EE 330
Lecture 12

Semiconductor Processes

Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFET
- BJT

Basic Semiconductor Processes

MOS (Metal Oxide Semiconductor)

1. NMOS — n-ch
2. PMOS — p-ch
3. CMOS — n-ch & p-ch
    - Basic Device: MOSFET
    - Niche Device: MESFET
    - Other Devices: Diode
BJT
Resistors
Capacitors
Schottky Diode

Basic Semiconductor Processes

Bipolar

1. T^2L
2. ECL
3. I^2L
4. Linear ICs
   - Basic Device: BJT (Bipolar Junction Transistor)
   - Niche Devices: HBJT (Heterojunction Bipolar Transistor)
     HBT
   - Other Devices: Diode
     Resistor
     Capacitor
     Schottky Diode
     JFET (Junction Field Effect Transistor)

Basic Semiconductor Processes

Other Processes

- Thin and Thick Film Processes
  - Basic Device: Resistor
- BiMOS or BiCMOS
  - Combines both MOS & Bipolar Processes
  - Basic Devices: MOSFET & BJT
- SiGe
  - BJT with HBT implementation
- SiGe / MOS
  - Combines HBT & MOSFET technology
- SOI / SOS (Silicon on Insulator / Silicon on Sapphire)
- Twin-Well & Twin Tub CMOS
  - Very similar to basic CMOS but more optimal transistor char.

Devices in Semiconductor Processes

- Standard CMOS Process
  - MOS Transistors
    - n-channel
    - p-channel
  - Capacitors
  - Resistors
  - Diodes
  - BJT (decent in some processes)
    - npn
    - pnp
  - JFET (in some processes)
    - n-channel
    - p-channel
- Standard Bipolar Process
  - BJT
    - npn
    - pnp
  - JFET
    - n-channel
    - p-channel
  - Diodes
  - Resistors
  - Capacitors

- Niche Devices
  - Photodetectors (photodiodes, phototransistors, photoresistors)
  - MESFET
  - HBT
  - Schottky Diode (not Shockley)
  - MEM Devices
  - TRIAC/SCR
  -

Basic Devices

- Standard CMOS Process
  - MOS Transistors
    - n-channel
    - p-channel
  - Capacitors
  - Resistors
  - Diodes
  - BJT (in some processes)
    - npn
    - pnp
  - JFET (in some processes)
    - n-channel
    - p-channel
- Niche Devices
  - Photodetectors
  - MESFET
  - Schottky Diode (not Shockley)
  - MEM Devices
  - Triac/SCR
  - ….

Primary Consideration in This Course

Some Consideration in This Course

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

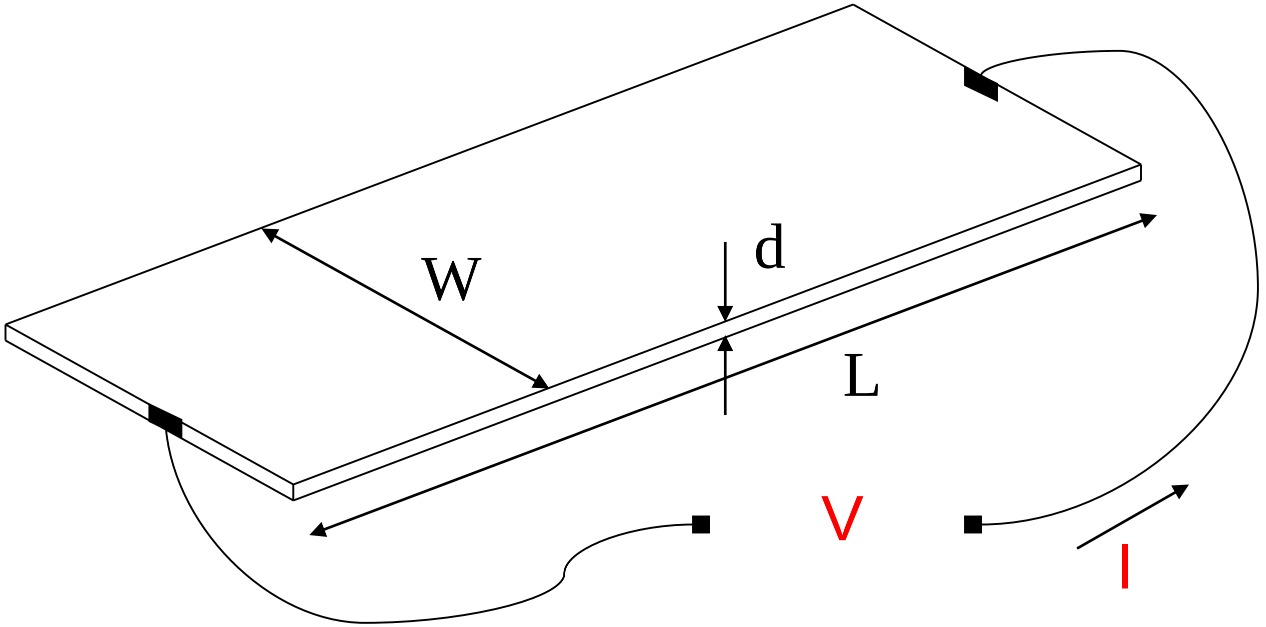
Resistors were discussed when considering interconnects so will only be briefly reviewed here

Resistors

- Generally thin-film devices
- Almost any thin-film layer can be used as a resistor
  - Diffused resistors
  - Poly Resistors
  - Metal Resistors
  - “Thin-film” adders (SiCr or NiCr)
- Subject to process variations, gradient effects and local random variations
- Often temperature and voltage dependent
  - Ambient temperature
  - Local Heating
- Nonlinearities often a cause of distortion when used in circuits
- Trimming possible resistors
  - Laser,links,switches

Have already modeled resistance as an interconnect
Modeling is the same as for a resistor so will briefly review

Resistor Model

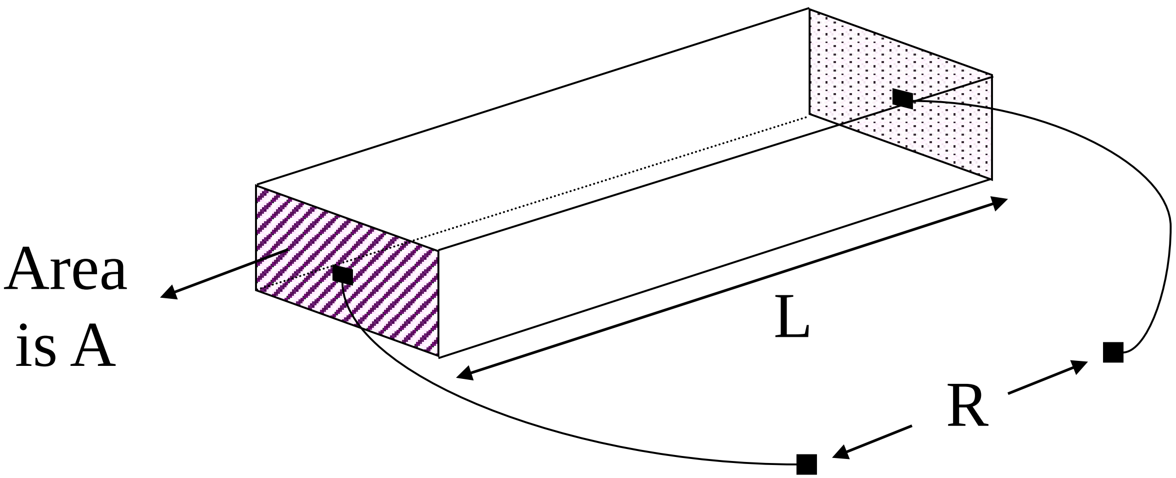


Model:

$$R = \frac{V}{I}$$

Resistivity

- Volumetric measure of conduction capability of a material

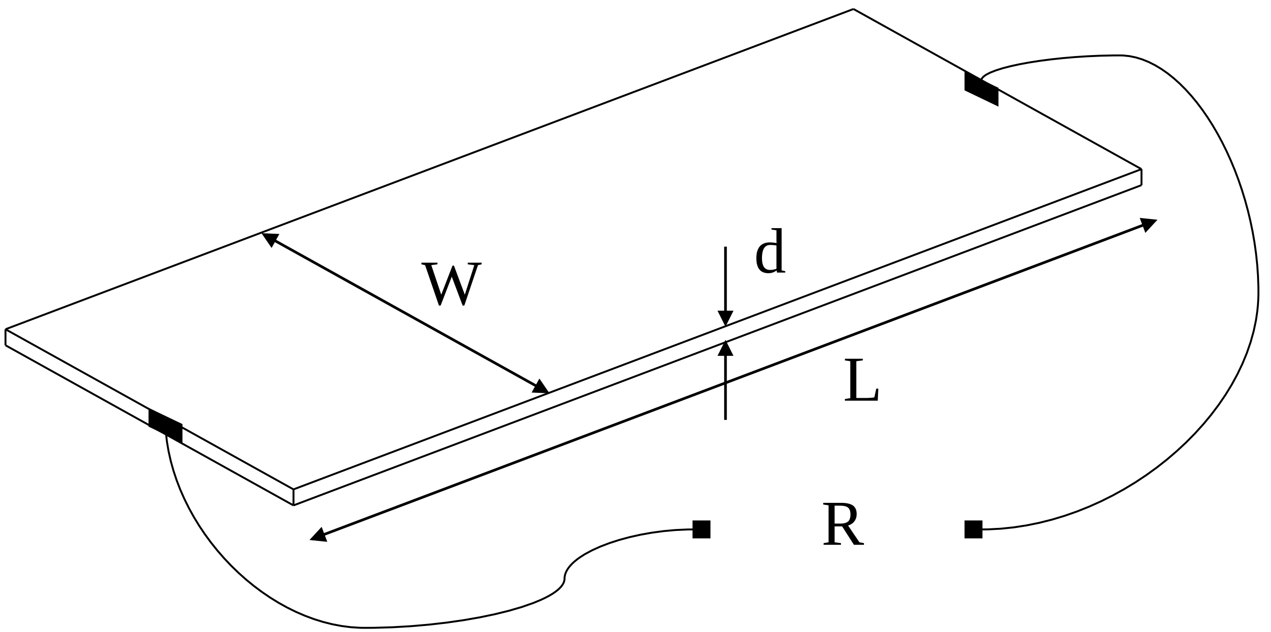


$$\rho = \frac{AR}{L}$$

units : ohm cm

for homogeneous material,
$\rho \perp A, R, L$

Sheet Resistance



$$R_{\square} = \frac{RW}{L}$$ (for d << w, d << L) units : ohms /□

for homogeneous materials, $R_{\square}$ is independent of W, L, R

Relationship between ρ and $R_\square$

$$R_\square = \frac{RW}{L}$$

$$\rho = \frac{AR}{L}$$

$$\Rightarrow \quad \rho = \frac{A}{W} R_\square$$

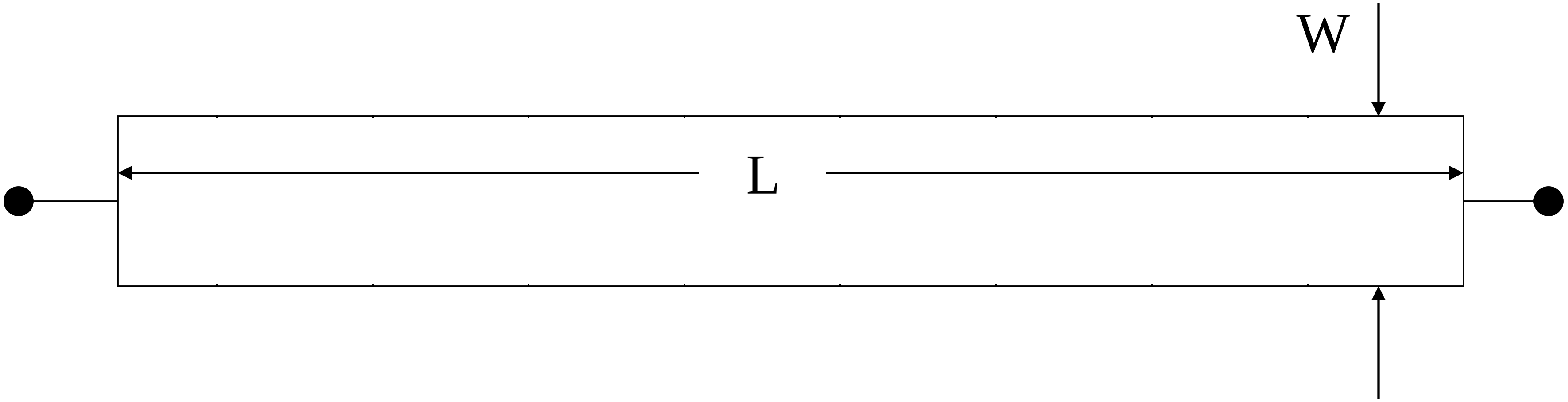
$$A = W \times d$$

$$\rho = \frac{A}{W} R_\square = \frac{\cancel{W}\, d}{\cancel{W}} R_\square = d \times R_\square$$

Number of squares, N_S, often used instead of L / W in determining resistance of film resistors

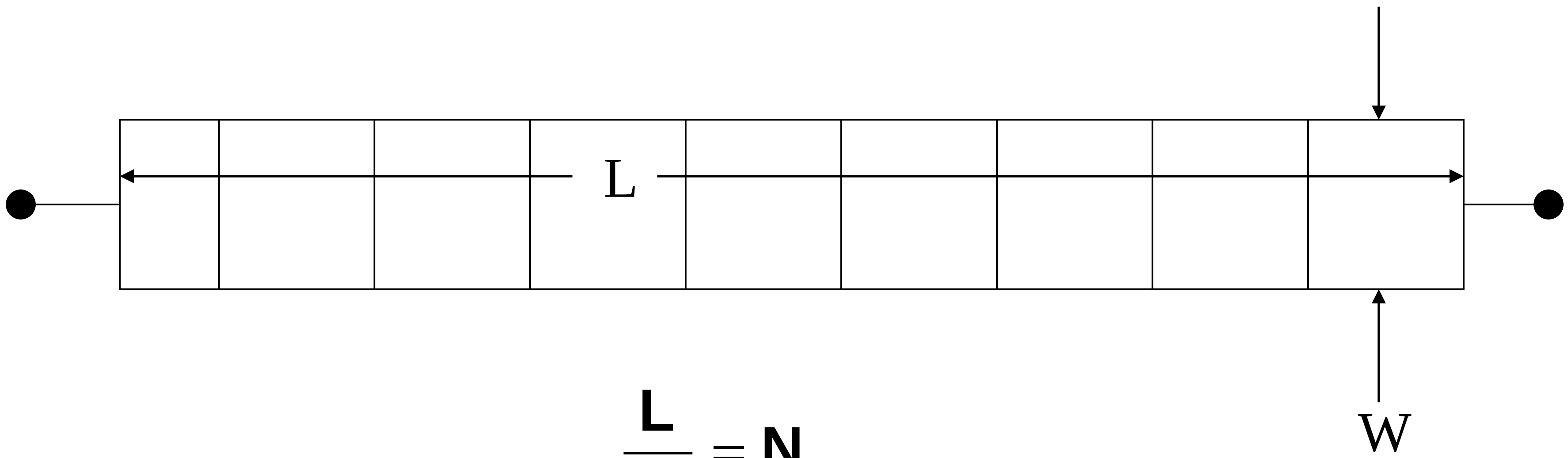
$$R = R_\square N_S$$

Example 1



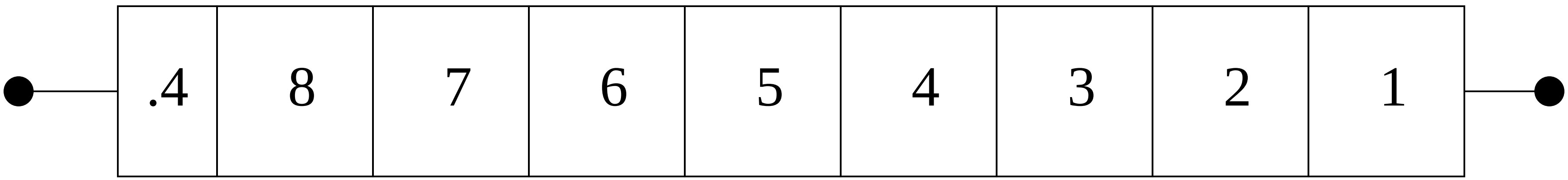
R = ?

Example 1



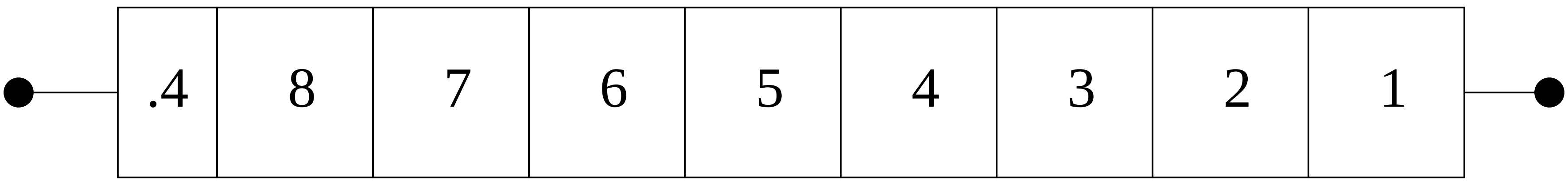
$$\frac{L}{W} = N_S$$

Example 1



R = ?

