# Lecture1: Basic physics of semiconductors

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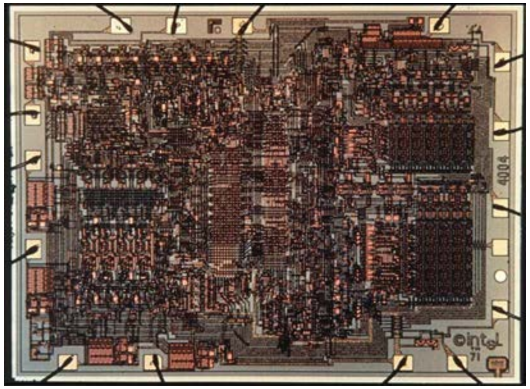
# Number of transistors

- The first microprocessor
  - In 1971, the first microprocessor was released. (Intel 4004)
  - It has about 2300 transistors.
  - It was designed by Federico Faggin.
  - Masatoshi Shima helped him.
- Recent CPU by Intel?
  - As of 2014, Haswell processor
  - It has about 1.4 billion transistors.
- How about GPU?
  - For example, NVIDIA TITAN V (~ 3,000 $)
  - It has about 21 billion transistors.
  - Price per transistor? 0.143 μ$...

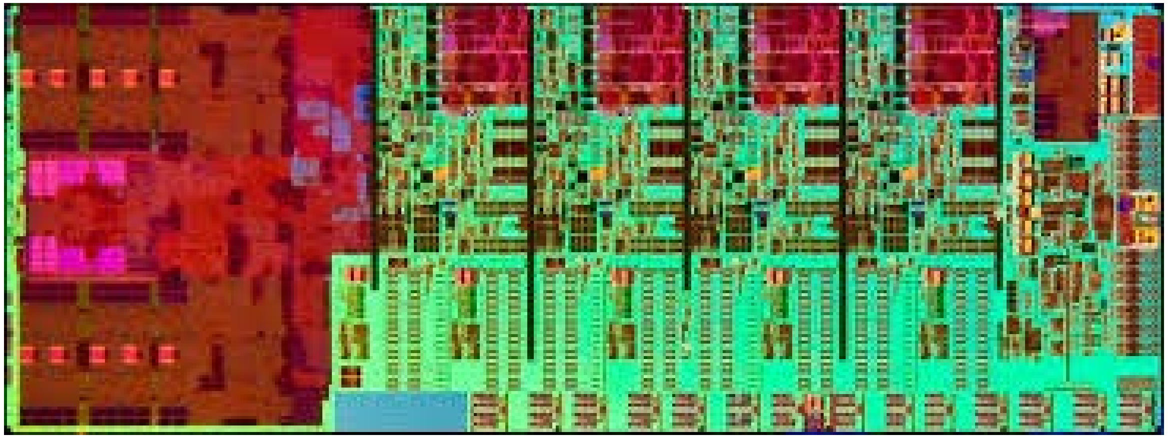
Federico Faggin
(Google images)

