EE 330
Lecture 13

Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFETs
- BJTs

Fall 2023 Exam Schedule

Exam 1	Friday Sept 22	
Exam 2	Friday Oct 20	
Exam 3	Friday Nov. 17	
Final	Monday Dec 11	12:00 – 2:00 p.m.

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 (Bipolar Junction Transistor)
  - JFET (Junction Field Effect Transistor)
  - 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: HBT (Heterojunction Bipolar Transistor)
- 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 (decent in some processes)
    - npn
    - pnp
  - JFET (in some processes)
    - n-channel
    - p-channel

Primary Consideration in This Course

- Standard Bipolar Process
  - BJT
    - npn
    - pnp
  - JFET
    - n-channel
    - p-channel
  - Diodes
  - Resistors
  - Capacitors

Some Consideration in This Course

(devices are available in some CMOS processes)

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

Some Consideration in This Course

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
- JFET
- MESFET

Basic Devices and Device Models

➡ Resistor
- Diode
- Capacitor
- MOSFET
- BJT

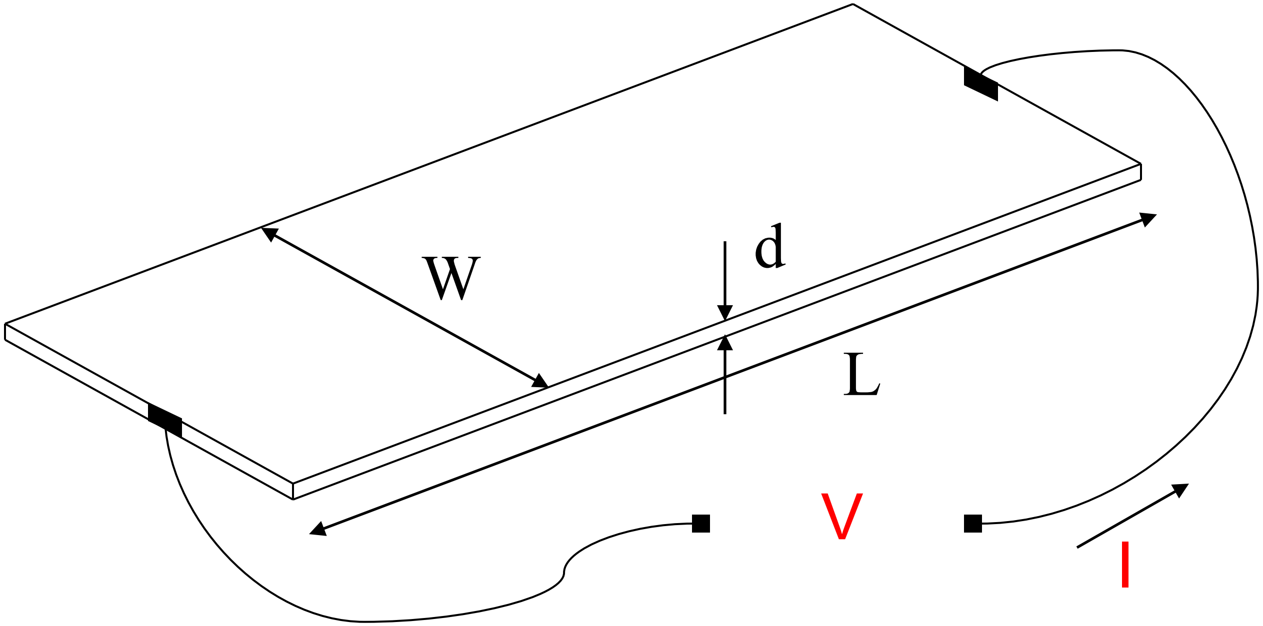
Resistors were discussed when considering interconnects so will only be briefly reviewed here

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

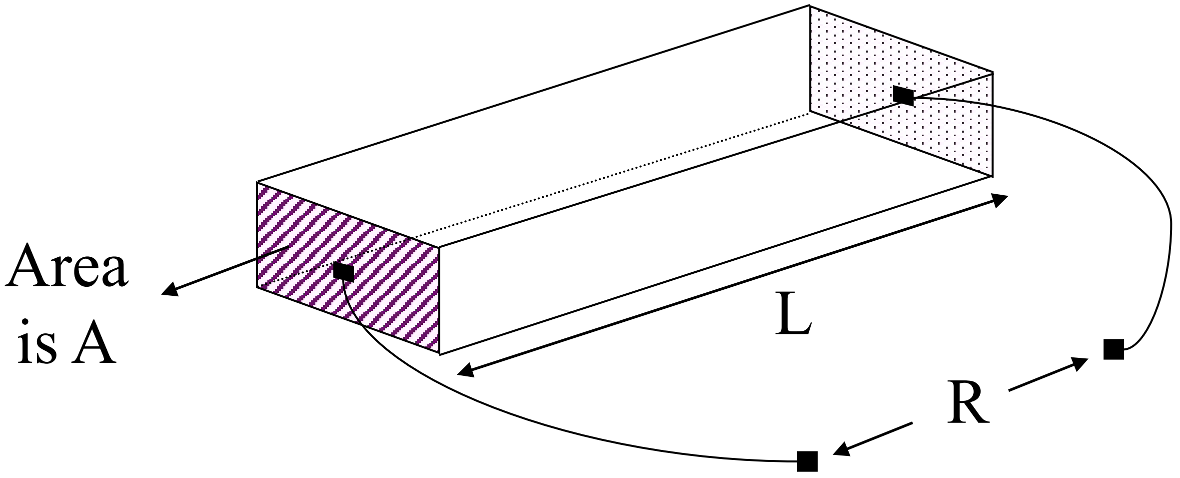


Model:

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

Resistivity

- Volumetric measure of conduction capability of a material

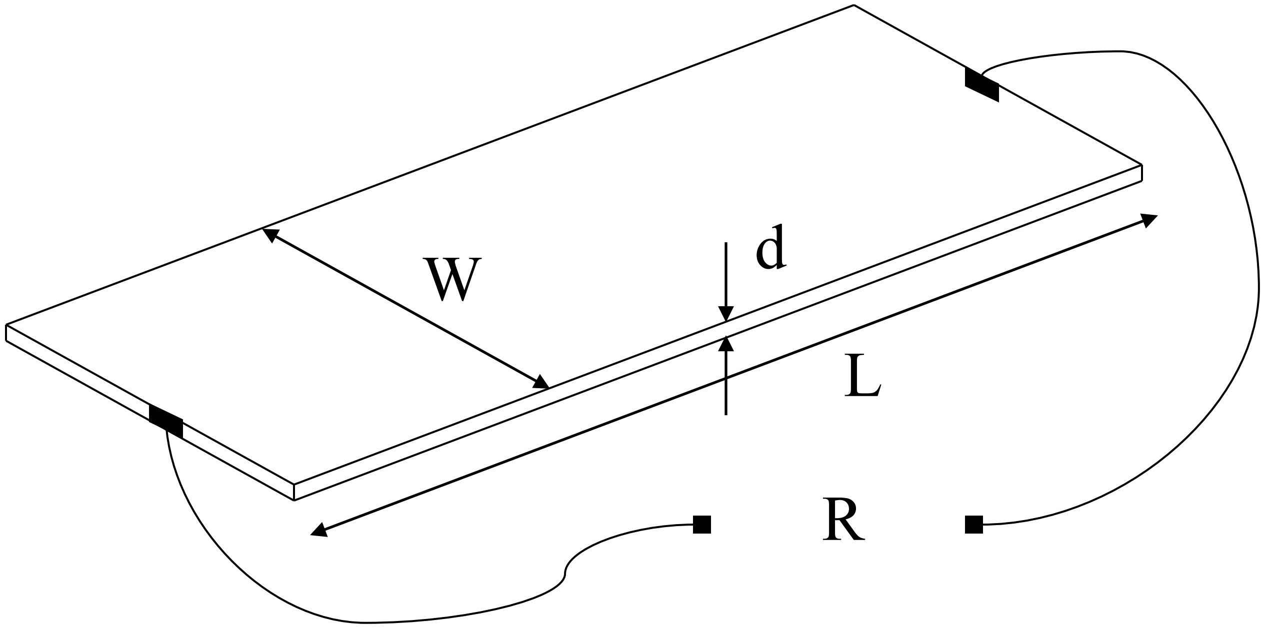


$$\rho = \frac{AR}{L}$$

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

units : ohm cm

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 $R_{\square}$

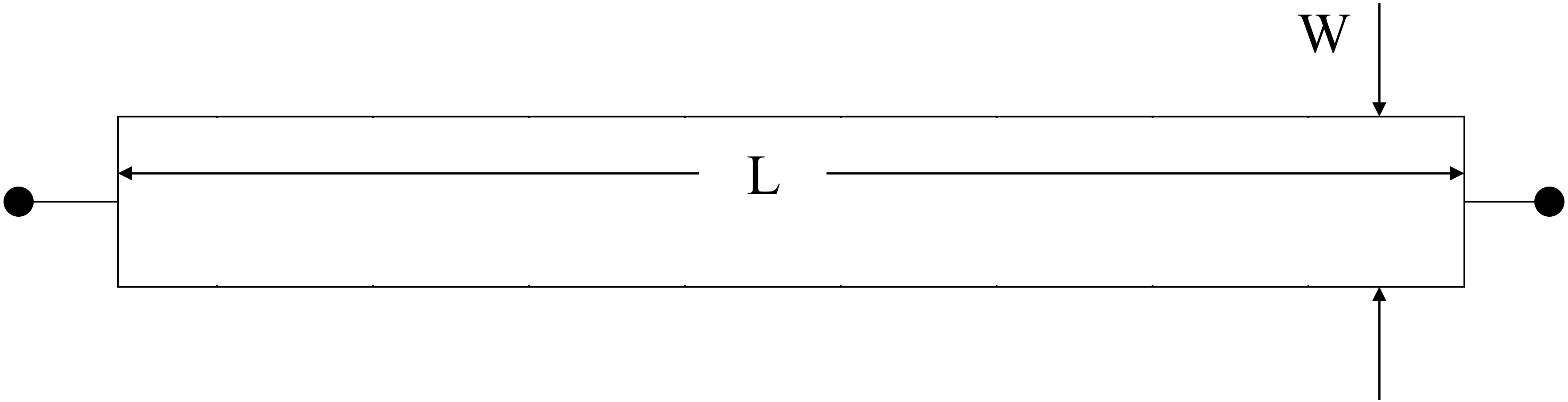
$$\left.\begin{array}{l} R_{\square} = \dfrac{RW}{L} \\[2ex] \rho = \dfrac{AR}{L} \end{array}\right\} \longrightarrow \begin{array}{l} \rho = \dfrac{A}{W} R_{\square} \\[2ex] A = W \times d \end{array}$$