Example 1

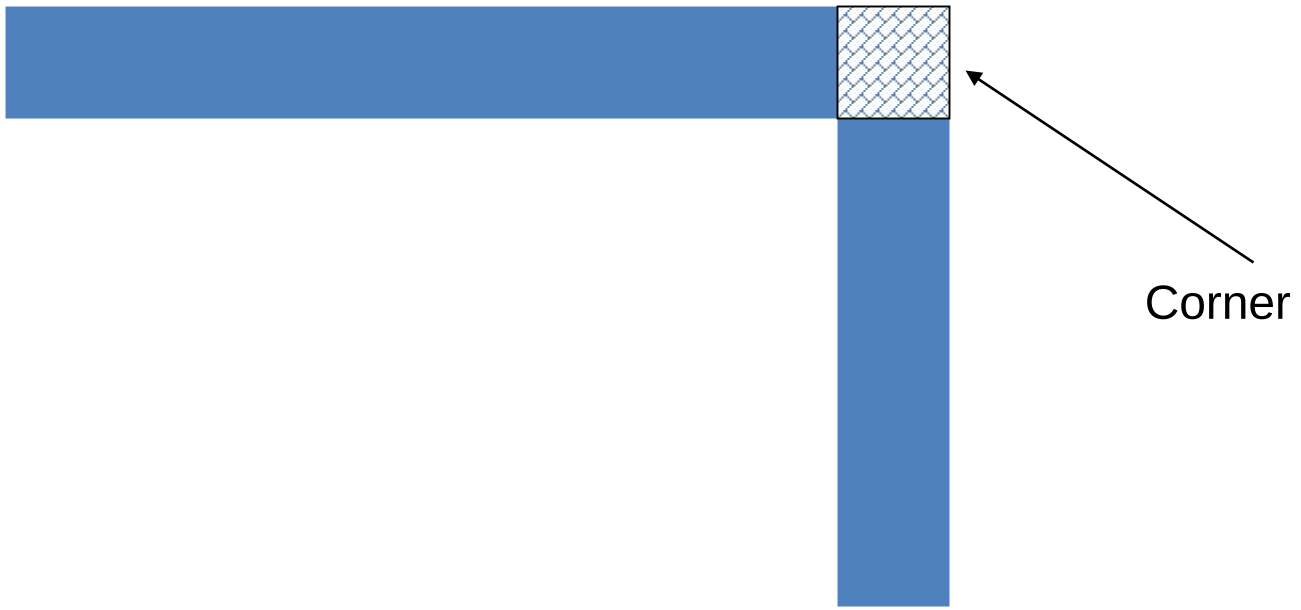


R = ?

$N_S = 8.4$

$\mathbf{R = R_{\square}\ (8.4)}$

Corners in Film Resistors

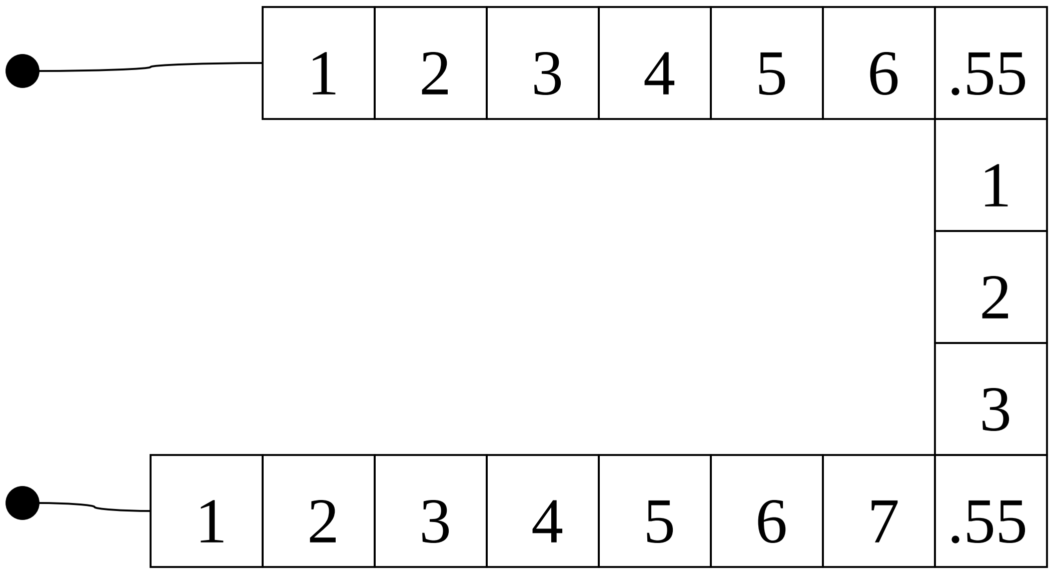


Rule of Thumb: .55 squares for each corner

Example 2

Determine R if $R_{\square} = 100\ \Omega / \square$

Example 2



$N_S = 17.1$

$R = (17.1)\ R_{s\square}$

$R = 1710\ \Omega$

Resistivity of Materials used in Semiconductor Processing

- Cu: 1.7*E*-6 Ω cm
- Al: 2.7*E*-4 Ωcm
- Gold: 2.4*E*-6 Ωcm
- Platinum: 3.0*E*-6 Ωcm
- Polysilicon: 1E-2 to 1E4 Ωcm*
- n-Si: typically .25 to 5 Ωcm* (but larger range possible)
- intrinsic Si: 2.5*E5* Ωcm
- SiO_2: *E*14 Ωcm

* But fixed in a given process

http://www.cleanroom.byu.edu/ResistivityCal.phtml

Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon

Dopant: (•) Arsenic ( ) Boron ( ) Phosphorus

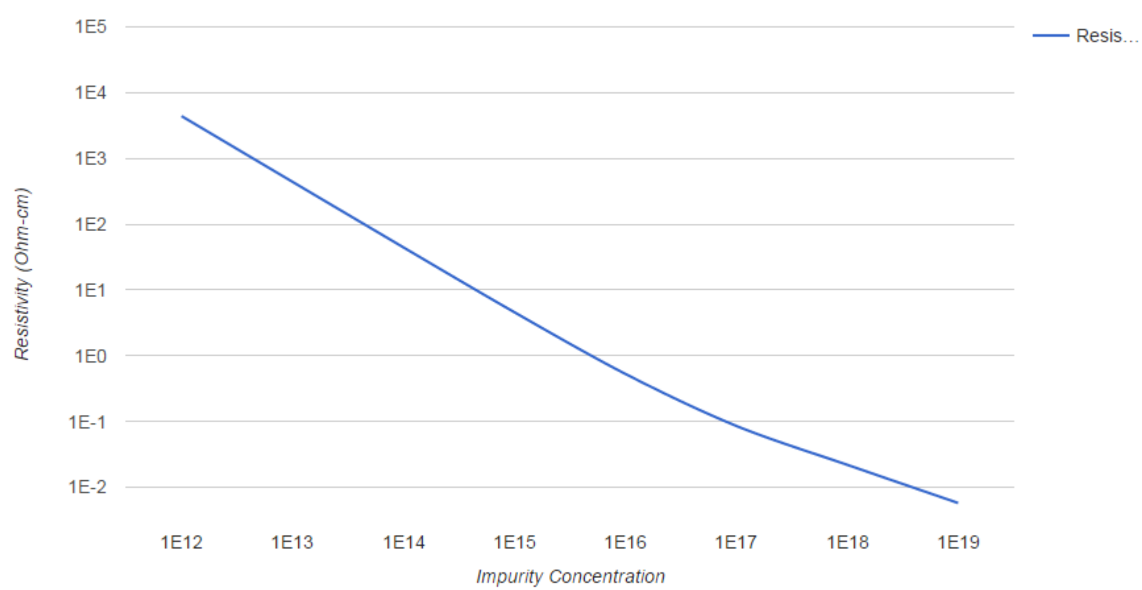
Impurity Concentration: 1e15 (cm^{-3})

Calculate | Export to CSV

Mobility: 1358.6941377290254 [cm^2/V-s]

Resistivity: 4.593746148183427 [Ω-cm]

Calculations are for a silicon substrate.



http://www.cleanroom.byu.edu/ResistivityCal.phtml

Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon

Dopant: ○ Arsenic ◉ Boron ○ Phosphorus

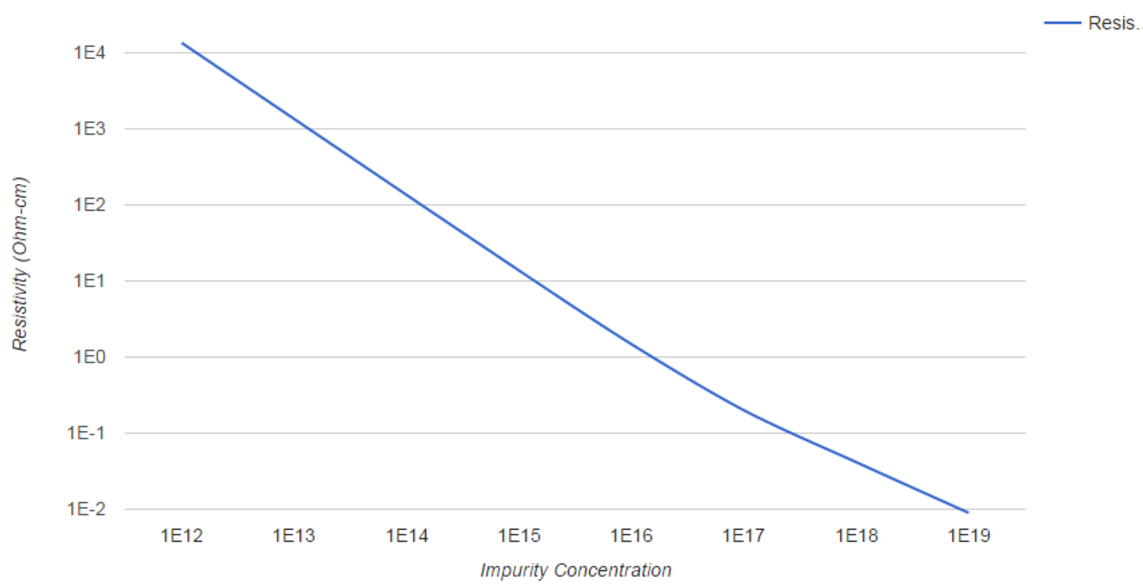
Impurity Concentration: 1e15 (cm^{-3})

Calculate | Export to CSV

Mobility: 461.9540345952693 [cm^2/V-s]

Resistivity: 13.511075765839905 [Ω-cm]

Calculations are for a silicon substrate.



