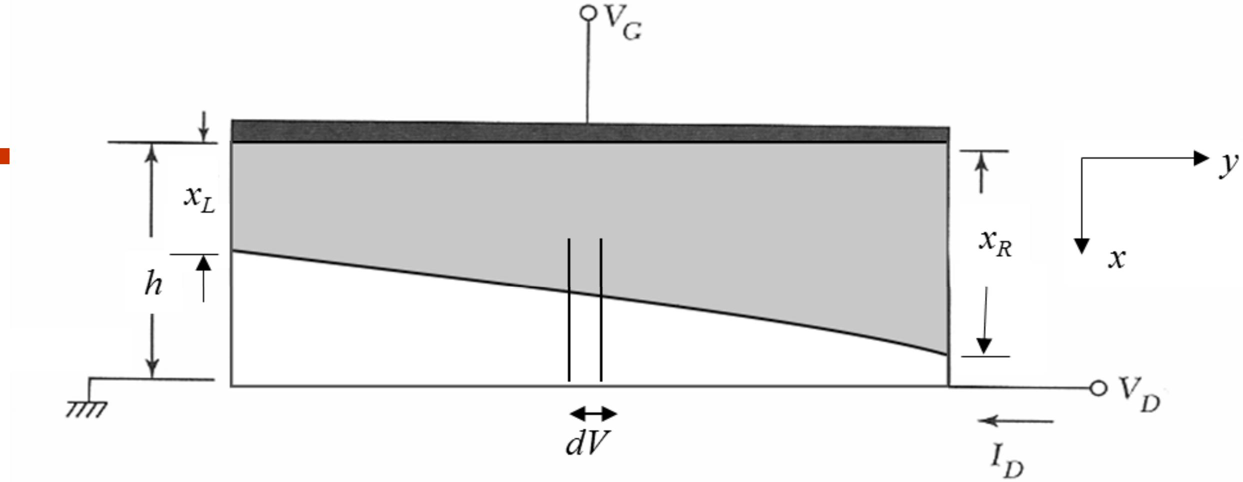
depletion width is a function of position $\quad x_n(y) = \sqrt{\dfrac{2\varepsilon(V_{bi} + V(y) - V_G)}{eN_D}}$

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



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

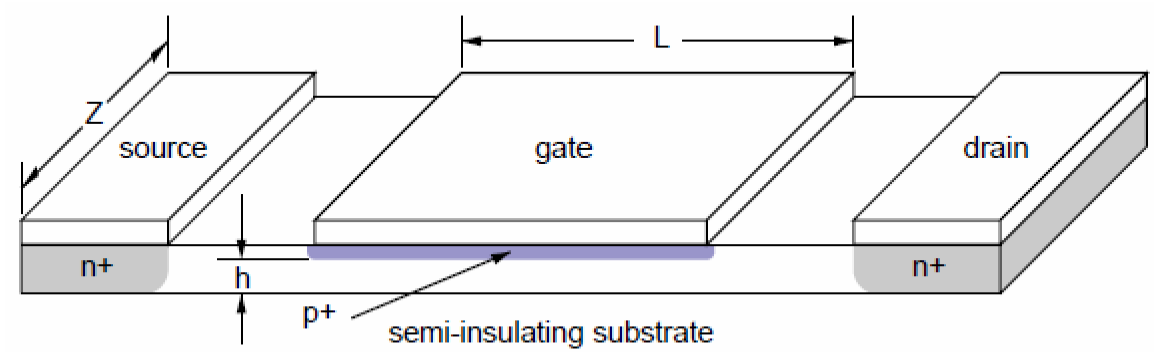
$$dV = \frac{eN_D x_n}{\varepsilon} dx_n$$

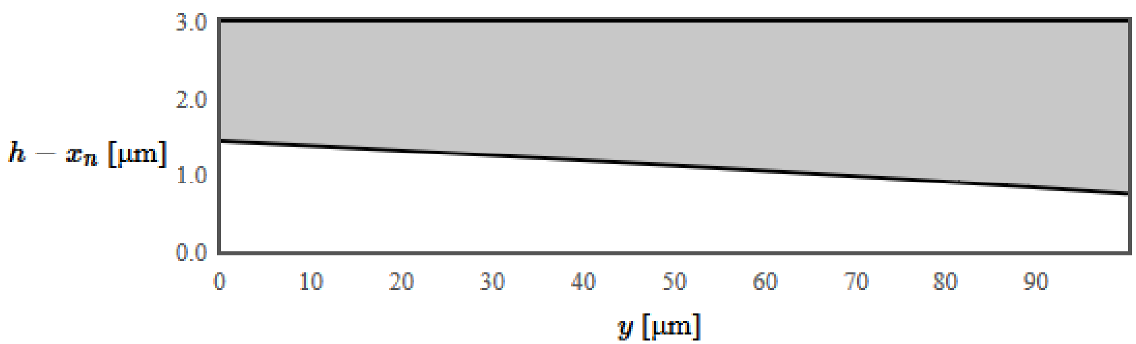
from last slide

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

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

JFET Gradual Channel Approximation





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$V_D =$	2	V
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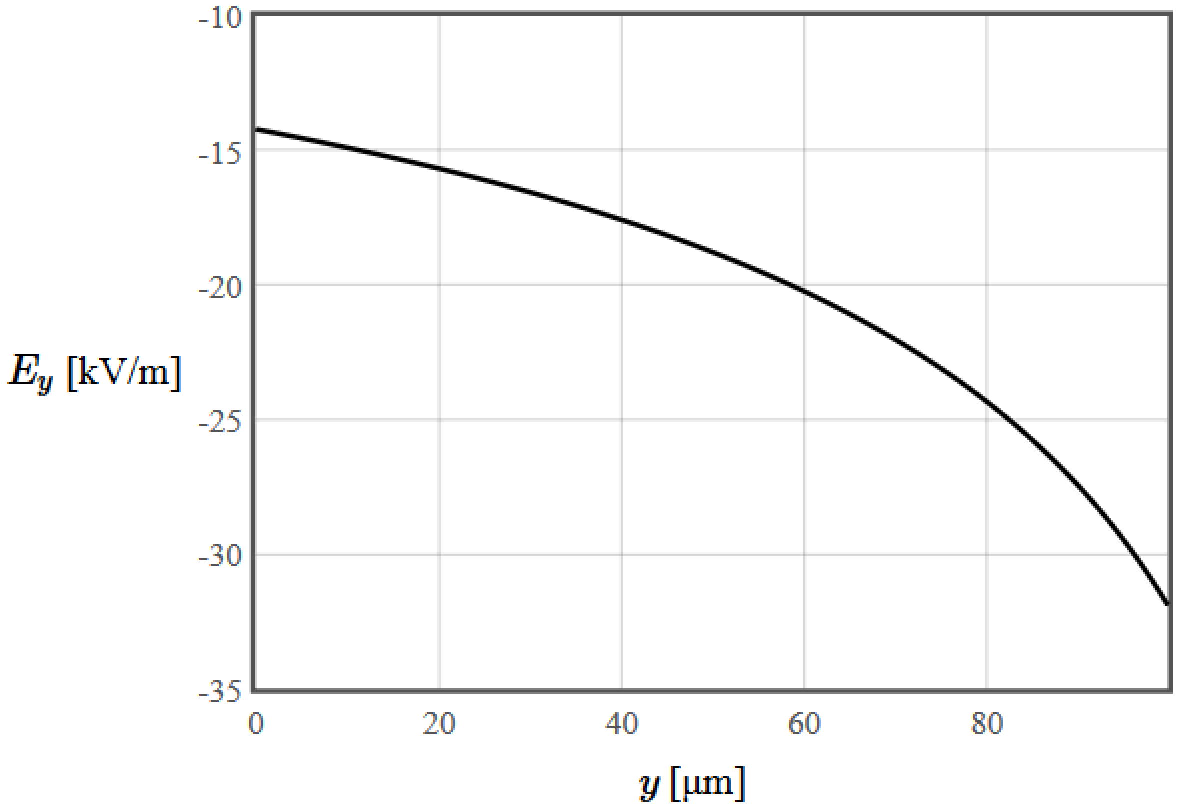
Replot