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

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

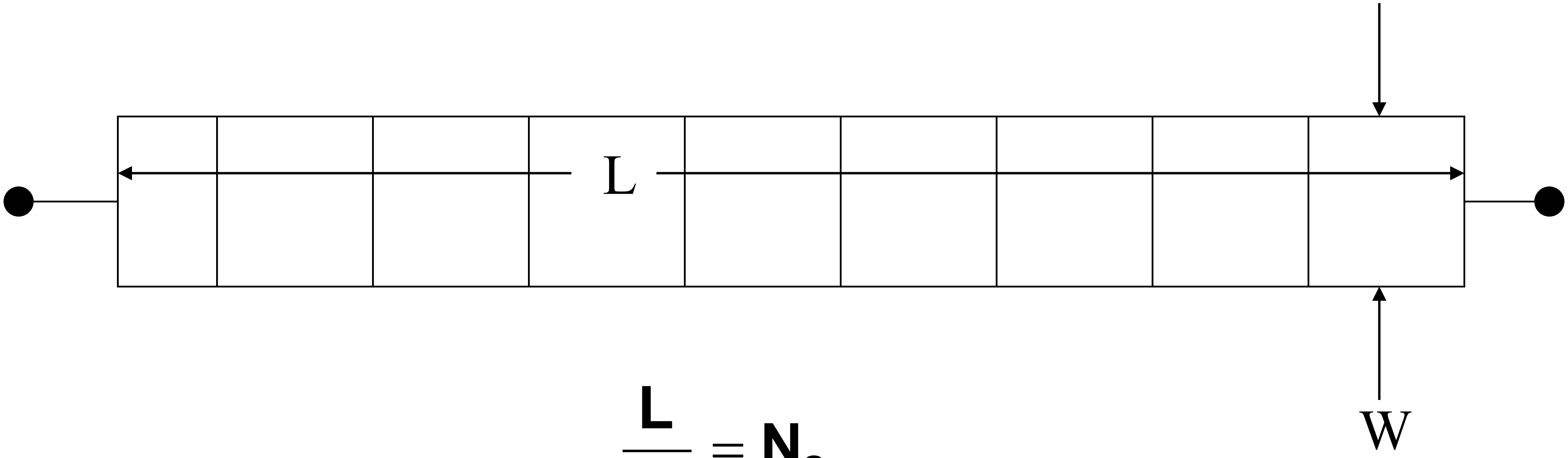
$$R = R_{\square} N_S$$

Example 1



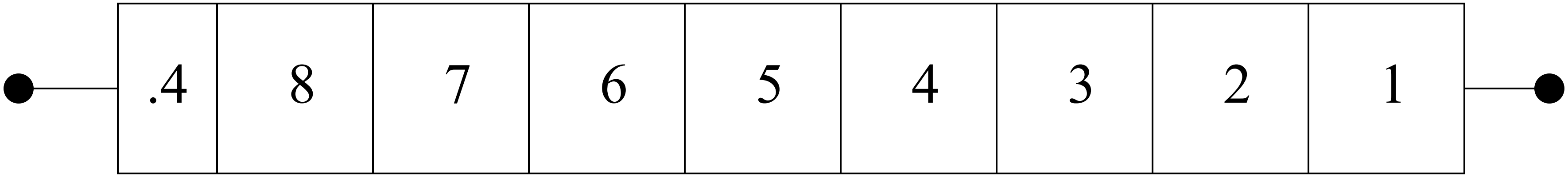
R = ?

Example 1



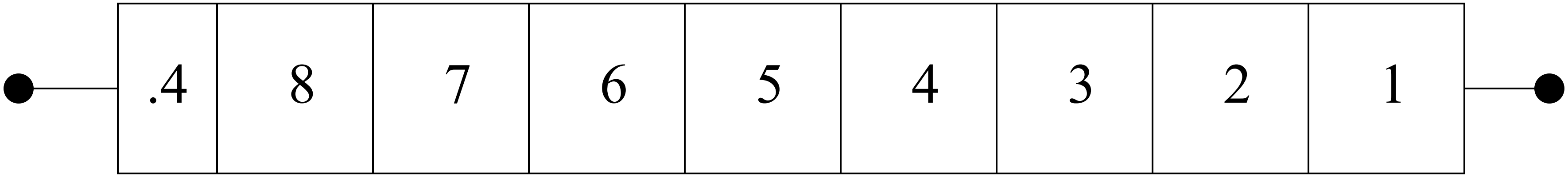
$$\frac{\mathbf{L}}{\mathbf{W}} = \mathbf{N_s}$$

Example 1



R = ?