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Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon

Dopant: ( ) Arsenic ( ) Boron (•) Phosphorus

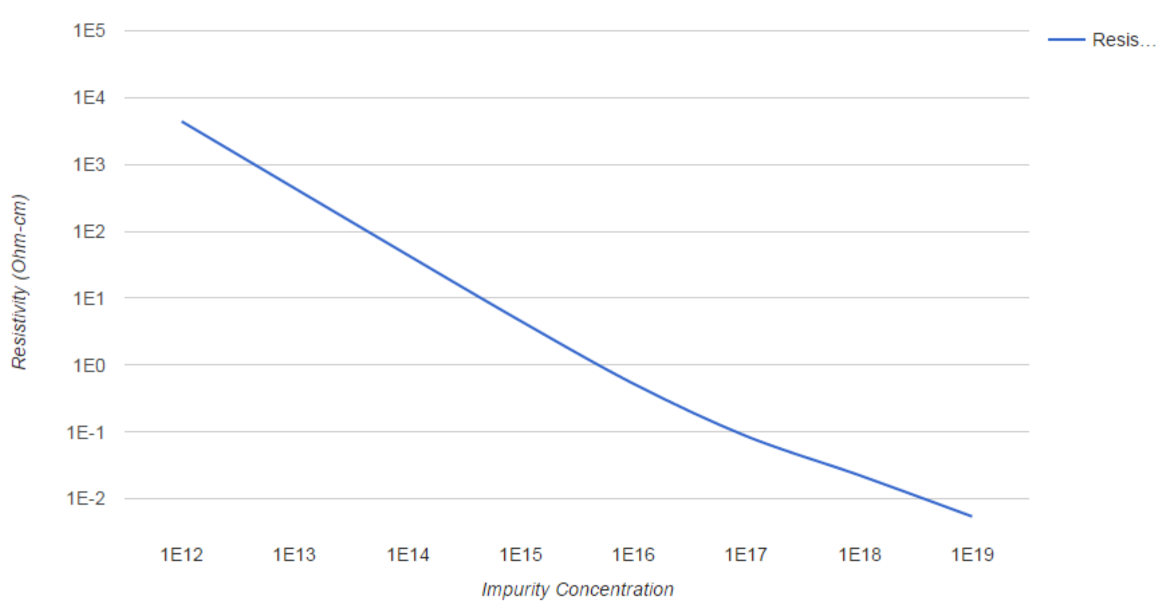
Impurity Concentration: 1e15 (cm^{-3})

Calculate | Export to CSV

Mobility: 1362.0563795030084 [cm^2/V-s]

Resistivity: 4.582406466925789 [Ω-cm]

Calculations are for a silicon substrate.



Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

$$\mathbf{TCR} = \left.\left(\frac{\mathbf{1}}{\mathbf{R}}\frac{\mathbf{dR}}{\mathbf{dT}}\right)\right|_{\text{op. temp}} \bullet \mathbf{10^6}\ \mathbf{ppm/^\circ C}$$

This diff eqn can easily be solved if TCR is a constant

$$R(T_2) = R(T_1)e^{\frac{T_2 - T_1}{10^6}\text{TCR}}$$

$$\boxed{R(T_2) \approx R(T_1)\left[1 + (T_2 - T_1)\frac{\text{TCR}}{10^6}\right]}$$

Identical Expressions for Capacitors

Voltage Coefficients

Used for indicating voltage sensitivity of resistors & capacitors

For a resistor:

$$\mathbf{VCR} = \left(\frac{1}{R}\frac{dR}{dV}\right)\Bigg|_{\text{ref voltage}} \bullet 10^6 \ \text{ppm/V}$$

This diff eqn can easily be solved if VCR is a constant

$$R(V_2) = R(V_1)\, e^{\frac{V_2 - V_1}{10^6} VCR}$$

$$\boxed{R(V_2) \approx R(V_1)\left[1 + (V_2 - V_1)\frac{VCR}{10^6}\right]}$$

Identical Expressions for Capacitors

Temperature and Voltage Coefficients

- Temperature and voltage coefficients often quite large for diffused resistors
- Temperature and voltage coefficients often quite small for poly and metal resistors

Type of layer	Sheet Resistance $\Omega/\square$	Accuracy %	Temperature Coefficient ppm/°C	Voltage Coefficient ppm/V
n + diff	30 - 50	20 - 40	200 - 1K	50 - 300
p + diff	50 -150	20 - 40	200 - 1K	50 - 300
n - well	2K - 4K	15 - 30	5K	10K
p - well	3K - 6K	15 - 30	5K	10K
pinched n - well	6K - 10K	25 - 40	10K	20K
pinched p - well	9K - 13K	25 - 40	10K	20K
first poly	20 - 40	25 - 40	500 - 1500	20 - 200
second poly	15 - 40	25 - 40	500 - 1500	20 - 200

From:F. Maloberti : Design of CMOS Analog Integrated Circuits - “Resistors, Capacitors, Switches”

Example: Determine the percent change in resistance of a 5K Polysilicon resistor as the temperature increases from 30^{o}C to 60^{o}C if the TCR is constant and equal to 1500 ppm/^{o}C