Si Ge GaAs

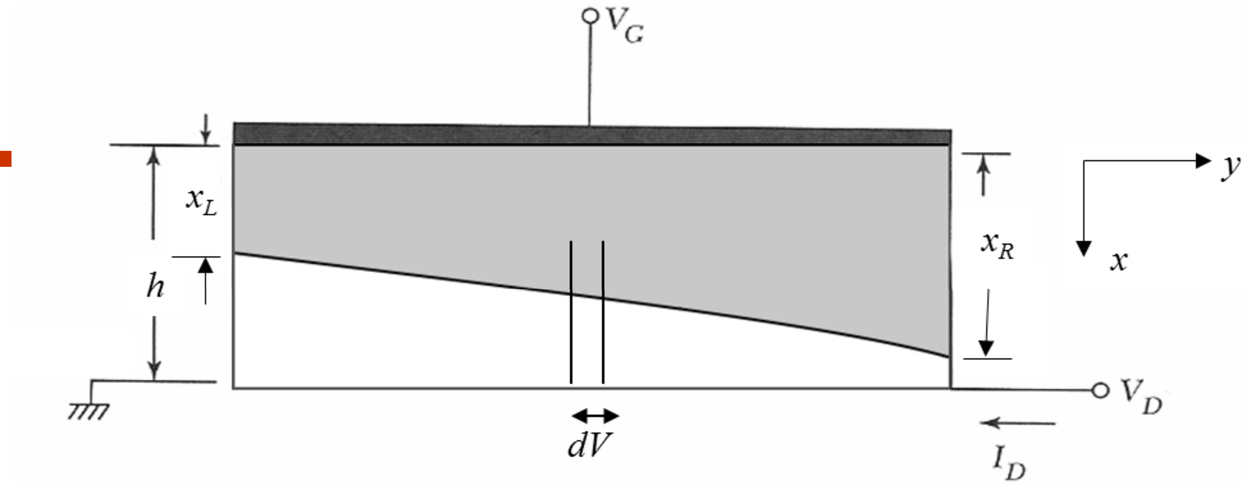
http://lampx.tugraz.at/~hadley/psd/L9/gradual.php

Electric field

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



JFET

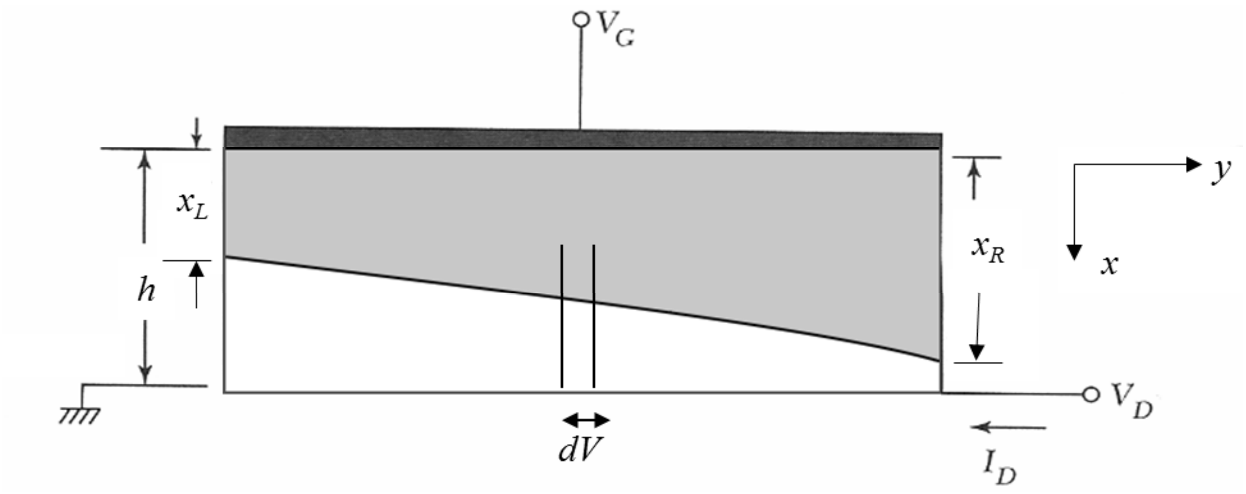


$$I_D dy = e\mu_n N_D Z(h - x_n(y))\frac{eN_D}{\varepsilon}x_n dx_n$$

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

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

JFET



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

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

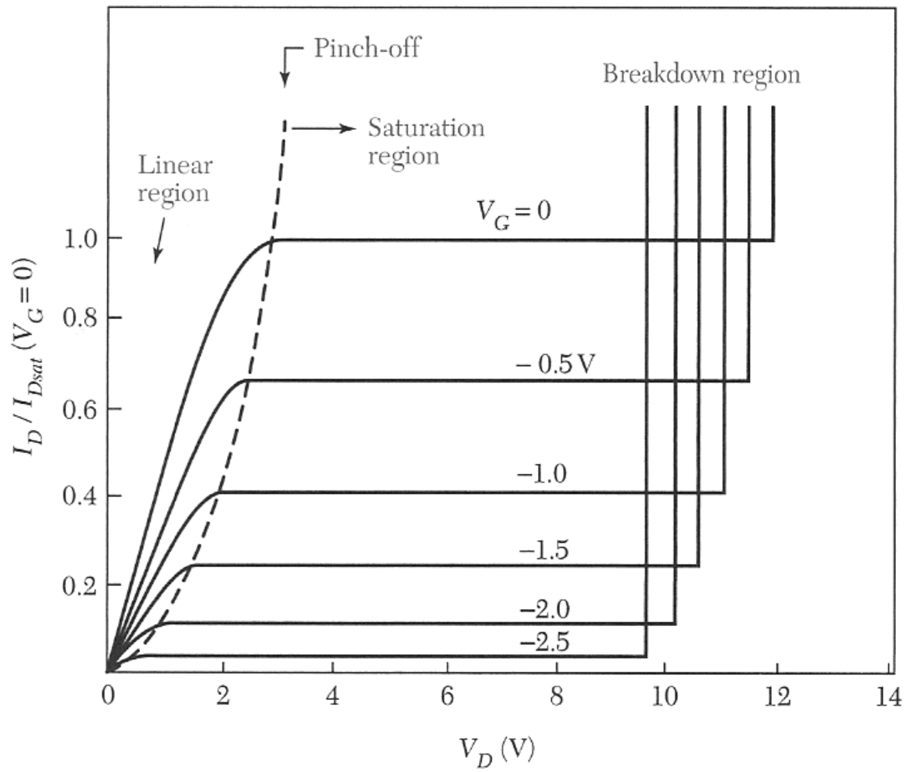
$$V_p = \frac{eN_D h^2}{2\epsilon_r \epsilon_0}$$

JFET - drain current

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

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

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

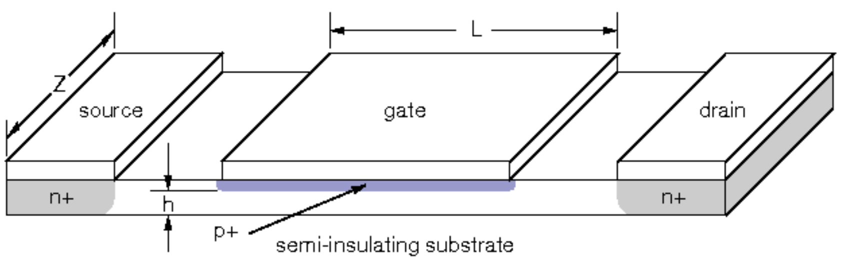
$$I_D = I_p \left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2} \right]$$

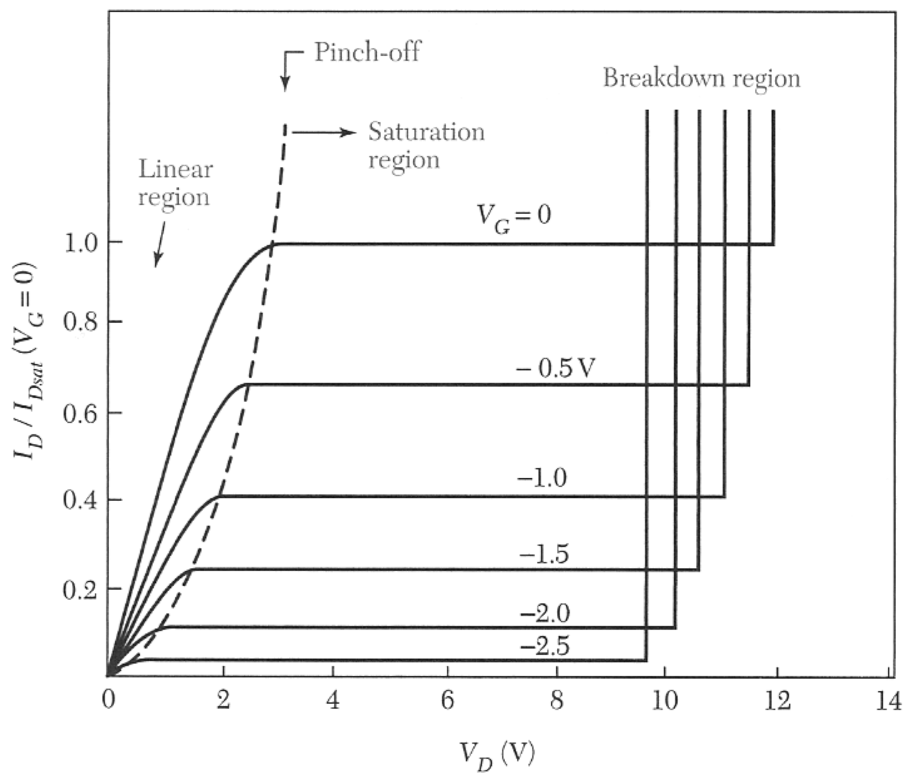
In the linear regime $V_D << V_{sat}$.

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

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

variable resistor





JFET - Saturation regime

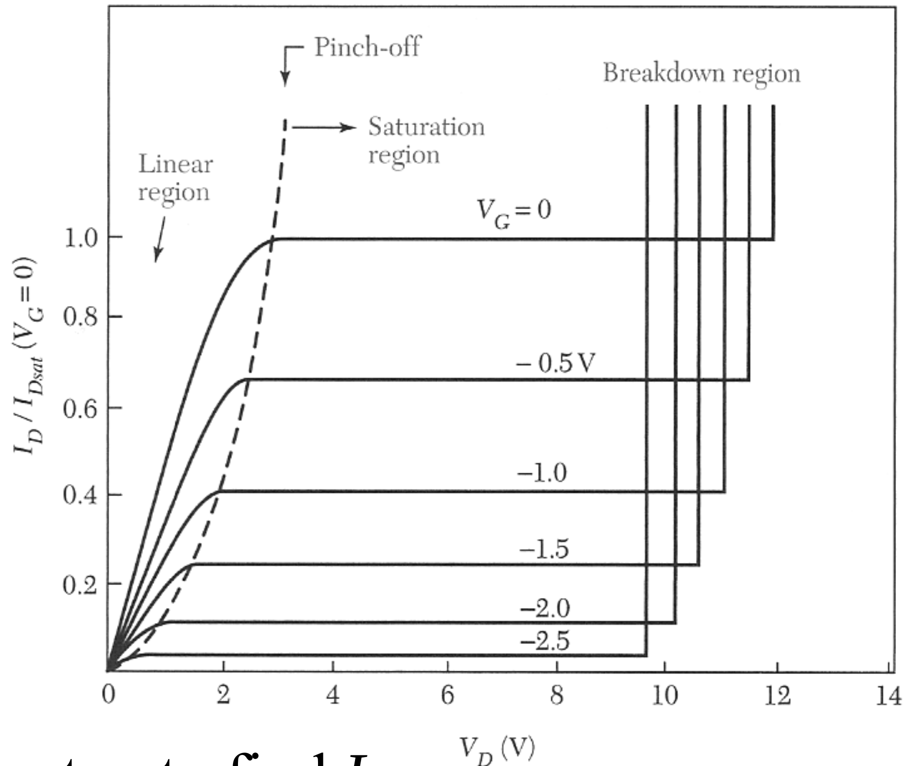
$$I_D = I_p\left[\frac{V_D}{V_p} - \frac{2}{3}\left(\frac{V_{bi}+V_D-V_G}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{bi}-V_G}{V_p}\right)^{3/2}\right]$$

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

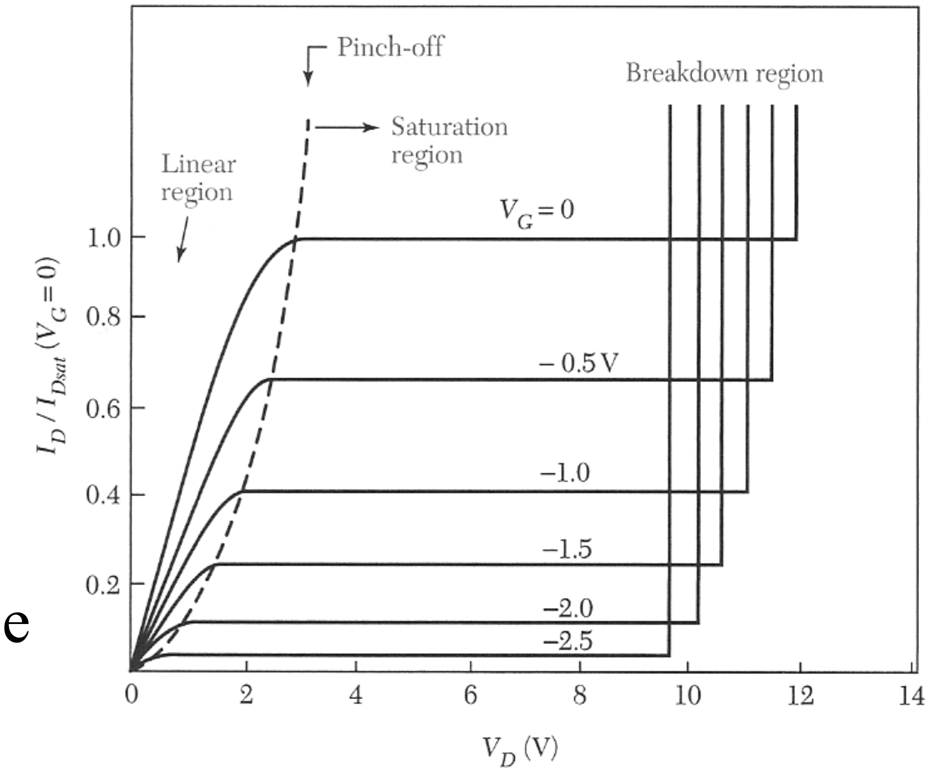
$$V_{sat} = V_p - V_{bi} + V_G$$

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

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

No V_D dependence

Voltage controlled current source



JFET - transconductance

In the saturation regime,

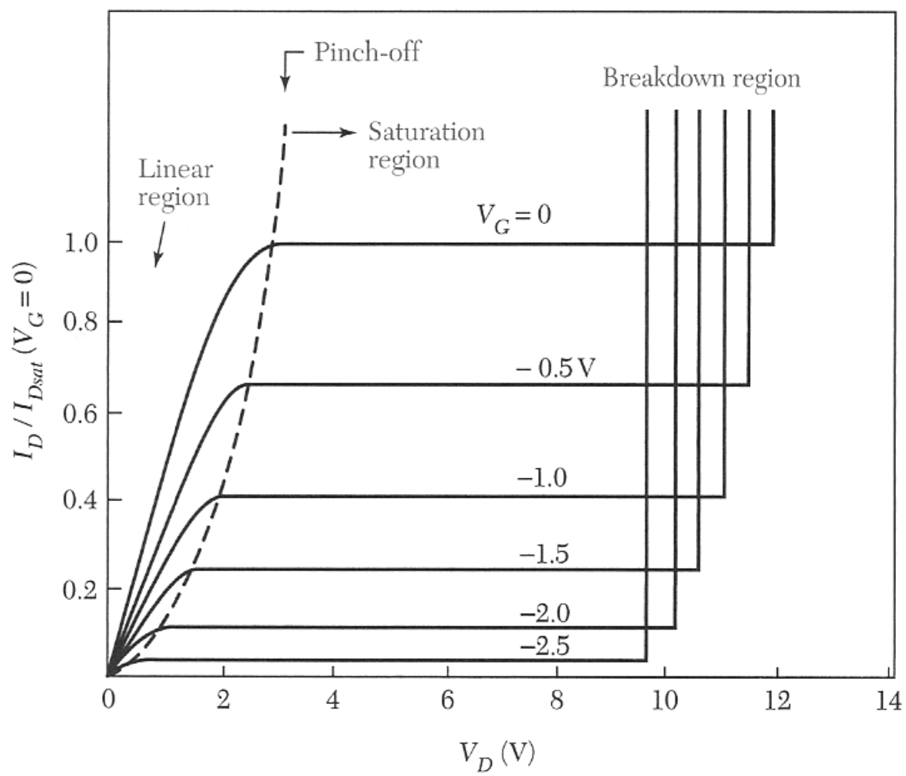
$$I_{sat} = I_p \left[\frac{1}{3} - \frac{V_{bi} - V_G}{V_p} + \frac{2}{3} \left(\frac{V_{bi} - V_G}{V_p} \right)^{3/2} \right]$$

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

↓

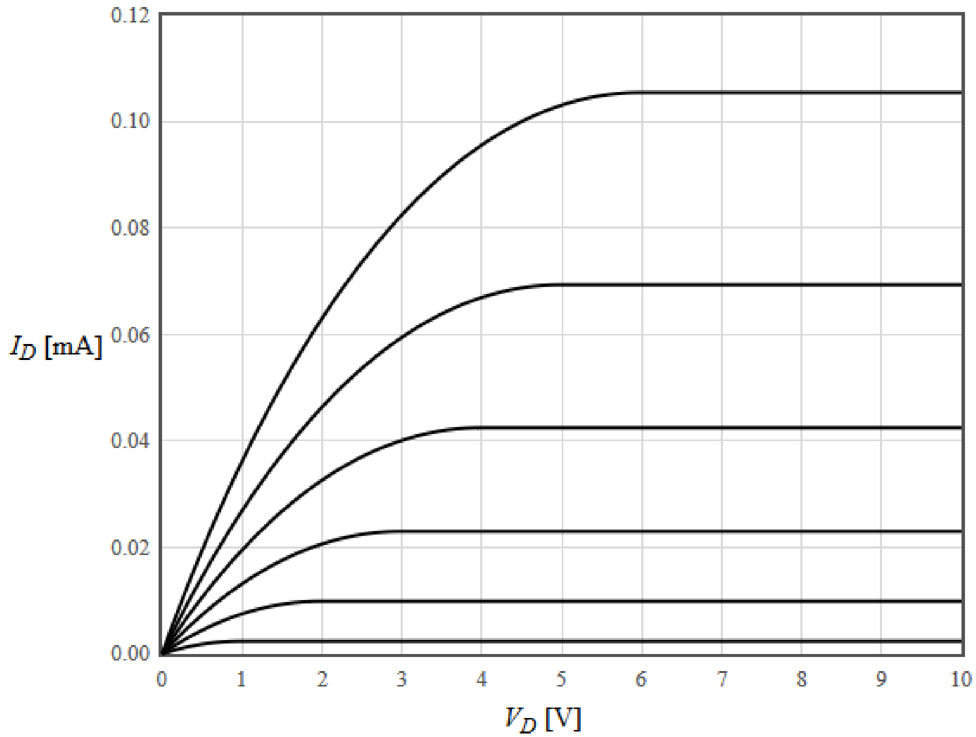
$$g_m = \frac{dI_{sat}}{dV_G} = \frac{I_p}{V_p} \left(1 - \sqrt{\frac{V_{bi} - V_G}{V_p}} \right)$$

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



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

Replot

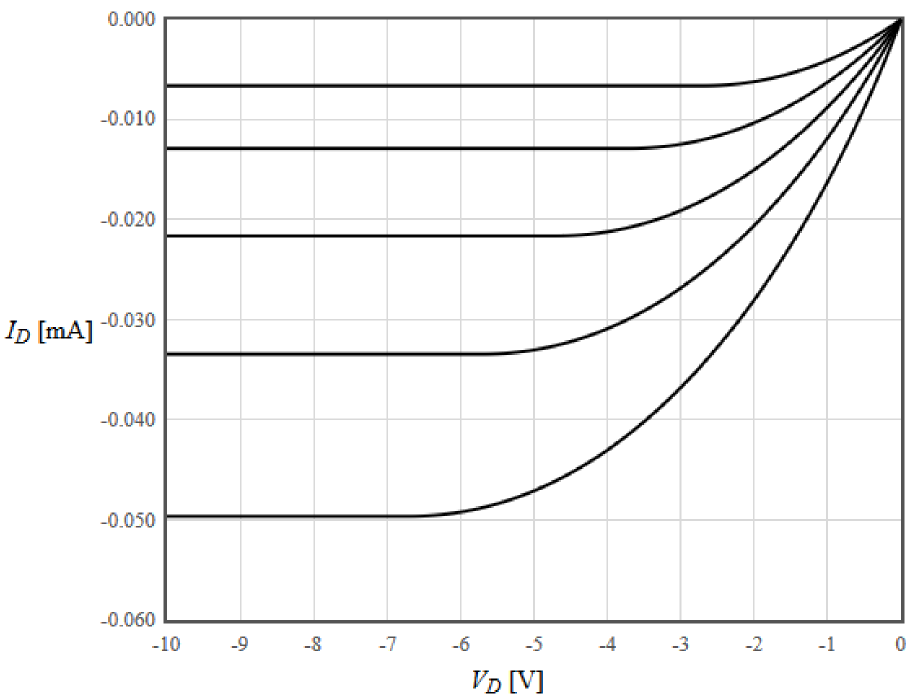
Si Ge GaAs

$E_g = 1.12$ eV; $n_i = 6.41e{+}9$ 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,

