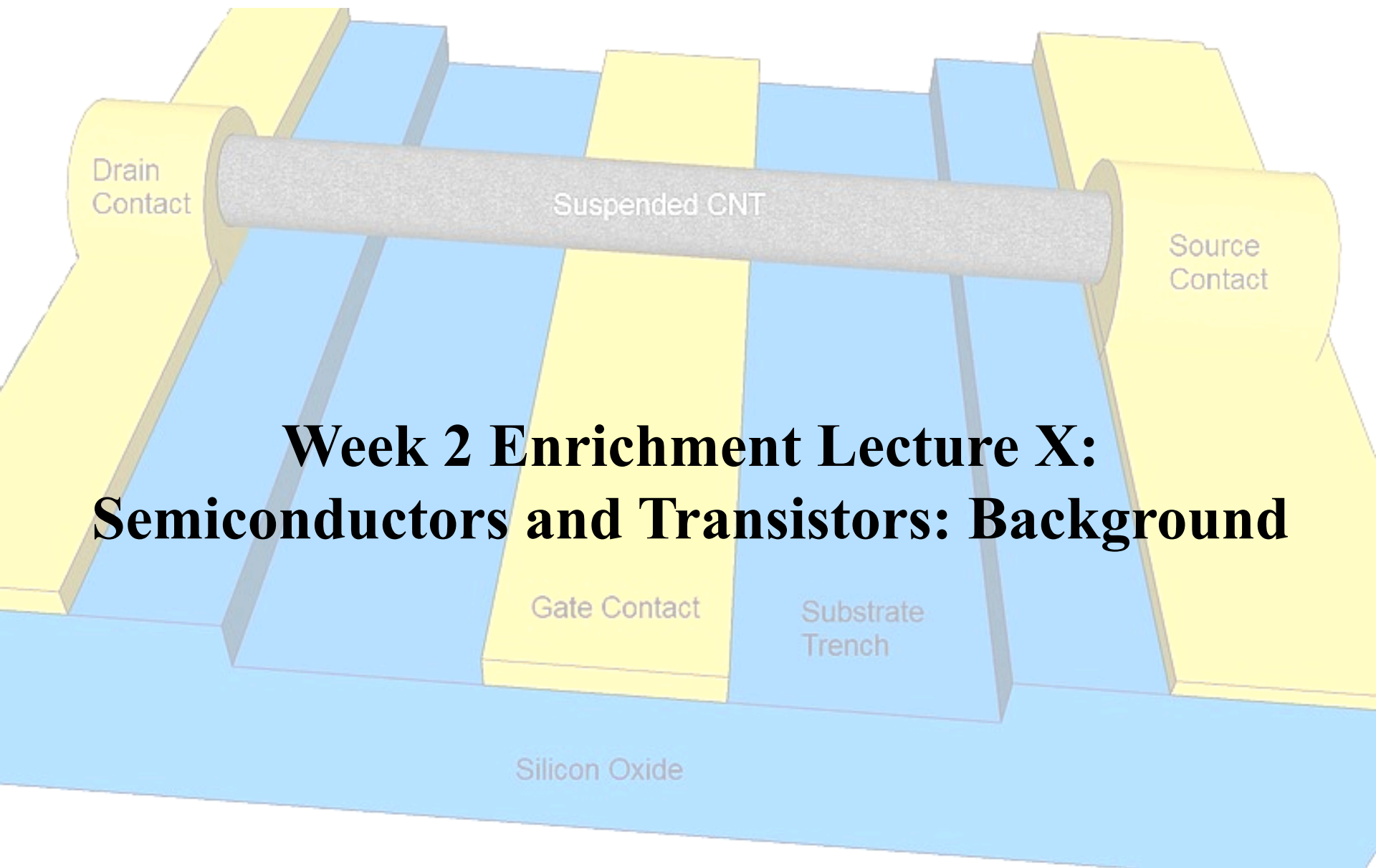
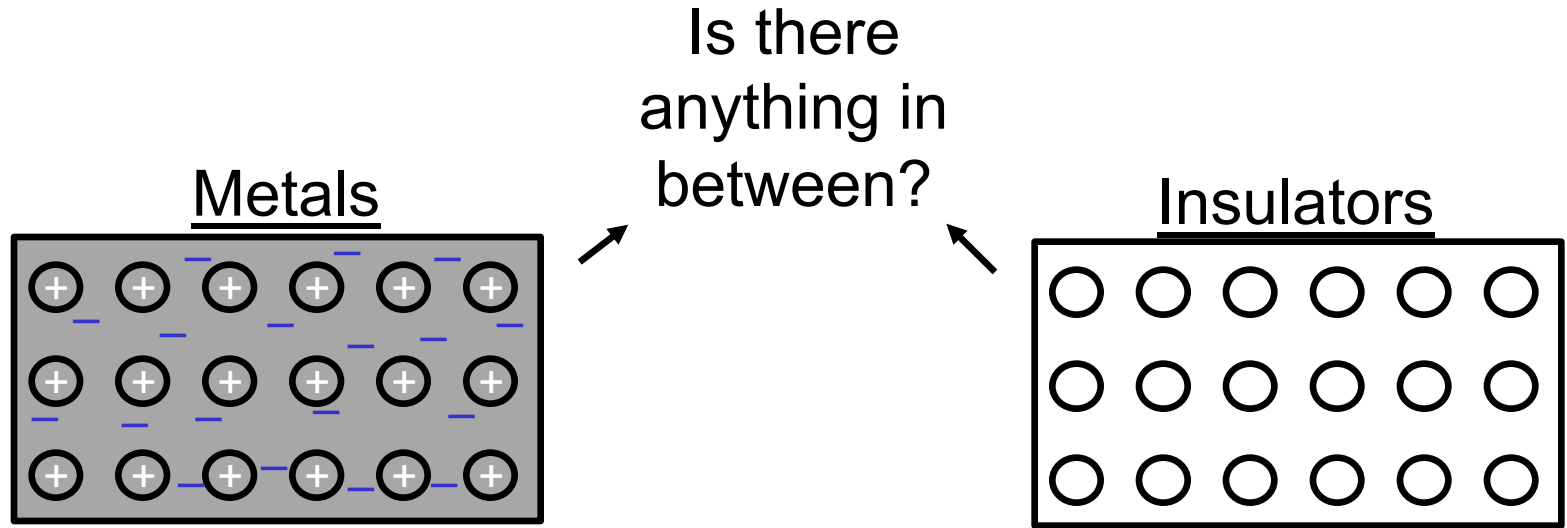


Nano-electronics



Week 2 Enrichment Lecture X: Semiconductors and Transistors: Background

Metals vs. Insulators



Positive ions and core electrons do not contribute to conduction, since they are fixed in place

The number of free electrons is equal to valency times number of positive ions, a **VERY** large number.

