Essentials of MOSFETs

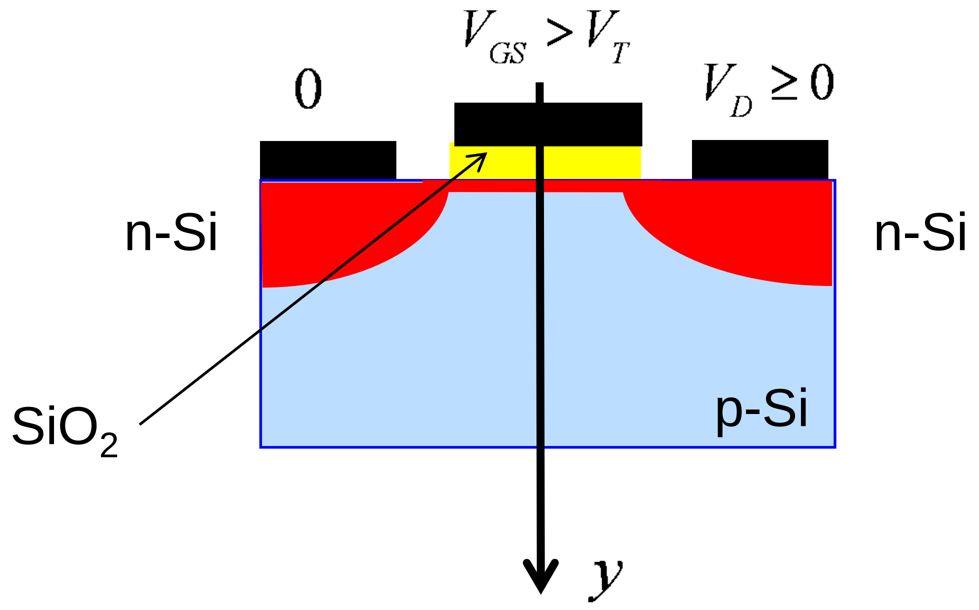
Unit 2: Essential Physics of the MOSFET

Lecture 2.2: Energy Band View of the MOSFET

Mark Lundstrom

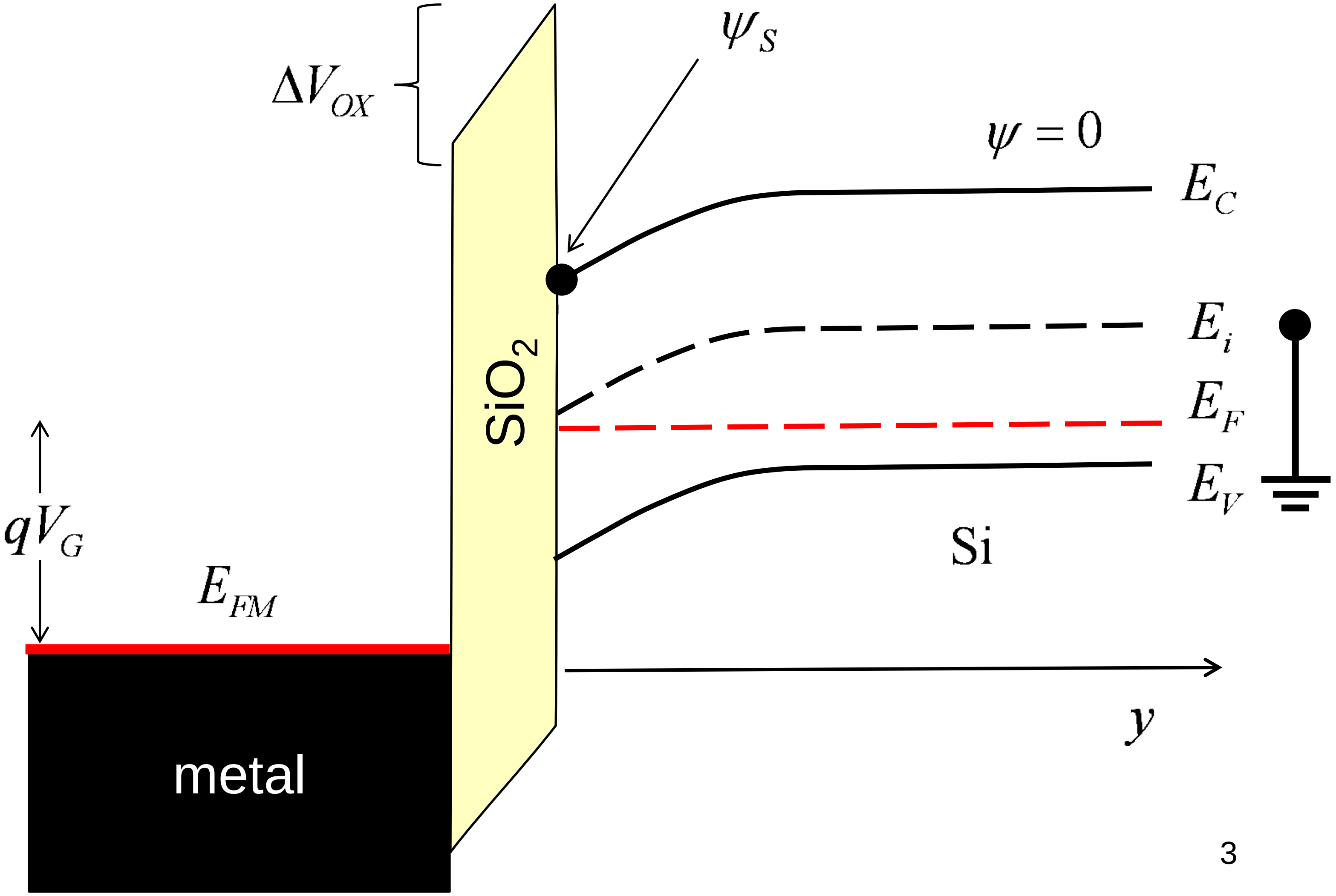
lundstro@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA

Understanding MOSFETs

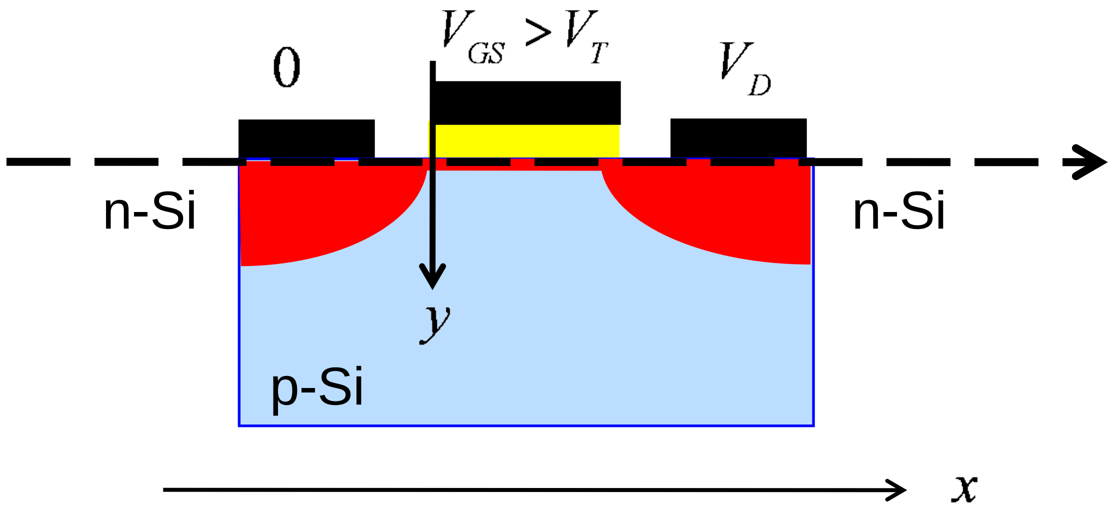


To understand any device, we should first draw an ***Energy Band Diagram***.