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



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

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

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

$N_D =$ 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

$V_D(\text{min}) =$ -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

Replot

Si Ge GaAs

$E_g = 1.12$ eV; $n_i =$ 6.41e+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

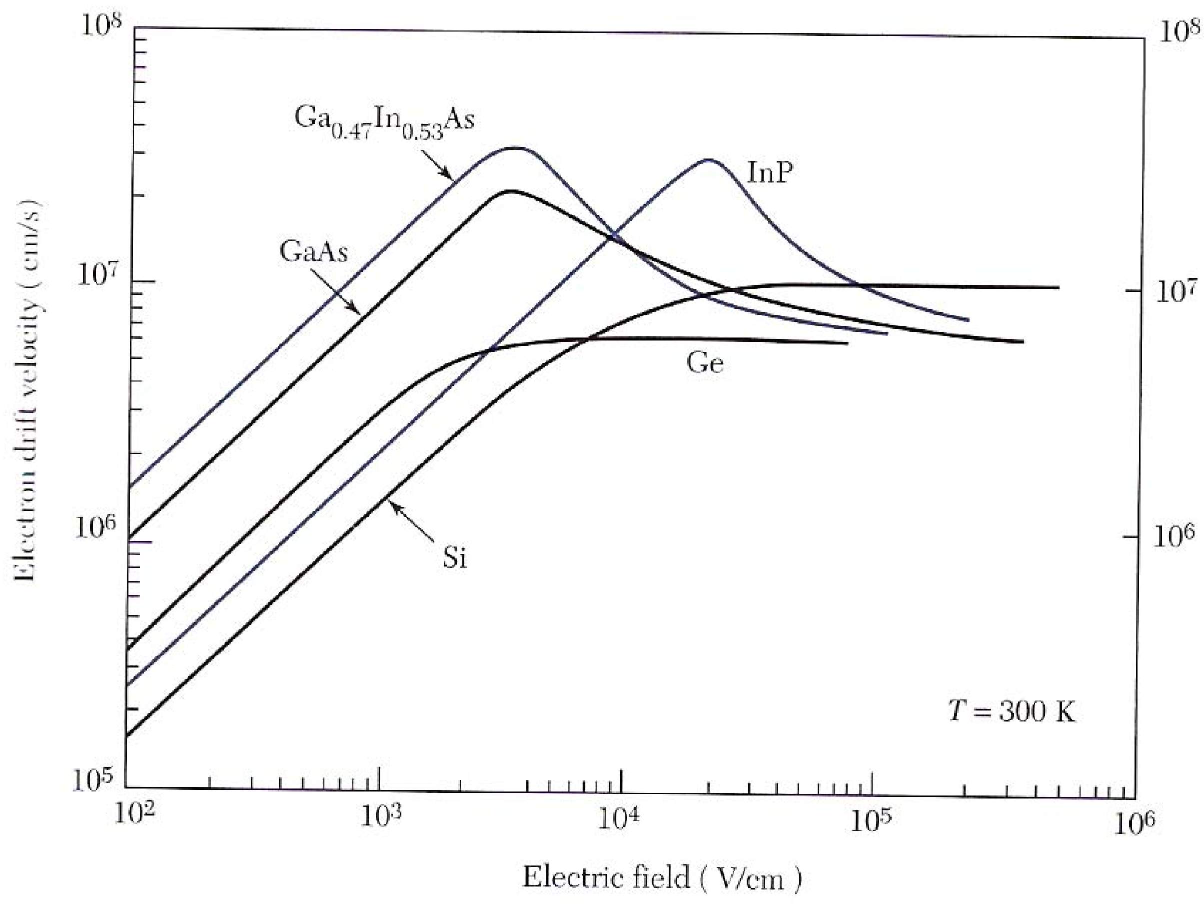
average capacitance: $C_G = ZL\dfrac{\varepsilon}{\bar{x}_n}$

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

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

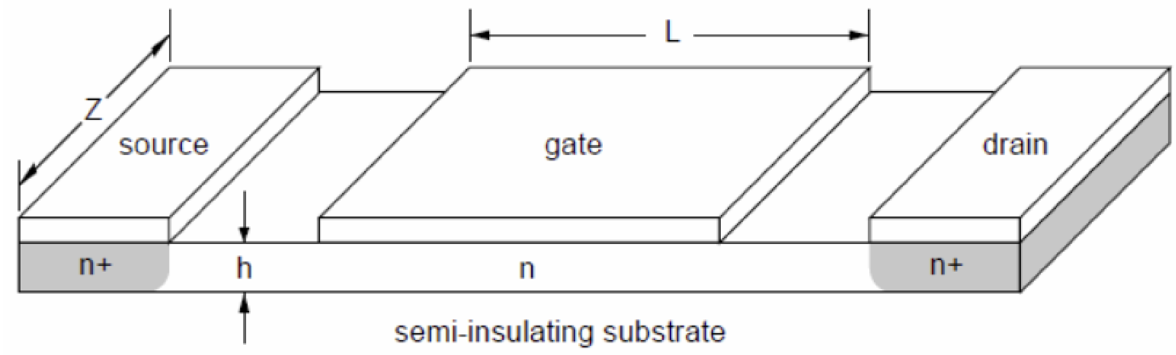
Ohm's law assumes $v_d = \mu E$

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

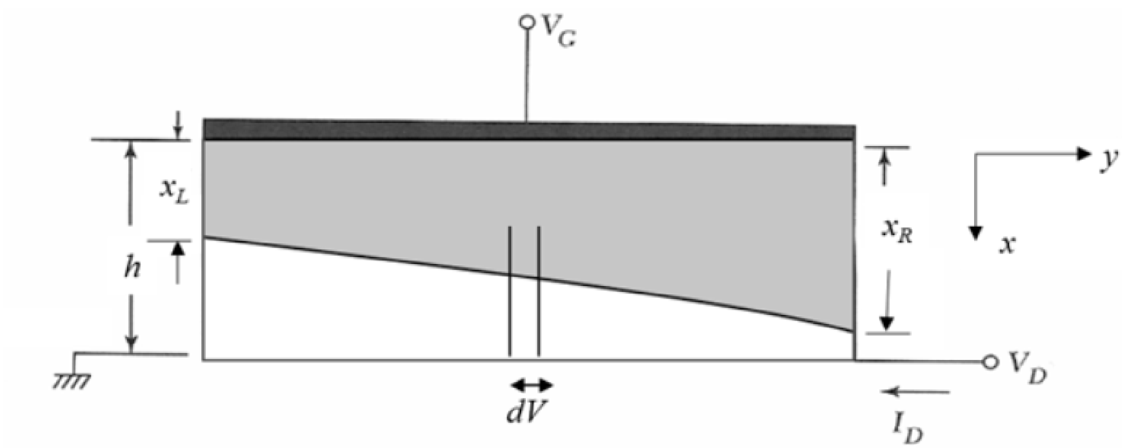


MESFET Gradual Channel Approximation

The description of a MESFET in the gradual channel approximation is almost the same as for a JFET. The difference is how the built-in voltage V_{bi} is calculated. Consider an n-channel MESFET.