Free electrons can move around, and therefore contribute to conduction.

$\sim 10^{23}$ per cm^3

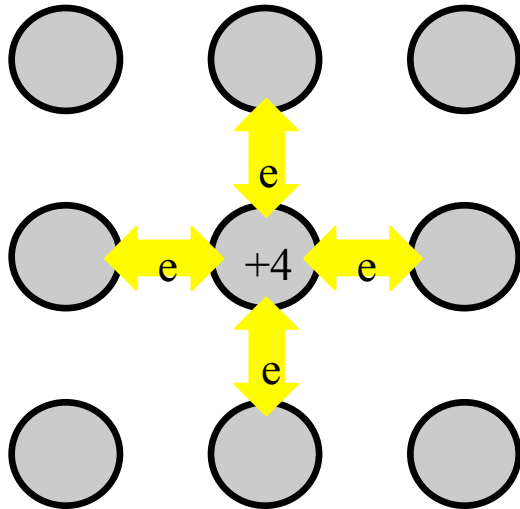
Atomic cores do not give up any valence electrons - all of them are involved in bonds between atoms.

No free electrons means no conduction, even if we apply a voltage.

Semiconductors

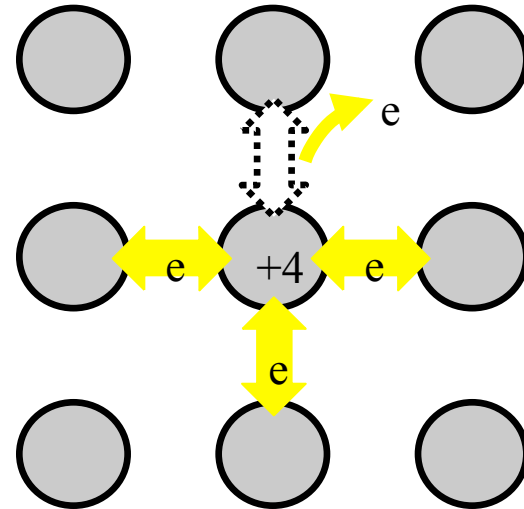
Consider a material where some of the electrons can be liberated from chemical bonds by just a little kick, e.g., a bit of heat.

Low Temperature



all electrons (including valence electrons)
are bound - NO conduction

High Temperature



some electrons are able to break
free and participate in conduction

This is a semiconductor. The conduction depends sensitively on the temperature of the material.

Semiconductors

Silicon is the most important example. It is the base material for all integrated circuits.

Silicon has a valency of 4, which means it has four electrons that can participate in chemical bonds.

PERIODIC TABLE OF THE ELEMENTS

PERIOD 1: H (1.0079)

PERIOD 2: Li (6.941), Be (9.0122)

PERIOD 3: Na (22.990), Mg (24.305)

PERIOD 4: K (39.098), Ca (40.078), Sc (44.956), Ti (47.867), V (50.942), Cr (51.996), Mn (54.938), Fe (55.845), Co (58.933), Ni (58.693), Cu (63.546), Zn (65.39), Ga (69.723), Ge (72.63), As (74.922), Se (78.96), Br (79.904), Kr (83.80)

PERIOD 5: Rb (85.468), Sr (87.62), Y (88.906), Zr (91.224), Nb (92.906), Mo (95.94), Tc (98), Ru (101.07), Rh (102.91), Pd (106.42), Ag (107.87), Cd (112.41), In (114.82), Sn (118.71), Sb (121.76), Te (127.60), I (126.905), Xe (131.29)

PERIOD 6: Cs (132.91), Ba (137.33), La-Lu (57-71), Hf (178.49), Ta (180.95), W (183.84), Re (186.21), Os (190.23), Ir (192.22), Pt (195.08), Au (196.97), Hg (200.59), Tl (204.38), Pb (207.2), Bi (208.98), Po (209), At (210), Rn (222)

PERIOD 7: Fr (223), Ra (226), Ac-Lr (89-103), Rf (104), Db (105), Sg (106), Bh (107), Hs (108), Mt (109), Uun (110), Uub (111), Uut (112), Uuq (114)

LANTHANIDE

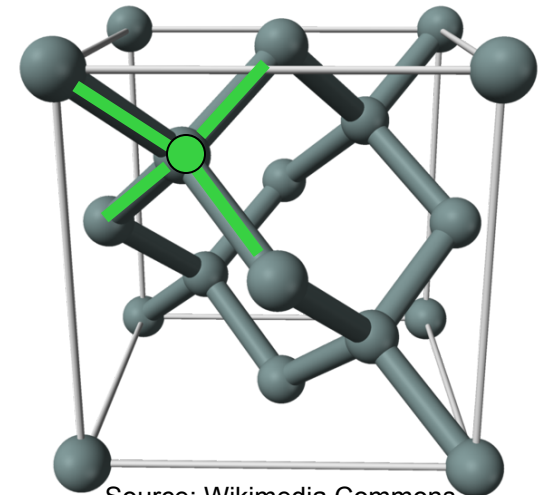
57 La (138.91), 58 Ce (140.12), 59 Pr (140.91), 60 Nd (144.24), 61 Pm (145), 62 Sm (150.36), 63 Eu (151.96), 64 Gd (157.25), 65 Tb (158.93), 66 Dy (162.50), 67 Ho (164.93), 68 Er (167.26), 69 Tm (168.93), 70 Yb (173.04), 71 Lu (174.97)

ACTINIDE

89 Ac (227), 90 Th (232.04), 91 Pa (231.04), 92 U (238.03), 93 Np (237), 94 Pu (244), 95 Am (243), 96 Cm (247), 97 Bk (247), 98 Cf (251), 99 Es (252), 100 Fm (257), 101 Md (258), 102 No (259), 103 Lr (262)

Editor: Ashya Vashan (ashya@periodni.com)