Example 1

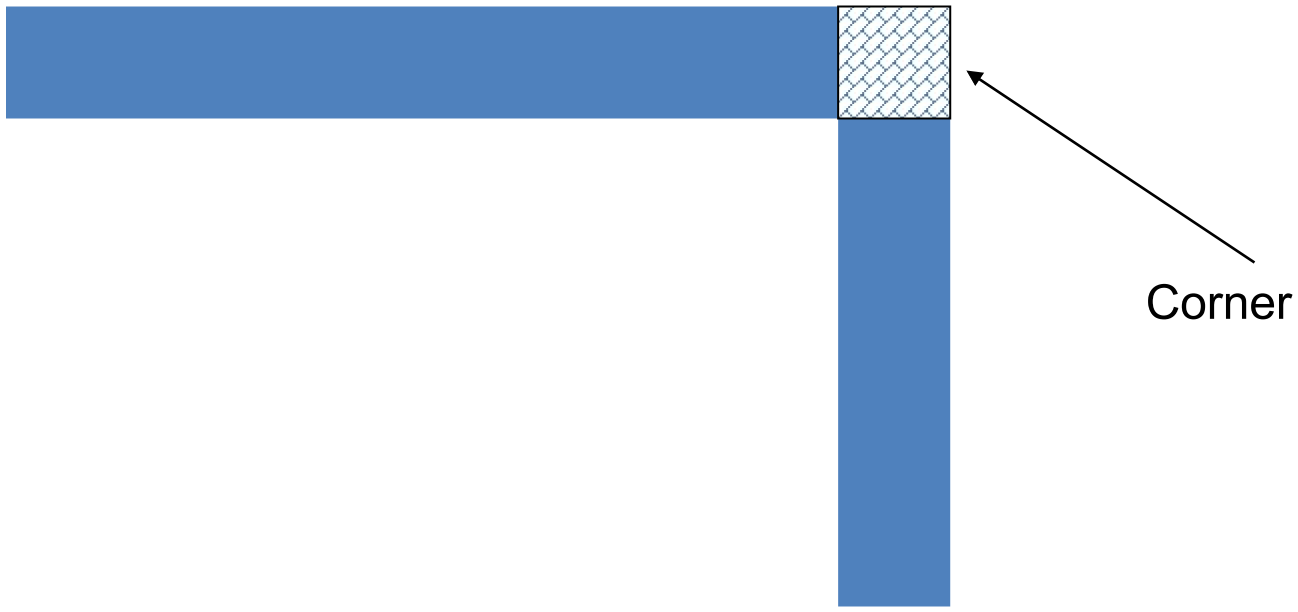


$R = ?$

$N_S = 8.4$

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

Corners in Film Resistors

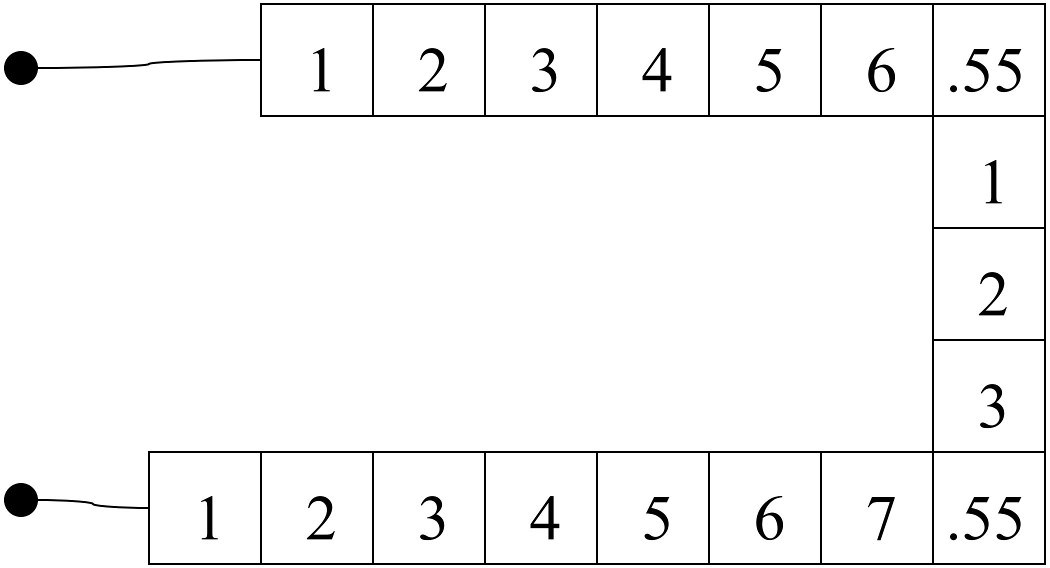


Rule of Thumb: .55 squares for each corner

Example 2

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

Example 2



$N_S=17.1$

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

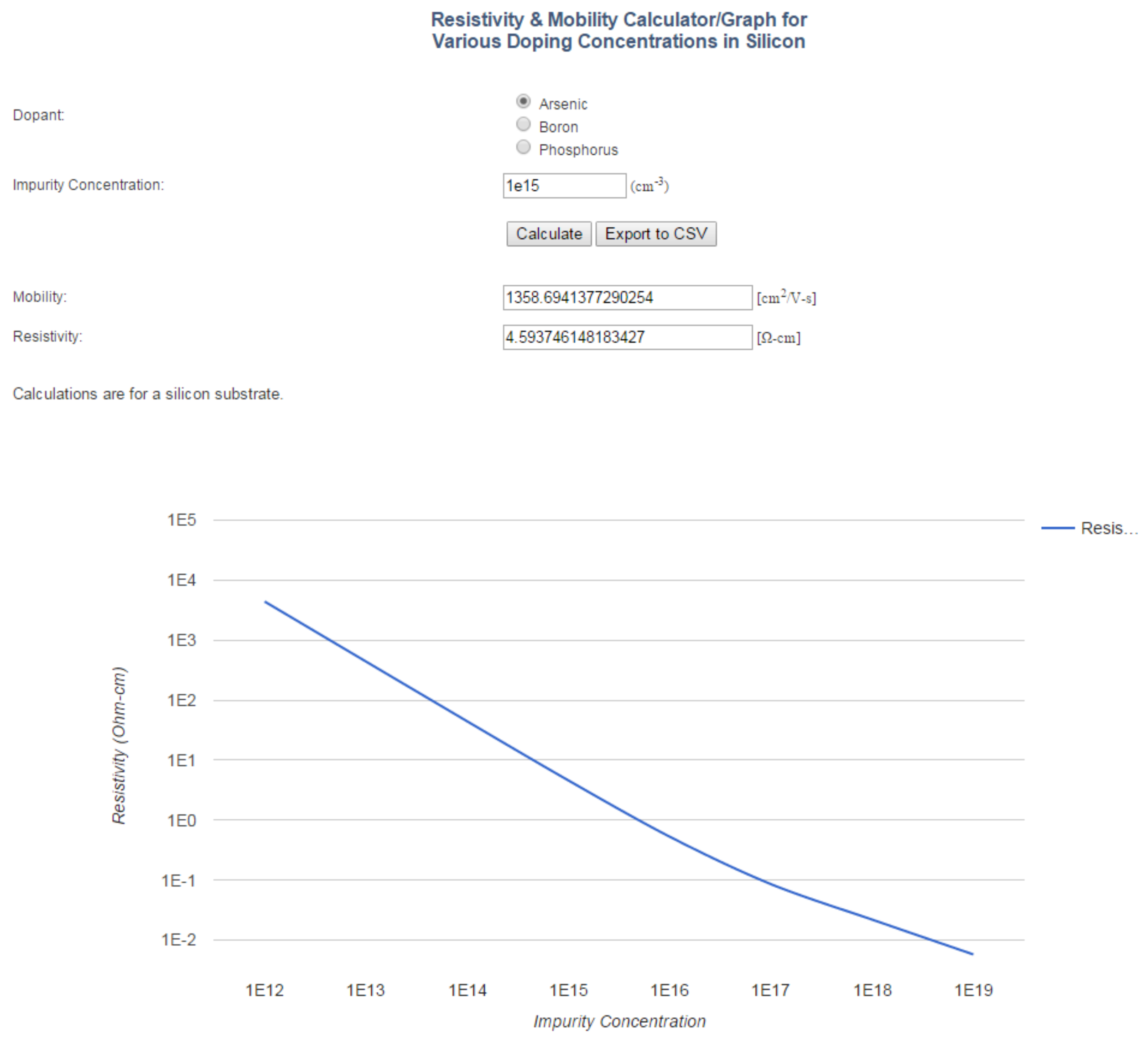
$R = 1710\ \Omega$

Resistivity of Materials used in Semiconductor Processing

- Cu: 1.7*E*-6 Ωcm
- Al: 2.7*E*-6 Ωcm
- Gold: 2.4*E*-6 Ωcm
- Platinum: 1.1*E*-5 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})

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})

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

Resistivity: 13.511075765839905 [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})

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:

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

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

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

If x is small, $e^{x} \cong 1 + x$

It follows that If TCR*(T_2-T_1) is small,

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

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

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

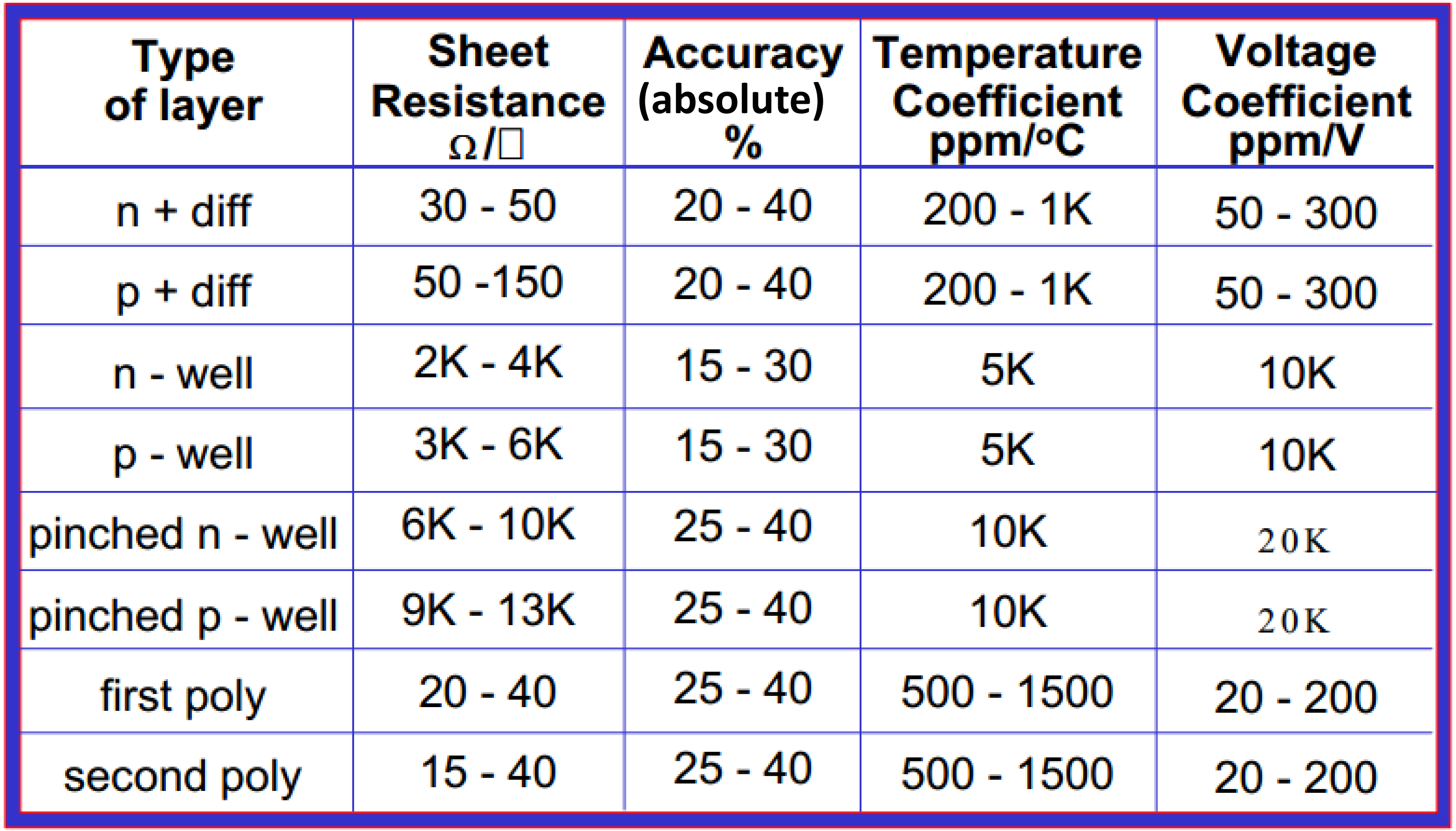
It follows that If VCR*(V_2-V_1) is small,

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

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 film (e.g. SiCr) resistors



Type of layer	Sheet Resistance Ω/□	Accuracy (absolute) %	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

(relative accuracy much better and can be controlled by designer)

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

MOS Passive RC Component Typical Performance Summary

Component Type	Range of Values	Absolute Accuracy	Relative Accuracy	Temperature Coefficient	Voltage Coefficient
MOSFET gate Cap.	6-7 fF/μm^2	10%	0.1%	20ppm/°C	±20ppm/V
Poly-Poly Capacitor	0.3-0.4 fF/μm^2	20%	0.1%	25ppm/°C	±50ppm/V
Metal-Metal Capacitor	0.1-1fF/μm^2	10%	0.6%	-40ppm/°C	±1ppm/V
Diffused Resistor	10-100 Ω/sq.	35%	2%	1500ppm/°C	200ppm/V
Ion Implanted Resistor	0.5-2 kΩ/sq.	15%	2%	400ppm/°C	800ppm/V
Poly Resistor	30-200 Ω/sq.	30%	2%	1500ppm/°C	100ppm/V
n-well Resistor	1-10 kΩ/sq.	40%	5%	8000ppm/°C	10kppm/V
Top Metal Resistor	30 mΩ/sq.	15%	2%	4000ppm/°C	-
Lower Metal Resistor	70 mΩ/sq.	28%	3%	4000ppm/°C	-