A MESFET consists of a semiconducting channel contacted by two ohmic contacts. The metal gate forms a Schottky contact above the channel. The current in the channel flows between the depletion layer of the Schottky diode and a semi-insulating substrate. When the Schottky contact is reverse biased, the depletion width expands and the channel becomes narrower. The thickness of the conducting channel is $h - x_n(y)$ where h is the thickness of the n-doped channel and $x_n(y)$ is the depletion width that depends on the position y along the channel. In the figure below, the gray region of the channel is depleted.



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

JFET / MESFET

JFET: small gate current (reverse leakage of the gate-to-channel junction)

More gate leakage than MOSFET, less than bipolar.

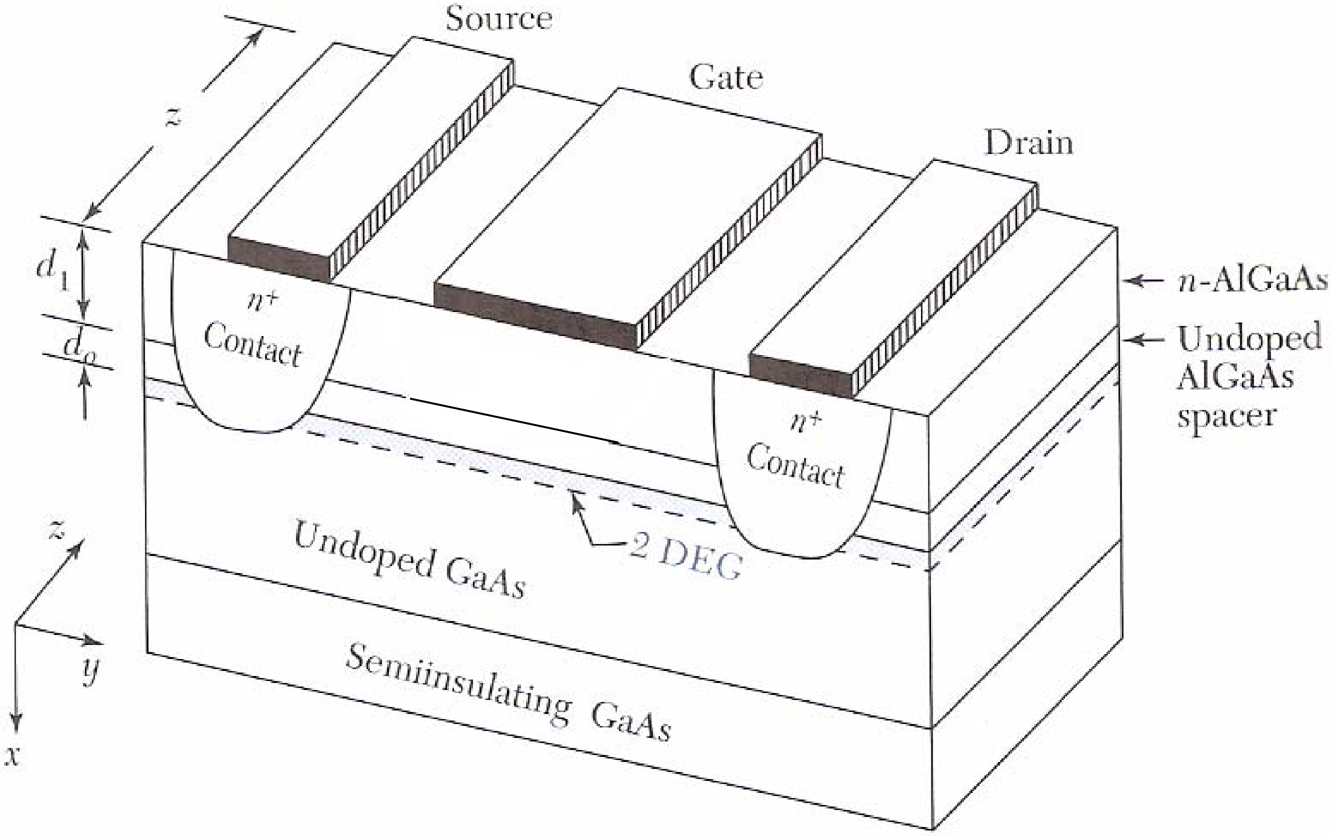
JFET has higher transconductance than the MOSFET.

Used in low-noise, high input-impedance op-amps and sometimes used in switching applications.

MESFET: usually constructed in compound semiconductor technologies lacking high quality surface passivation such as GaAs, InP, or SiC, and are faster but more expensive than silicon-based JFETs or MOSFETs. Production MESFETs are operated up to approximately 30 GHz, and are commonly used for microwave frequency communications and radar. Majority carrier device (like Schottky diode).

MODFET (HEMT)

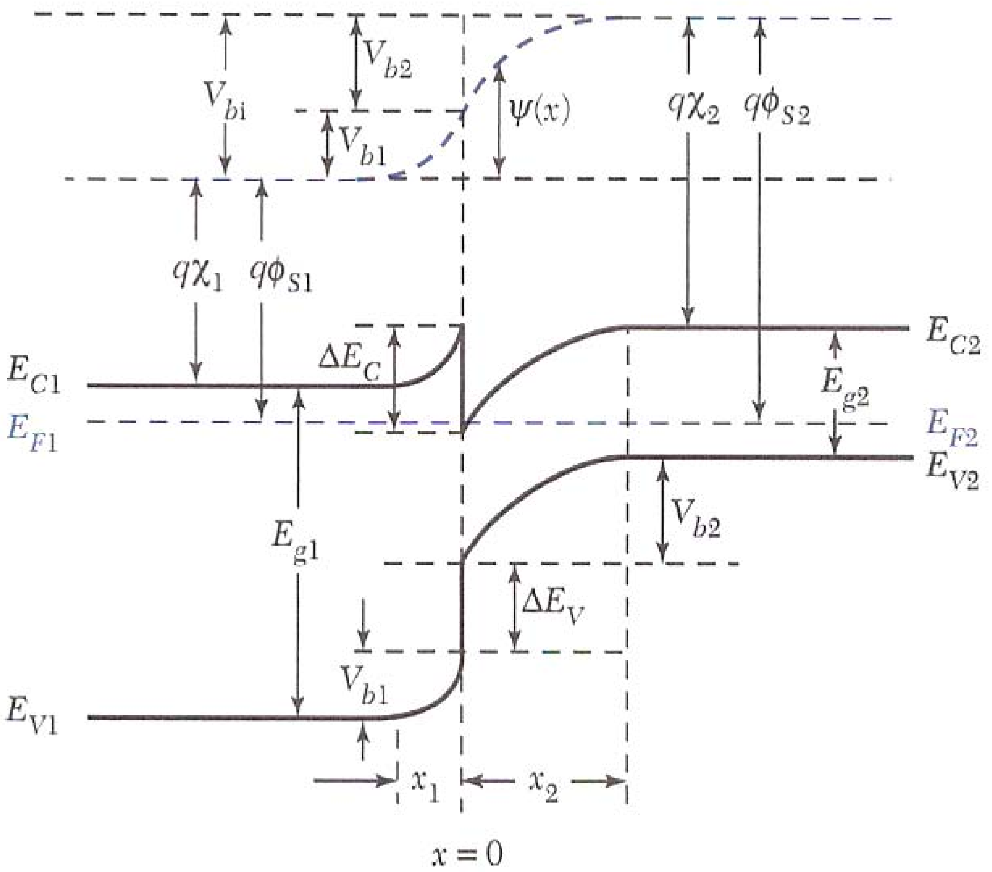
Modulation doped field effect transistor (MODFET)
High electron mobility transistor (HEMT)



