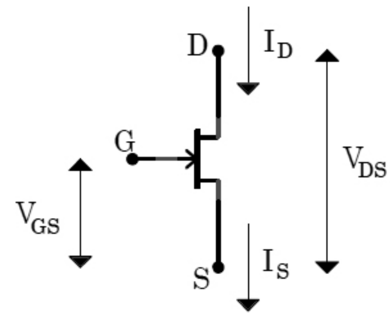
Physics 120A - Prof. David Kleinfeld - 13 May 2014
(Preliminary) Notes on N-channel FETs

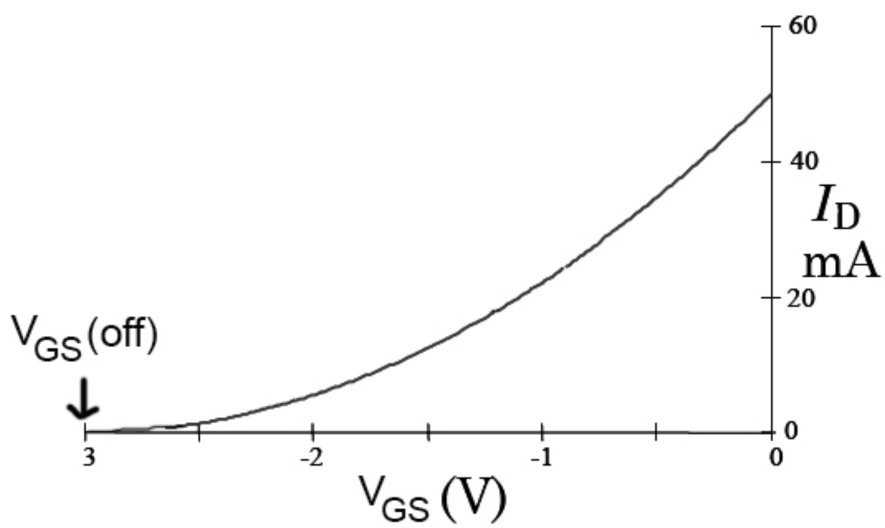


The basics

$I_G = 0$

In active region, device characteristics are defined by[1]:

1. $V_{GS}(\text{off}) \le V_{GS} \le 0$
2. $V_{DS} > V_{GS} - V_{GS}(\text{off})$, or equivalently $V_{DS} > |V_{GS}(\text{off})| - |V_{GS}|$
3. $I_D = I_S$
4. I_D is function of V_{GS}, with $I_D = I_{DSS}\left(1-\dfrac{V_{GS}}{V_{GS}(\text{off})}\right)^2$



5. I_D is independent of V_{DS} (ideal current source)

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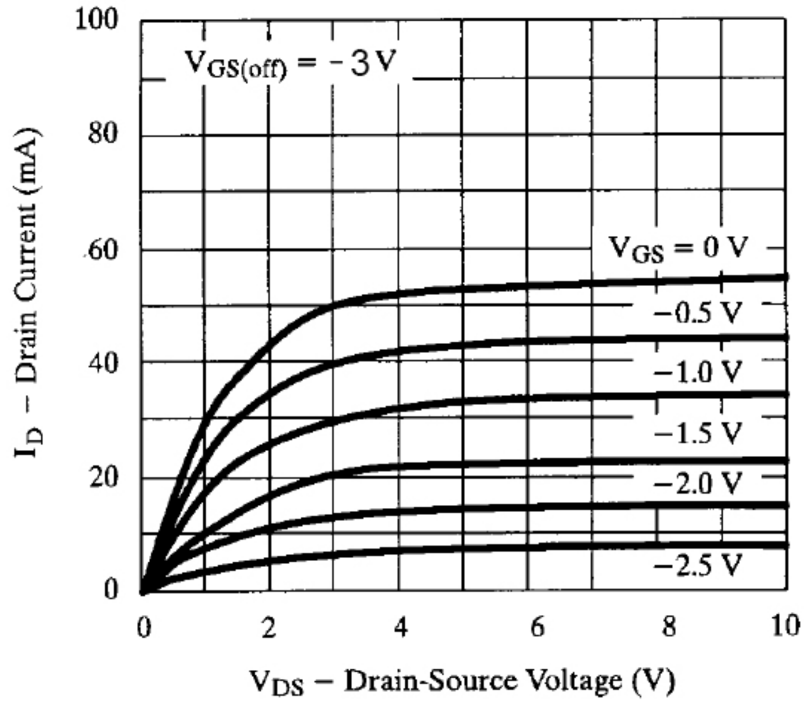
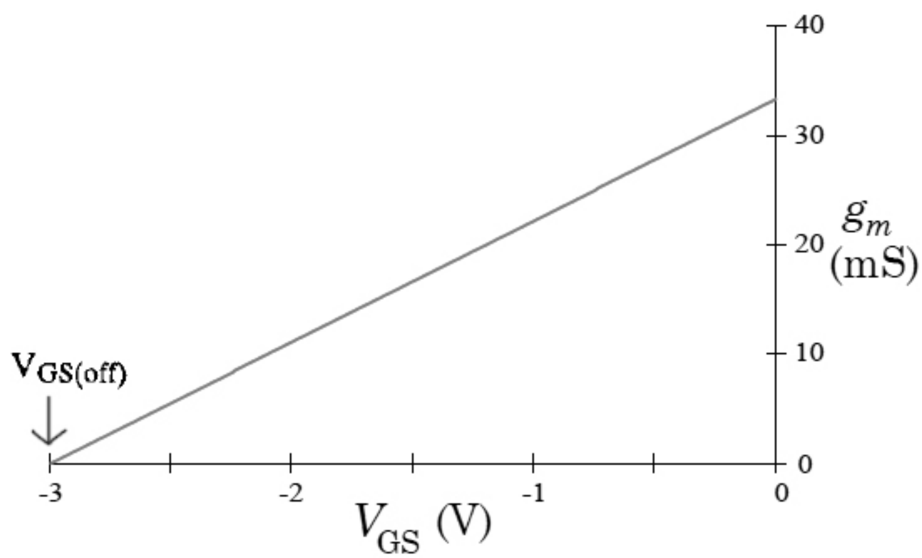
[1] The turn-off gate-to-source voltage $V_{GS}(\text{off})$ has a number of aliases, such as threshold voltage or pinch-off voltage, denoted $V_{GS}(\text{off}) = V_T = V_P = V_{PO} = V_{P0}$ The active region is also called the "saturation region" or "pentode region".



