Lecture 3: Controlling current by modulating a barrier

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We derived the IV characteristics of this device using simple arguments, but to really understand the device, we need to draw and Energy Band Diagram.
Kroemer’s lemma of proven ignorance

“If, in discussing a semiconductor problem, you cannot draw an **Energy Band Diagram**, this shows that you don’t know what you are talking about.”

corollary:

“If you can draw one, but don’t, then your audience won’t know what you are talking about.”

silicon energy levels / energy bands

Si atom (At. no. 14)

$N_A \approx 5 \times 10^{22} \text{ cm}^{-3}$

4 nearest neighbors

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silicon energy levels / energy bands

Si crystal

- conduction “band”
- valence “band”

mostly filled states

mostly empty states

\[ E_G = 1.1 \text{ eV} \]
The Fermi function is given by

\[
f_0(E) = \frac{1}{1 + e^{(E - E_F)/k_B T}}
\]

where \(E\) is the energy, \(E_F\) is the Fermi energy, \(k_B\) is the Boltzmann constant, and \(T\) is the temperature in Kelvin.

The Fermi function describes the probability of an electron being in a state at a given energy. There is a small probability of being empty or filled for states far from the Fermi energy. At the Fermi energy, the probability of being empty is equal to the probability of being filled.

- Mostly empty states are found below the Fermi level \(E_F\).
- Mostly filled states are found above the Fermi level \(E_F\).
n-type semiconductor

\[ n_0 = N_C e^{\frac{(E_F - E_C)}{k_B T_L}} \]

\[ n_0 p_0 = n_i^2 \]
p-type semiconductor

\[ p_0 = N_v e^{\frac{(E_v - E_F)}{k_B T_L}} \]

\[ n_0 p_0 = n_i^2 \]
equilibrium energy band diagram

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source

channel

drain

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1) Equilibrium: Fermi level is constant

2) Changes in electrostatic potential, change the electron’s energy.

\[ E_C = E_{C0} - q \psi(x) \]

\[ E_V = E_{V0} - q \psi(x) \]
\[ E_C(x) = E_{C0} - q\psi(x) \]
\[ E_V(x) = E_{V0} - q\psi(x) \]
What effect does a gate voltage have?

The slope of the energy band gives the electric field.

\[ E_C(x) = E_{C0} - q\psi(x) \]
\[ E_V(x) = E_{V0} - q\psi(x) \]
A positive gate voltage will lower the electron energy in the channel.
effect of gate voltage

\[ E_C = E_{C0} - q\psi_s \]

\[ n_0 = N_C e^{(E_F - E_C)/k_B T_L} \text{ /cm}^3 \]
What if we apply a 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.

\[ E_C = E_{C0} - q\psi_s \]
effect of gate and drain voltage

\[ E_C(x) = E_{C0} - q \psi_s(x) \]

\[ E_{F2} = E_{F1} - qV_{DS} \]
how transistors work

2007 N-MOSFET

Electron energy vs. position

$V_{DS} = 0.05 \text{ V}$

$V_{GS}$

$E_C$

(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)
MOSFETs are barrier controlled devices

1) “Well-tempered MOSFET”

\[ Q_n(0) \approx -C_{ox} \left( V_G - V_T \right) \]

2) region under strong control of gate

3) Additional increases in \( V_{DS} \) beyond \( V_{DSAT} \) drop near the drain and have a small effect on \( I_D \)
top of the barrier / virtual source

\[ I_D = -WQ_n(x)\langle \nu_x(x) \rangle \]
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.
For a review of semiconductor fundamentals, see:


The MOSFET as a barrier-controlled device is discussed in: