Fundamentals of Nanoelectronics

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Lecture 1: Energy Level Diagram

Ref. Chapter 1.1

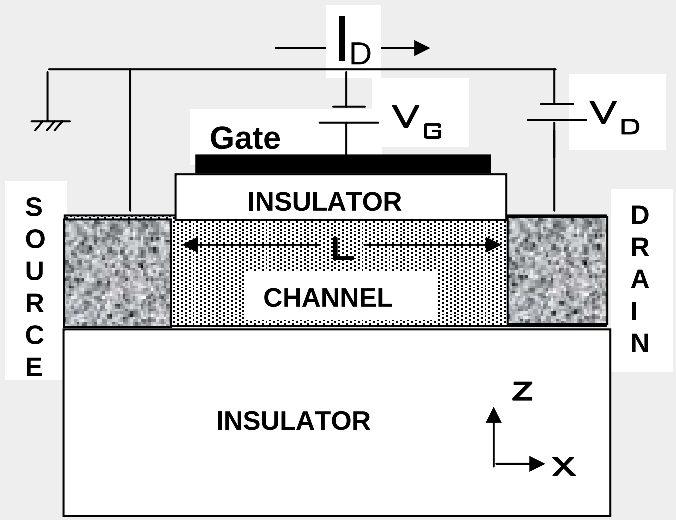
Network for Computational Nanotechnology

NCN nanoHUB online simulations and more

Transistors

00:00

Field Effect Transistor



- Denote the channel length as ‘L’

- Since the source and drain regions are very good conductors it is the resistance of the channel region that limits the current and determines how much current will flow through the device when voltage is applied. Please do note that as the devices are getting smaller the parasitic resistances in the contacts become important compared to the channel resistance but that’s something we can ignore to start with.

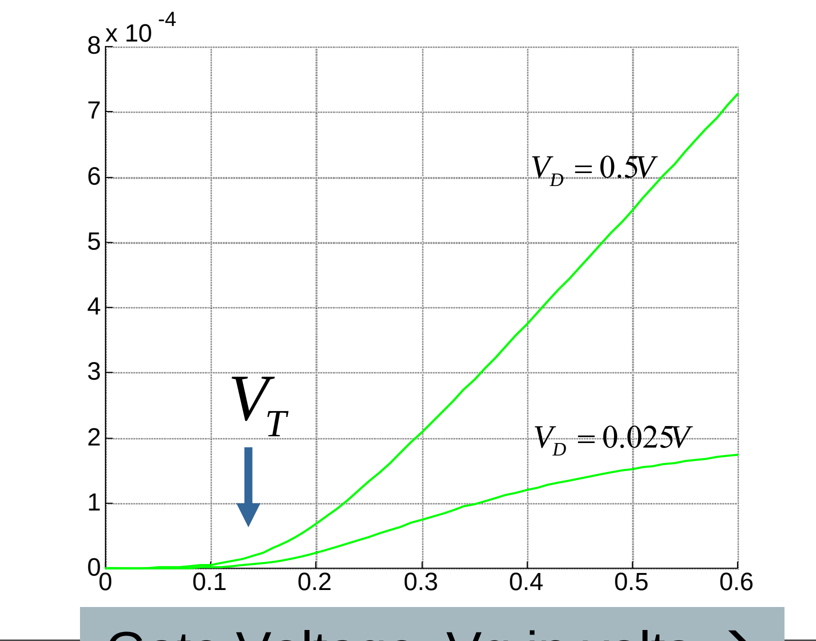
- We are interested in the current that flows from Source to Drain, I_D (perpendicular to the cross section of the channel). In the absence of good fabrication, leakage current (in the z direction) can exist in the insulator due to V_G. This current increases as the insulator thickness is reduced and is problematic for nano-scale FET’s.

- There are two types of current-voltage characteristics: One is I_D as a function of drain voltage when a constant gate voltage is applied. The other is I_D as a function of gate voltage when a constant drain voltage is applied. We are mostly interested in the first one.

Transistor: I vs. V curves

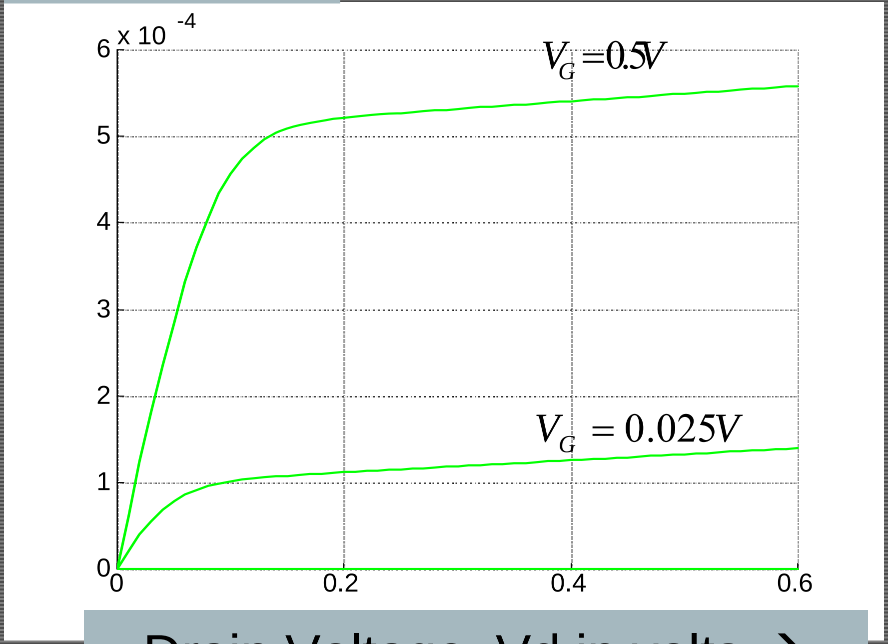
05:06

Drain Current
I in Amperes



Gate Voltage, Vg in volts →

Drain Current
I in Amperes

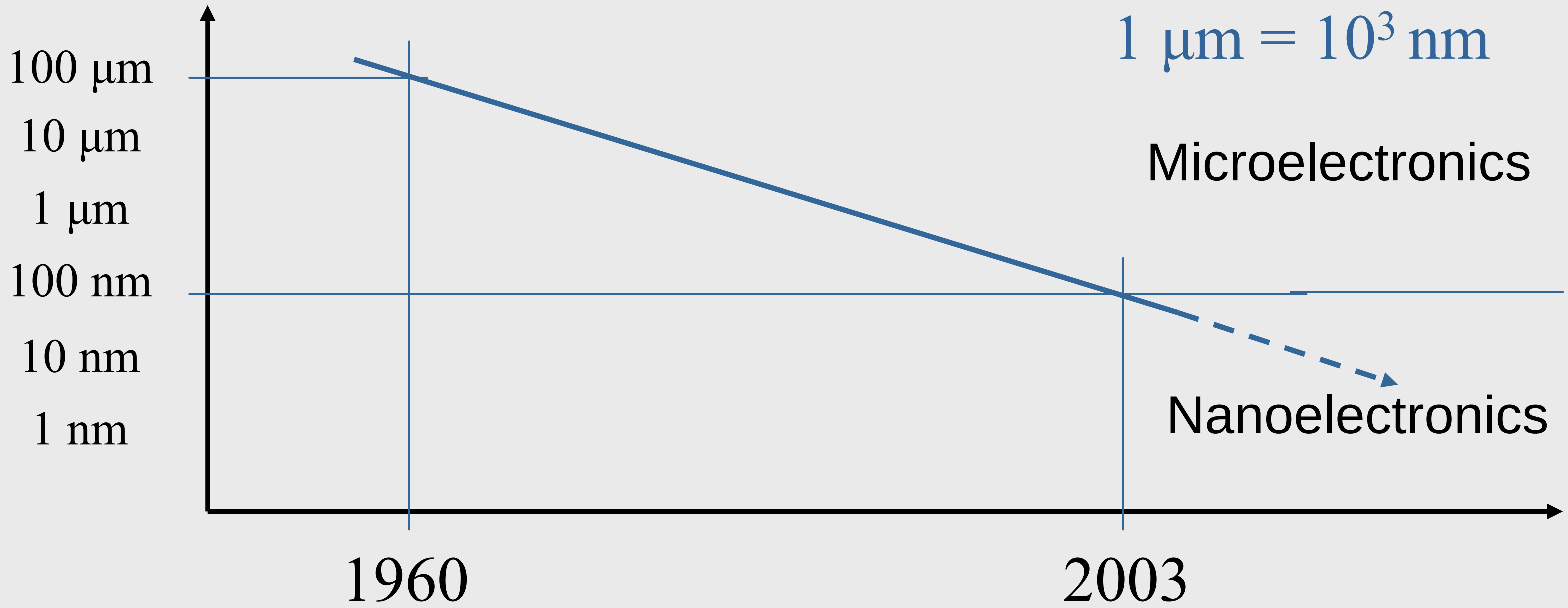


Drain Voltage, Vd in volts →

What is the physics behind these curves?

Transistor Scaling: 1960-2003

09:00



How far will transistor scaling go?

Energy Level Diagram

19:02

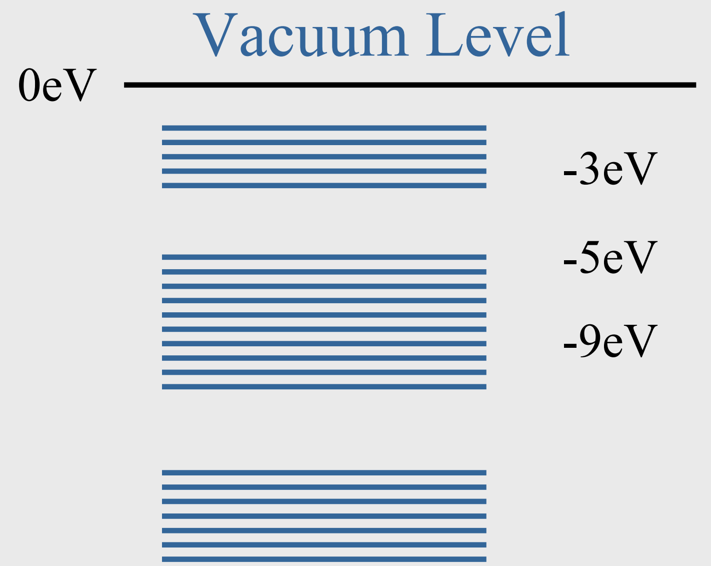
How do we understand the I-V characteristics?

- Begin by understanding the band diagram which describes the energy levels in the device e.g. in silicon. (See right)
- But how do we know that these energy levels form bands and where they are?
- Experimentally, filled levels are determined from Photoemission Spectroscopy (PES)

$S + h\nu \rightarrow S^{+} + e^{-}$ (hν should be big enough to knock out an electron; typically $h\nu$ > 5eV for semiconductors)

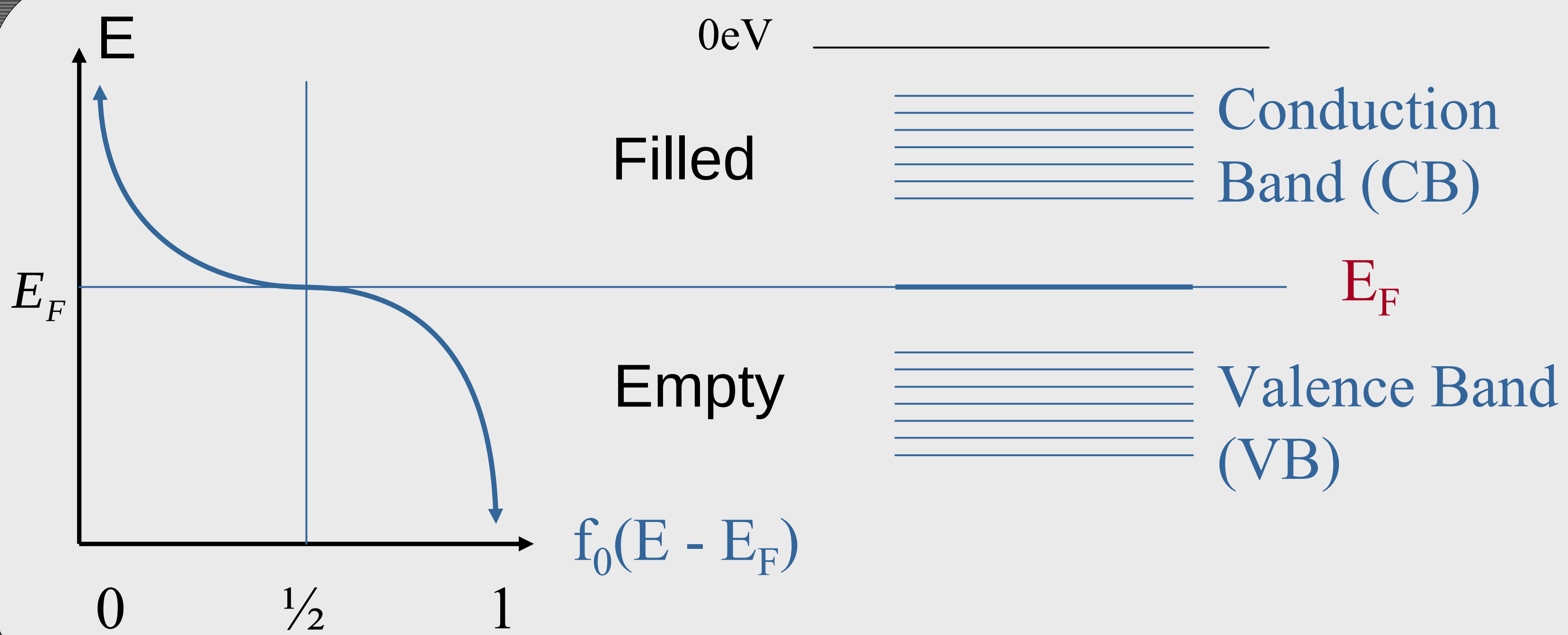
- Empty levels determined from Inverse Photoemission Spectroscopy (IPE)

$S + e^{-} \rightarrow S^{-} + h\nu$



Fermi Energy

29:00

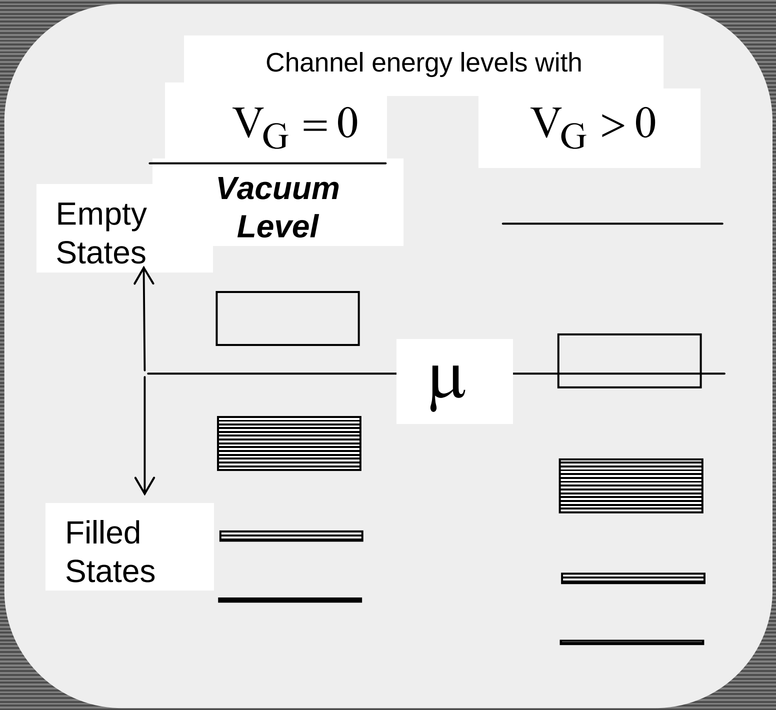


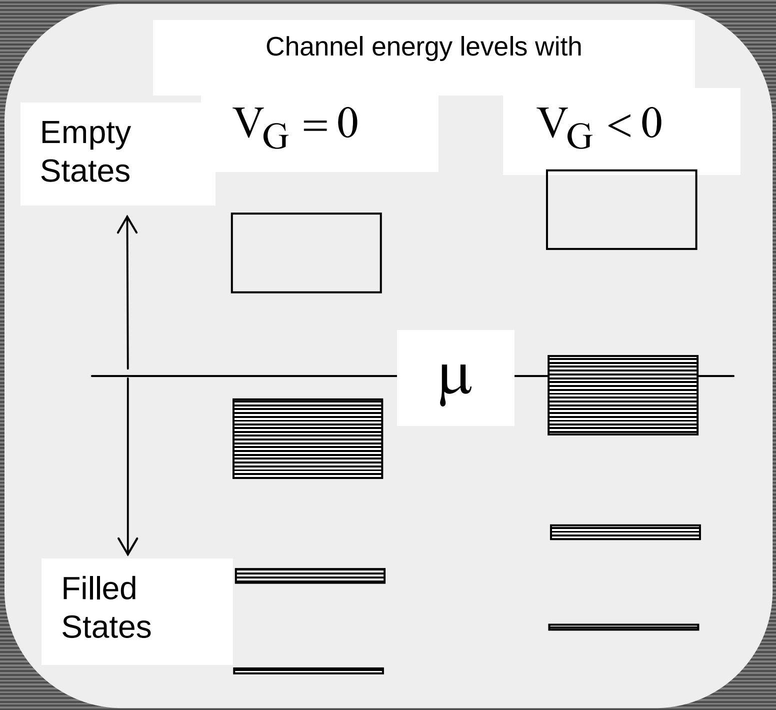
Fermi Function: $f_0(E) = 1/\left(e^{E/k_BT} + 1\right)$

Gate Bias

33:54

Fermi energy (or electrochemical potential) is held fixed by source and drain reservoirs