Normal to the channel

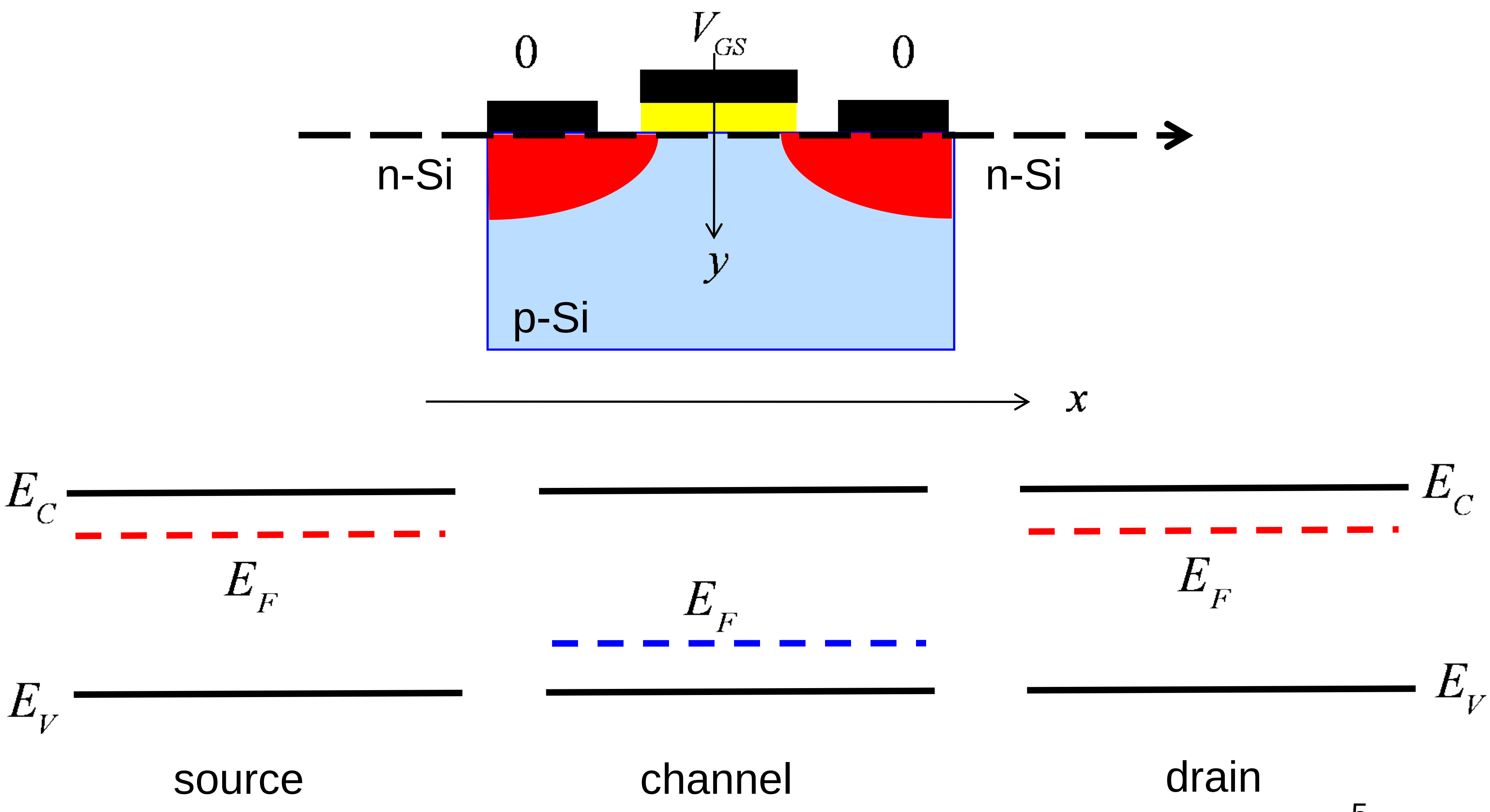


Along the channel

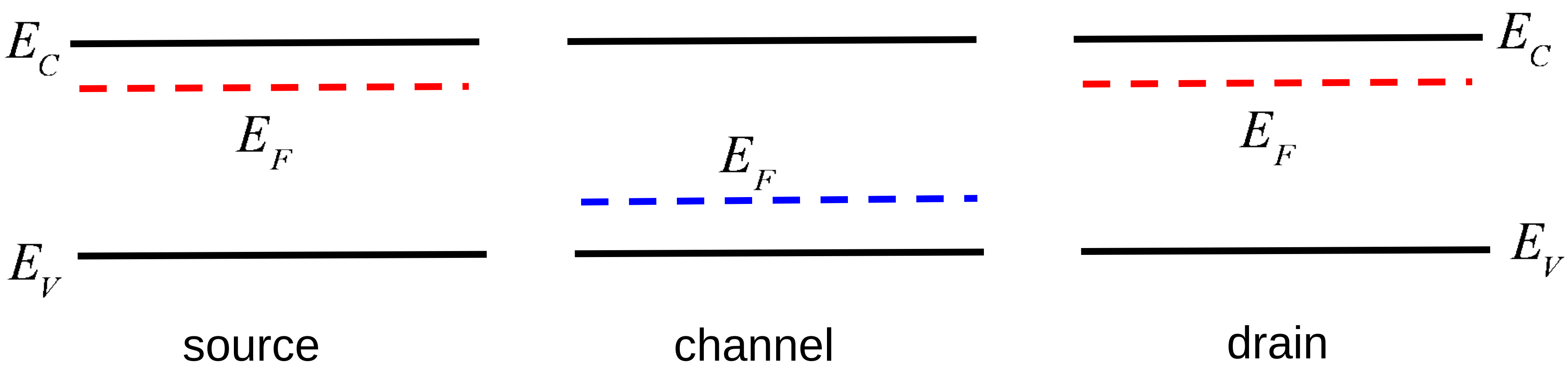


To understand this device, we should first draw an ***Energy Band Diagram***.