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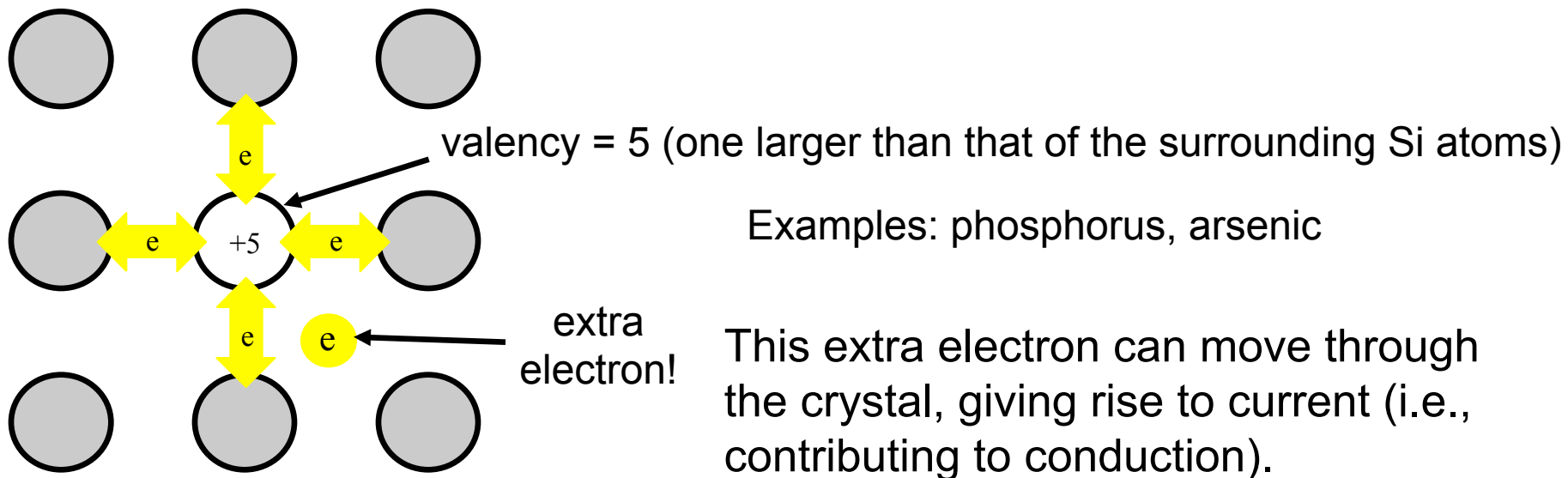
Source: Wikimedia Commons

It crystallizes in a structure where each atom has four neighbors. Thus each of the neighbors gets to use one electron in a covalent bond.

Doping of Semiconductors

Conduction can also be modified by adding impurities.

Doped semiconductor: impurities added on purpose!
These impurities substitute for a silicon atom.

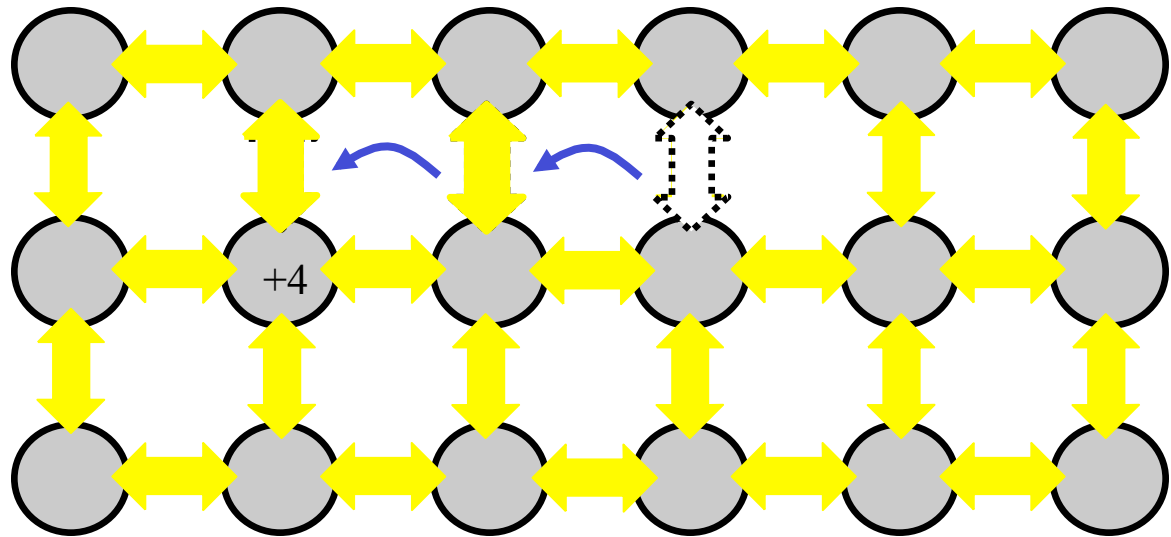


Donor impurity – one that gives up an extra electron.

Note: the crystal is still electrically neutral (no net charge) !!

Electrons and holes

Consider a lattice where one electron has been freed from its bond, and has moved away, leaving a vacancy.



If electrons cascade from the right to the left, filling the vacancy...

then, effectively, the vacancy (with a + charge) moves from the left to the right...