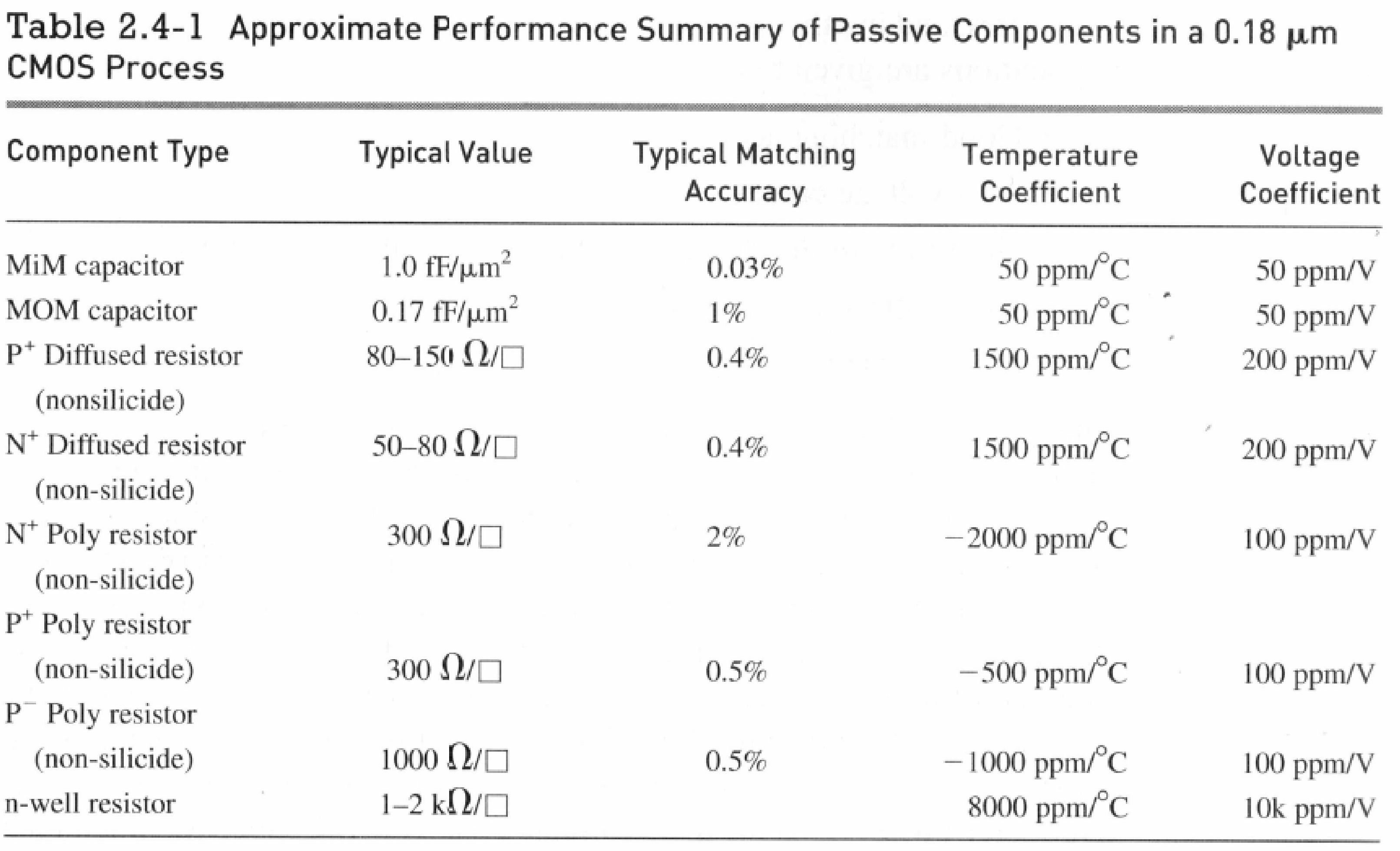
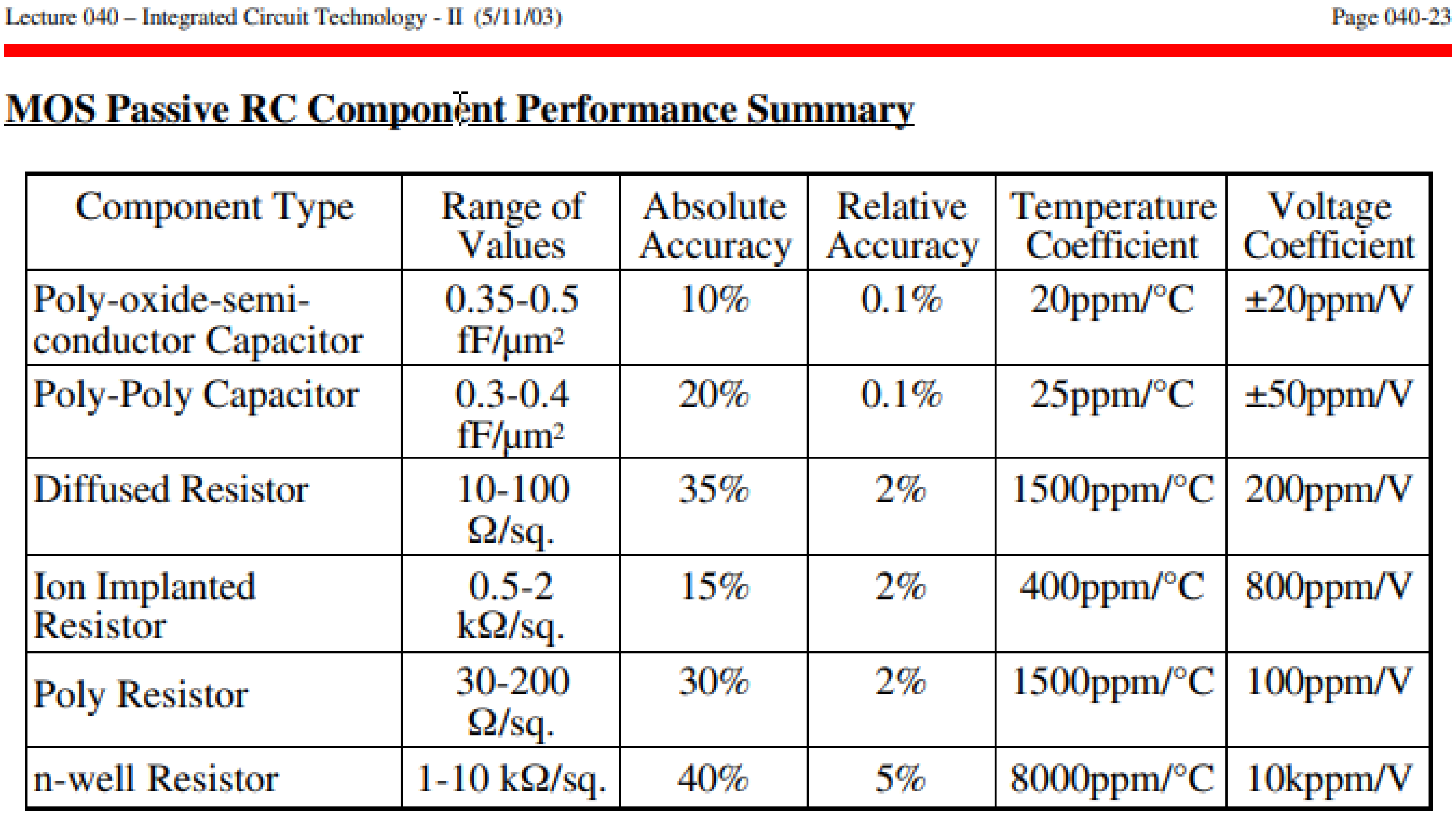


Table 2.4-1 Approximate Performance Summary of Passive Components in a 0.18 μm CMOS Process

Component Type	Typical Value	Typical Matching Accuracy	Temperature Coefficient	Voltage Coefficient
MiM capacitor	1.0 $\text{fF}/\mu\text{m}^2$	0.03%	50 ppm/°C	50 ppm/V
MOM capacitor	0.17 $\text{fF}/\mu\text{m}^2$	1%	50 ppm/°C	50 ppm/V
P^+ Diffused resistor (nonsilicide)	80–150 $\Omega/\square$	0.4%	1500 ppm/°C	200 ppm/V
N^+ Diffused resistor (non-silicide)	50–80 $\Omega/\square$	0.4%	1500 ppm/°C	200 ppm/V
N^+ Poly resistor (non-silicide)	300 $\Omega/\square$	2%	−2000 ppm/°C	100 ppm/V
P^+ Poly resistor (non-silicide)	300 $\Omega/\square$	0.5%	−500 ppm/°C	100 ppm/V
P^- Poly resistor (non-silicide)	1000 $\Omega/\square$	0.5%	−1000 ppm/°C	100 ppm/V
n-well resistor	1–2 $\text{k}\Omega/\square$		8000 ppm/°C	10k ppm/V

From Allen Holberg Third Edition



Lecture 040 – Integrated Circuit Technology - II (5/11/03) Page 040-23

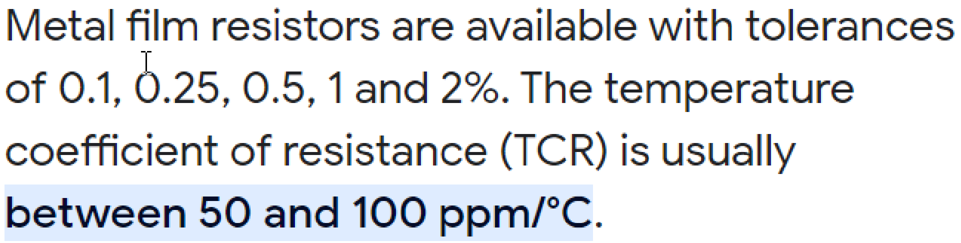
MOS Passive RC Component Performance Summary

Component Type	Range of Values	Absolute Accuracy	Relative Accuracy	Temperature Coefficient	Voltage Coefficient
Poly-oxide-semi-conductor Capacitor	0.35-0.5 fF/μm^2	10%	0.1%	20ppm/°C	±20ppm/V
Poly-Poly Capacitor	0.3-0.4 fF/μm^2	20%	0.1%	25ppm/°C	±50ppm/V
Diffused Resistor	10-100 Ω/sq.	35%	2%	1500ppm/°C	200ppm/V
Ion Implanted Resistor	0.5-2 kΩ/sq.	15%	2%	400ppm/°C	800ppm/V
Poly Resistor	30-200 Ω/sq.	30%	2%	1500ppm/°C	100ppm/V
n-well Resistor	1-10 kΩ/sq.	40%	5%	8000ppm/°C	10kppm/V

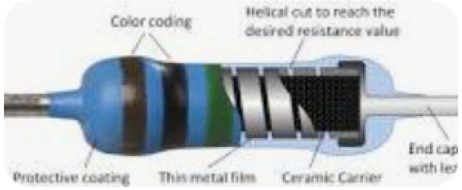
From ECE 6440 Lecture by P. Allen

Layer	R/□ [Ω/□]	T_C [ppm/°C] @ T = 25 °C	V_C [ppm/V]	B_C [ppm/V]
N+ poly	100	-800	50	50
P+ poly	180	200	50	50
N+ diffusion	50	1500	500	-500
P+ diffusion	100	1600	500	-500
N-well	1000	-1500	20,000	30,000

How does TCR of Integrated Resistors Compare with Low-Cost Discrete Resistors?



Metal film resistors are available with tolerances of 0.1, 0.25, 0.5, 1 and 2%. The temperature coefficient of resistance (TCR) is usually between 50 and 100 ppm/°C.



Integrated resistors typically have a much larger TCR but there are some special processes that provide resistors with excellent thermal stability ($$$)

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

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

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

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

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

Thus the resistor increases by 4.5%

Did not need $R(T_1)$ to answer this question !

What is $R(T_1)$ as stated in this example ? 5K?