Equilibrium E-band diagram



Three separate semiconductors



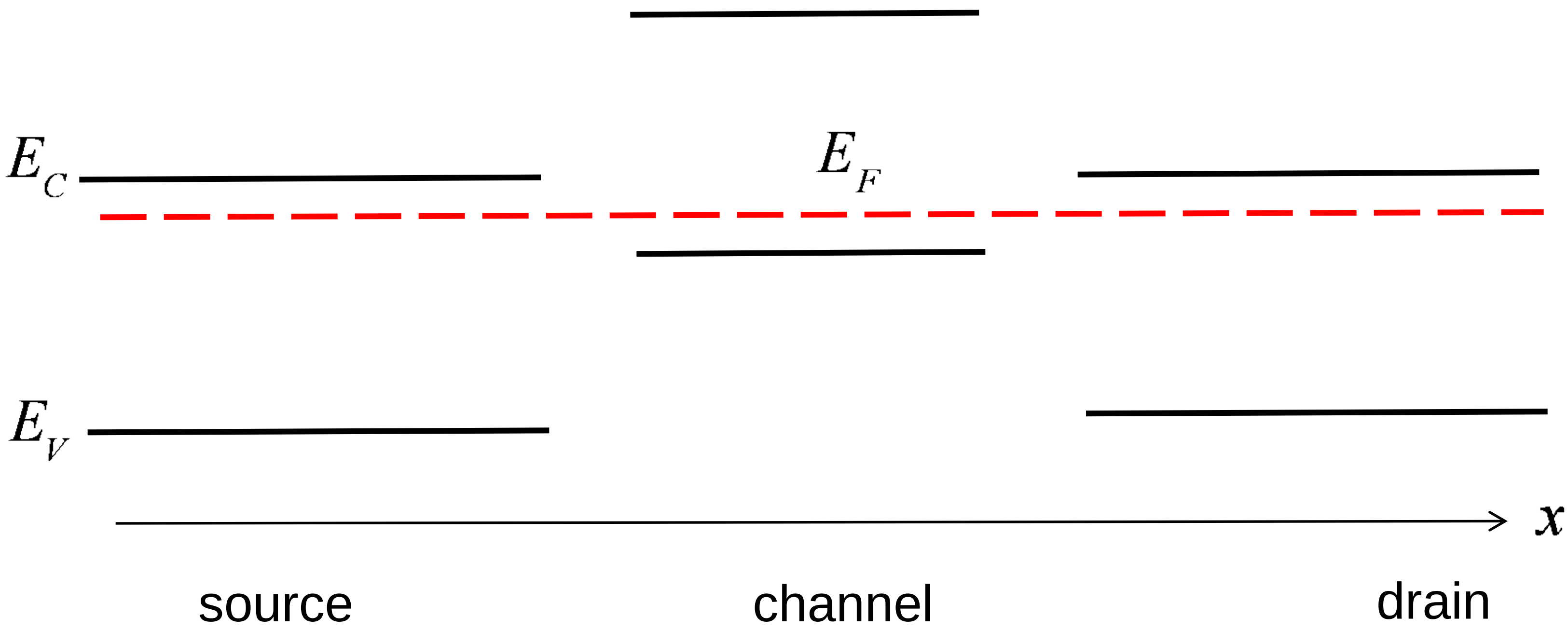
1) Equilibrium: Fermi level is constant

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

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

$$E_V(x) = E_{V0} - q\psi(x)$$

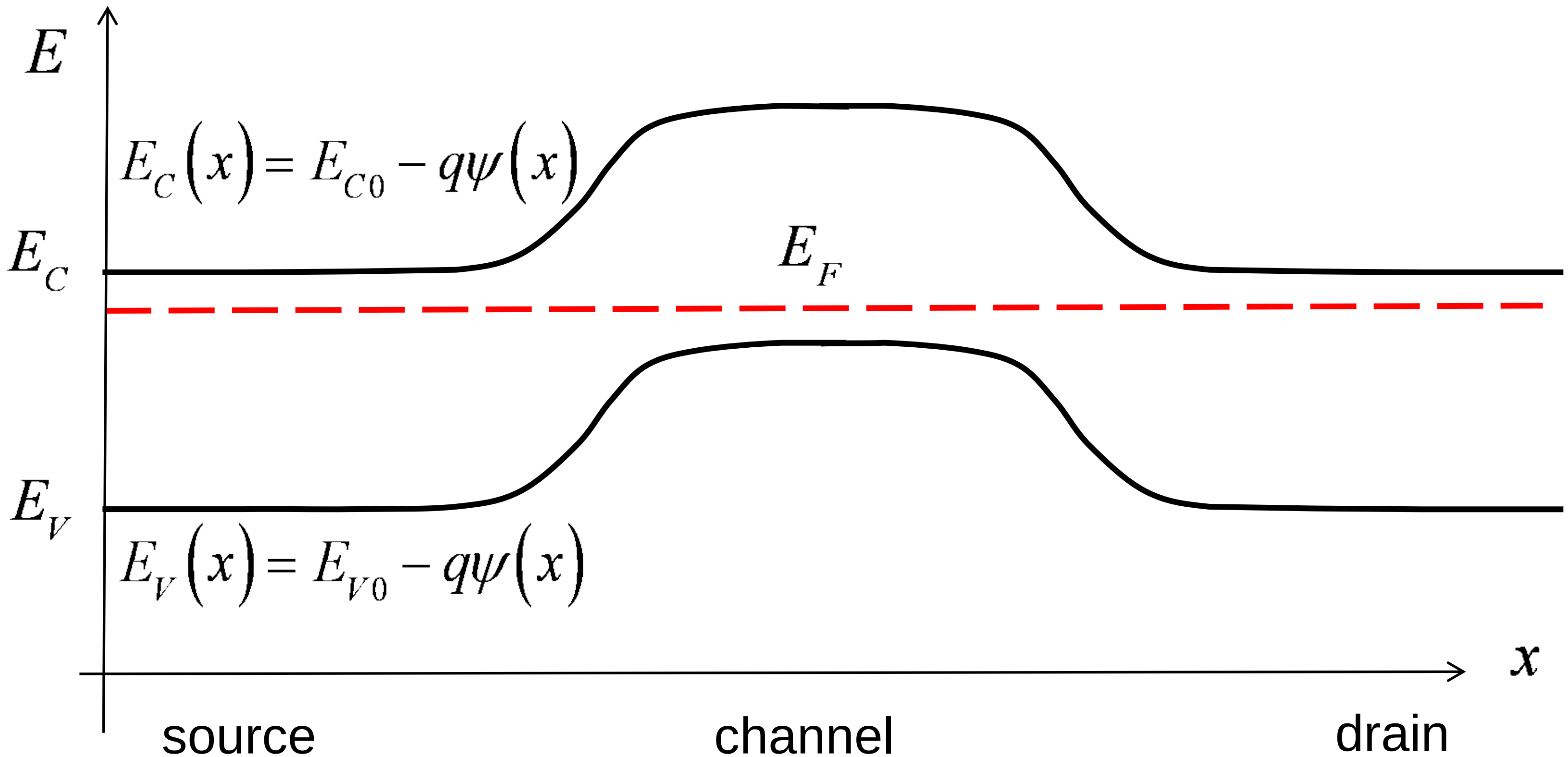
Putting the three pieces together



$$E_C(x) = E_{C0} - q\psi(x)$$
$$E_V(x) = E_{V0} - q\psi(x)$$

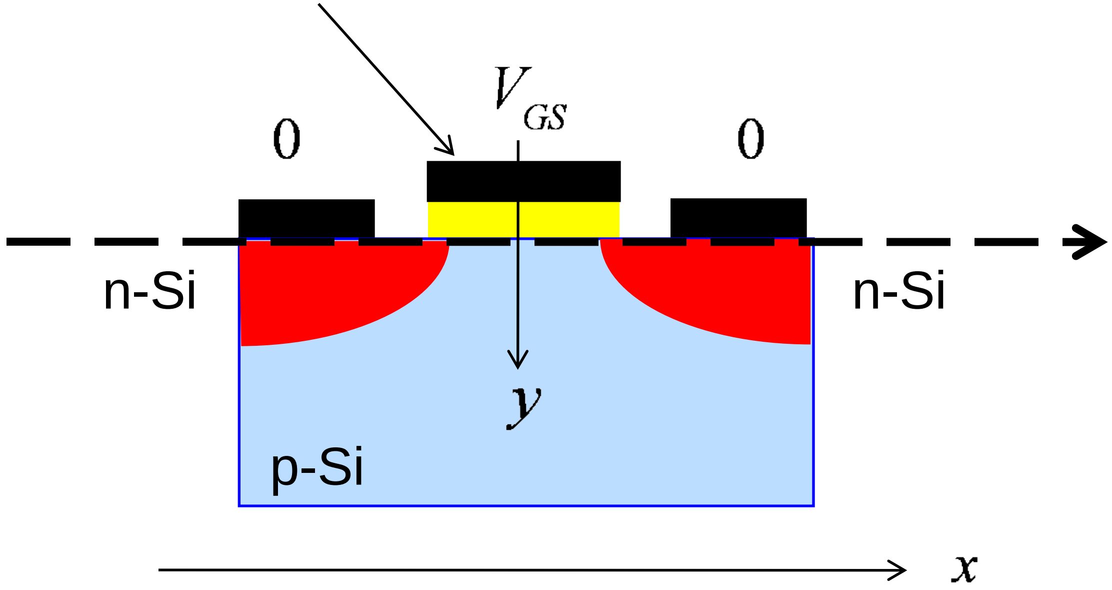
Final result

Now, what effect does a gate voltage have?