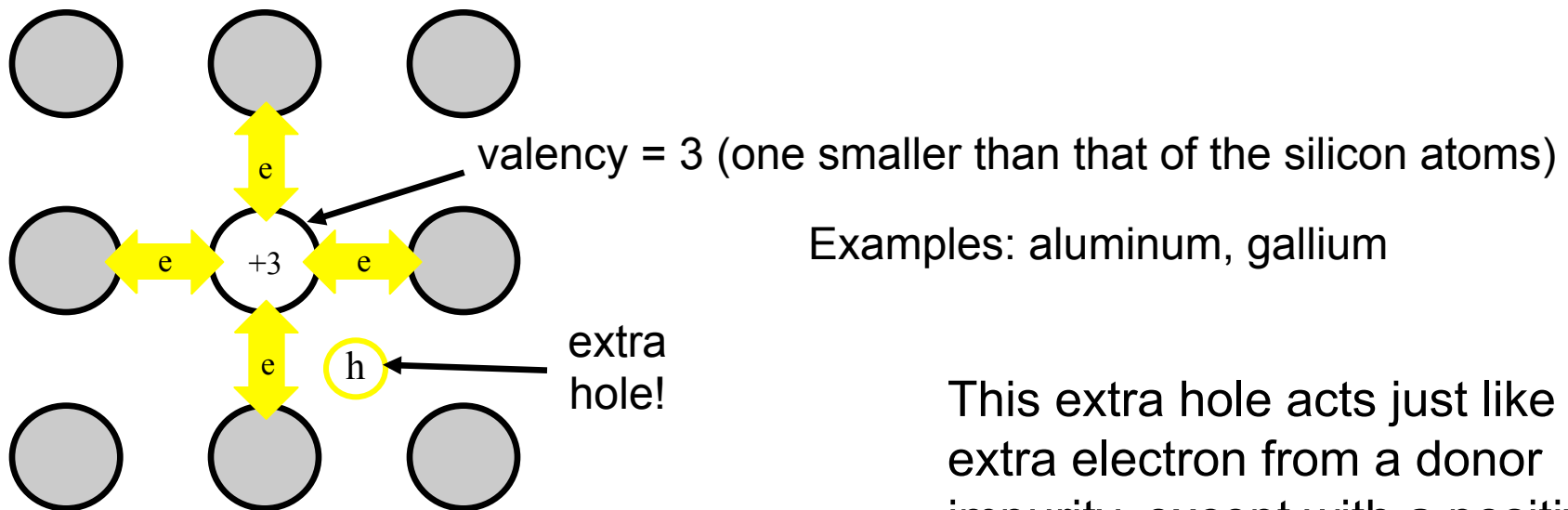
————→ POSITIVE CURRENT TO THE RIGHT!!

Conduction in semiconductors can occur via electrons (with negative charge) or holes (with positive charge), or both.

Acceptor impurities - holes

We saw that adding a valence-5 atom can give us extra electrons.

We can also create extra holes by adding a valence-3 atom.



Acceptor impurity – one less electron.

This extra hole acts just like an extra electron from a donor impurity, except with a positive (instead of negative) charge.

Donors and acceptors

Intrinsic semiconductor – one with no impurities intentionally added

n-type semiconductor: donors added.

$$N_e > 0, N_h \approx 0.$$

p-type semiconductor: acceptors added.

$$N_e \approx 0, N_h > 0.$$

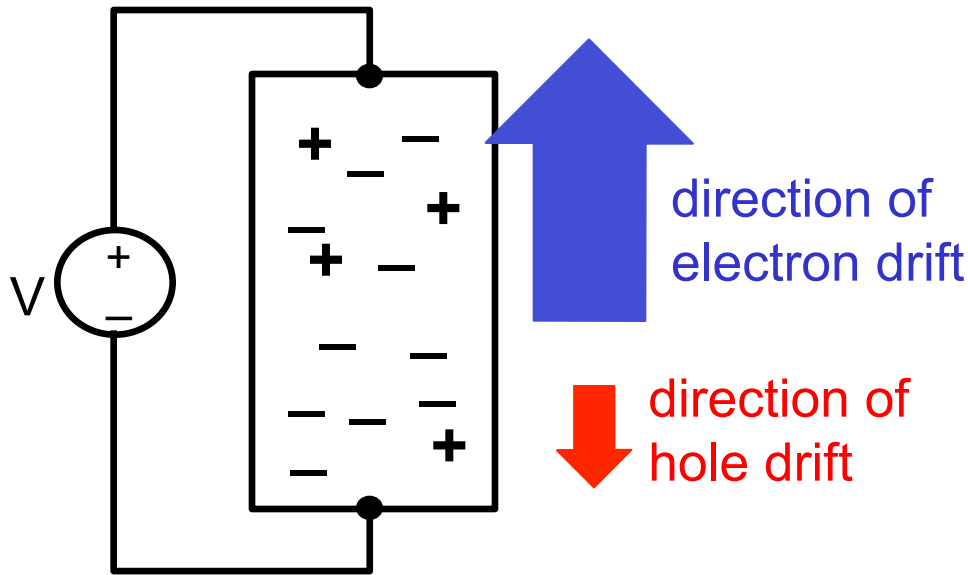
Compensated semiconductor: both donors and acceptors added, in approximately equal amounts.

$$N_e \approx N_h > 0.$$

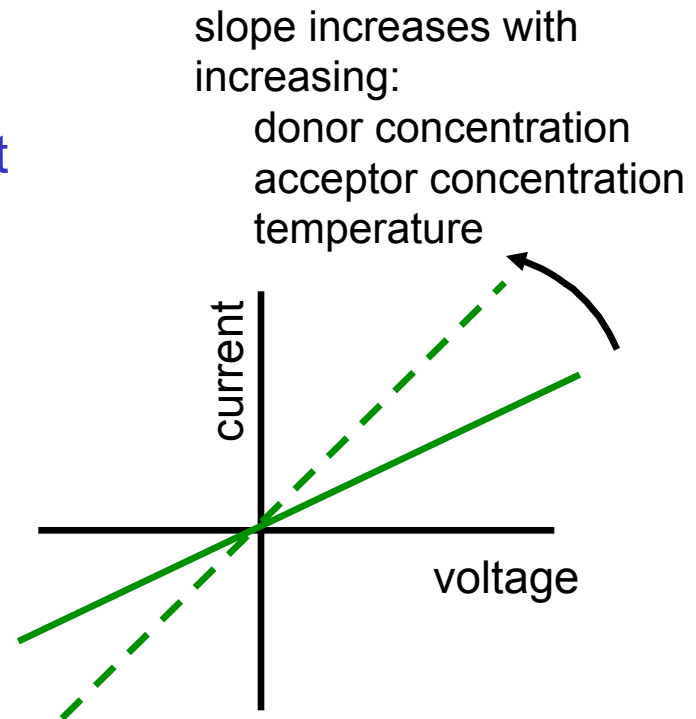
Partially compensated semiconductor: $N_e \neq N_h \neq 0$.

Ohm's Law and semiconductors

A homogeneous semiconductor is *ohmic*.
(That is, the plot of current vs. voltage, the I-V curve, is a straight line. Ohm's law, $V=IR$, applies.)