It is around 5K but if we want to be specific, would need to specify T

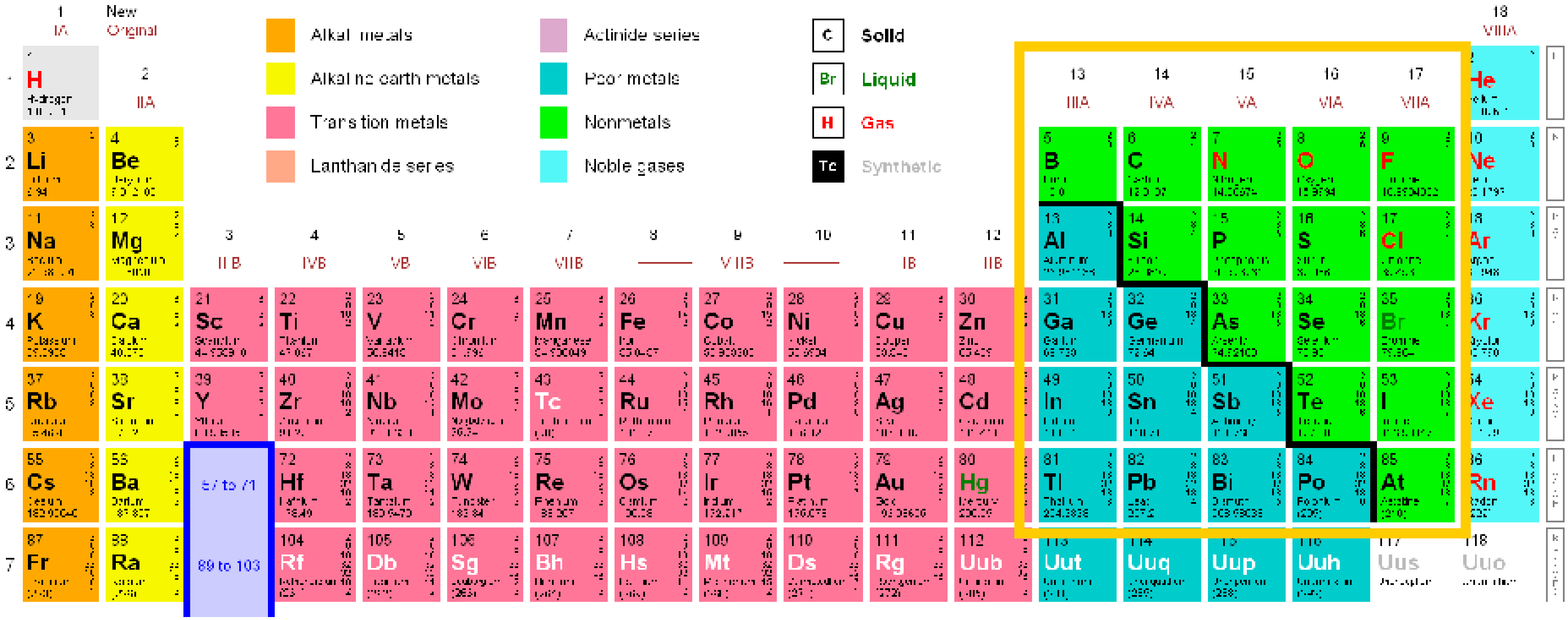
Basic Devices and Device Models

- Resistor

➡ Diode

- Capacitor
- MOSFET
- BJT

Periodic Table of the Elements

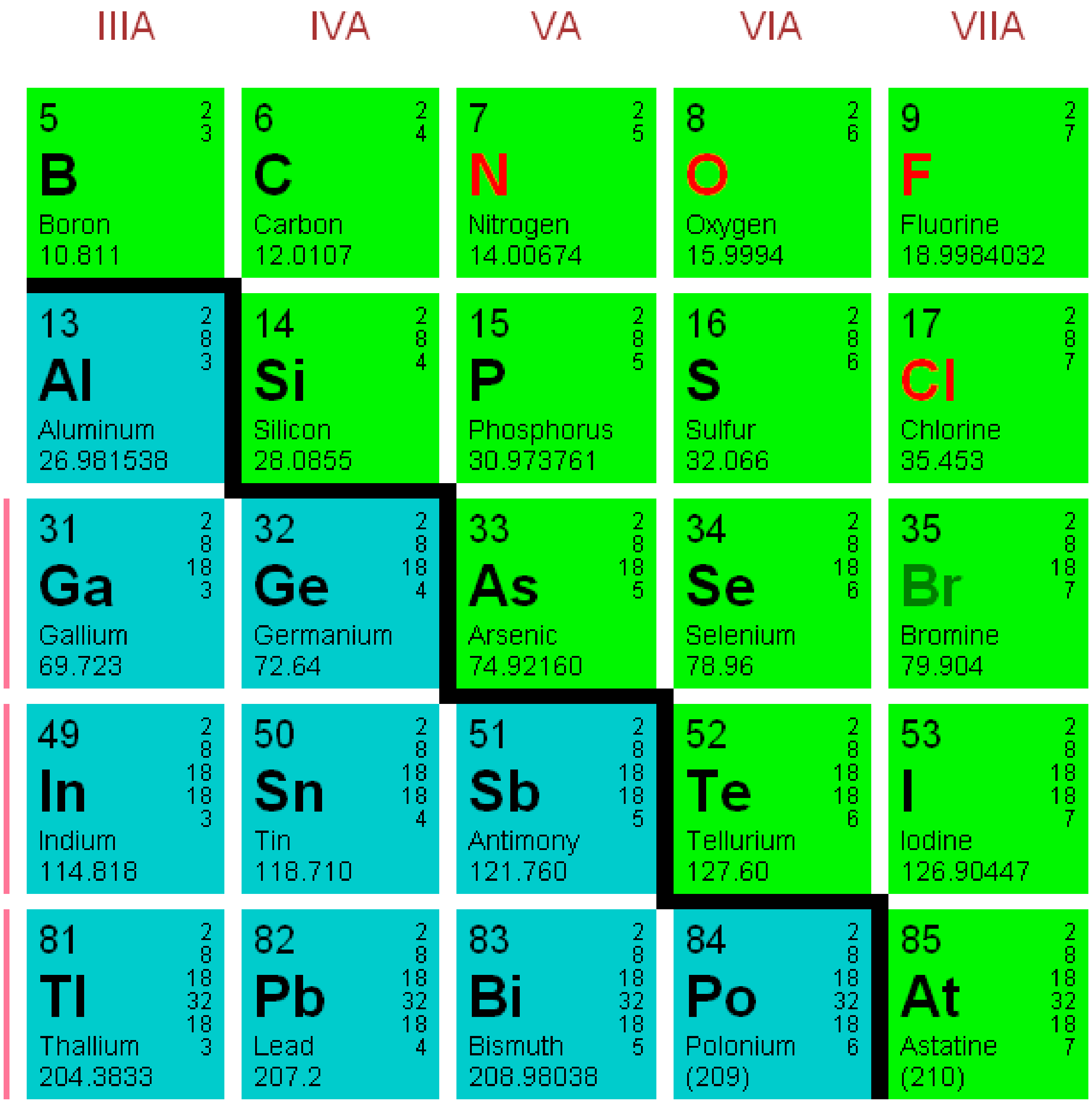


🟧 Alkali metals
🟨 Alkaline earth metals
🟥 Transition metals
🟧 Lanthanide series
🟪 Actinide series
🟦 Poor metals
🟩 Nonmetals
🟦 Noble gases

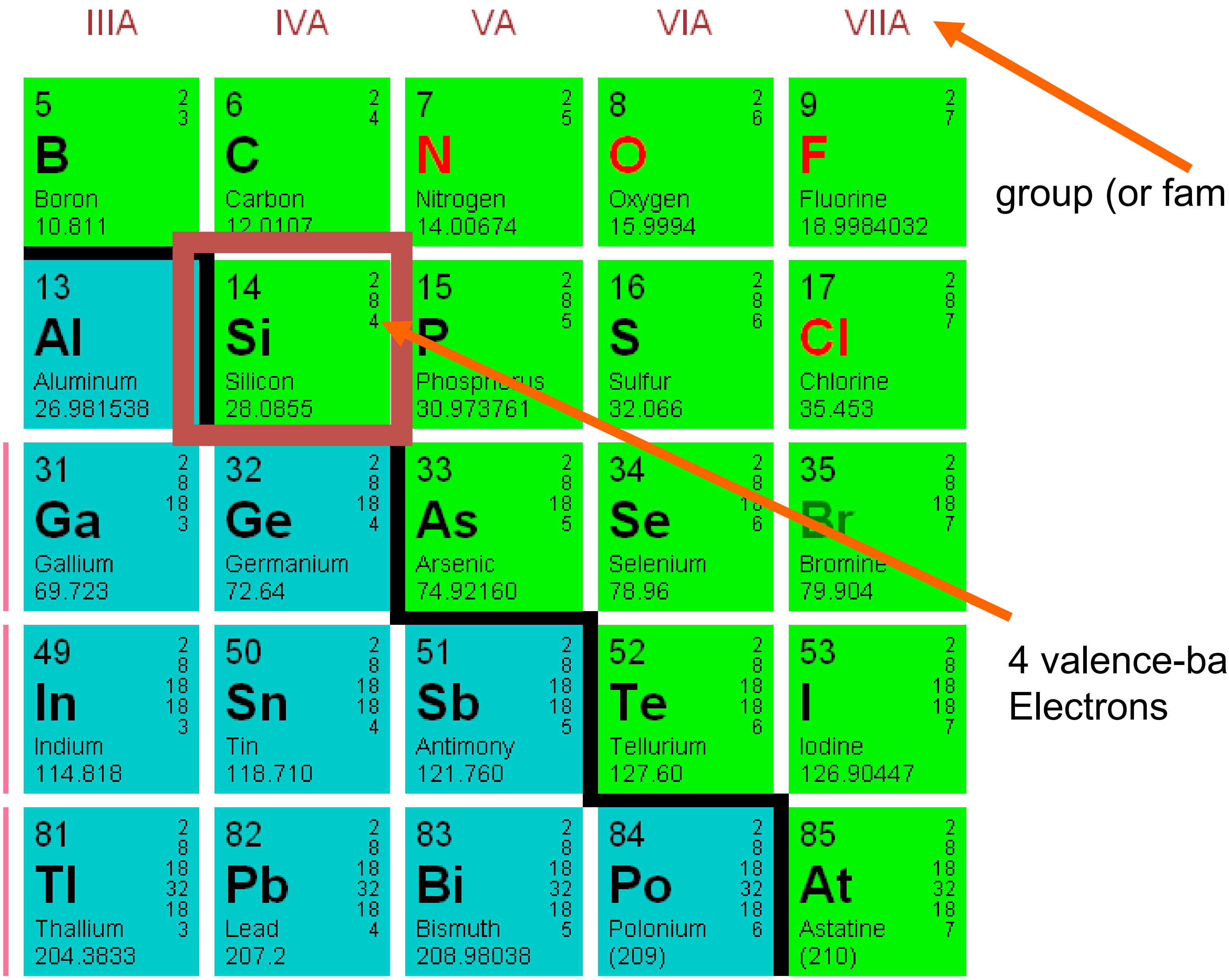
C Solid
Br Liquid
H Gas
Tc Synthetic

	1 IA	2 IIA	3 III B	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 to 71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 to 103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

