**MOSFET vs JFET**

- Insulated gate can be at any voltage relative to the source, but body must be reverse biased (or zero) w.r.t. the source!
- Both enhancement-mode and depletion-mode are possible, but most often enhancement-mode.
- Zero DC gate current!
- Most widely used as a switch for VLSI digital logic circuits.
- Discrete devices are usually only used for high power transistors and for analog switches.
- Easily destroyed by static electricity!
- 4-terminal device:

  ![Diagram](sn.png)

- Diode junction gate must be reverse biased (or zero) relative to source!
- Depletion mode only!
- Slight DC gate leakage current.
- Found both as discrete transistors and in ICs (but not VLSI).
  - Current sources or input transistors in op-amps, for example.
- This is the only type used in your FET-1 lab.
- 3-terminal device:

  ![Diagram](sn.png)
N vs P and JFET vs MOSFET

Note: $I_{DSS}$ is the drain current with gate connected to source.

Remember, you must not forward bias the JFET gate junction!
Dependence of Current on $V_{DS}$

Small $V_{DS}$: channel looks ~ like a resistor ("linear" region).

Large $V_{DS}$: channel looks ~ like a current source ("saturated" region).

Different values of $V_{GS}$

Careful! “Saturated” has opposite meanings between FETs and BJTs.
NMOS FET

Current Source!

Saturated FET

2N3904

More slope

Different values of $V_{GS}$

BJT

Note how $Z_{out}$ of collector (or drain) goes down as $I_C$ (or $I_D$) goes up.

Less slope

Different values of $V_{BE}$

Saturated BJT

$V_{DS}$

$V_{CE}$

$V_{DS}$

$V_{CE}$
\[ I_D \approx 2k \left[ (V_{GS} - V_T) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \]  

“Linear” region

\[ I_D \approx k (V_{GS} - V_T)^2 \]  

“Saturation region.” Quadratic dependence on \( V_{GS} \), not exponential as in BJTs!

Note how \( V_{DS} \) needs to be quite large (compared with a BJT), especially for large current, to be in the saturation (normal operation) region.
You can buy JFETs with the gate and source tied together internally, making a simple-to-use, 2-terminal current source.

Load

Upper FET must have larger $I_{DSS}$

(The upper FET has a more negative $V_{GS}$, but the two FETs here must carry the same current.)

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2N5485 N-Channel JFET

![Transfer Characteristics Diagram](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{DSS}$</td>
<td>1.0 mA</td>
<td>5.0 mA</td>
</tr>
<tr>
<td>$V_{DS} = 15 V, V_{GS} = 0$</td>
<td>5484</td>
<td>5485</td>
</tr>
<tr>
<td>$V_{DS} = 15 V, I_D = 10 nA$</td>
<td>5484</td>
<td>5485</td>
</tr>
<tr>
<td>$V_{GS(off)}$</td>
<td>-0.3 V</td>
<td>-0.5 V</td>
</tr>
<tr>
<td>$V_{DS}$</td>
<td>-3.0 V</td>
<td>-4.0 V</td>
</tr>
</tbody>
</table>

Note from above how FETs are not very predictable! In the graph below the upper set of 3 curves are for $V_{GS(off)} = -4.5$ V, and the lower for $V_{GS(off)} = -2.5$ V.

Transfer Characteristics

Load

$R_S = \frac{V_{GS}}{I_D} = \frac{0.8 V}{2 mA} = 400 \Omega$
JFET Current Source

ON CHARACTERISTICS

<table>
<thead>
<tr>
<th>$I_{DSS}$</th>
<th>Zero-Gate Voltage Drain Current*</th>
<th>$V_{GSS} = 15$ V, $V_{DS} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5484</td>
<td>1.0 mA</td>
<td>5.0 mA</td>
</tr>
<tr>
<td>5485</td>
<td>4.0 mA</td>
<td>10 mA</td>
</tr>
<tr>
<td>5486</td>
<td>8.0 mA</td>
<td>20 mA</td>
</tr>
</tbody>
</table>

Maximum Current

$V_1 = 15$ Vdc

$J3 \quad 6.869$ mA

4 mA Current

$V_1 = 15$ Vdc

$J3 \quad 4.254$ mA

$R = \frac{0.5V}{4mA} = 125 \Omega$

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DC sweep with no source resistor

\[ Z_{\text{out}} = \frac{\Delta V}{\Delta I} = \frac{12 - 7}{6.79 - 6.65} = 35k\Omega \]
DC sweep with $R_S = 125$ ohm

\[
Z_{\text{out}} = \frac{\Delta V}{\Delta I} = \frac{12 - 7}{4.22 - 4.16} = 83 \text{k} \Omega
\]
Measuring the FET Threshold Voltage

\[ I_D = k(V_{GS} - V_T)^2 \]

\[ V_{GS} = V_T + \frac{1}{\sqrt{k}} \sqrt{I_D} \]

Measure \( I_D \) as a function of \( V_{GS} \) in the saturation region.

