The Transistor: First proposed by Lilienfeld in 1930 (but he could never really get it to work right because of surface states)

Field-effect transistor:
Using a gate C, Lilienfeld thought that it should be possible to modulate the current from A to B.

This is conceptually very similar to the vacuum triode, which was used as the amplifier at the time.

In 1947, Bardeen and Brattain invented the Ge point contact transistor. They wanted to make the Field-Effect Transistor, but ended up with a Bipolar Transistor, and got the Nobel Prize anyway. Schockley then developed the bipolar junction transistor.
Finally, the total diode current is the sum of the hole and electron currents across the p-n junction and is given by:

\[ I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p}\Delta p_n + \frac{qAD_n}{L_n}\Delta n_p \]

\[ I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV_{\text{bias}}/kT} - 1\right) = I_0(e^{qV_{\text{bias}}/kT} - 1) \]

Field effect devices: The electric field of a gate or grid is used to modulate the number of charges (i.e. electron current) moving from the source to the drain.

In a triode, the charges are electrons accelerated through a vacuum.
Categorization chart of various field effect transistors

We should also include the Modulation-doped FET or MODFET (also known as HEMT)
Schematic description of the JFET problem

\[ \mathbf{J}_N = q \mu_n n \mathbf{x} + q D_N \nabla n \]

\[ J_N = J_{Ny} = q \mu_n N_D \mathbf{y} = -q \mu_n N_D \frac{dV}{dy} \]

Integrating the drift equation with respect to \( x \) and \( z \), we can derive the total current passing through the transistor channel

\[
I_D = - \int \int J_{Ny} \, dx \, dz = -Z \int_{W(1)}^{2a-W(0)} J_{Ny} \, dx = 2Z \int_{W(1)}^{a} q \mu_n N_D \frac{dV}{dy} \, dx \\
= 2qZ \mu_n N_D a \frac{dV}{dy} \left( 1 - \frac{W}{a} \right)
\]

\[
\int_0^L I_D \, dy = I_D L = 2qZ \mu_n N_D a \int_{V(0)}^{V_D} \left[ 1 - \frac{W(V)}{a} \right] \, dV
\]

\[
I_D = \frac{2qZ \mu_n N_D a}{L} \int_0^{V_D} \left[ 1 - \frac{W(V)}{a} \right] \, dV
\]
To find the relationship $W(V)/a$, we need to derive the depletion width as a function of voltage:

$$W(V) = \left[ \frac{2K_S \varepsilon_0}{qN_D} (V_{bi} - V_A) \right]^{1/2} = \left[ \frac{2K_S \varepsilon_0}{qN_D} (V_{bi} + V - V_G) \right]^{1/2}$$

$$a = \left[ \frac{2K_S \varepsilon_0}{qN_D} (V_{bi} - V_F) \right]^{1/2}$$

Note that $W$ approaches $a$ when the gate voltage $V_g$ approaches the pinchoff voltage $V_p$.

Next, we substitute into our original equation and obtain:

$$I_D = \frac{2qZ\mu_n N_D a}{L} \int_0^{V_D} \left[ 1 - \frac{W(V)}{a} \right] dV$$

$$I_D = \frac{2qZ\mu_n N_D a}{L} \left\{ V_D - \frac{2}{3} (V_{bi} - V_P) \left[ \left( \frac{V_D + V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} - \left( \frac{V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} \right] \right\}$$

for $0 \leq V_D \leq V_{\text{Dsat}}$, $V_P \leq V_G \leq 0$

Note: This relationship only applies below pinchoff:

$$I_D = \frac{2qZ\mu_n N_D a}{L} \left\{ V_D - \frac{2}{3} (V_{bi} - V_P) \left[ \left( \frac{V_D + V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} - \left( \frac{V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} \right] \right\}$$

for $0 \leq V_D \leq V_{\text{Dsat}}$, $V_P \leq V_G \leq 0$

To find the relationship above pinchoff, we use:

$$I_D|_{V_D > V_{\text{Dsat}}} = I_D|_{V_D = V_{\text{Dsat}}} = I_{\text{Dsat}}$$

Thus, we derive the saturation current $I_{\text{Dsat}}$:

$$I_{\text{Dsat}} = \frac{2qZ\mu_n N_D a}{L} \left\{ V_{\text{Dsat}} - \frac{2}{3} (V_{bi} - V_P) \left[ \left( \frac{V_{\text{Dsat}} + V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} - \left( \frac{V_{bi} - V_G}{V_{bi} - V_P} \right)^{3/2} \right] \right\}$$
We can simplify this relationship some more by noting that $W$ approaches $a$ when $V(L) = V_{Dsat}$

Then,

$$a = \left[ \frac{2K_\text{r} \varepsilon_0}{qN_D} (V_{bi} + V_{Dsat} - V_G) \right]^{1/2}$$

$$V_{Dsat} = V_G - V_F$$

$$I_{Dsat} = \frac{2qZ\mu_n N_D a}{L} \left\{ V_G - V_F - \frac{2}{3} (V_{bi} - V_F) \left[ 1 - \left( \frac{V_{bi} - V_G}{V_{bi} - V_F} \right)^{3/2} \right] \right\}$$

$$I_{Dsat} = I_{D0}(1 - V_G/V_F)^2$$

where $I_{D0} = I_{Dsat}/V_G=0$

Calculating the pinch-off voltage $V_p$

The total voltage equal to the built-in barrier potential $V_{bi}$ is:

$$d_n = (2eV_{bi}/[qN_D])^{1/2}$$

As the reverse voltage increases, a value $V_p$ is reached at which the depletion layer extends all the way across the channel thickness $a$. From this we can obtain:

$$V_p + V_{bi} = (q/2 \varepsilon)N_D a^2$$

Calculating $f_T$

$$f_T = L/v_d = L/\mu E_x$$
Theoretical $I_D$-$V_D$ characteristics assuming $V_{bi}=1V$ and $V_{P}=-2.5V$ ($I_{D0}=I_{Dsat}$ at $V_G=0$)

Experimental I-V characteristics of a TI 2N3823 n-channel FET
Another equation for the saturation voltage can be given by:

\[
V_{D_{\text{sat}}} = V_P - V_G - V_B = \frac{qN_Da^2}{2\varepsilon_s} - V_G - \frac{kT}{q} \ln\left(\frac{N_D N_a}{n_i^2}\right).
\]

\[
V_B \text{(breakdown voltage)} = V_D + V_G
\]
Summary for some common characteristics used in JFETs

Table 1 Field-Effect Equations for Specific Charge Distributions in a Rectangular Structure for Reflected-Type JFET (Total Channel Depth 2a)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common Factor</th>
<th>A: All Charge at y = 2a</th>
<th>B: Uniform</th>
<th>C: All Charge at y = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{max}$</td>
<td>$\frac{2Z\mu pa}{L}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$V_P$</td>
<td>$4\rho a^2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$I_P$</td>
<td>$\frac{8Z\mu^2 a^3}{\epsilon_L}$</td>
<td>1</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>$g_{max}V_P/I_P$</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Circuit symbols for depletion and enhancement JFETs.

$I_{Dsat} = I_P \left[1 - \left(\frac{V_G + V_{bl}}{V_P}\right)\right]^2$. 


The channel can either be normally on or normally off, depending on the depletion width at zero bias on the gate:

Why would we want to choose a material other than Silicon?

\[ v = \frac{\mu \varepsilon_x}{1 + \mu \varepsilon_x / v_s} \]

\[ I_D = qN_D \frac{\mu \varepsilon_x}{1 + \mu \varepsilon_x / v_s} (a - h)Z. \]
Electric field profiles and current-voltage characteristics of a Si MESFET under various gate and drain biasing conditions

Channel crosssection, electric field, drift velocity and space-charge distribution of a GaAs MESFET operated in the current-saturation region
Time-response for a field-effect transistor: We need to use an equivalent circuit of a MESFET:

\[
\tau = \frac{L}{\mu \sigma_{xs}} = \frac{L^2}{\mu V_D}
\]

\[
f_T = \frac{g_m}{2\pi C_{GS}} \left( = \frac{1}{2\pi \tau} = \frac{v_s}{2\pi L} \right).
\]

\[
f_{\text{max}} \approx \frac{f_T}{2\sqrt{r_1 + f_T r_3}}
\]

Theoretical cutoff frequency \(f_T\) as a function of gate length for Si, GaAs and InP.
Current carrying capacity is extremely important for any transistor and will determine the ultimate device geometry.