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



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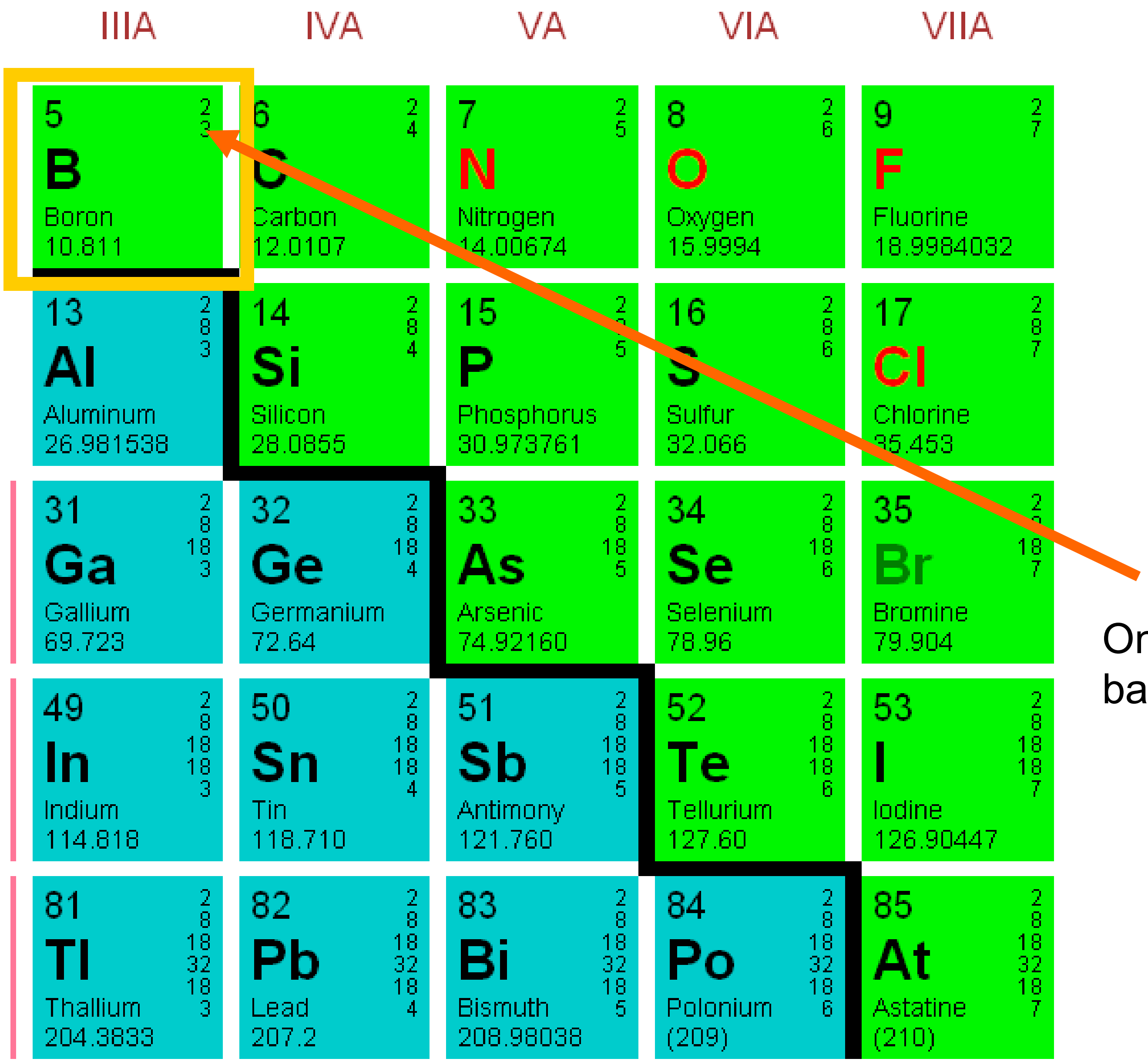
group (or family)

4 valence-band Electrons

All elements in group IV have 4 valence-band electrons



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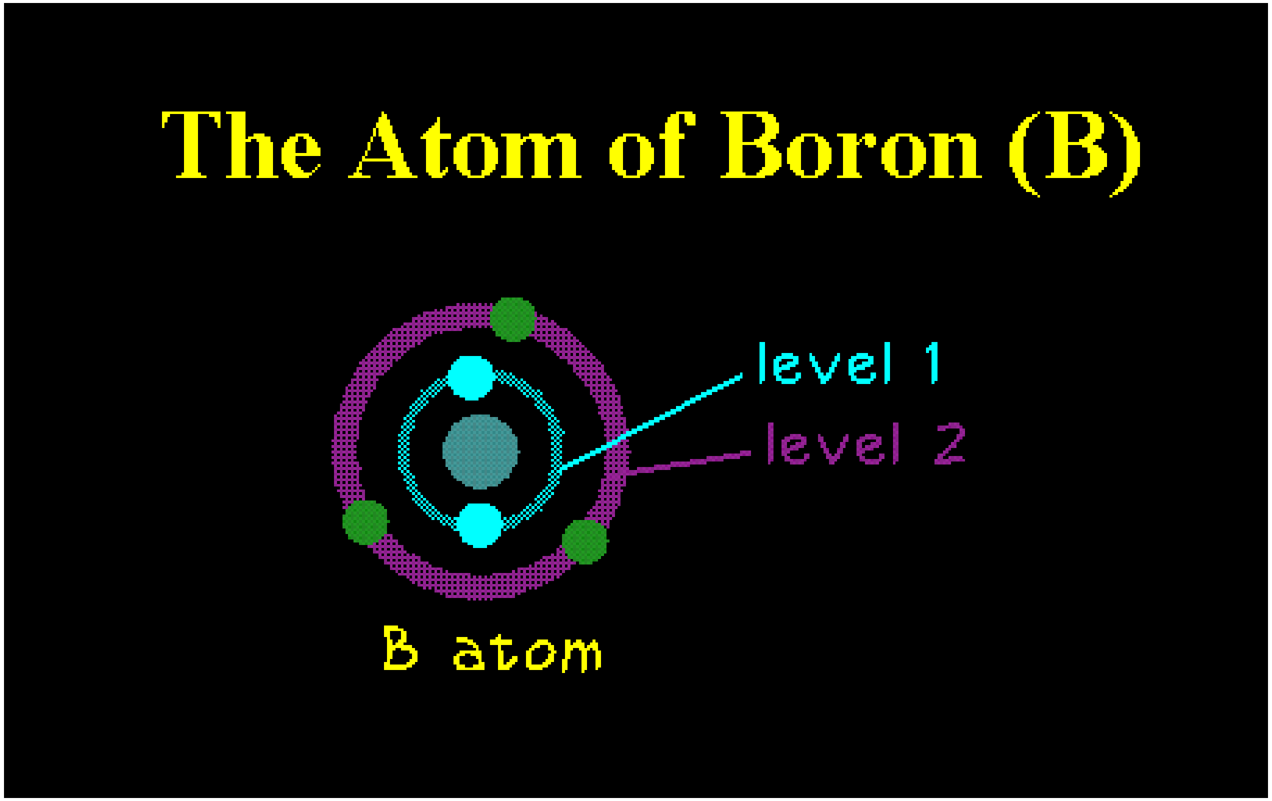
49 **In** Indium 114.818 2 8 18 18 3	50 **Sn** Tin 118.710 2 8 18 18 4	51 **Sb** Antimony 121.760 2 8 18 18 5	52 **Te** Tellurium 127.60 2 8 18 18 6	53 **I** Iodine 126.90447 2 8 18 18 7
81 **Tl** Thallium 204.3833 2 8 18 32 18 3	82 **Pb** Lead 207.2 2 8 18 32 18 4	83 **Bi** Bismuth 208.98038 2 8 18 32 18 5	84 **Po** Polonium (209) 2 8 18 32 18 6	85 **At** Astatine (210) 2 8 18 32 18 7

Only 3 Valence-band Electrons

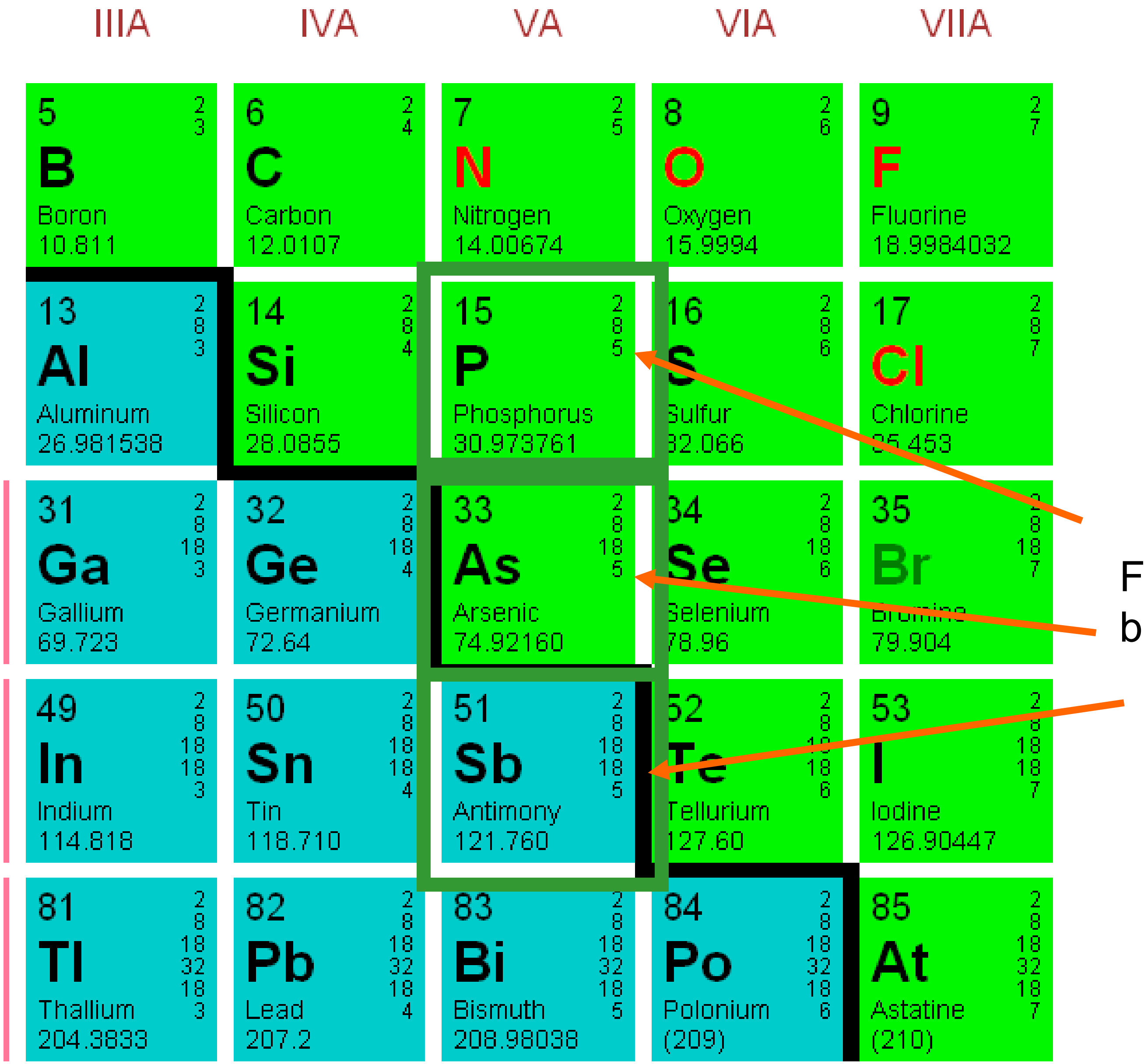
Serves as an "acceptor" of electrons

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



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
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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