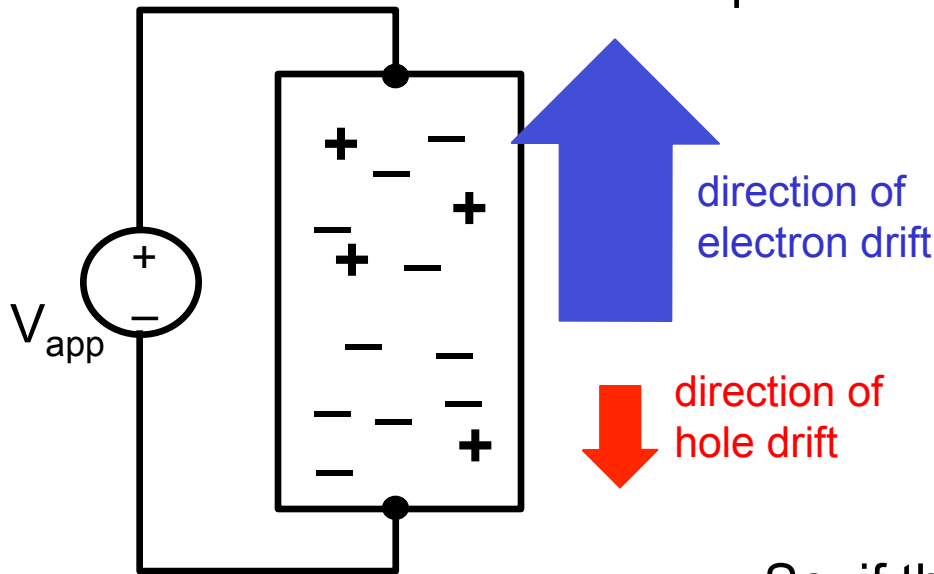


In this illustration, the semiconductor has $N_e > N_h$.



Drift currents – response to an applied voltage

“Drift current” – the net current that flows as the charge carriers (electrons and holes) respond to a voltage.



In this illustration, the semiconductor has $N_e > N_h$.

Recall that current is: $j = N e v_{ave}$
where:

N = number of charge carriers
(per unit volume)

e = the charge on them

v_{ave} = their average velocity

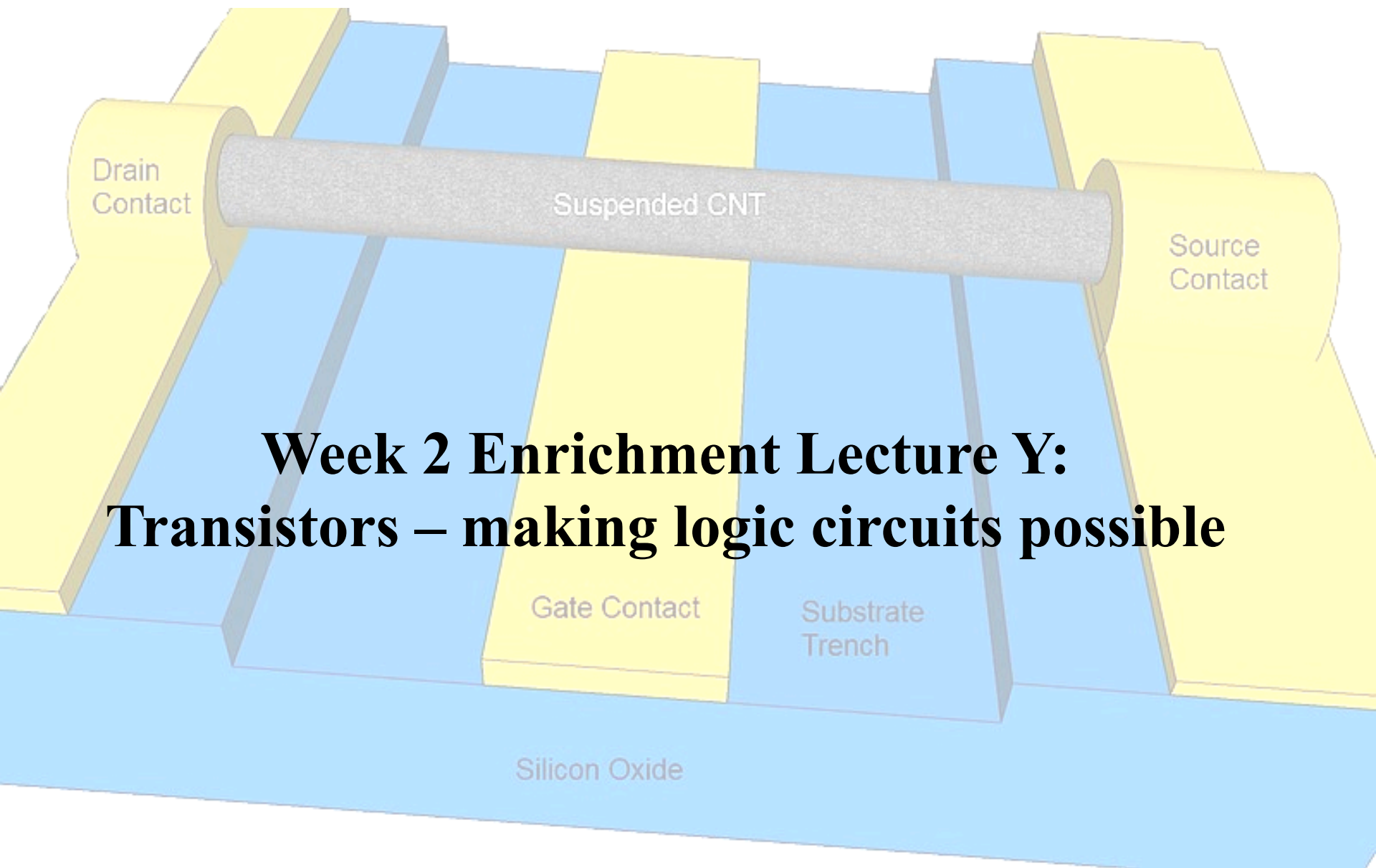
So, if the velocity of the electrons points up, then $j_{electrons}$ points down, since for electrons, e is negative.

→ net drift current: $j_{drift} = j_{electrons} + j_{holes}$
points down in this picture.