For small changes in gate voltage, we can calculate the changes in source or drain current. The constant of proportionality is referred to as the transconductance, denoted g_m, where

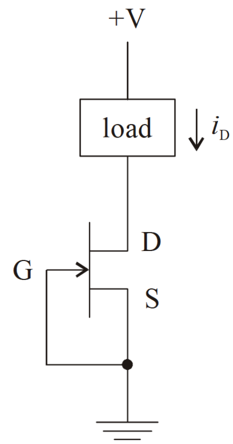
$$g_m = \frac{dI_S}{dV_{GS}} = \frac{dI_D}{dV_{GS}} = 2\frac{I_{DSS}}{-V_{GS}(off)}\left(1 - \frac{V_{GS}}{V_{GS}(off)}\right)$$



so that $\Delta I_S = g_m\, \Delta V_{GS}$. The transconductance plays a role analogous to β with bipolar junction transistors, but is *not* a constant, *i.e.*, it depends of V_{DS}!

Current Sources

Let's now consider the worlds simplest current source.



Here $V_{GS} = 0$ so the current is forced to be I_{DSS}. This can be accomplished so long as the load line can accommodate $V_{DS} > V_{GS} - V_{GS}(\text{off})$, *i.e.*, maintain a value of V_{DS} in the active region. The load line is given by (ignoring the transconductance $1/g_m$):

$$0 = -V_{DD} + I_D R_{Load} + V_{DS}$$

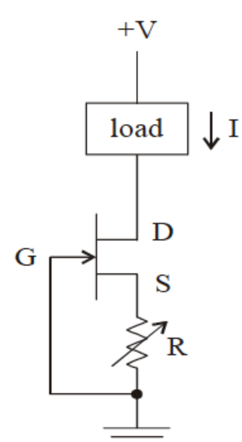
$$V_{DD} - I_{DSS} R_{Load} > -V_{GS}(\text{off})$$

which implies

$$R_{Load} < \frac{V_{DD} + V_{GS}(\text{off})}{I_{DSS}}$$

Here, we slide along the (flat) line of $I_D = I_{DSS}$ so long as $V_{DS} > -V_{GS}(\text{off})$. This simple device suffers only from having a value of I_D that is no adjustable!

A more sophisticated source uses a resistor between the source and ground to determine I_D.



Here we have $V_G = 0$. The loop equation encompassing the gate and source satisfies (ignoring the transconductance $1/g_m$):

$0 = -V_G + V_{GS} + I_S R_S$

or

$$I_D = I_S = -\frac{V_{GS}}{R_S}\ .$$

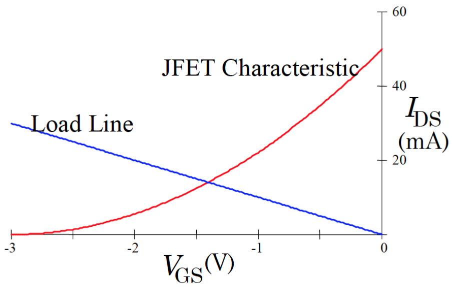
The other equation that relates I_D and V_{GS} is the constitutive equation $I_D = I_{DSS}\left(1-\frac{V_{GS}}{V_{GS}(\text{off})}\right)^2$.