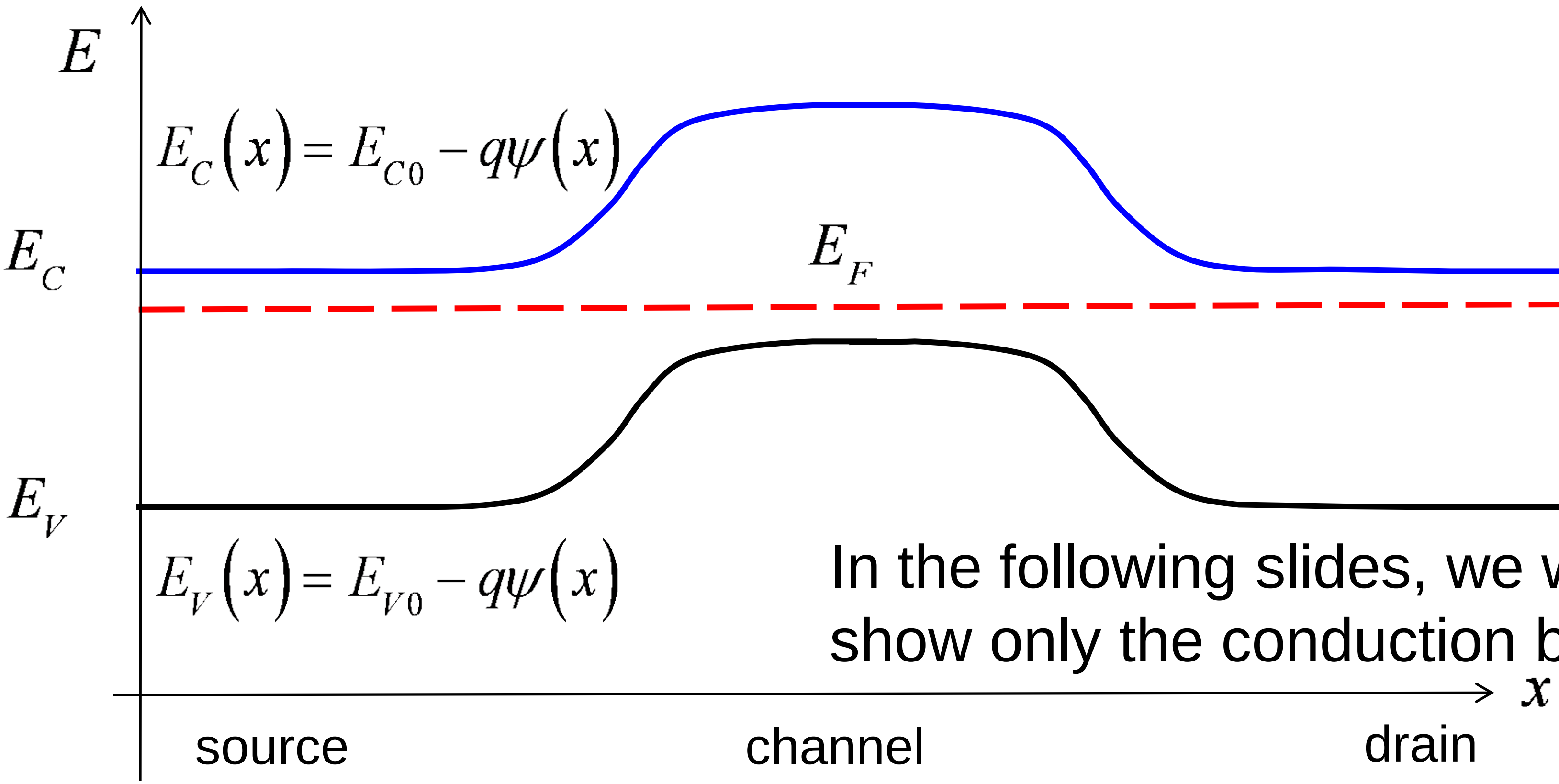
Equilibrium energy band diagram

A positive gate voltage will **increase** the electrostatic potential in the channel and therefore **lower** the electron energy in the channel.



N-channel MOSFET: only electrons

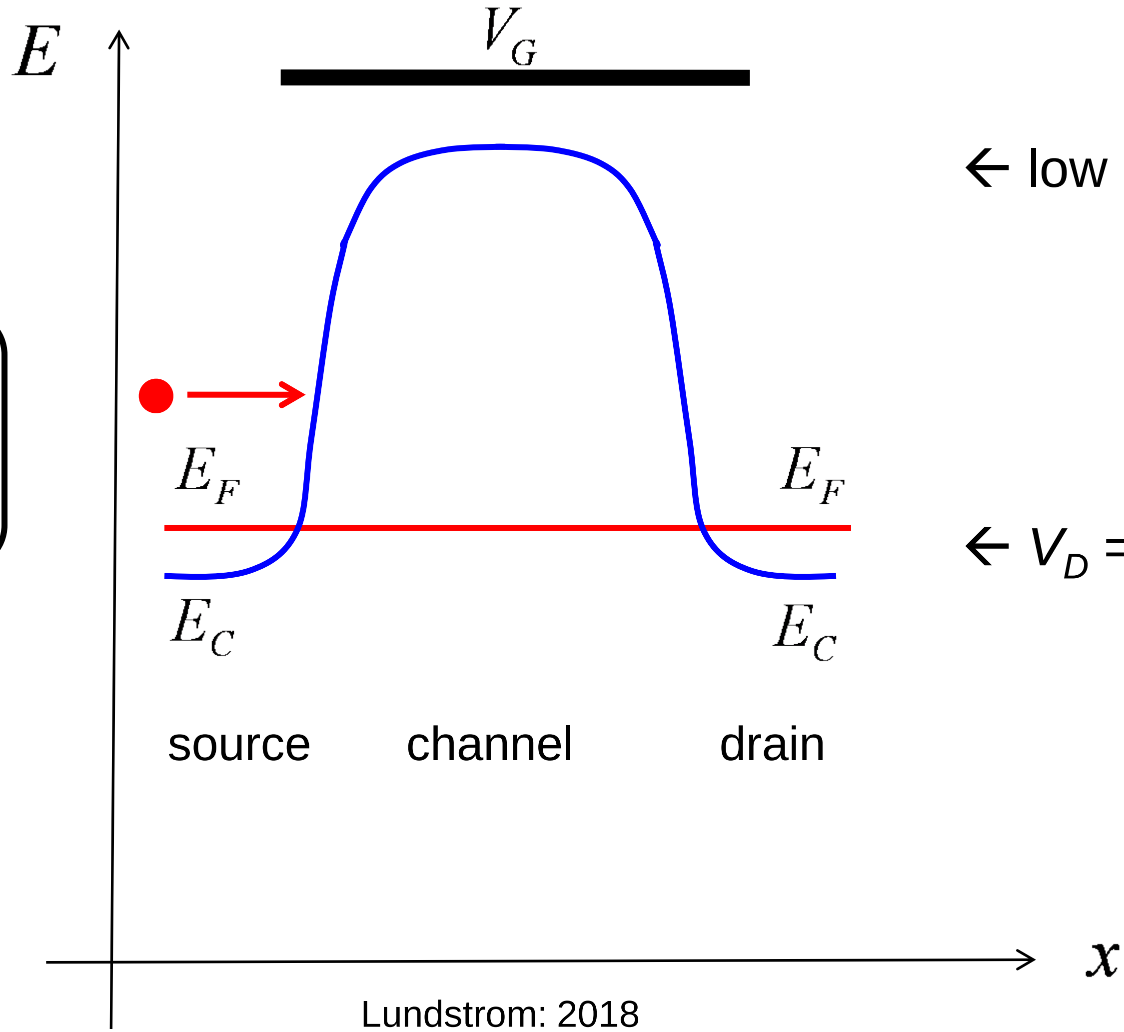
Now, what effect does a gate voltage have?



In the following slides, we will show only the conduction band.