# Die shot

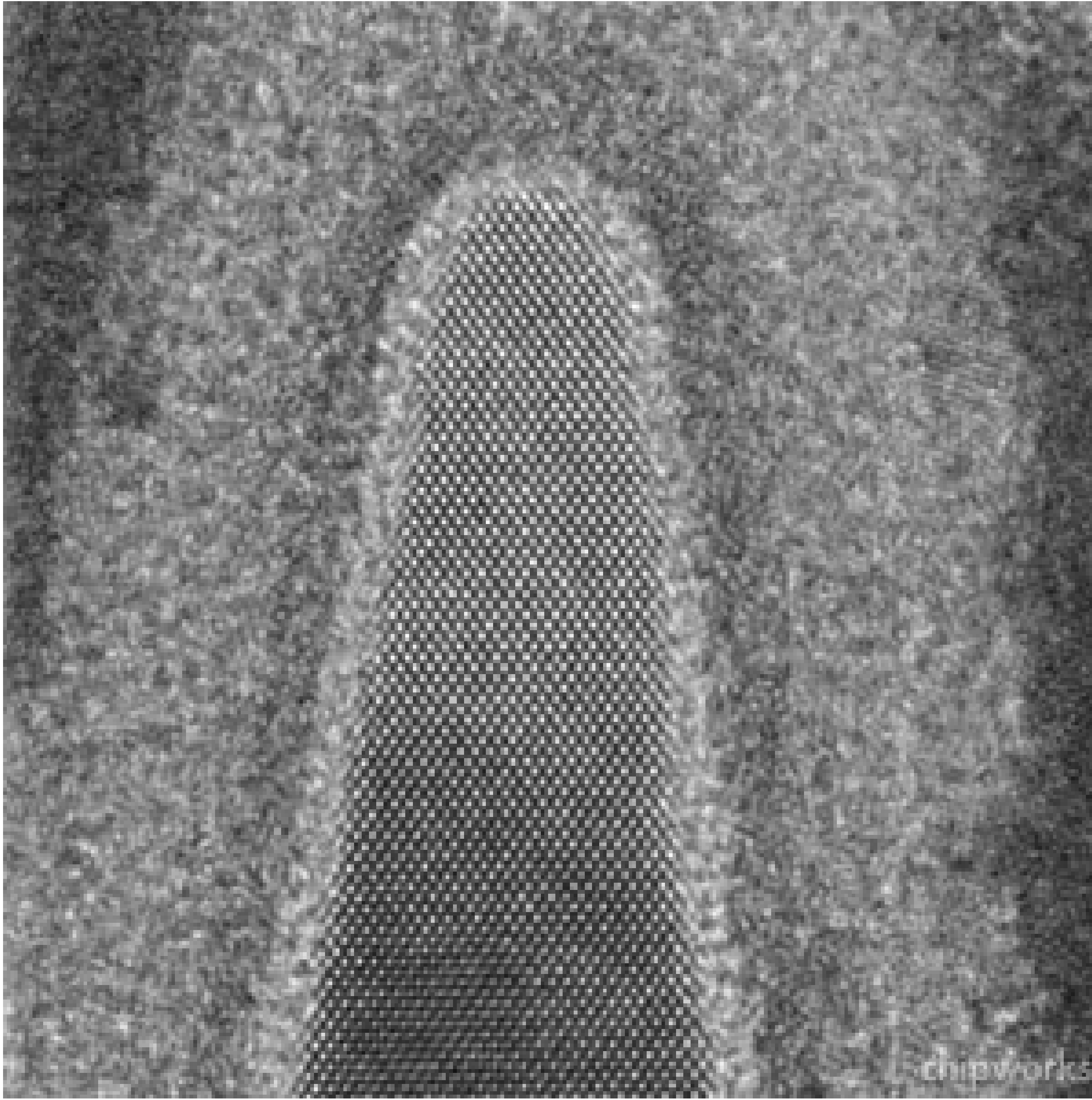
- More than 40 years between them




(1971)
Die size: 12 sq mm
Min. feature size: 10 micron
Max. clock speed: 740 kHz



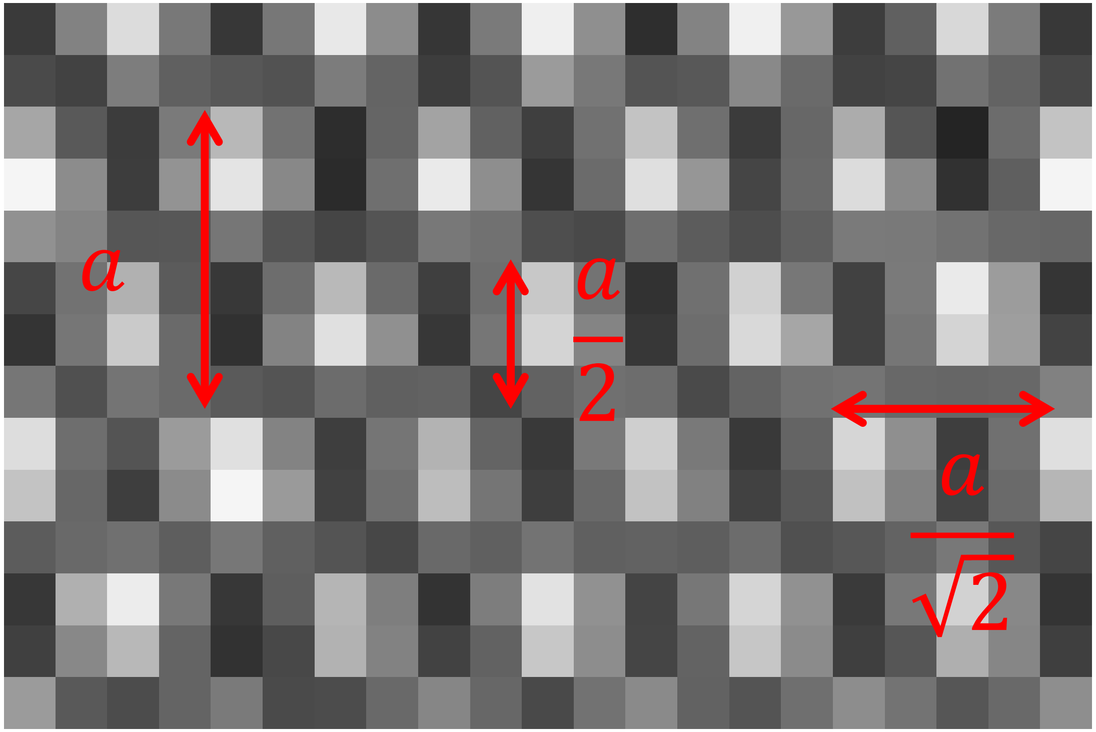
(2014)
Die size: 177 sq mm
Min. feature size: 22 nm




TEM image of a FinFET (Chipworks Blog)

# Magnified version of Si region

- What is the value of $a$?