$$R(T_2) \cong R(T_1)\left[1+(T_2-T_1)\frac{TCR}{10^6}\right]$$

$$R(T_2) \cong R(T_1)\left[1+\left(30^oC\right)\frac{1500}{10^6}\right]$$

$$R(T_2) \cong R(T_1)[1+.045]$$

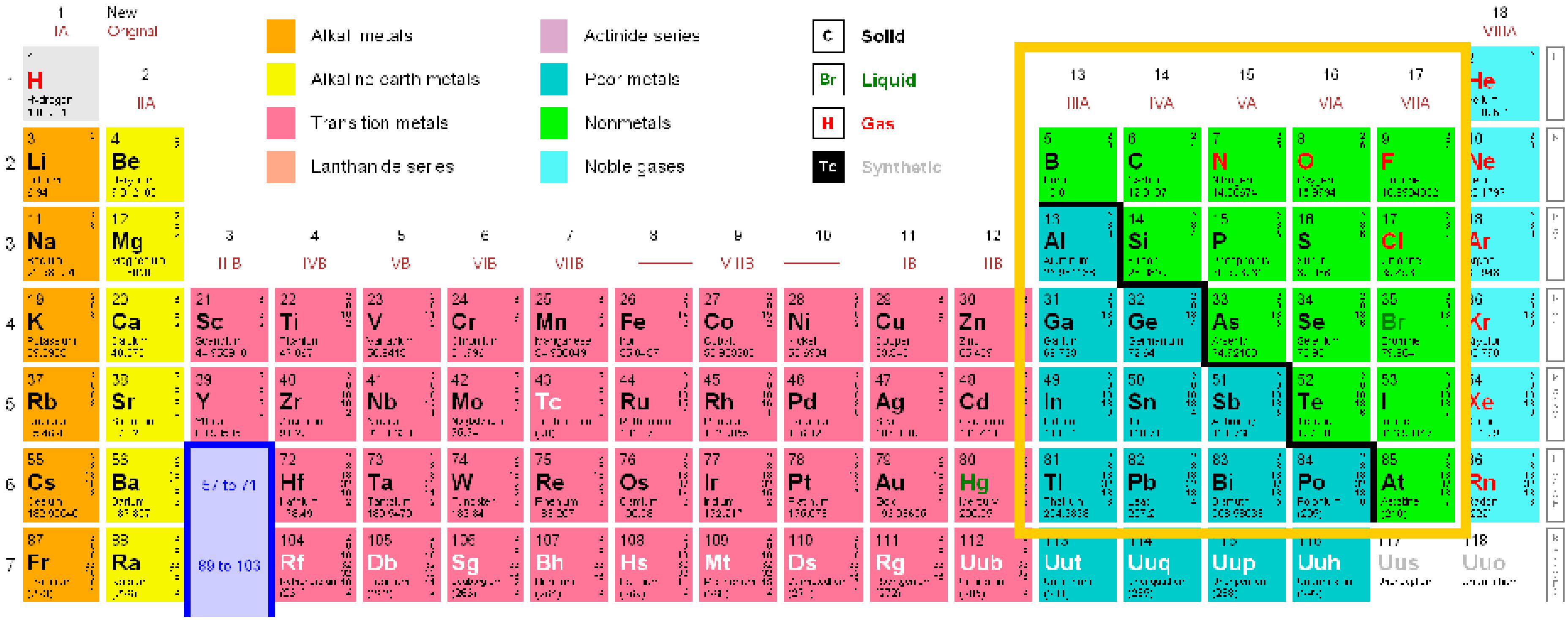
$$R(T_2) \cong R(T_1)[1.045]$$

Thus the resistor increases by 4.5%

Basic Devices and Device Models

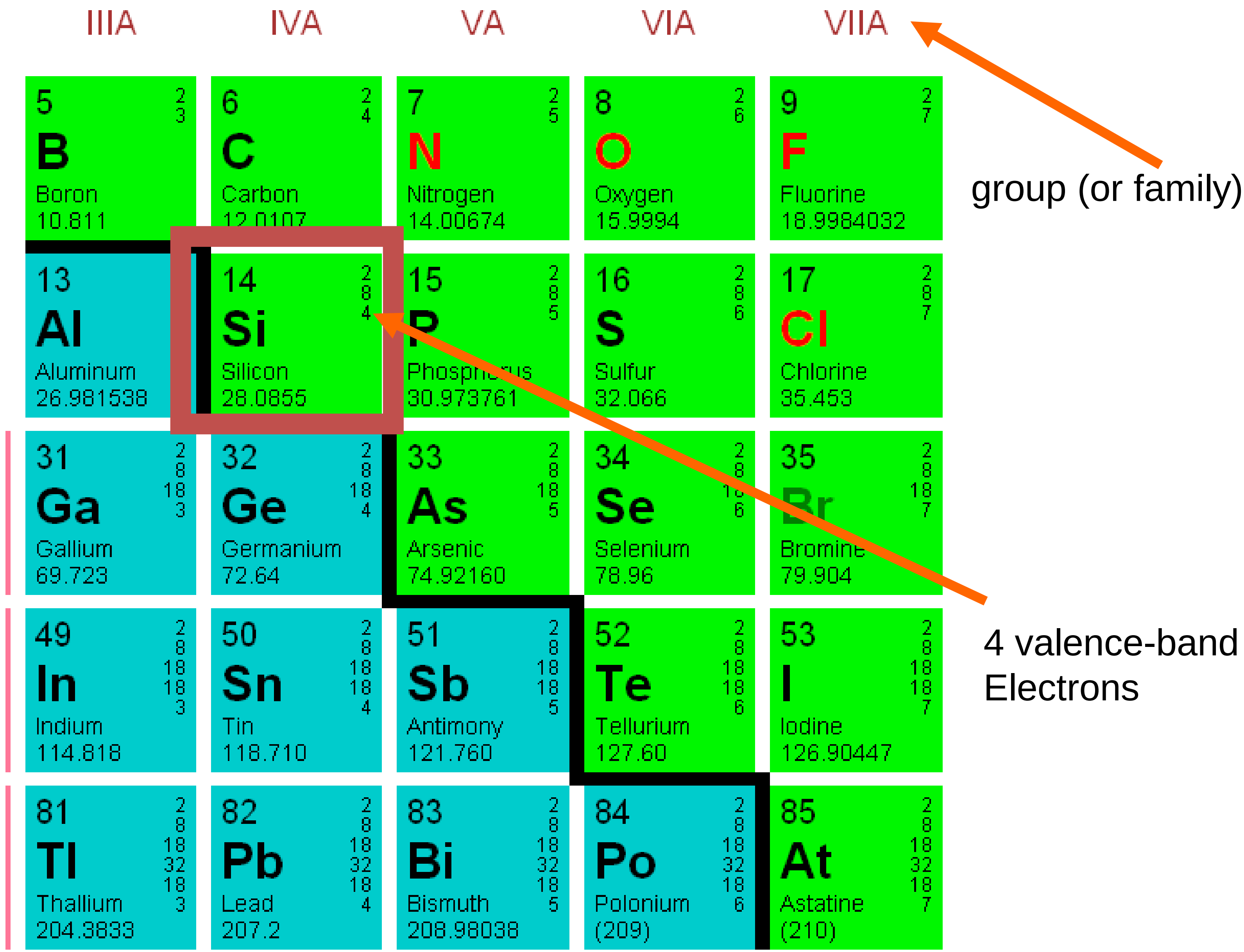
- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

Periodic Table of the Elements

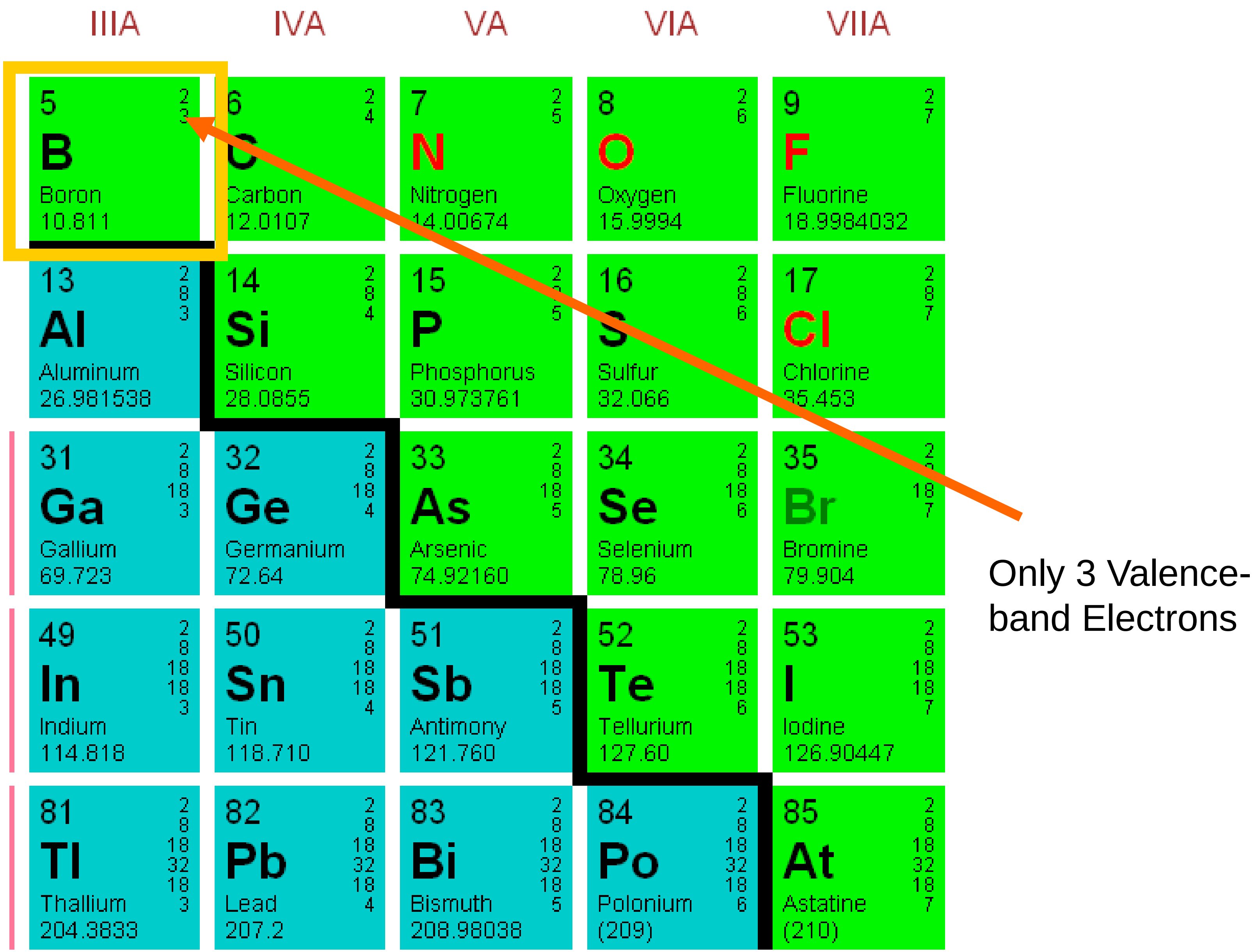


http://www.dayah.com/periodic/Images/periodic%20table.png

IIIA	IVA	VA	VIA	VIIA
5 **B** Boron 10.811 2 3	6 **C** Carbon 12.0107 2 4	7 **N** Nitrogen 14.00674 2 5	8 **O** Oxygen 15.9994 2 6	9 **F** Fluorine 18.9984032 2 7
13 **Al** Aluminum 26.981538 2 8 3	14 **Si** Silicon 28.0855 2 8 4	15 **P** Phosphorus 30.973761 2 8 5	16 **S** Sulfur 32.066 2 8 6	17 **Cl** Chlorine 35.453 2 8 7
31 **Ga** Gallium 69.723 2 8 18 3	32 **Ge** Germanium 72.64 2 8 18 4	33 **As** Arsenic 74.92160 2 8 18 5	34 **Se** Selenium 78.96 2 8 18 6	35 **Br** Bromine 79.904 2 8 18 7
49 **In** Indium 114.818 2 8 18 18 3	50 **Sn** Tin 118.710 2 8 18 18 4	51 **Sb** Antimony 121.760 2 8 18 18 5	52 **Te** Tellurium 127.60 2 8 18 18 6	53 **I** Iodine 126.90447 2 8 18 18 7
81 **Tl** Thallium 204.3833 2 8 18 32 18 3	82 **Pb** Lead 207.2 2 8 18 32 18 4	83 **Bi** Bismuth 208.98038 2 8 18 32 18 5	84 **Po** Polonium (209) 2 8 18 32 18 6	85 **At** Astatine (210) 2 8 18 32 18 7



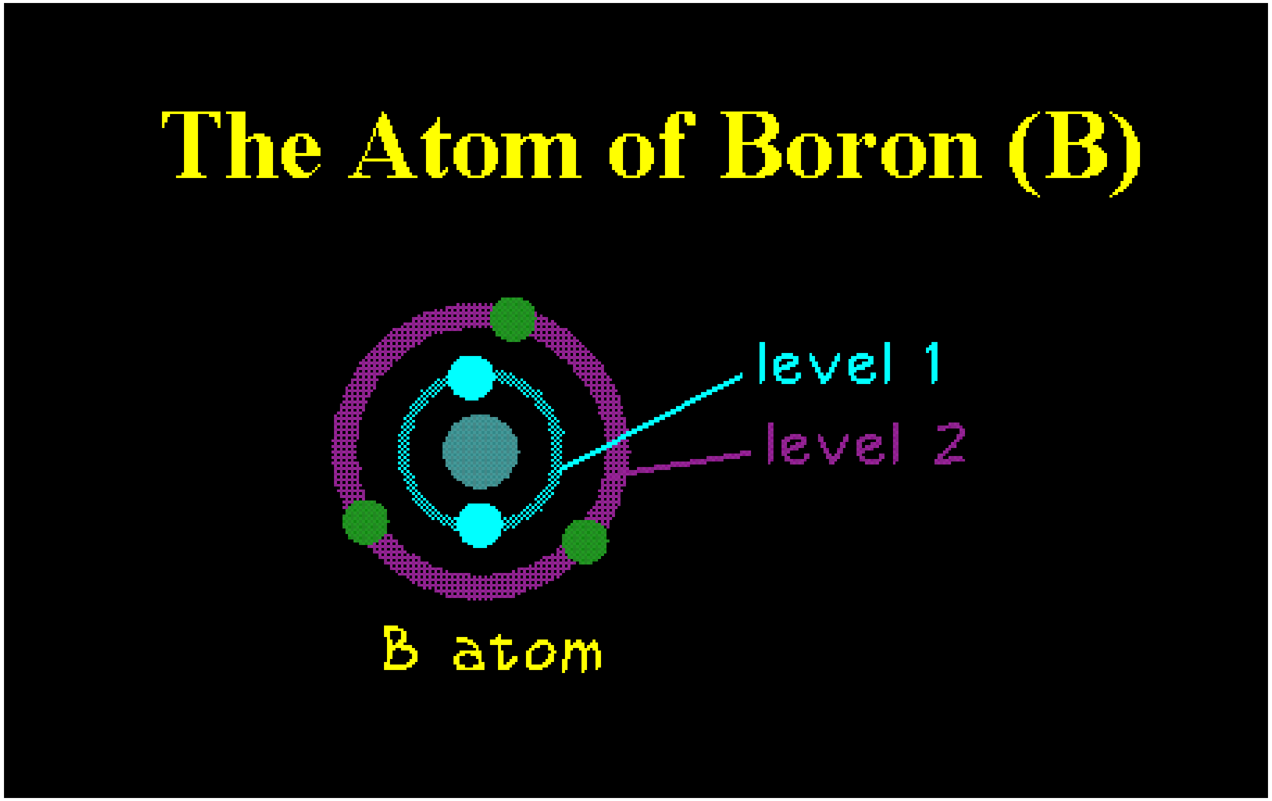
All elements in group IV have 4 valence-band electrons



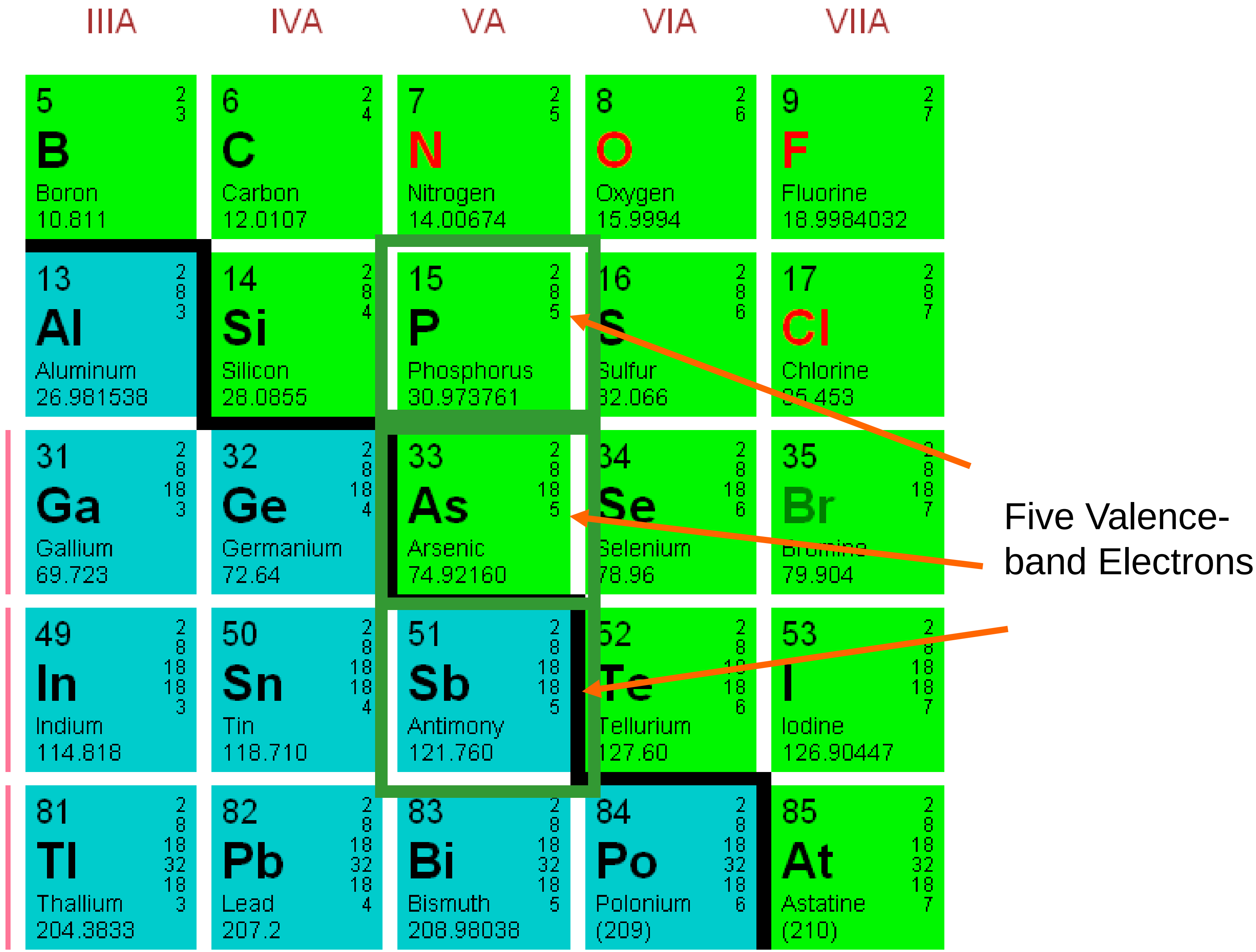
Serves as an "acceptor" of electrons

Acts as a p-type impurity when used as a silicon dopant

All elements in group III have 3 valence-band electrons



http://www.oftc.usyd.edu.au/edweb/devices/semicdev/doping4.html

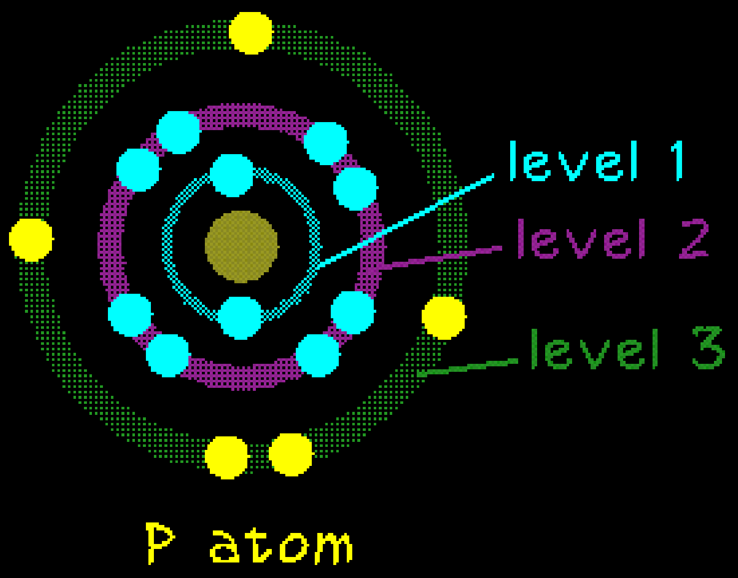


Serves as an “donor ” of electrons

Acts as an n-type impurity when used as a silicon dopant

All elements in group V have 5 valence-band electrons

The Atom of Phosphorus (P)



15 2 8 5

P

Phosphorus

30.973762

$[Ne]3s^2\ 3p^3$

5 2 3

B

Boron

10.811

$1s^2\ 2s^2\ 2p^1$

14 2 8 4

Si

Silicon

28.0855

$[Ne]3s^2\ 3p^2$

33 2 8 18 5

As

Arsenic

74.92160

$[Ar]3d^{10}\ 4s^2\ 4p^3$

51 2 8 18 18 5

Sb

Antimony

121.760

$[Kr]4d^{10}\ 5s^2\ 5p^3$

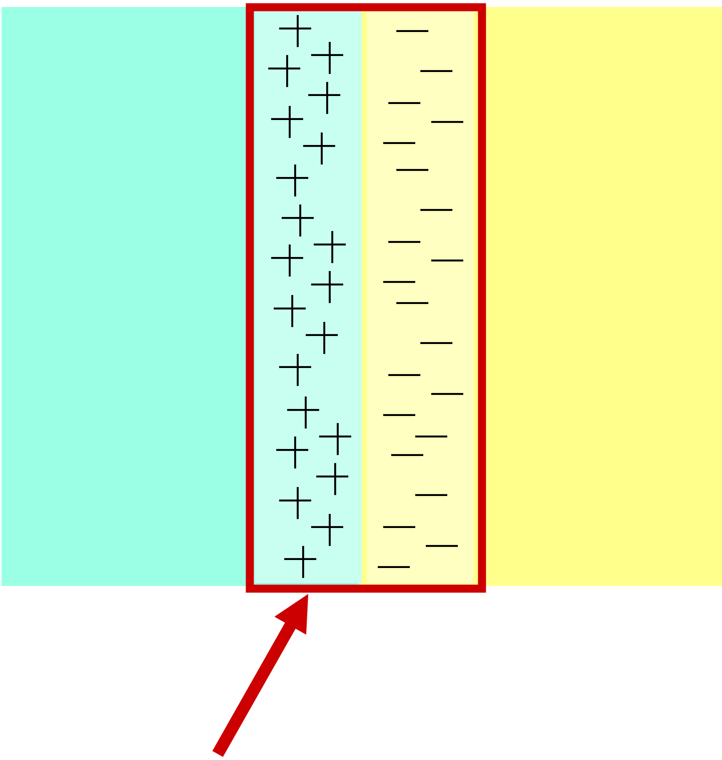
Silicon Dopants in Semiconductor Processes

B (Boron) widely used a dopant for creating p-type regions

P (Phosphorus) widely used a dopant for creating n-type regions
(bulk doping, diffuses fast)

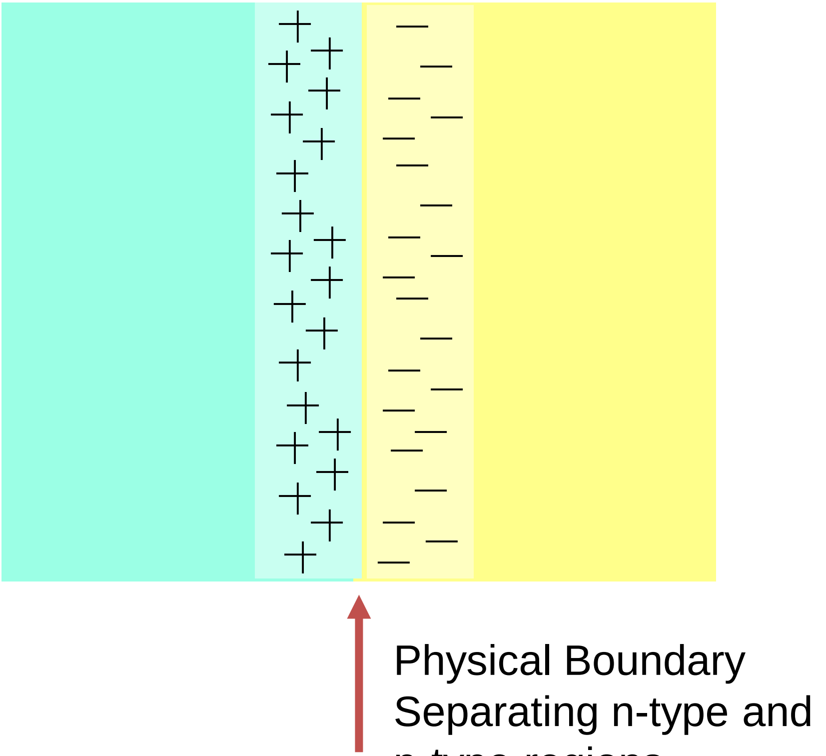
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



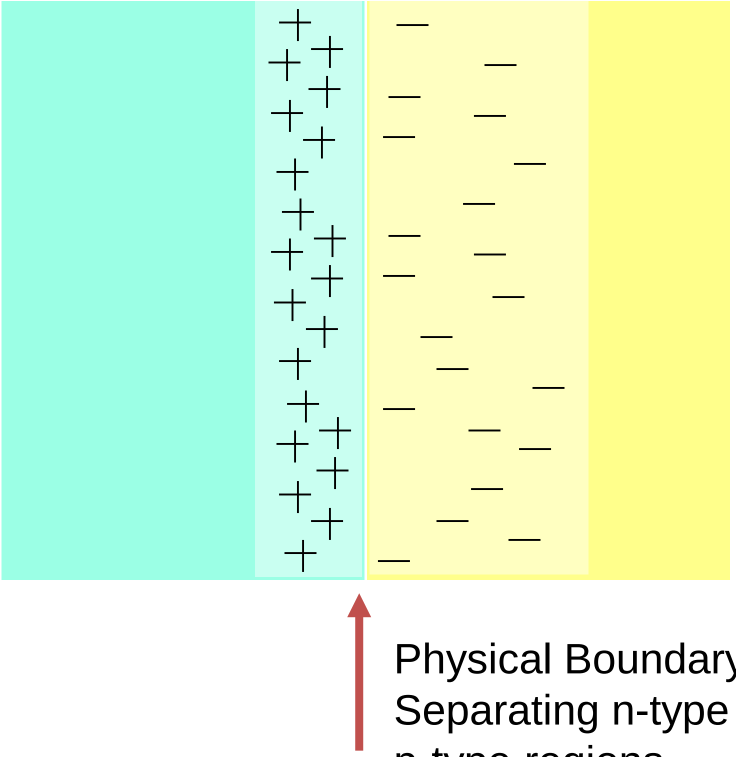
Depletion region created that is ionized but void of carriers

pn Junctions



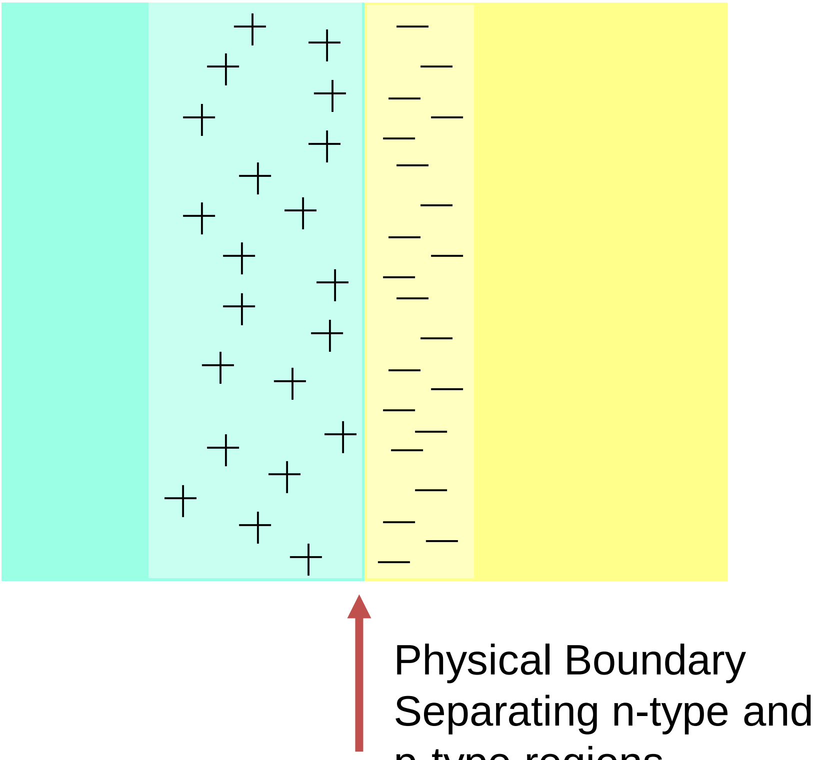
If doping levels identical, depletion region extends equally into n-type and p-type regions

pn Junctions



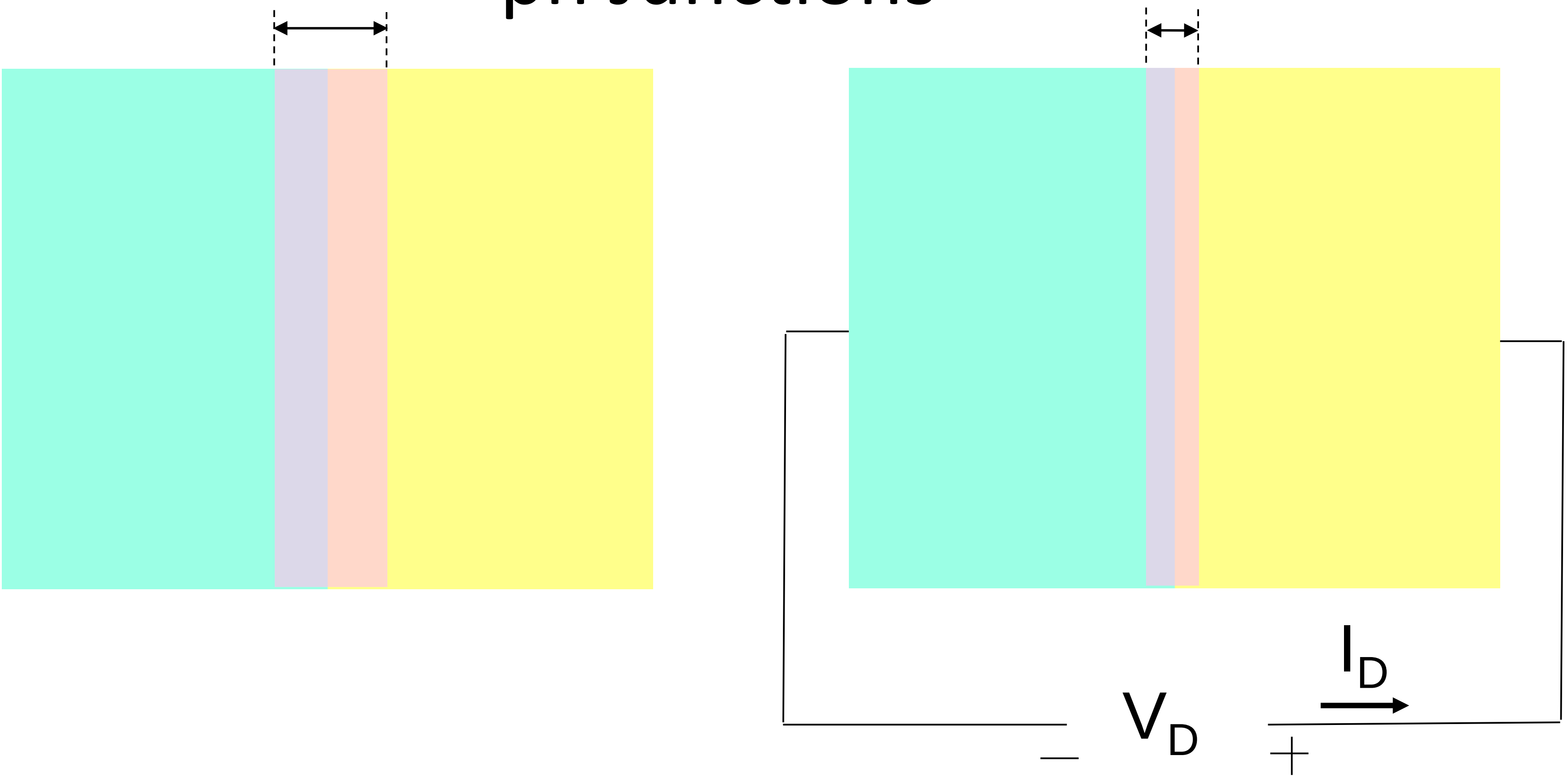
Extends farther into p-type region if p-doping lower than n-doping

pn Junctions



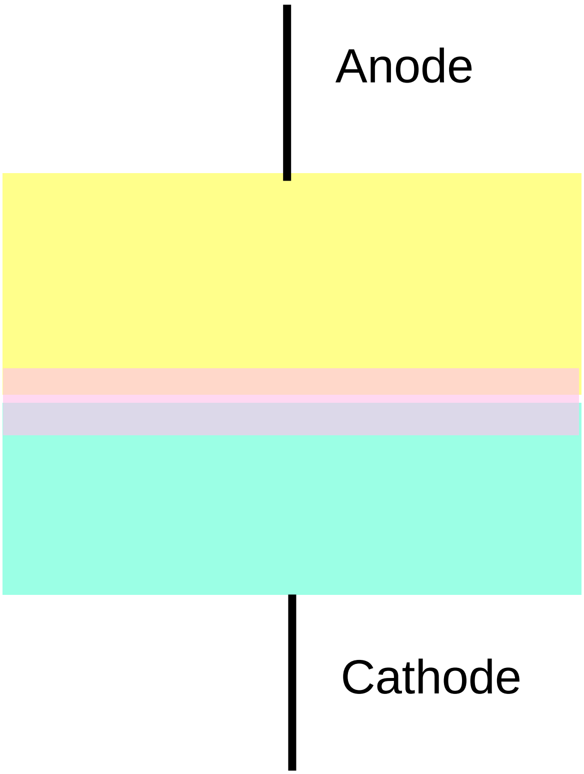
Extends farther into n-type region if n-doping lower than p-doping

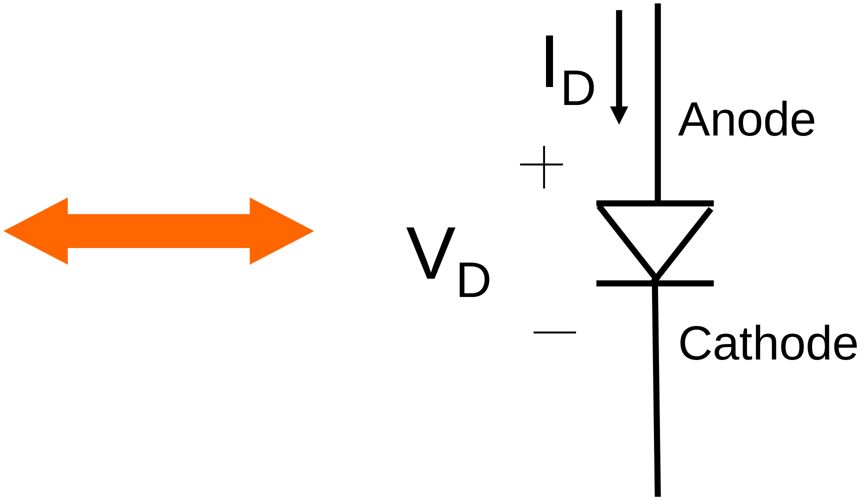
pn Junctions



- Positive voltages across the p to n junction are referred to forward bias
- Negative voltages across the p to n junction are referred to reverse bias
- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases
- Current is very small under revere bias

pn Junctions

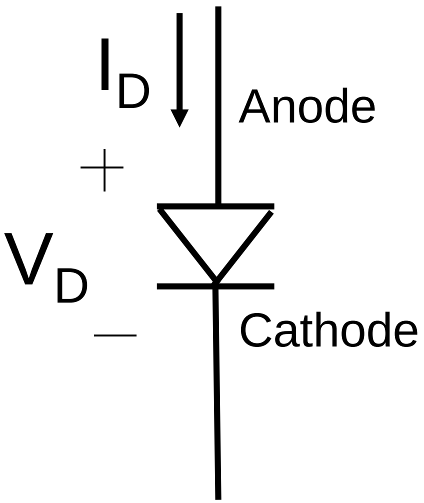




Circuit Symbol

pn Junctions

- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases



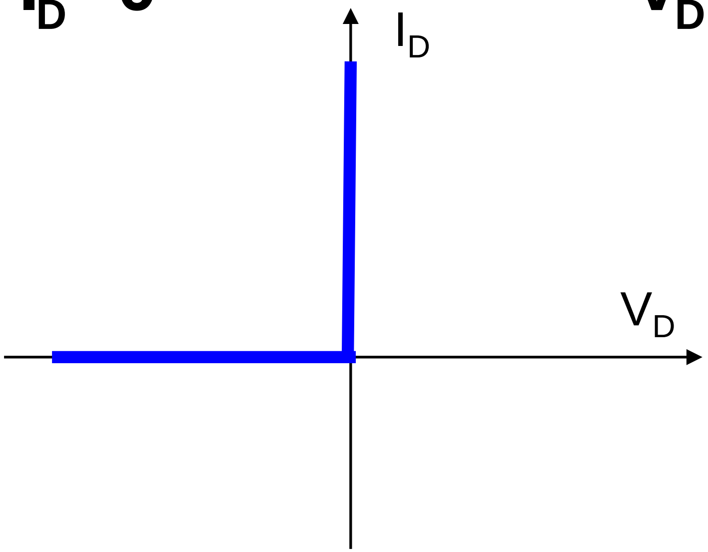
Simple Diode Model:

$V_D = 0$

$I_D = 0$

$I_D > 0$

$V_D < 0$



Simple model often referred to as the “Ideal” diode model

End of Lecture 12