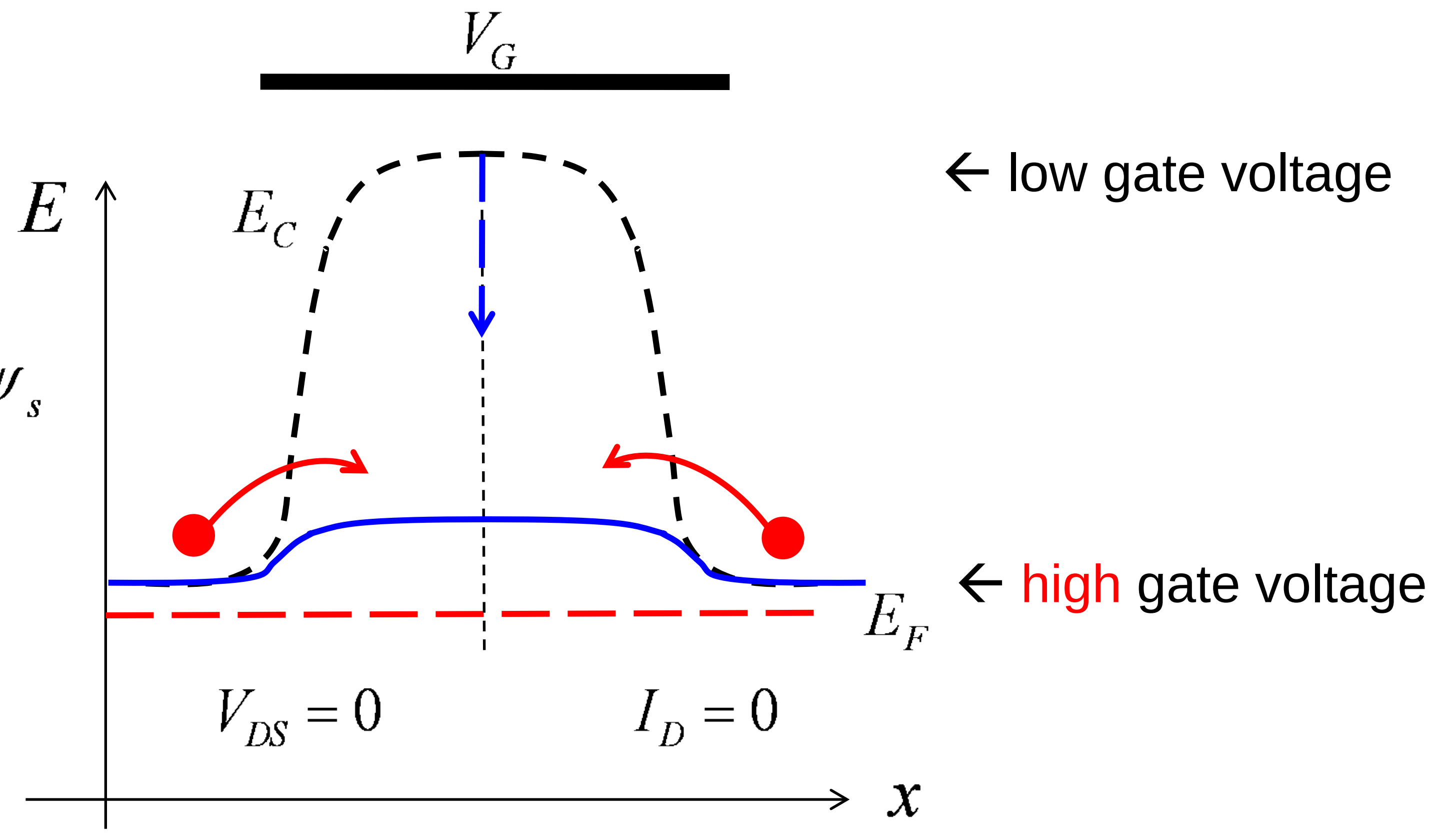
The transistor as a barrier controlled device

$$E = -qV$$

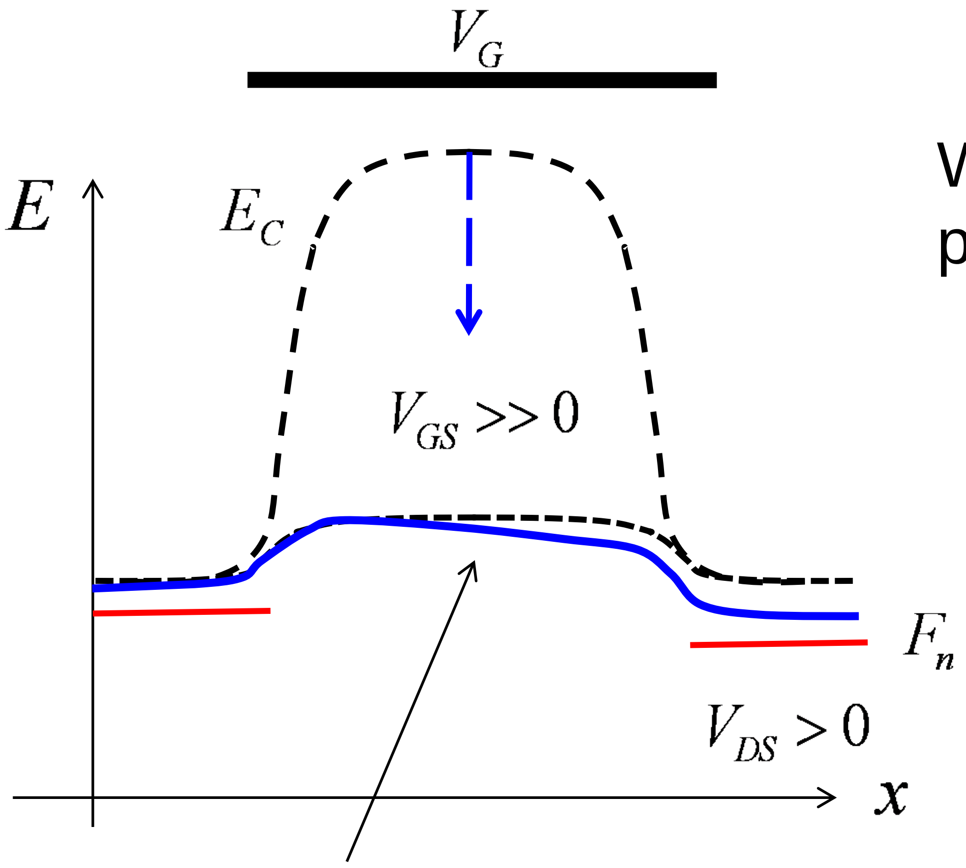


Examine effect of gate voltage first

$$E_C = E_{C0} - q\psi_s$$



Now add a small drain voltage



constant electric field
substantial electron density

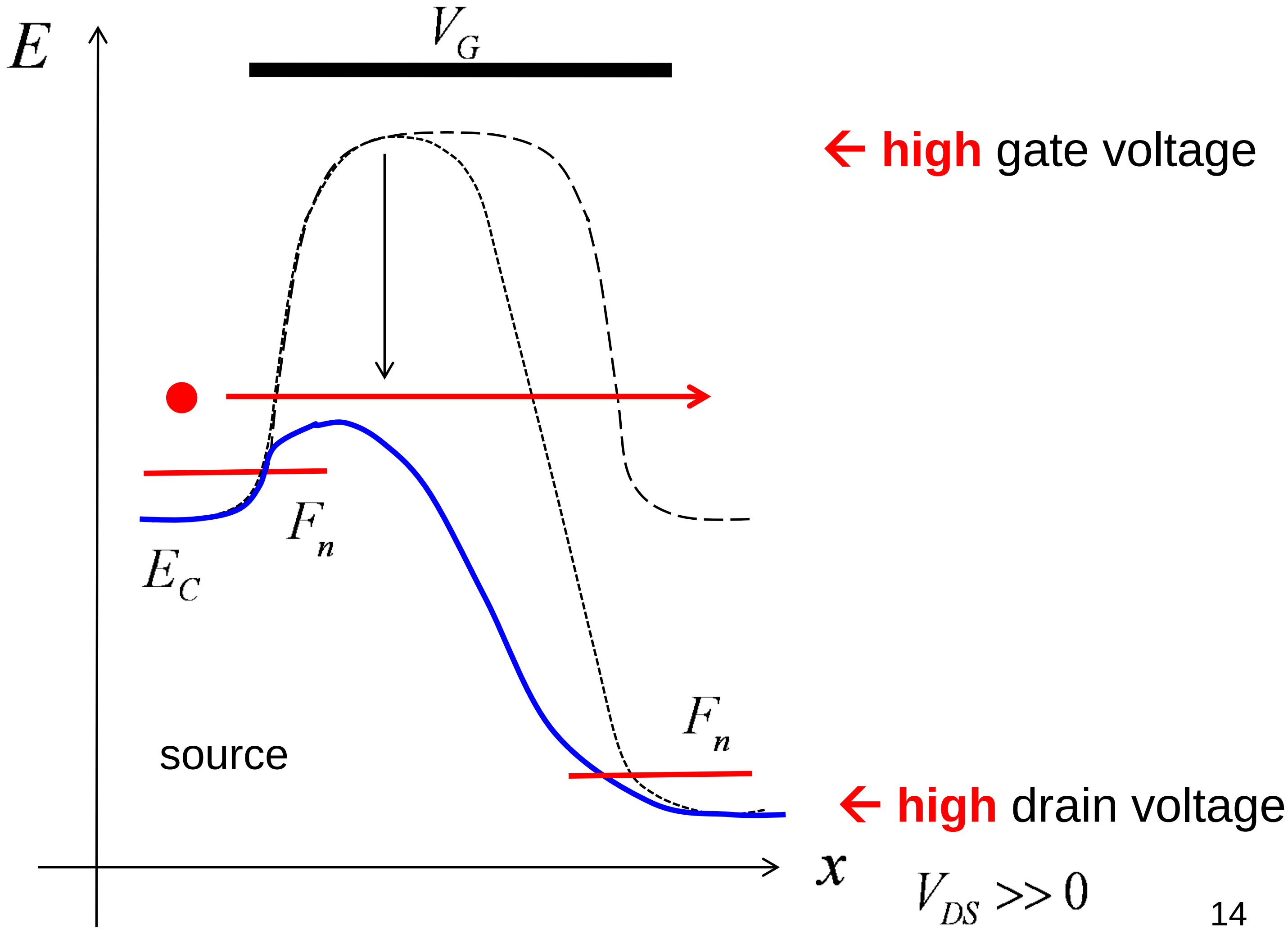
What if we apply a small positive voltage to the drain?