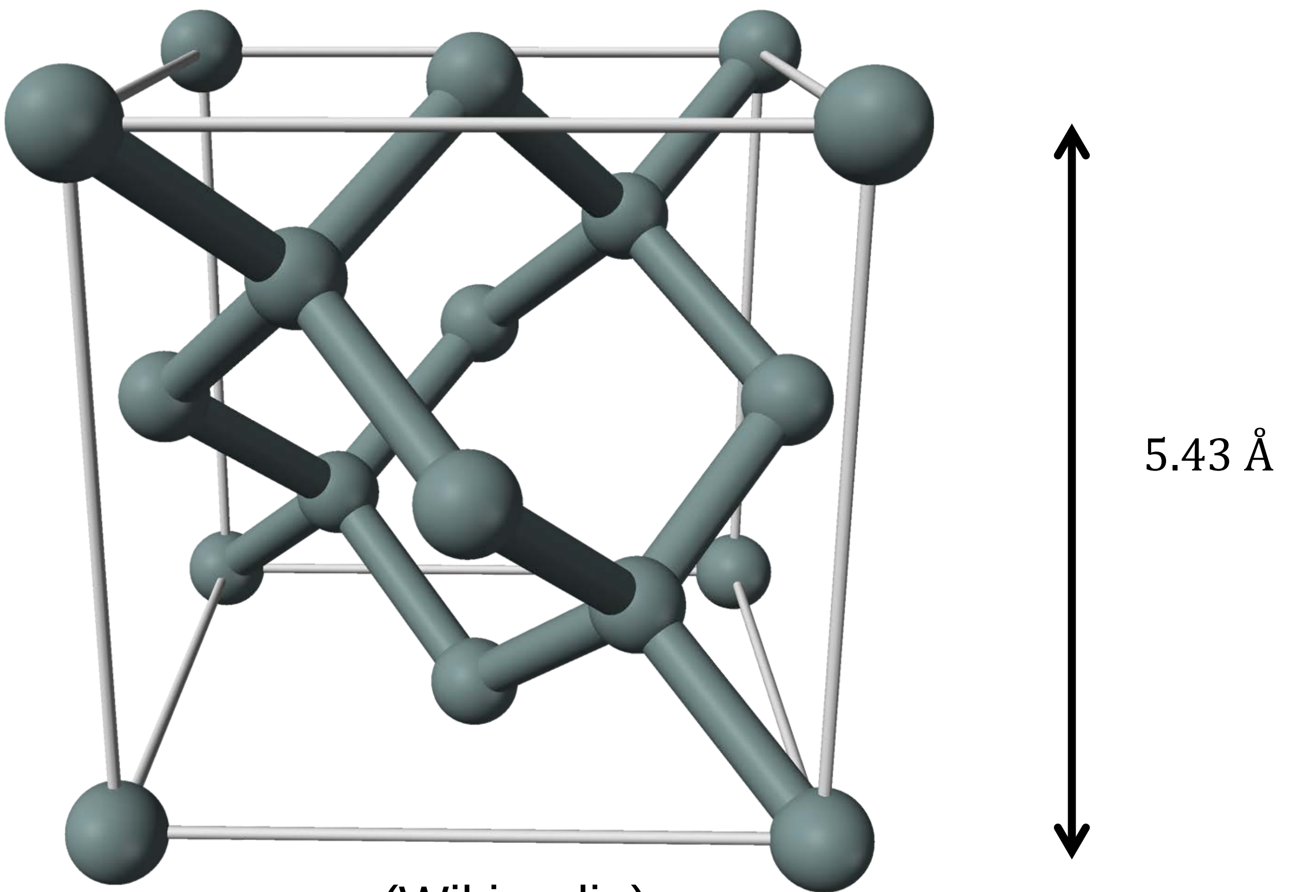


# Let’s play a demo!

- The demo program was written by Mr. Sunghyeon Kim.
  - During his winter internship