Your Take-Home Lessons

- Current in semiconductors can be carried either by electrons or holes (which have opposite charges)
- Impurities in semiconductors can be either “donors” – giving up an extra electron – or “acceptors” – creating an extra hole.
- “Drift” currents – the motion of charges in semiconductors when a voltage is applied

Nano-Electronics

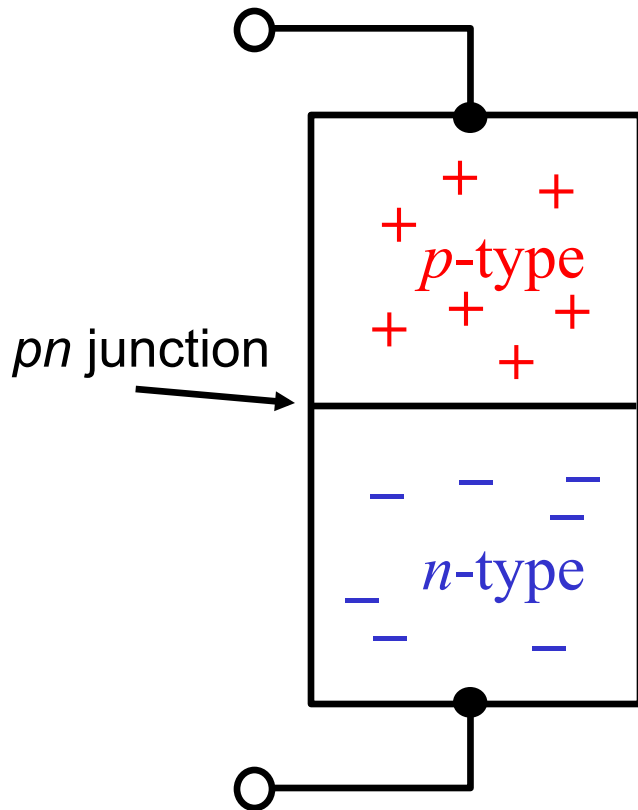


Week 2 Enrichment Lecture Y: Transistors – making logic circuits possible

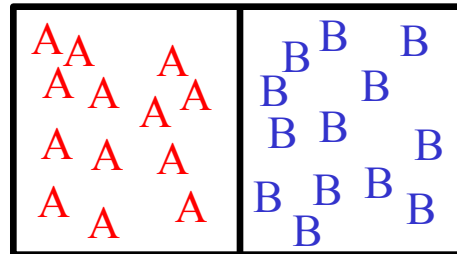
The *pn* junction

What happens if we put *p*-type silicon next to *n*-type silicon, creating a junction?

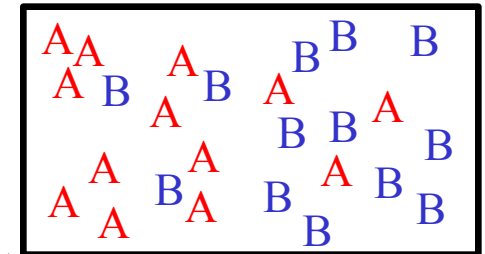
This is exactly analogous to putting containers of two different gases next to each other.



Two different gases in adjacent boxes



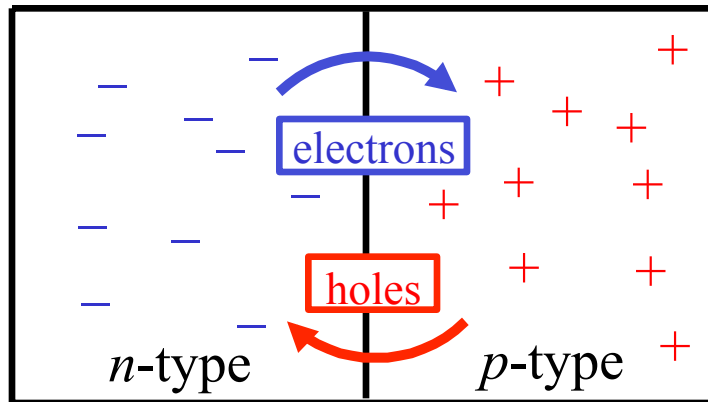
diffusion of A to the right, and B to the left



remove the partition

“Diffusion current” – the net current that flows due to the tendency of charge carrier concentrations to equalize in a volume

The *pn* junction



Electrons diffuse to the right
(which corresponds to a current
flowing to the left)

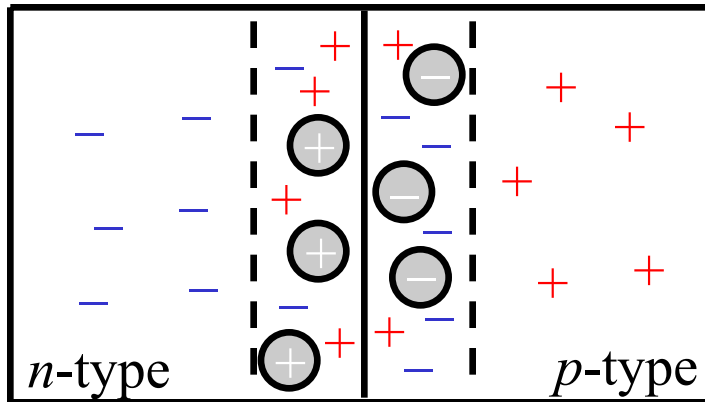
Holes diffuse to the left
(which also corresponds to a
current flowing to the left)

net diffusion current: $j_{\text{diff}} = j_{\text{electrons}} + j_{\text{holes}}$ points to the left.

Note: diffusion current will flow, even if there is no applied voltage, until the carrier concentration is constant throughout.

The depletion region

The region near the junction is interesting.



Diffusing **electrons** leave behind fixed positive charges.

Diffusing **holes** leave behind fixed negative charges.

- Recombination of free electrons with free holes leaves the area very close to the junction *depleted* of mobile charge carriers.
- The left-behind fixed charges give rise to a voltage. In the above diagram, that voltage pushes electrons to the left and holes to the right (i.e., in the opposite direction from the diffusion).
- These new drift currents, which oppose the diffusion currents, grow until they are large enough to cancel the diffusion currents.

Why does this matter?

The depletion voltage – that is, the voltage that spontaneously appears across the depletion region due to diffusion – is the key to making devices.

A voltage applied from outside can either increase the depletion voltage or oppose (and thereby diminish) it, depending on the sign.