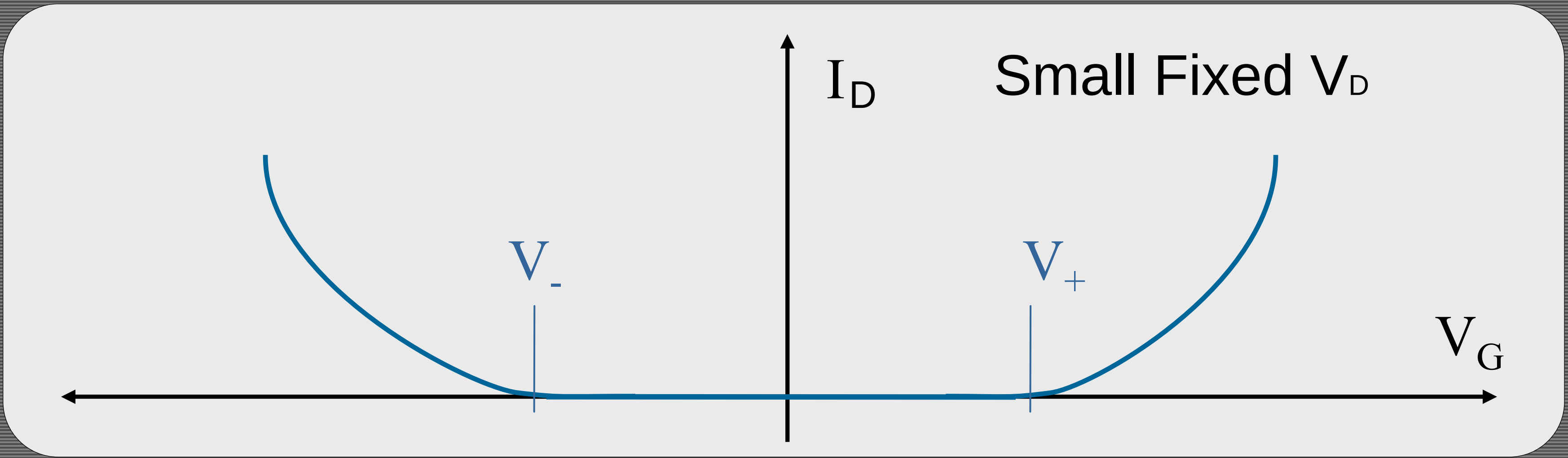




- Apply a *positive* gate voltage and band energy levels move *down*.

- Apply a *negative* gate voltage and band energy levels move *up*.

Gate Bias & Conduction

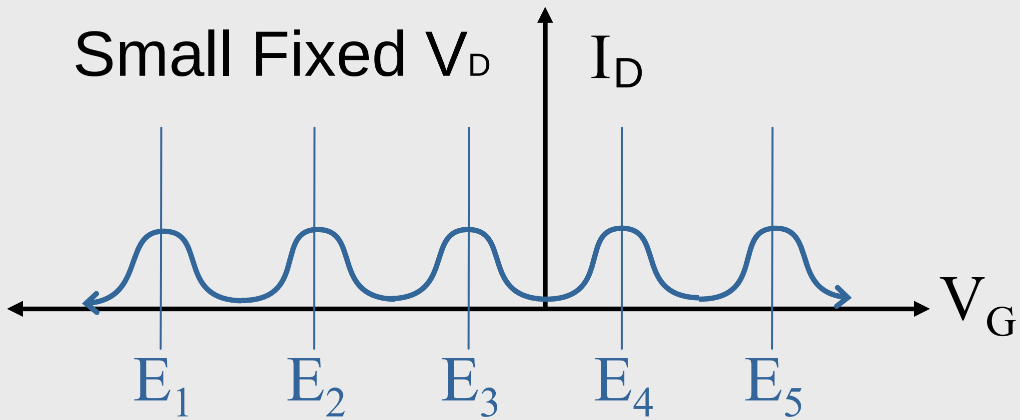


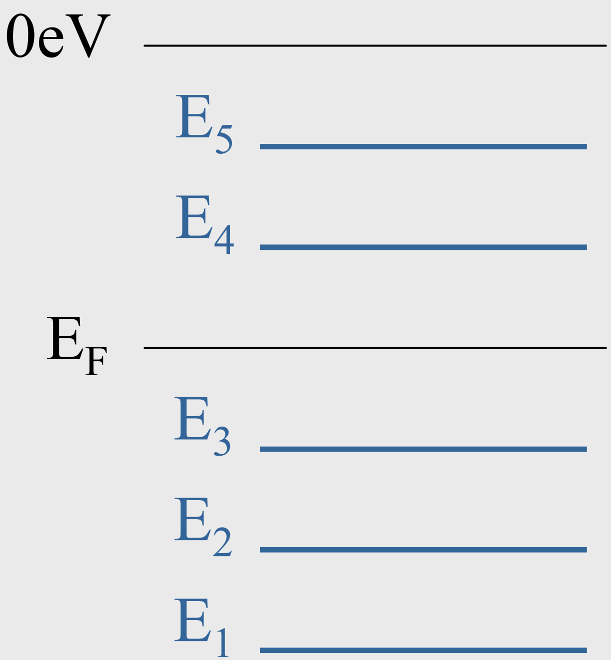
- V_-, the negative bias activation voltage, depends on how far the Fermi energy is from the *valence* band

- V_+, the *positive* bias activation voltage, depends on how far the Fermi energy is from the *conduction* band

A Simple Energy Level Scenario

Peaks occur where E_F crosses an energy level due to an applied V_G bias





What if we had a carbon nano-tube or a hydrogen molecule? *Answer: Different energy levels but same basic story.*