To understand any device, we should first draw an *Energy Band Diagram*. 

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To understand this device, we should first draw an *Energy Band Diagram*. 
1) Equilibrium: Fermi level is constant

2) Changes in electrostatic potential, change the electron’s energy.
   \[ E_c(y) = E_{c0} - q\phi(y) \]
   \[ E_v(y) = E_{v0} - q\phi(y) \]
Putting the 3 pieces together (equilibrium)

\[ E_C(y) = E_{C0} - q\phi(y) \]
\[ E_F(y) = E_{F0} - q\phi(y) \]

Final result: one semiconductor with 3 regions

Now, what effect does a gate voltage have?

\[ E_C(y) = E_{C0} - q\phi(y) \]
\[ E_F(y) = E_{F0} - q\phi(y) \]
A positive gate voltage will **increase** the electrostatic potential in the channel and therefore **lower** the electron energy in the channel.

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**the transistor as a barrier controlled device**

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A positive gate voltage will **increase** the electrostatic potential in the channel and therefore **lower** the electron energy in the channel.
the transistor as a barrier controlled device

\[ E = -qV \]

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effect of gate voltage first

Now add a small drain voltage

What if we apply a small positive voltage to the drain?

1) The Fermi level in the drain is lowered.

2) The conduction band is lowered too, but the electron density stays the same.
how transistors work

2007 N-MOSFET
L = 100 nm

V_G S
E
C

V_G S
Lundstrom ECE 305 F15

understanding DIBL

threshold voltage
V_T (V_DS)

V_DS = V_DD
V_DS = 0.05 V

V_T SAT
V_T LIN
V_DD

I_{ON}

E
C

V_G S

V_G S

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understanding DIBL

transfer characteristics:

\[
\log_{10} I_D (\text{mA/\mu m})
\]

\[
V_{DS} = V_{DD}
\]

\[
V_{DS} = 0.05 \text{ V}
\]

\[
DIBL = \frac{\Delta V_{GS}}{\Delta V_{DS}} (\text{mV/V})
\]

understanding DIBL

\[
E
\]

\[
V_G
\]

DIBL

\[
F_n
\]

\[
F_n (\text{low } V_{DS})
\]

\[
F_n (\text{high } V_{DS})
\]

source channel drain

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We have been discussing energy band diagrams from the source to the drain along the top of the Si, but more generally, we should look at the 2D energy band diagram.
2D energy band diagram on n-MOSFET

(a) device

(b) equilibrium (flat band)

(c) equilibrium ($\psi_s > 0$)

(d) non-equilibrium with $V_G$ and $V_D > 0$ applied


essential physics of a transistor

A MOSFET (and most transistors) are barrier-controlled devices.
limits to barrier control: quantum tunneling

from M. Luisier, ETH Zurich / Purdue