1) The Fermi level in the drain is lowered.

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

Now increase the drain voltage

ON-state

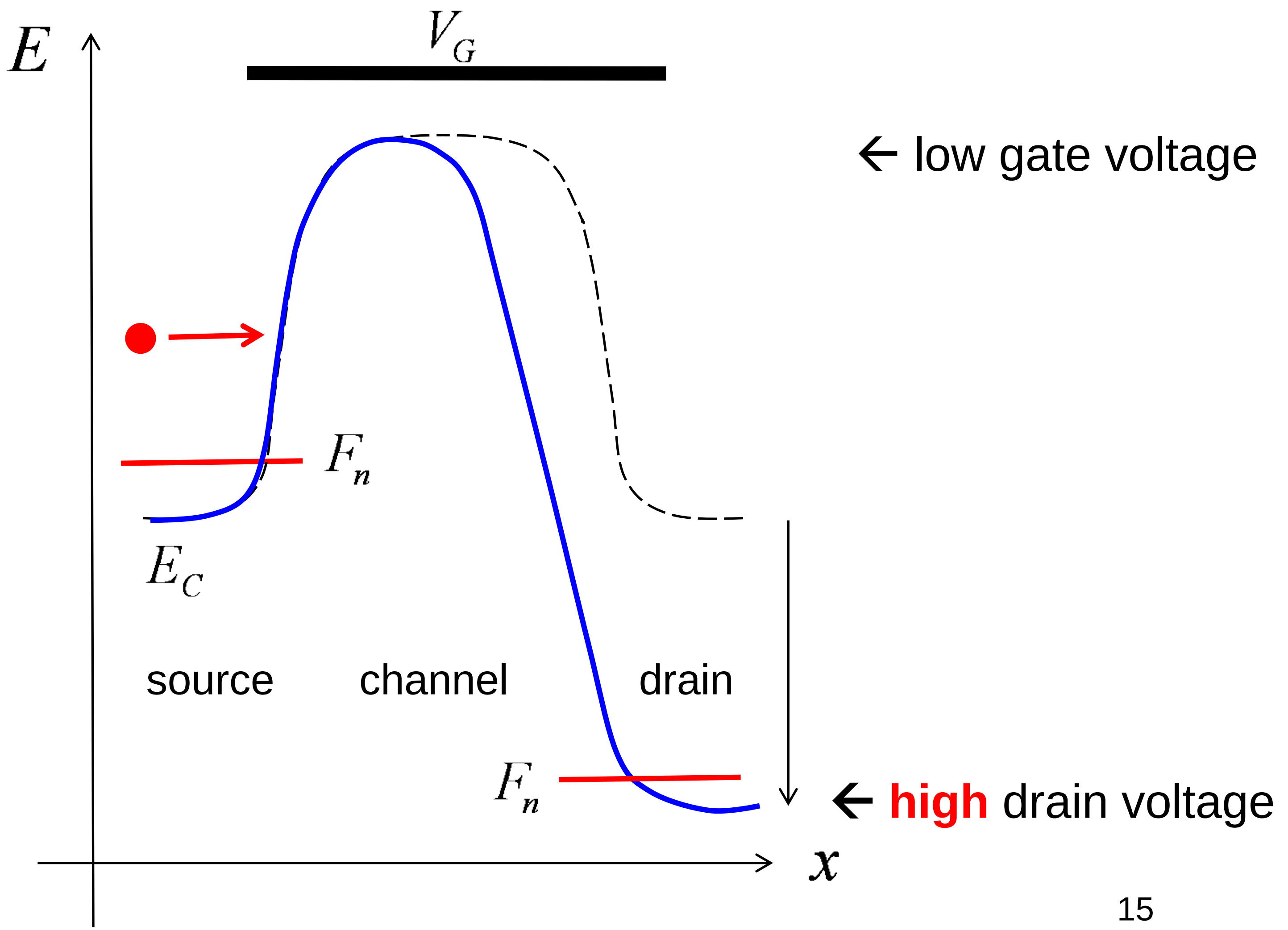


$V_{DS} >> 0$

Lundstrom: 2018

Now remove the gate voltage

OFF-state



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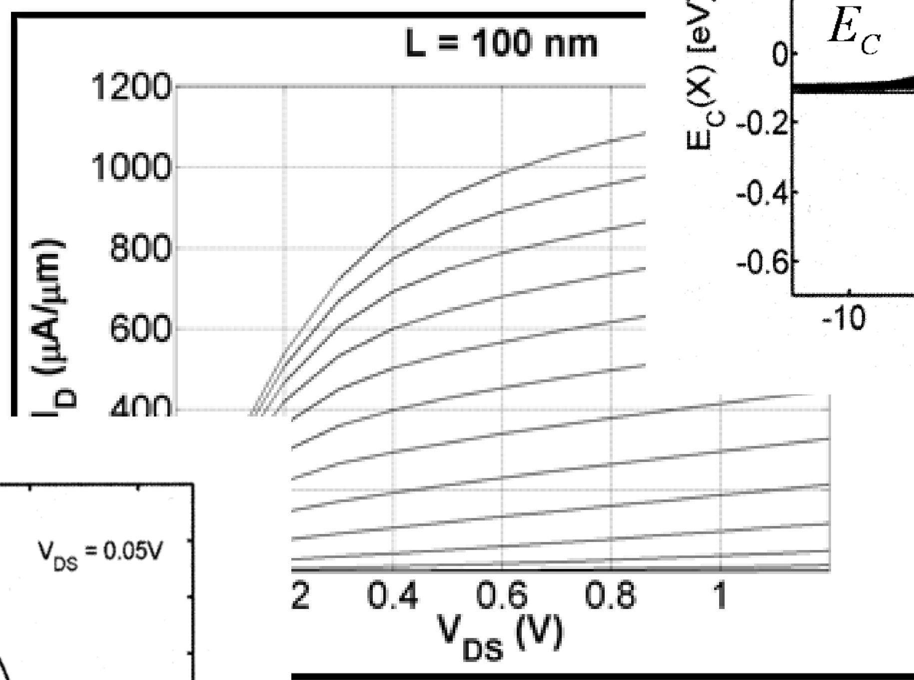
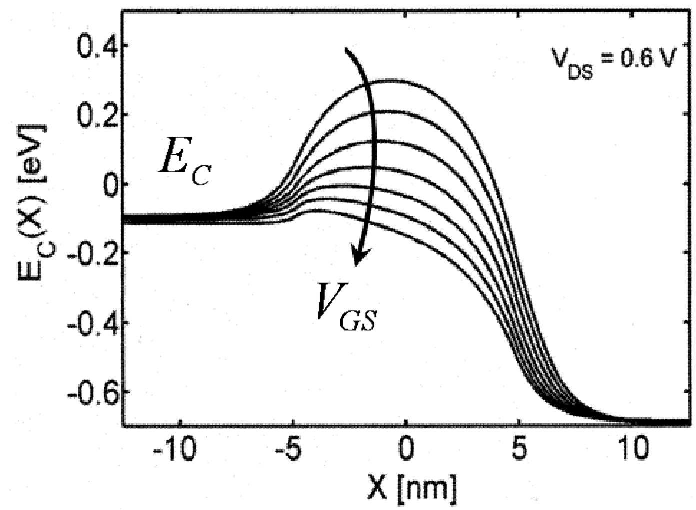
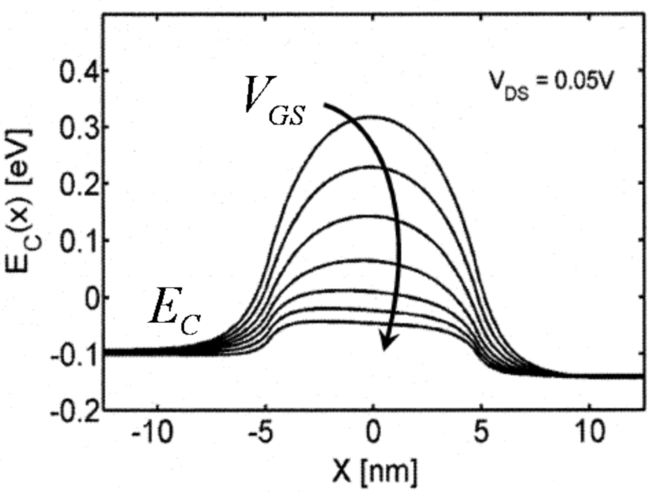
How transistors work