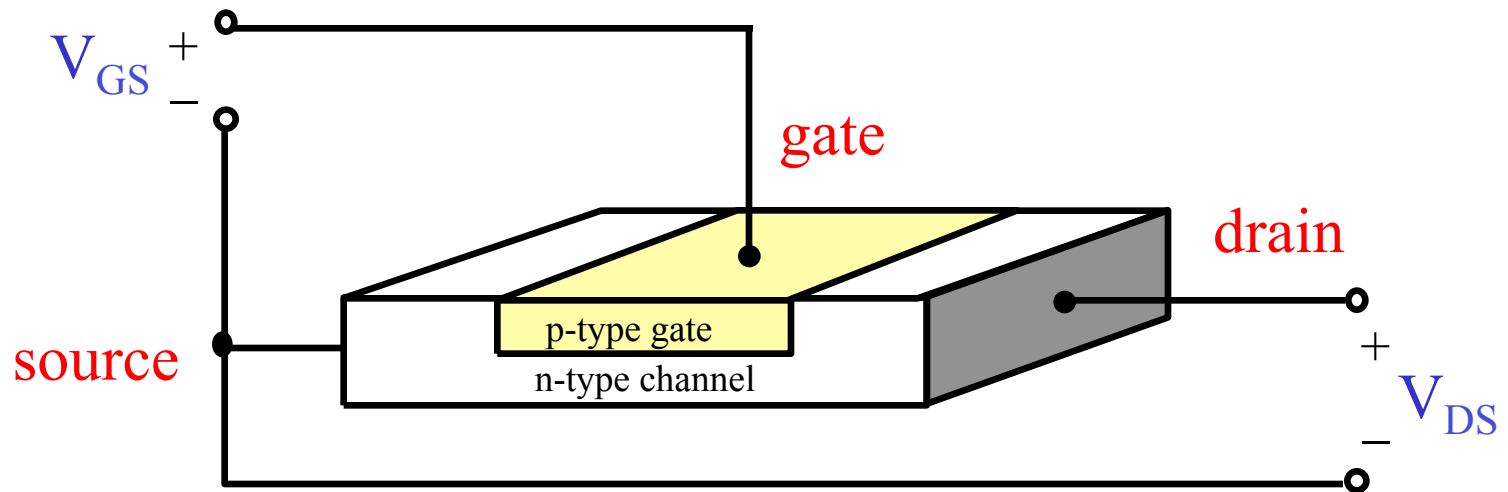
That means: we can control the thickness of the depletion region by applying an external voltage across the *pn* junction.

- if the applied bias reinforces the depletion voltage: the depletion region gets thicker. Since it contains few mobile charges, no current can flow across it.
- if the applied bias opposes the depletion voltage: the depletion region gets thinner. Current can flow across the thin depleted zone.

This is the basis upon which transistors and diodes work.

A key example: the field-effect transistor (FET)

A transistor is a three-terminal device.



In the usual operation, the gate is biased negative, so that there is a large depletion region and no current flows through the gate electrode.

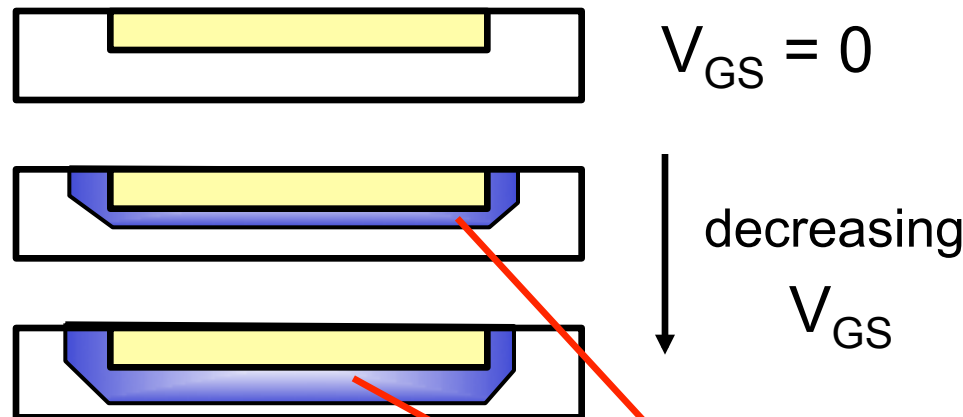
Even though no current flows through the gate, it still controls the amount of current that flows from source to drain.

FET operation

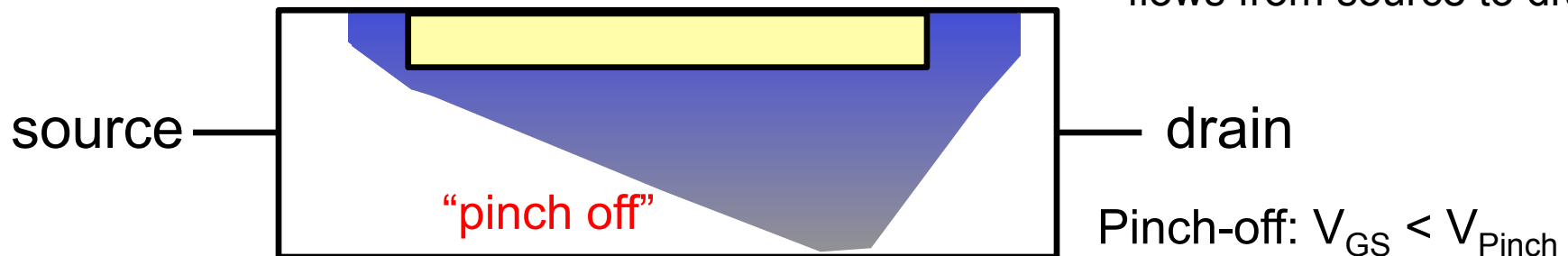
When $V_{GS} = 0$, the channel between source and drain is large.

As V_{GS} decreases, the depletion region grows, making the channel smaller. Current flows less easily from source to drain.

When V_{GS} is negative enough, the channel is **pinched off**, and no current flows from source to drain.