We are free to pick a desired current, denoted I_{DQ}, with $I_{DQ} < I_{DSS}$. Then the required value of R_S is found from

$$I_{DQ} = I_{DSS}\left(1+\frac{I_{DQ}R_S}{V_{GS}(\text{off})}\right)^2$$

for which

$$R_S = \frac{-V_{GS}(\text{off})}{I_{DQ}}\left(1-\sqrt{\frac{I_{DQ}}{I_{DSS}}}\right).$$



As an example relevant to the laboratory 7 (2N5485), the choice I_{DQ} = 0.4 mA with I_{DSS} = 8 mA and V_{GS}(off) = - 3 V, we find R_S = 5.8 kΩ.

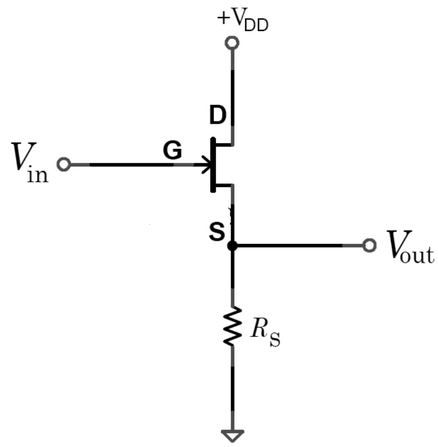
The load line for I_D versus V_{DS} is found by computing the voltage drops along the loop, *i.e.*,

$0 = - V_{DD} + V_{DS} + I_D R_L + I_S R_S$.

Thus $I_D = \frac{V_{DD} - V_{DS}}{R_S + R_L}$ and we slide along a curve of constant I_D.

These current sources are independent of fluctuations in the power supply voltage and largely independent of g_m.

Source Followers



The analysis is rather similar to that for the BJT emitter follower.

Left loop
$0 = - V_{in} + V_{GS} + R_S I_S$

so $I_D = \dfrac{V_{in} - V_{GS}}{R_S}$ and
$V_{out} = I_D R_S = V_{in} - V_{GS}$.

If we include the nonzero value of g_m, these are modified to:

$0 = - V_{in} + V_{GS} + (1/g_m) I_S + R_S I_S$

so $I_D = \dfrac{V_{in} - V_{GS}}{R_S + 1/g_m}$ and

$V_{out} = I_D R_S = \dfrac{g_m R_S}{1 + g_m R_S}\left(V_{in} - V_{GS}\right)$

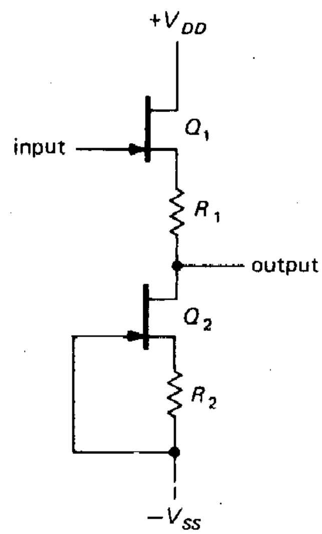
Recall that $V_{GS} < 0$ so the offset is positive.

Right loop
$0 = - V_{DD} + V_{DS} + (1/g_m) I_S + R_S I_D$

so $I_D = \dfrac{V_{DD} - V_{DS}}{R_S + 1/g_m}$

This defines the load line for I_D versus V_{DS}. Here, changes in the input cause us to move along the load line as the V_{GS} changes. with changes in V_{in}.

An improved follower may be built in which the offset voltage VGS(off) in minimized. We use a current source to define the current through Rs, as show below.



Here we may write an expression for the equilibrium current (ignoring g_m):

$0 = - V_{in} + V_{GS}\ (Q1) + I_{DQ}\ R_1 + V_{out}$

But we previously solved for the self limiting current source, where $I_{DQ} = -\dfrac{V_{GS}(Q_2)}{R_2}$.

Then

$0 = - V_{in} + V_{GS}\ (Q1)\ -\dfrac{V_{GS}(Q_2)}{R_2}\ R_1 + V_{out}$

For $R_1 = R_2$ the output voltage is exactly the input voltage and we have a perfect follower with a very large input impedance.