# Crystal structure of Si

- Diamond cubic crystal structure



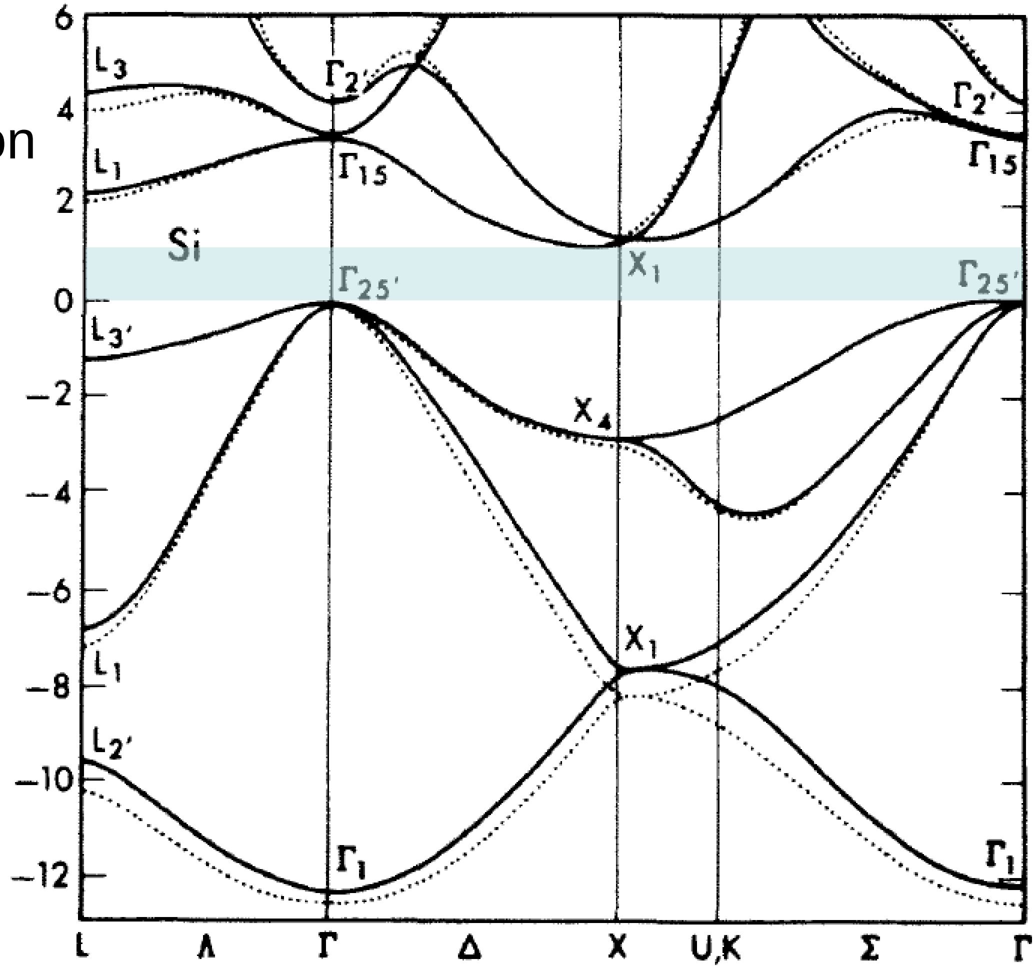

(Wikipedia)

# Band structure

- Band structure of silicon (Band gap ~ 1.12eV)

Conduction bands

Valence bands




(J. R. Chelikowsky and M. L. Cohen, PRB, vol. 14, p. 556, 1976)

# Thermal energy

- At zero temperature, the total energy is minimized.
  - All electrons are in the valence bands.
- At higher temperatures, the electrons gain thermal energy.
- Concept of holes
  - When freed from a covalent bond, an electron leaves a “void” behind.
  - It – the void – is called a “hole.”

(Google Image)

# Intrinsic carrier density

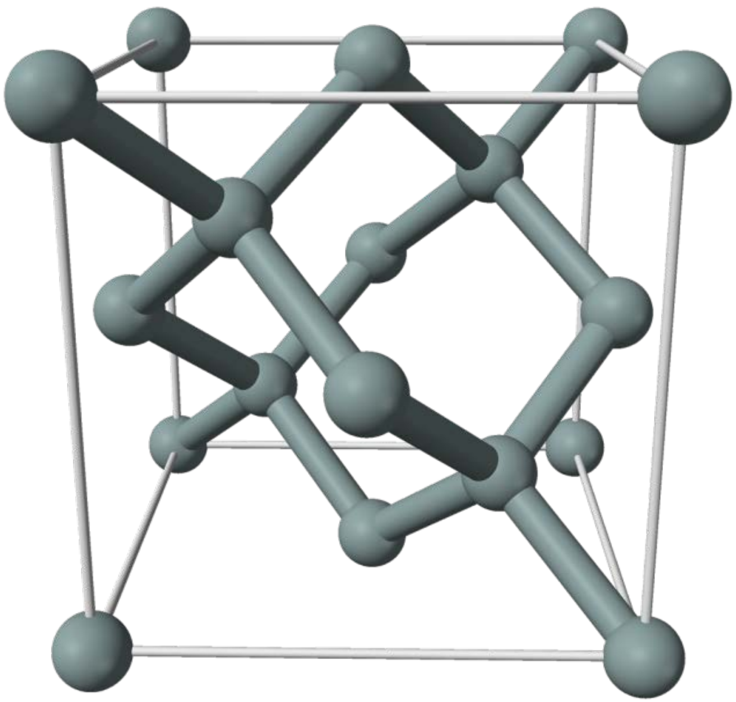
- What is the intrinsic carrier density, $n_i$?
  - How many "free" electrons are created at a given temperature?
  - (Assume the intrinsic material.)
- Expression of $n_i$

$$n_i = 5.2 \times 10^{15}\, T^{1.5} \exp \frac{-E_g}{2k_B T} \quad [electrons/cm^3]$$