Plot \( V_{GS} \) vs the square root of \( I_D \), and extrapolate to zero current.

This is something that you will do in the lab next week.
Measuring the FET Threshold Voltage

\[ I_D = k(V_{GS} - V_T)^2 \]

\[ V_{GS} = V_T + \frac{1}{\sqrt{k}} \sqrt{I_D} \]

Measure \( I_D \) as a function of \( V_{GS} \) in the saturation region.

Plot \( V_{GS} \) vs the square root of \( I_D \), and extrapolate to zero current.

Example from the textbook, but note that the x,y scales are interchanged.
MOSFET Subthreshold Region

\[ I_D = k e^{(V_{GS} - V_T)} \]

For very low \( V_{GS} \) the channel doesn’t really exist, and the FET conducts from drain to source via thermally excited minority carriers, giving an exponential dependence.

MOSFETs are not often operated in this region. (Exception: large, low-noise amplifier input FETs, such as used in SCIPP labs for silicon-strip detectors, push into this region.)

Note: all the V and I scales depend on the FET type and geometry (e.g. length and width of the channel).
Transconductance

- Amplifiers and current sources operate in the “saturation” region of a FET (don’t confuse with the saturation region of a BJT, which is where you don’t want to operate a BJT amplifier).

\[
I_D = k (V_{GS} - V_T)^2
\]

\[
g_m \equiv \frac{dI_D}{dV_{GS}} = 2k (V_{GS} - V_T)
\]

\[
g_m = 2 \sqrt{kI_D}
\]

\[
I_C = I_S \left( e^{V_{BE}/V_T} - 1 \right)
\]

\[
g_m \equiv \frac{dI_C}{dV_{BE}} = \frac{I_S}{V_T} e^{V_{BE}/V_T}
\]

\[
g_m = \frac{I_C}{V_T} = \frac{1}{r_e}
\]

The FET transconductance improves only as the square root of current, while the BJT goes linear with current. In general, the BJT will make a higher gain amplifier (voltage or current amp), but…
JFET Amplifiers

Source Follower

Note that $Z_{\text{out}}$ does not depend on the output impedance of the driving voltage source.

\[ Z_{\text{out}} = \frac{1}{g_m} R_S \]

Common-Source Amp

Generally the performance is poor compared with a BJT amp, except for the input impedance. For a JFET it is spectacularly high! This can often be an overwhelming reason to use a FET.

RG can be a very large resistance!

\[ \text{Gain} = -g_m R_D \]
JFET Amplifiers

• Typically, the place you want to use a JFET amplifier is where you need very high input impedance, for example because your signal source has a very high impedance (cannot deliver much current).
  – Probably best used in differential amps or source-followers, not common-source amps.

• Another example is where the base current of a bipolar transistor will cause a significant error.
  – The LF411 Op-amp that you will soon use in several circuits uses JFETs at its inputs. This is very nice, because the current flowing into the inputs is negligible in all cases.

• Otherwise, bipolar transistors will usually give much better performance in terms of gain, predictability, etc.
JFET Amplifiers

• You need to keep in mind:
  – The gate-source junction must be reverse biased at all times (or at worst, zero volts).
  – The gate does need some bias current, although it can be very small.
  – The drain-to-source voltage cannot be too small, especially if the drain current is substantial. For a bipolar transistor the collector-emitter voltage can be a fraction of a volt, but for a JFET count on a few volts.
  – Unlike the case of a bipolar transistor, there is no simple formula for the transconductance. You must consult the data sheet, and it will be small compared with the bipolar transistor transconductance.
    • Or equivalently, the effective dynamic resistance of the source will be a few hundred ohms, not the bipolar transistor value of 25 divided by the current in mA.
Very high impedance source is no problem (except at very high frequency)

Voltage division between $Z_{\text{out}}$ of the JFET source ($1/g_m$) and $R_S$.

JFET has rather high output impedance, so a BJT follower is useful to boost the output drive.
JFET Follower Gain

\[ G = \frac{R_g g_m}{1 + R_g g_m} = \frac{3.9 \cdot 4}{1 + 3.9 \cdot 4} = 0.94 \]
Improving Follower Performance

Replace the source resistor by a JFET (or BJT) current source.
Gain with current source = 0.993!

The lack of high frequency performance is related to the high driving source impedance. We will see how to improve this with a “bootstrap”.

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