**Fig. 22** I-V characteristic of a power MESFET; $I_D$ is the drain current under forward gate bias, $V_B$ is the breakdown voltage, and $(I_{DD}, V_{DD})$ is the operating biasing point. (After DiLorenzo and Wiseman, Ref. 48.)

The total current which can be amplified by the transistor depends on the channel doping and the channel depth.

**Fig. 23** Calculated channel depth as a function of channel doping for a GaAs MESFET with various gate lengths and maximum channel currents per unit gate width. (After Fukui, Ref. 26.)
Ultimately, there is a compromise between power output and frequency.

Here we show the state-of-the-art power vs. frequency curve for a GaAs MESFET.

Various gate configurations for GaAs MESFETs.
Power MESFET with plated heat sink and interdigital source and drain fingers for high current operation

Various gate configurations to improve the device performance
A cross-sectional view of a double heterostructure MESFET is shown in the image. The device consists of layers of AlInAs and GaInAs with a substrate of InP. The band diagram illustrates the geometry and operation principle of this very short-channel FET.

A V-groove FET is also depicted, showing the geometry and operation principle of this type of FET.
As the drain voltage is increased, the inversion voltage is reduced.
Complementary MOS (or CMOS) provides the basis of modern Silicon electronics.

The saturation current can be controlled by adjusting the gate voltage.
Ideal threshold voltage dependence: The threshold voltage should only depend on the number of dopants and the dielectric constant. However, there are extra charges in the oxide and on the surface, which make our lives somewhat more complicated.

\[ V_T = 2\phi_F + \frac{K_S x_0}{K_0} \sqrt{\frac{4qN_A \phi_F}{K_S \varepsilon_0}} \quad \ldots \text{ideal } n\text{-channel (p-bulk) devices} \]

\[ V_T = 2\phi_F - \frac{K_S x_0}{K_0} \sqrt{\frac{4qN_D (-\phi_F)}{K_S \varepsilon_0}} \quad \ldots \text{ideal } p\text{-channel (n-bulk) devices} \]

Impurities in oxide and at interface provide extra charges which need to be considered.

- \( Q_m \): Mobile ionic charge
- \( Q_{ot} \): Oxide trapped charge
- \( Q_f \): Oxide fixed charge
- \( Q_d \): Interface trap charge

\[ V = V_{FR} = \frac{Q_l}{C_i} \]
As the dopant concentration is changed, the workfunction difference is also changed.

Threshold voltage for a MOSFET transistor

\[ V_T = \Phi_{ms} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} + 2\Phi_F \]

Threshold voltage
Interfacial and trapped charges
Metal semiconductor workfunction difference
Charges from depleted dopants
Definition of the threshold voltage

The threshold voltage is dependent on the dopant concentration too. This is a way the MOSFET $V_T$ can be tuned.

Crossection throught the gate of a narrow-channel MOSFET
Figure 17.5 Visualization of surface scattering at the Si–SiO₂ interface.

\[
\bar{\mu}_n = \frac{\int_{0}^{x_c(y)} \mu_n(x, y)n(x, y)\,dx}{\int_{0}^{x_c(y)} n(x, y)\,dx}
\]

Figure 15.5 First charge-coupled device comprising eight three-phase elements and input-output gates and diodes, shown (a) in plan view and (b) schematically in its cross-sectional view. (From Tranter et al. Reprinted with permission.)
Modulation doping is used to create a high mobility channel underneath a gate.

Band structures of various common heterostructures:

(a) Al$_{0.3}$Ga$_{0.7}$As/GaAs
(b) GaAs/Ge
(c) InP/In$_{0.53}$Ga$_{0.47}$As
(d) Al$_{0.48}$In$_{0.52}$As/InP
The concept of modulation doping:

We can build a “Quantum Well” in which carriers prefer to stay, and provide these carriers by using “donor” layers which are heavily doped, but do not contribute to large amounts of scattering.

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**RAM**

*(Random Access Memory)*

- access any bit of information in a matrix of bits independently.
- two types: static and dynamic.
- SRAM --- retain data stored indefinitely.
- DRAM --- refresh stored data periodically.
Nowadays, MOSFETs are very common field effect transistors, and are the backbone of digital logic circuits and memory.

Now, there are two categories of commonly used transistors:

Field effect transistors (source, gate, drain)

Bipolar transistors (emitter, base, collector)
This is where this has lead…