V_T = Threshold voltage = voltage where charge is depleted

Heterostructure

pn junction formed from two semiconductors with different band gaps



MODFET/HEMT

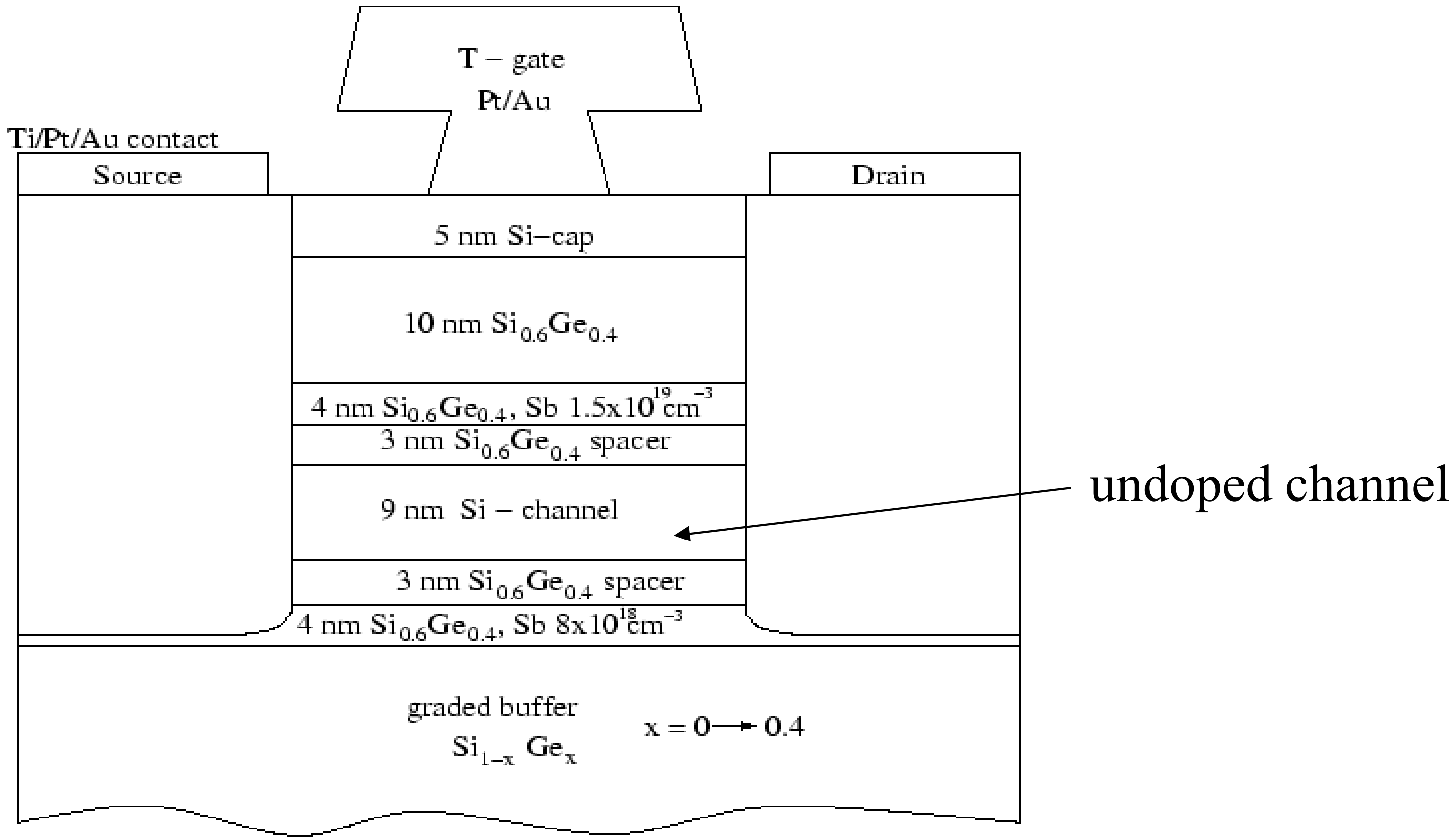


Figure 3.3: S-MODFET structure.

HEMT: HEMT devices are found in cell phones, electronic warfare systems, microwave and millimeter wave communications, radar, and radio astronomy.

PhD Thesis Sergey Smirnov

http://www.iue.tuwien.ac.at/phd/smirnov/node71.html

MODFET (HEMT)

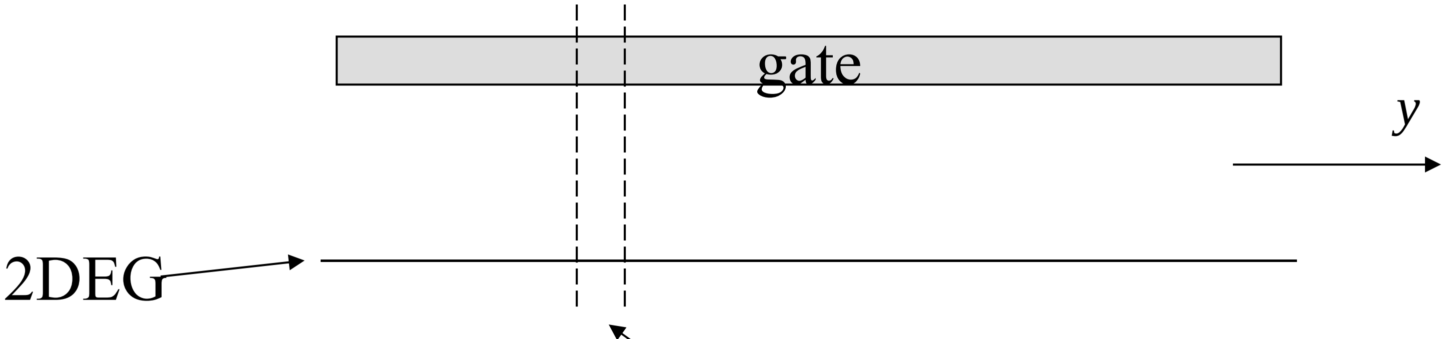
$$j = nev_d = ne\mu_n E_y$$

$$I = jZt = Ze\mu_n n_s E_y \qquad n = \frac{n_s}{t}$$

t is the thickness of the 2DEG
n_s is the sheet charge at the interface in C/cm^2.

$V_G - V(y)$ is the voltage between the gate and the 2DEG

$n_s = 0$ when $V_G - V(y) = V_T$



$q = CV$

$$-en_s(y) = -C_g\left(V_G - V(y) - V_T\right)$$

MODFET (HEMT)

$-en_s(y) = C_g\left(V_G - V_B(y) - V_T\right)$ is the charge on the 2DEG at point y

The charge is zero when $V_G - V_B(y) = V_T$

solve for n_s

$$n_s(y) = \frac{-C_g\left(V_G - V_B(y) - V_T\right)}{e}$$

Substitute this in Ohm's law:

$$I = jZt = Ze\mu_n n_s E_y$$

MODFET (HEMT)

$$I = jZt = Ze\mu_n n_s E_y$$

$$n_s(y) = \frac{-C_g\left(V_G - V(y) - V_T\right)}{e}$$

substitute n_s in the top equation and substitute $E_y = \frac{-dV(y)}{dy}$

$$I = Z\mu_n C\left(V_G - V_T - V(y)\right)\frac{dV(y)}{dy}$$

integrate along the length of the channel

$$\int_0^L I\,dy = \int_0^{V_D} Z\mu_n C\left(V_G - V_T - V(y)\right)dV$$

$$\boxed{I_D = \frac{Z}{L}\mu_n C\left[\left(V_G - V_T\right)V_D - \frac{V_D^2}{2}\right]}$$