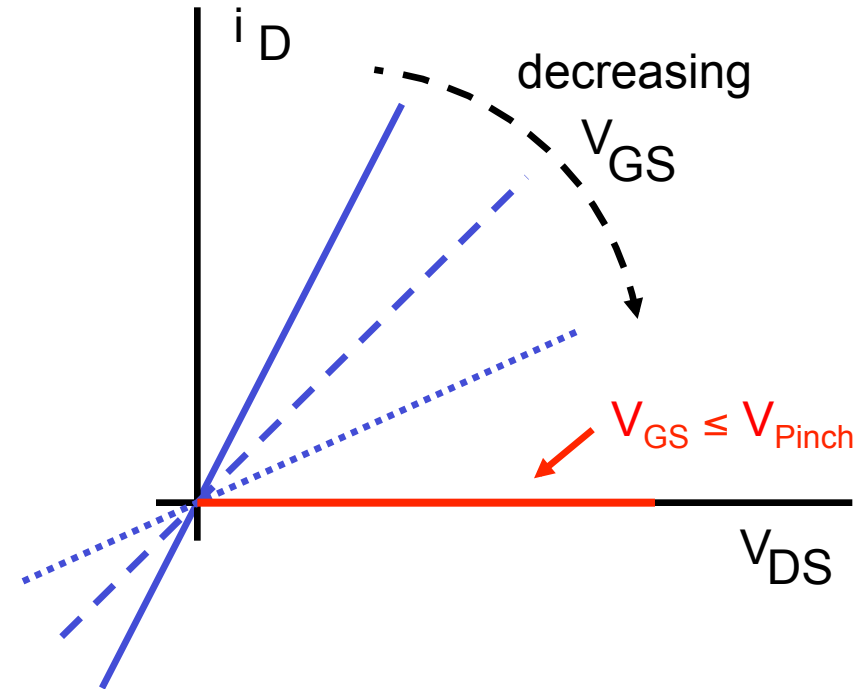
depletion
(caused by the effect of the field applied to the gate)



A FET is a voltage-controlled resistor

For reasonably small values of $|V_{DS}|$, the drain current i_D is proportional to the voltage V_{DS} ; that is, the device behaves as a resistor between source and drain.

The resistance (the inverse of the slope of the line) is determined by the gate voltage.

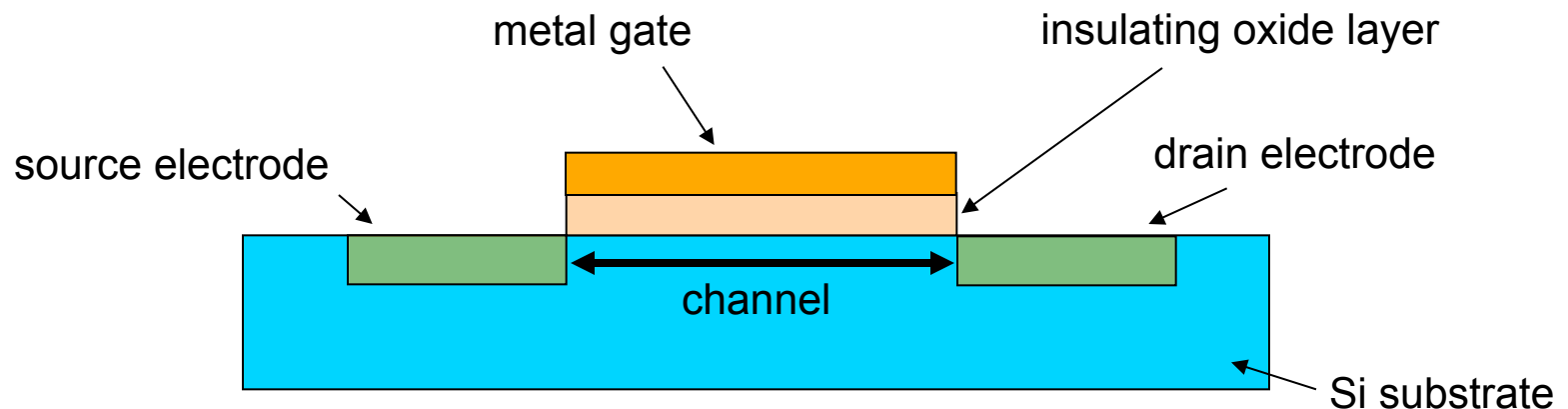


A voltage-controlled resistor!

This allows us to control the flow of current from source to drain, without dissipating any power in the gate (since the gate current is always zero).

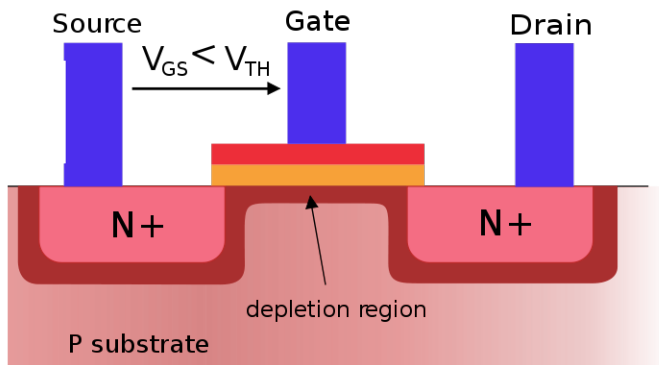
MOSFETs

MOSFET: Metal-oxide-silicon FET



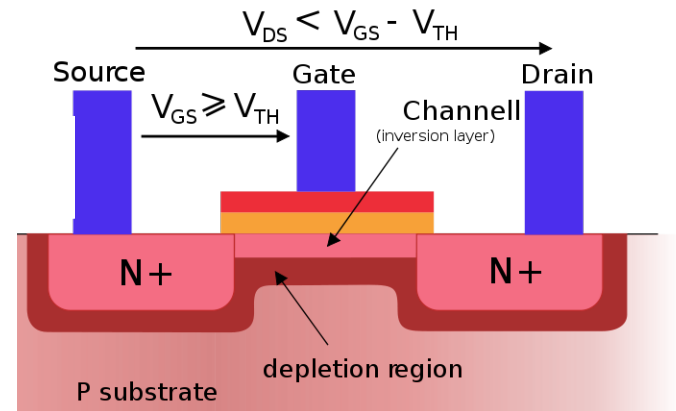
- replaces the doped silicon gate with a metal and a thin insulating layer (oxide)
- operating principle is similar
- MOSFETs are the most commonly used form of transistors

MOSFET operating regimes



Source: Wikimedia commons

No current flows.



Linear operating region (ohmic mode)

Current flows
through the channel.

Your Take-Home Lessons

- Putting a p -type semiconductor adjacent to an n -type semiconductor creates a pn junction.
- The region near the junction becomes depleted of charge carriers.
- We can use a voltage to control the thickness of the depletion region. This is the basis by which transistors and diodes operate.
- MOSFET: the most common transistor architecture