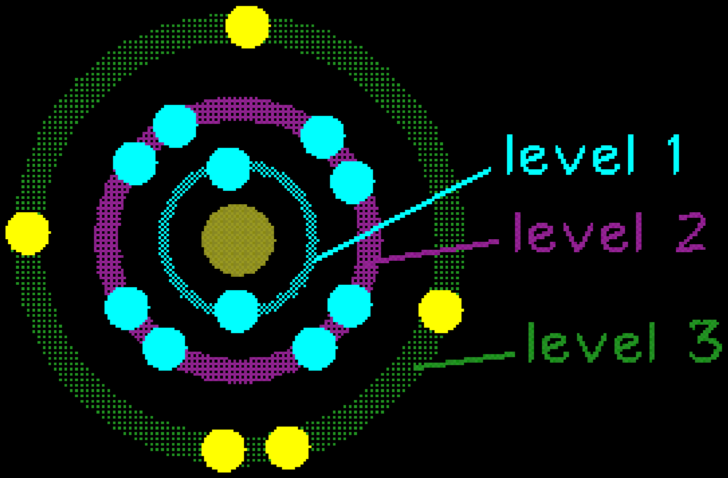
Five Valence-band Electrons

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)



P atom

5

B

Boron

10.811

2
3

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

14

Si

Silicon

28.0855

2
8
4

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

15

P

Phosphorus

30.973762

2
8
5

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

33

As

Arsenic

74.92160

2
8
18
5

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

51

Sb

Antimony

121.760

2
8
18
18
5

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

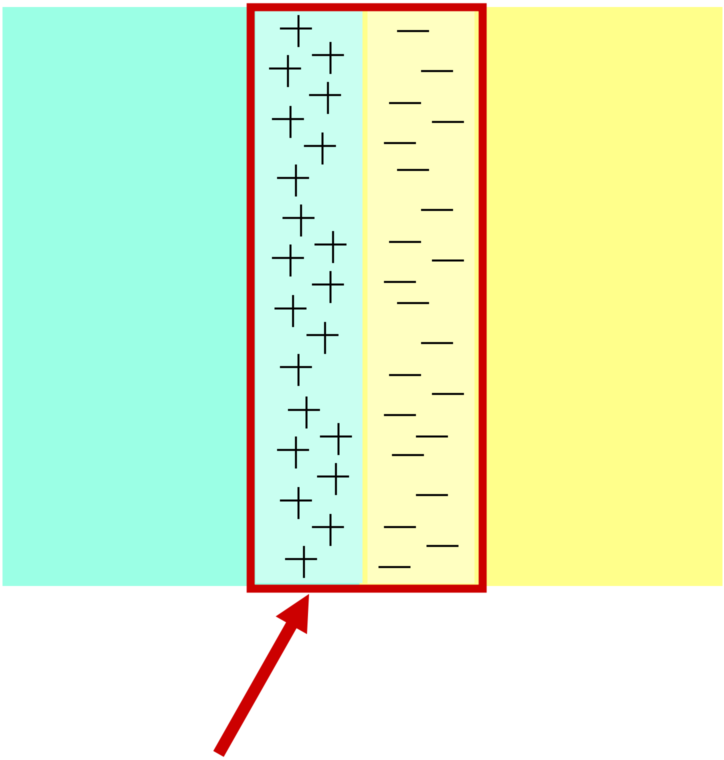
Silicon Dopants in Semiconductor Processes

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

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

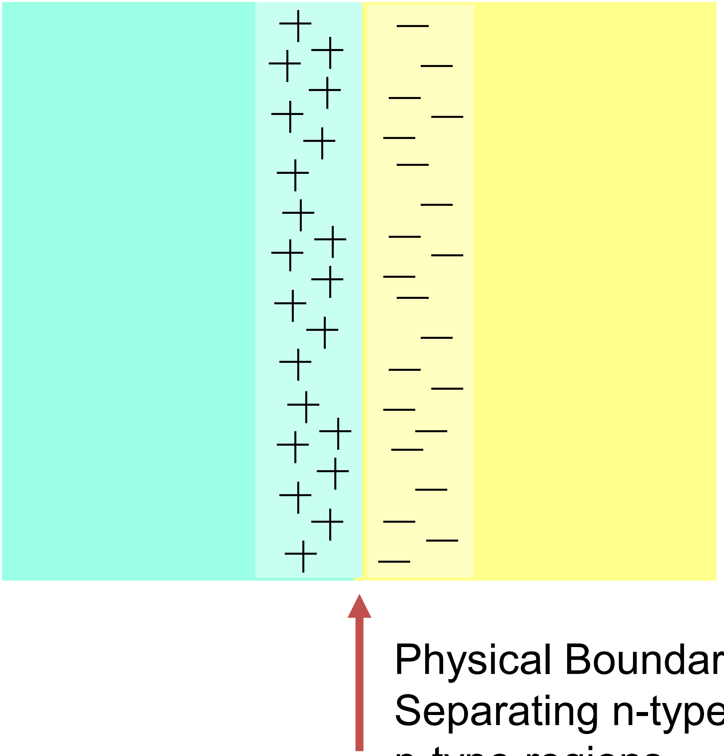
As (Arsenic) widely used dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



Depletion region created that is ionized but void of carriers

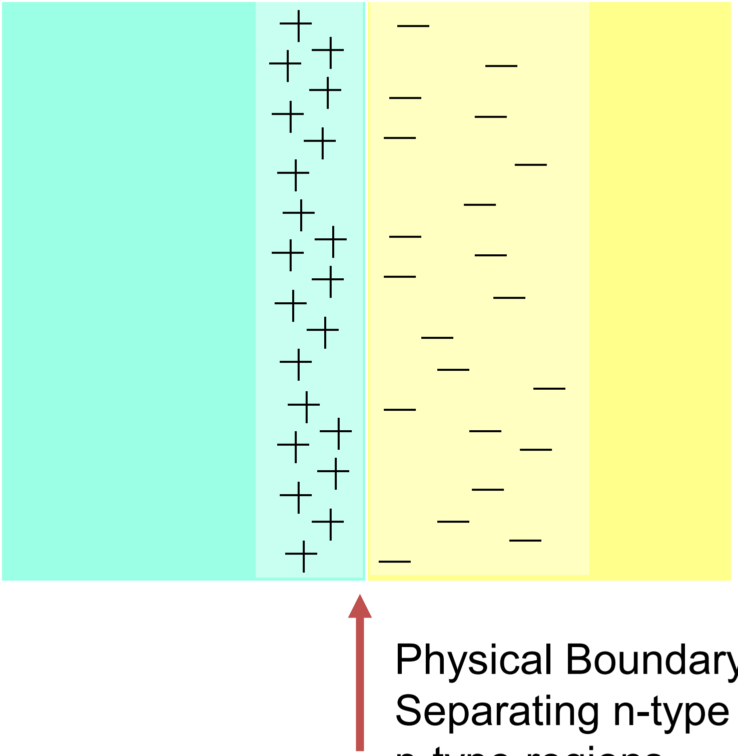
pn Junctions



Physical Boundary Separating n-type and p-type regions

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

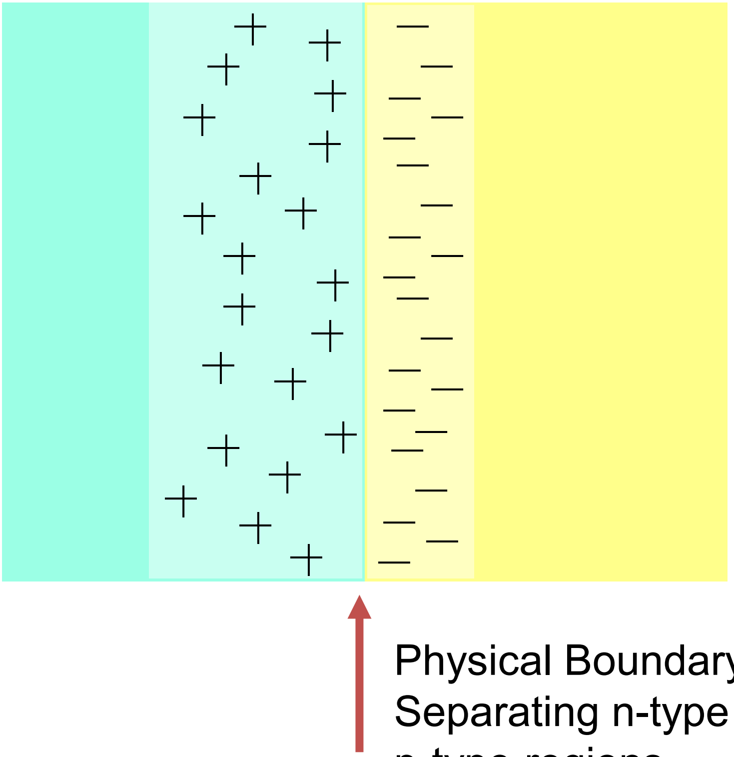
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

