Transistors III: FETs

- 3-terminal device like a BJT

- New names for the connections
  - Drain (input) … sort of like collector
  - Source (output) … sort of like emitter
  - Gate (controls flow) … sort of like base

- 2 broad types
  - Junction FETs (JFETs)
  - Metal-oxide-semiconductor (MOSFETs)
** Principle of Operation **

- Made from a conducting piece of silicon
  - This is called the *channel*
  - *Drain* on one end
  - *Source* on the other
  - In the middle a *gate* is embedded

- **Current regulation**
  - If the gate is at a negative voltage there is a charge **depletion zone** around the gate
    - Current cannot flow in this zone
    - Expands as the gate becomes more negative
  - Controls the conductivity of the channel

- **At a pinch off voltage** the current stops \((V_p)\)
  - Think of pinching a hose to cut off the flow of water
JFETs vs. MOSFETs

- JFET gate forms a diode junction with the channel. Input impedance $\sim 10^{12} \, \Omega$.

- MOSFET has an insulating layer for better input impedance (up to $10^{14} \, \Omega$).

- MOSFETs have an extra terminal called the **body**. Usually just connected to the source to remove charge.

- MOSFETs are generally used for power circuits and digital circuits.

- Many other types now available.
FETs vs. BJTs

**FET Pros**
- The gate of a FET draws almost no current (i.e. pA range).
- FETs have almost infinite input impedance.
- Can frequently make a better amplifier circuit with a FET.
- Can operate bi-directionally sometimes.

**FET cons**
- FETs are more complicated than BJTs
  - complicated operational model.
- FET have even larger parameter spreads than BJTs.
FET properties

- Can be a n-channel or a p-channel
  - N-channel like npn
  - P-channel like pnp
- Gate may be centered on some diagrams
  - Have to figure out which is which from “context”
  - Source & Drain are nearly identical
  - Can be used backwards with almost same performance
- **N-channel** usually faster than **P-channel** due to higher mobility of electrons vs holes moving in the channel.

n-channel JFET (left)  
p-channel JFET (right)
Gate Voltage Rules

$V_p = \text{pinch-off voltage: this is an intrinsic parameter of the JFET.}$

- $V_{GS} < V_p$
  - $\Rightarrow I_D = 0$
- For $V_{GS} > 0.6$ V
  - $\Rightarrow$ Device Fails!!!
  - $\Rightarrow$ Try to keep $V_{GS} < 0$
- $V_p < V_{GS} < 0.6$ V
  - $\Rightarrow I_D$ depends on both $V_{GS}$ & $V_{DS}$
  - $\Rightarrow$ A complete description would require a 2D function: $I_D (V_{GS}, V_{DS})$
**Linear and Saturation Regions**

**Linear Region:** \( V_{DS} < V_{GS} - V_P \)

\[ \rightarrow I_D = k \left[ 2(V_{GS} - V_P) V_{DS} - V_{DS}^2 \right] \]

**Saturation Region:** \( V_{DS} > V_{GS} - V_P \)

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

- \( V_p \) is the **pinch-off** voltage
  - It’s negative for n-channel.
- Voltage where conductance stops
- **Huge** manufacturing spread

- \( k \) is a constant
  - Depends on the physical size of the channel (length/width)
  - Depends on the manufacturing details
Ideal Performance vs. Reality

![Graph showing ideal performance vs. reality for drain current vs. source-drain voltage. The graphs compare actual data points with model predictions.]
## SPECIFICATIONS (\(T_A = 25^\circ\text{C}\) UNLESS OTHERWISE NOTED)

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<tr>
<td>Gate-Source Breakdown Voltage</td>
<td>(V_{(BR)GSS})</td>
<td>(I_G = -1\ \mu\text{A}, V_{DS} = 0\ \text{V})</td>
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<td>Gate-Source Cutoff Voltage</td>
<td>(V_{GSOFF})</td>
<td>(V_{DS} = 20 \ \text{V}, I_D = 1\ \text{nA})</td>
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<td>Saturation Drain Current(^b)</td>
<td>(I_{DSS})</td>
<td>(V_{DS} = 20 \ \text{V}, V_{GS} = 0\ \text{V})</td>
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<td>Gate Reverse Current</td>
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<td>Gate Operating Current</td>
<td>(I_G)</td>
<td>(V_{DS} = 20 \ \text{V}, I_D = 200\ \mu\text{A})</td>
<td>(T_A = 125^\circ\text{C})</td>
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<td>(V_{GS})</td>
<td>(V_{DS} = 20 \ \text{V}, I_D = 200\ \mu\text{A})</td>
<td>(I_D = 50\ \mu\text{A})</td>
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<td>Gate-Source Forward Voltage</td>
<td>(V_{GS(F)})</td>
<td>(I_G = 1\ \text{mA}, V_{DS} = 0 \ \text{V})</td>
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<td>Common-Source Forward Transconductance</td>
<td>(g_{fs})</td>
<td>(V_{DS} = 20 \ \text{V}, V_{GS} = 0 \ \text{V})</td>
<td>(f = 1\ \text{kHz})</td>
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<td>Common-Source Output Conductance</td>
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<td>(I_G = 1\ \text{mA}, V_{DS} = 0 \ \text{V})</td>
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Solving for the current graphically

Transfer Characteristics

\[ I_D \text{ – Drain Current (mA)} \]

\[ V_{GS(\text{off})} = -2 \text{ V} \quad V_{DS} = 20 \text{ V} \]

\[ T_A = -55^\circ \text{C} \]

\[ 25^\circ \text{C} \]

\[ 125^\circ \text{C} \]

\[ V_{gs} = -IR \]

[Vishay 2N3958 datasheet]
Transconductance in the Saturation Region

- There is a quiescent current given by $I_D$.
- Use lower case symbols to represent small changes around the quiescent values.
- **Transconductance**: $g_m = \frac{i_d}{v_{gs}}$ 
  - Just the slope of $I_D$ vs $V_{GS}$ in the saturated region.
  - **Depends on $I_D$.**
- Smaller variation for $V_{GS} < 0$ V.
- Units: $\Omega^{-1}$=mho (pronounced “Moe”) 
  - $\mu$mho or umho for $10^{-6}$ mho. 
  - mmho for $10^{-3}$ mho. 
  - Sometimes see $\Omega$