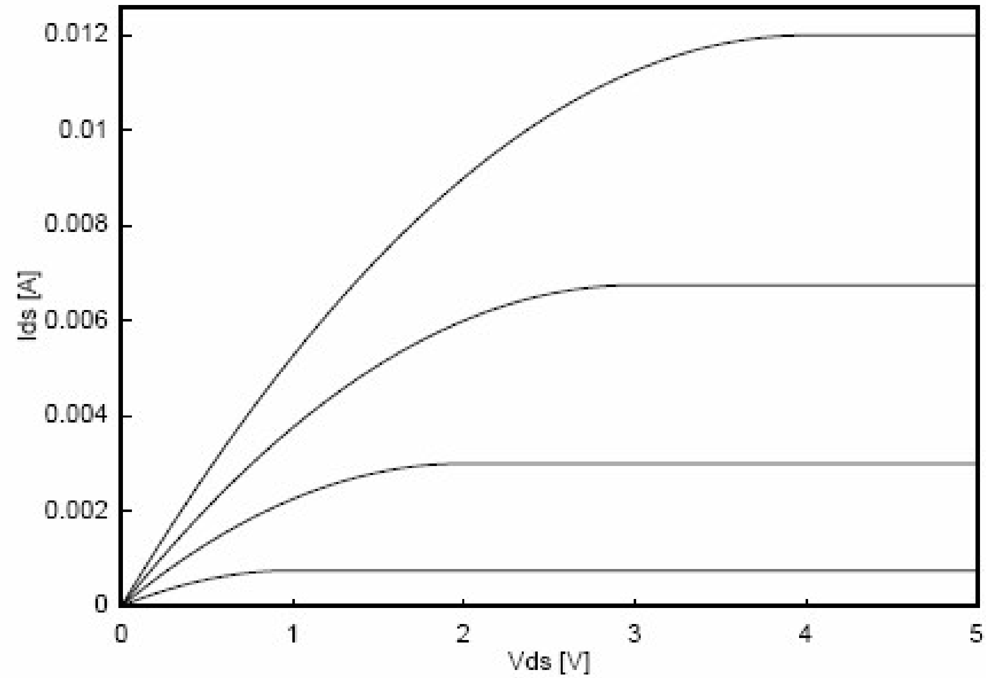
MODFET (HEMT)

$$I = \frac{Z}{L}\mu_n C\left[\left(V_G - V_T\right)V_D - \frac{V_D^2}{2}\right]$$

$$\frac{dI}{dV_D} = \frac{Z}{L}\mu_n C\left[\left(V_G - V_T\right) - V_D\right] = 0$$

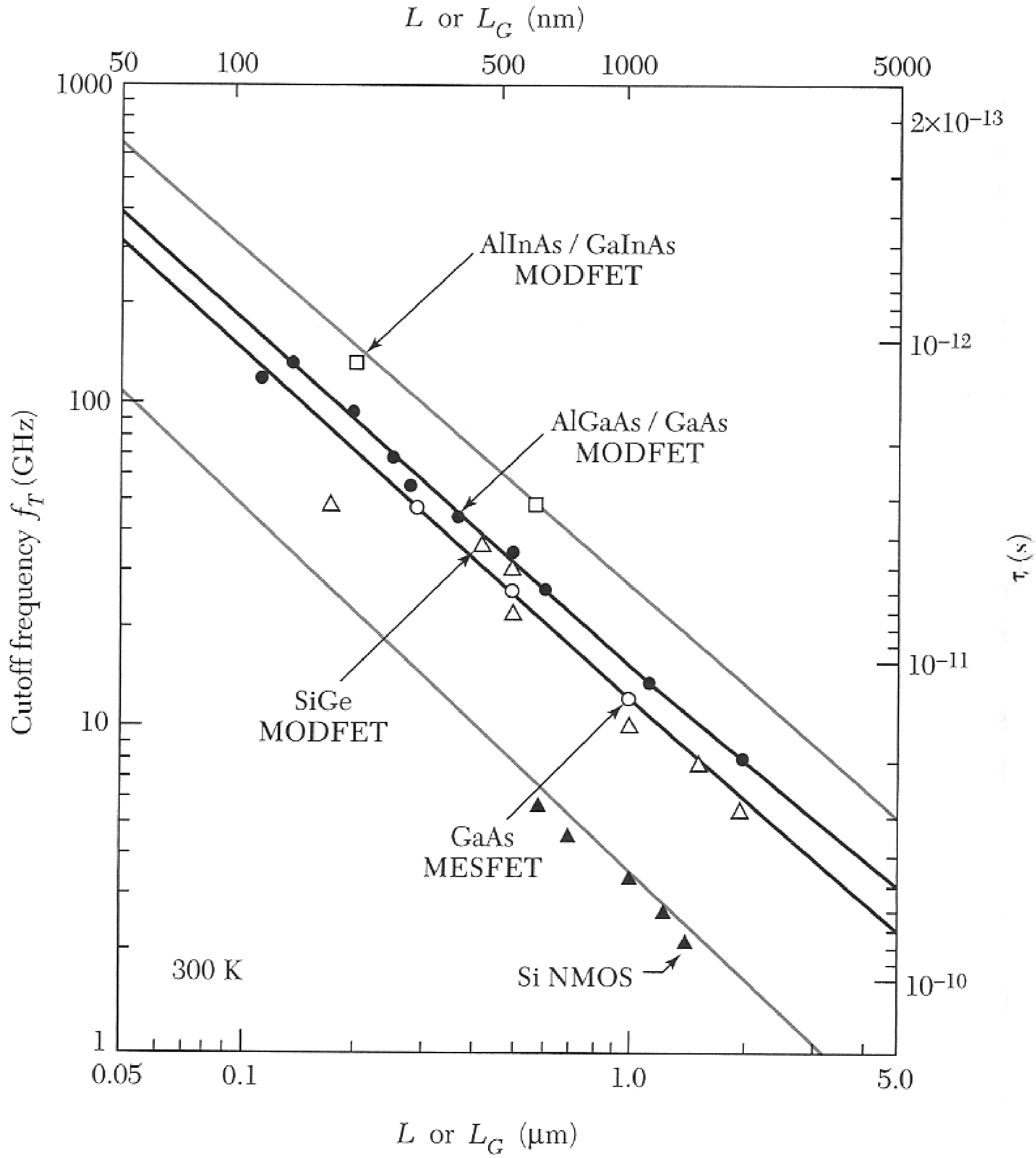
Set the derivative = 0 to find saturation voltage

$$V_{sat} = \left(V_G - V_T\right)$$



Substitute the saturation voltage into the formula at the top to find saturation current

$$I_{sat} = \frac{Z}{2L}\mu_n C\left(V_G - V_T\right)^2$$


L or L_G (nm)
50
100
500
1000
5000
1000
100
10
1
0.05
0.1
1.0
5.0
L or L_G (μm)
Cutoff frequency f_T (GHz)
τ (s)
2×10^{-13}
10^{-12}
10^{-11}
10^{-10}
AlInAs / GaInAs
MODFET
AlGaAs / GaAs
MODFET
SiGe
MODFET
GaAs
MESFET
Si NMOS
300 K

MODFET/HEMT

HEMT: HEMT devices are found in many types of equipment ranging from cell phones and DBS receivers to electronic warfare systems, microwave and millimeter wave communications, radar, and radio astronomy. 600 GHz