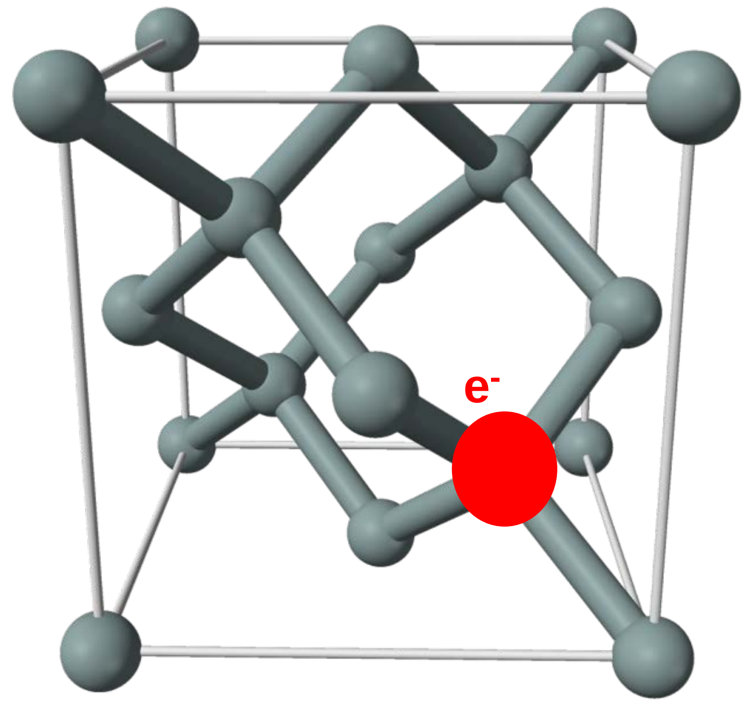
  - Boltzmann constant, $k_B$
  - Useful number for silicon: 1 X $10^{10}$ $cm^{-3}$ at 300 K

# Impurity atom

- The phosphorus atom has 5 valence electrons.
  - Additional electron (**e$^-$** in the right figure) serves as a charge carrier.



Pure silicon




Silicon with “impurity” atom
(For example, phosphorus)

# Impurity atoms

- One impurity atom contributes a “free” electron.
  – If 2 (, 3, 4, 5, …) phosphorus atoms are introduced?
  – 2 (, 3, 4, 5, …) additional electrons will be generated!
- More specifically,
  – When the density of the phosphorus atom is $N$ $[atoms/cm^3]$,
  – The electron density becomes $N$ $[electrons/cm^3]$.
- Typical value? (Feeling about the numbers)
  – $10^{15}$ $[atoms/cm^3]$ : Almost no impurity
  – $10^{17}$ $[atoms/cm^3]$ : Low (or moderate) impurity density
  – $10^{19}$ $[atoms/cm^3]$ : High impurity density (Not extremely high)
- What is it good for?
  – Conductivity can be changed drastically.

# n-type? p-type?

- Phosphorus has 5 valence electrons.
  - Therefore, it contributes an electron.
  - n-type
- Boron has 3 valence electrons.
  - It cannot provide 4 valence electrons to complete 4 bonds.
  - Instead, it contributes a hole.
  - p-type

# Minority carrier density

- Majority vs. minority
  - In the n-type semiconductor, electrons are majority carriers.
  - On the other hand, holes are minority carriers.

  - At equilibrium,

$$np = n_i^2$$