2007 N-MOSFET



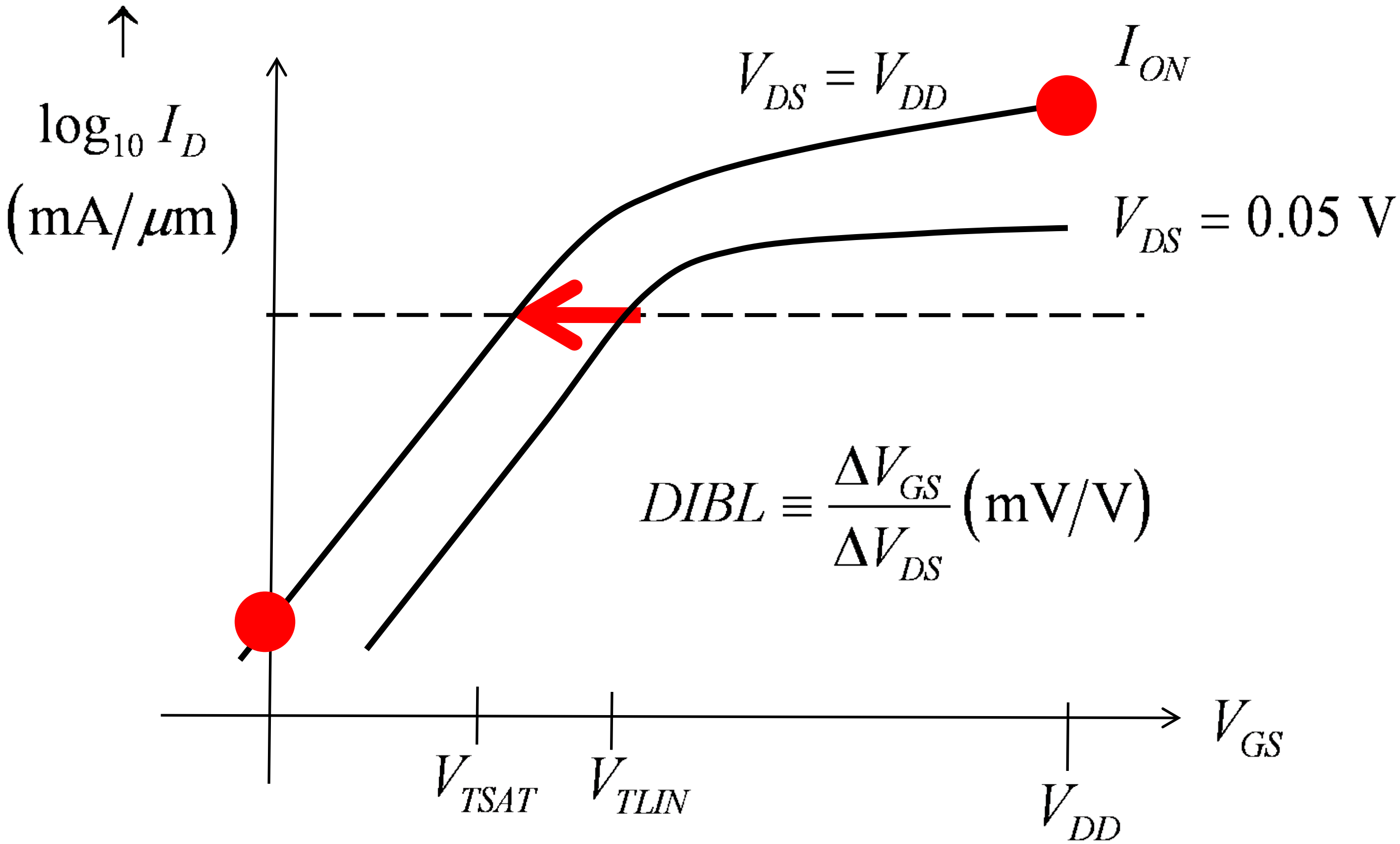




tesy, Shuji Ikeda, ATDF, Dec. 2007)

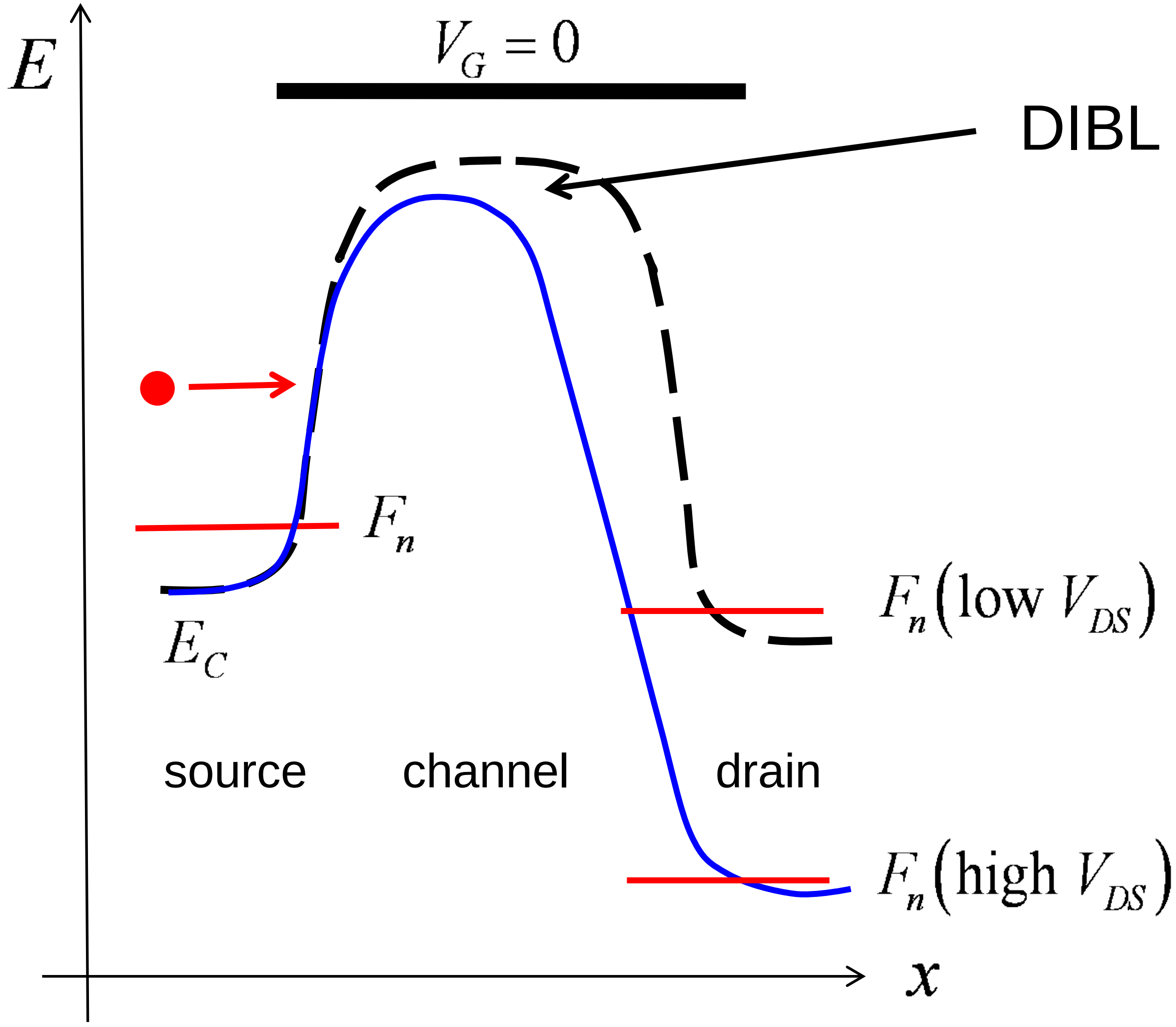
DIBL

transfer characteristics:

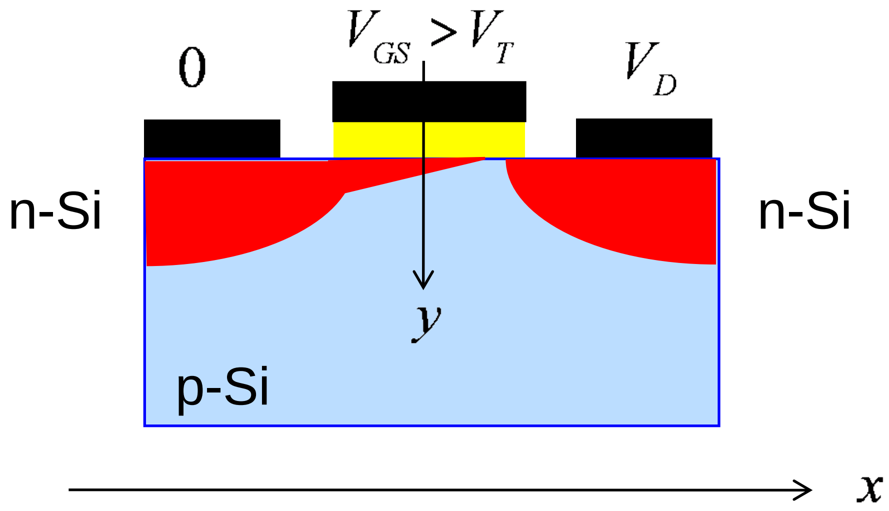


Lundstrom: 2018

Understanding DIBL with an e-band diagram



2D energy band diagrams



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.

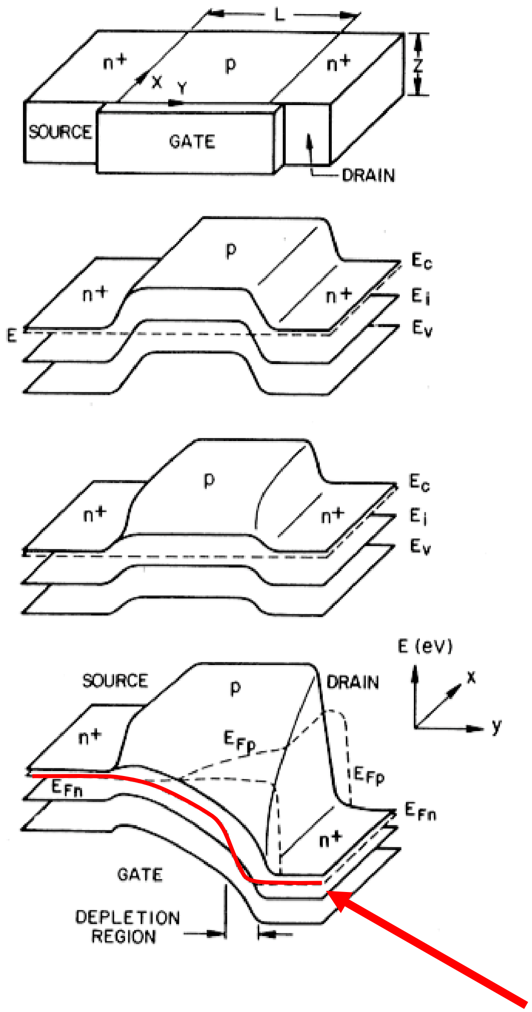
2D energy band diagram on n-MOSFET

(a)

(b)

(c)

(d)



a) device

b) equilibrium (flat band)

c) equilibrium ($\psi_S > 0$)

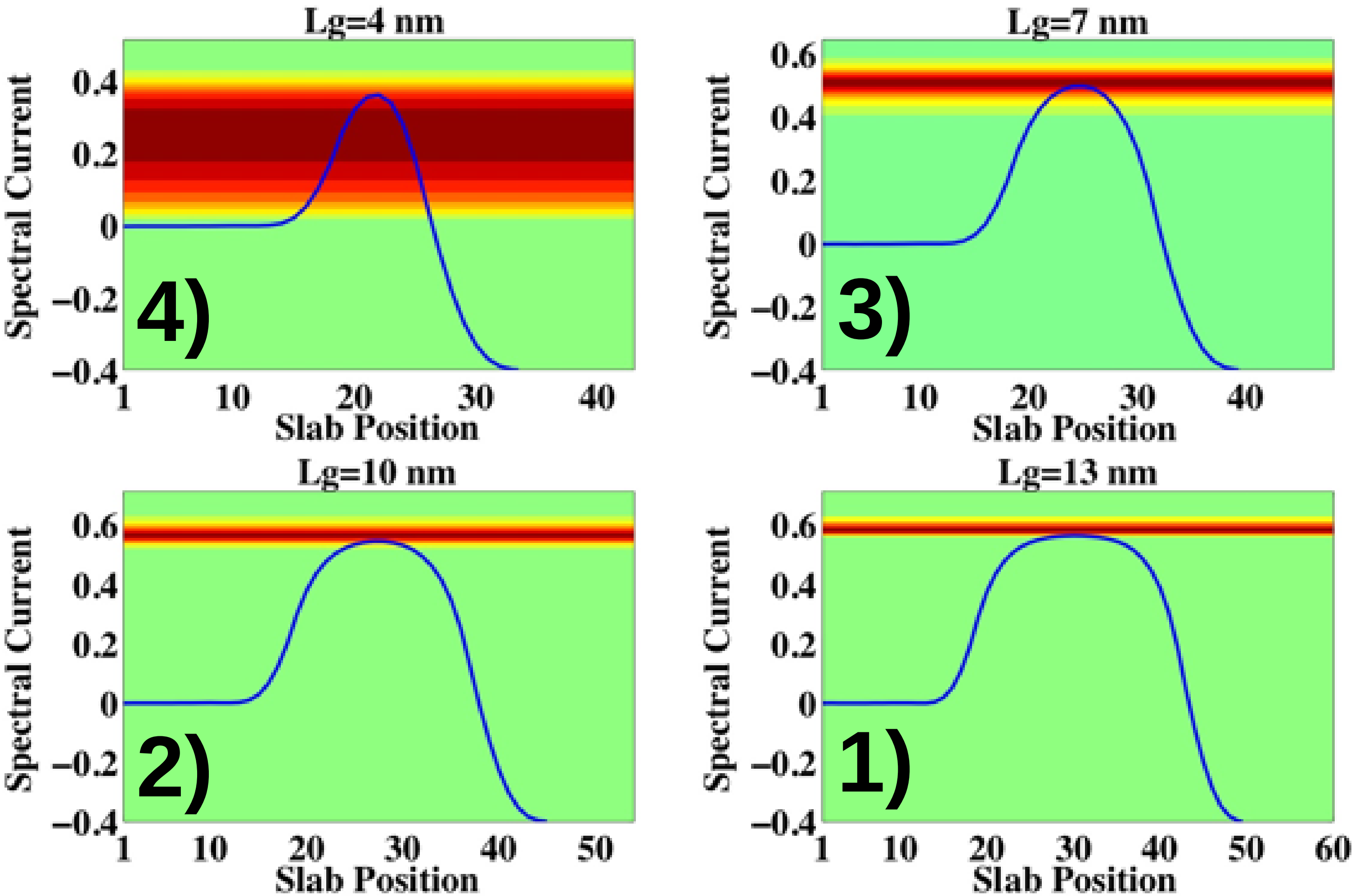
d) non-equilibrium with V_G and $V_D > 0$ applied

S.M. Sze, Physics of Semiconductor Devices, 1981.

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

Summary

1) Energy band diagrams provide a qualitative understanding of how MOSFETs operate.

2) MOSFETs are barrier controlled devices – the drain current is controlled by the height of an energy barrier between the source and channel.

3) In a well-designed transistor, the height of the energy barrier is strongly controlled by the gate voltage and weakly by the drain voltage (DIBL).

Next topic:

In the next lecture, we will discuss traditional MOSFET theory, which describes the IV characteristics with simple analytical expressions.