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

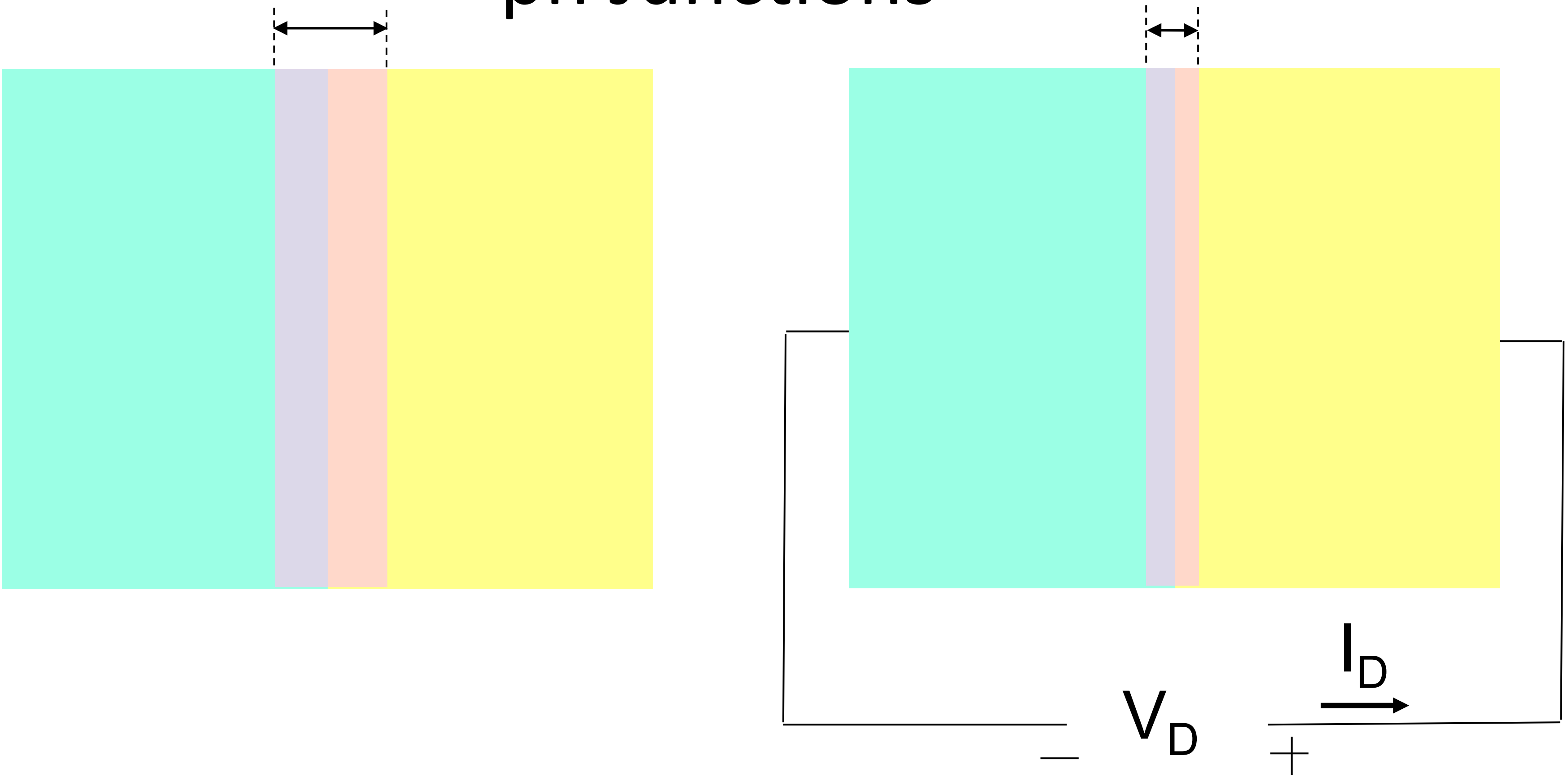
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

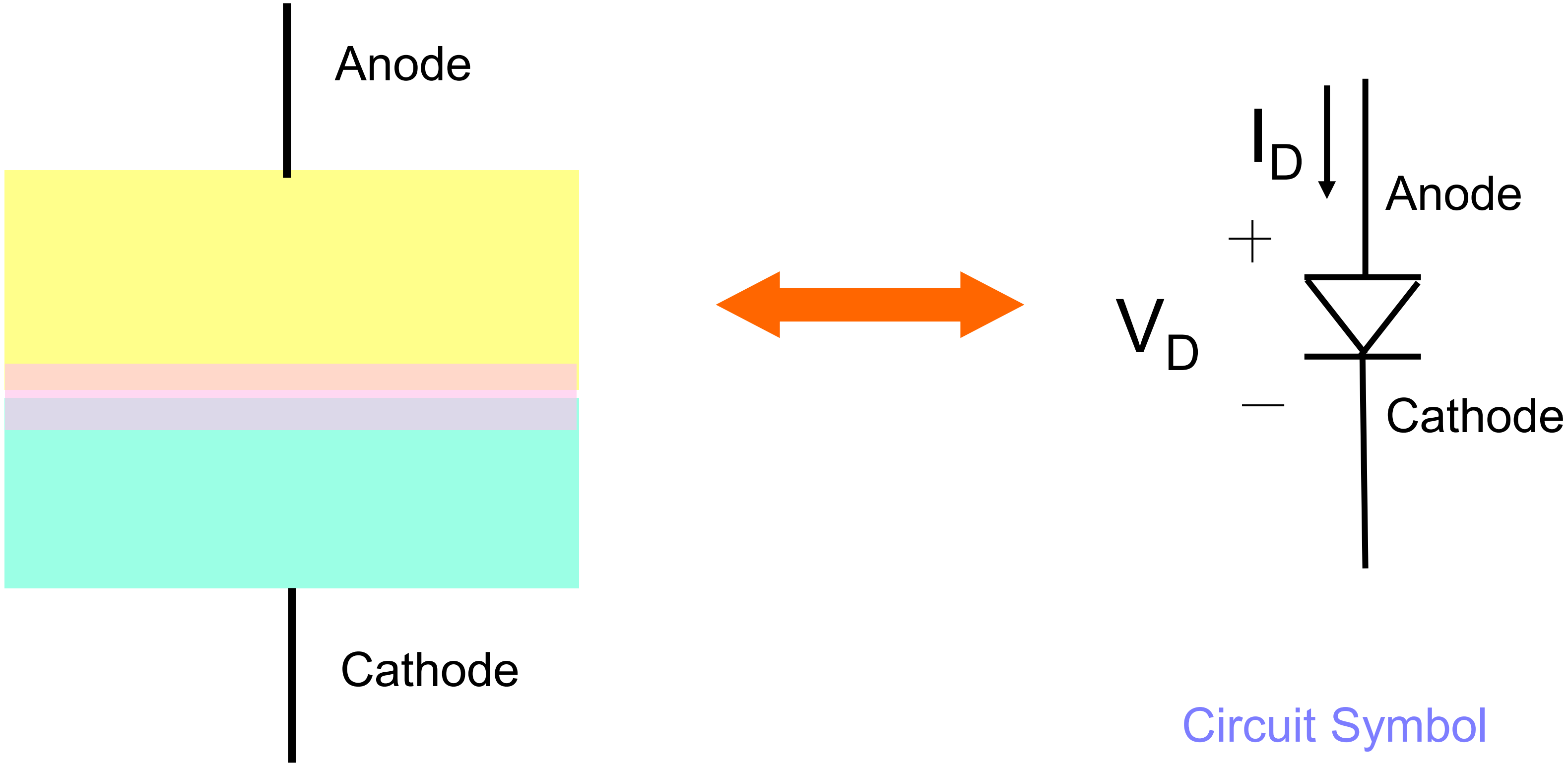
Extends farther into n-type region if n-doping lower than p-doping

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 <u>very rapidly</u> as forward bias increases
- Current is very small under revere bias

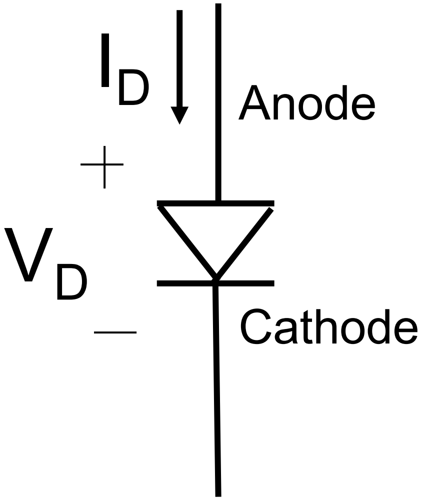
pn Junctions



Circuit Symbol

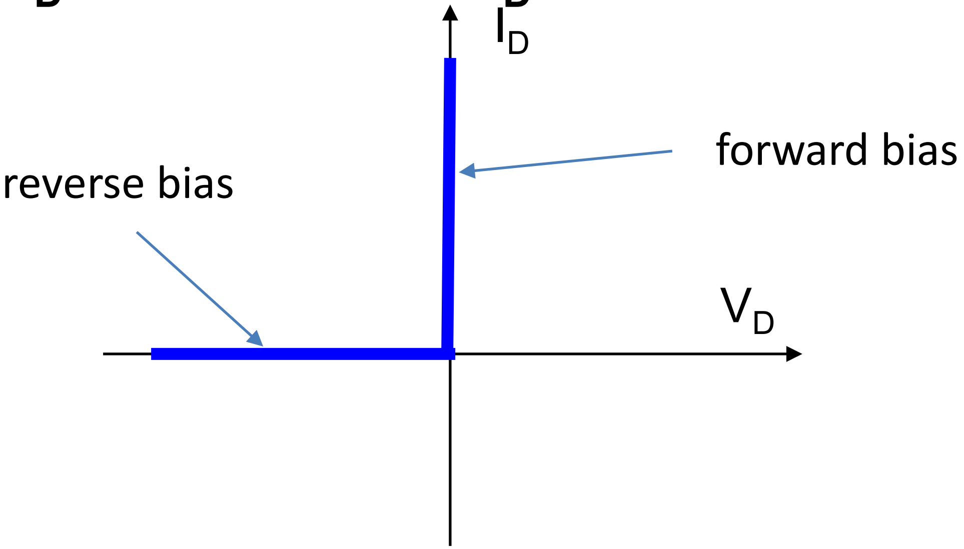
pn Junctions

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



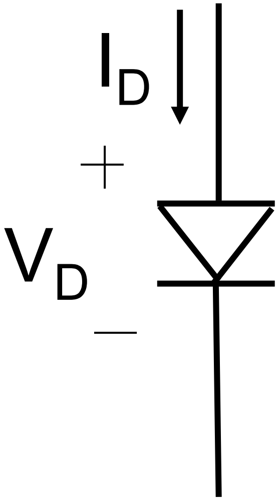
Simple Diode Model:

V_D=0	**I_D>0**	Forward bias
I_D=0	**V_D<0**	Reverse bias

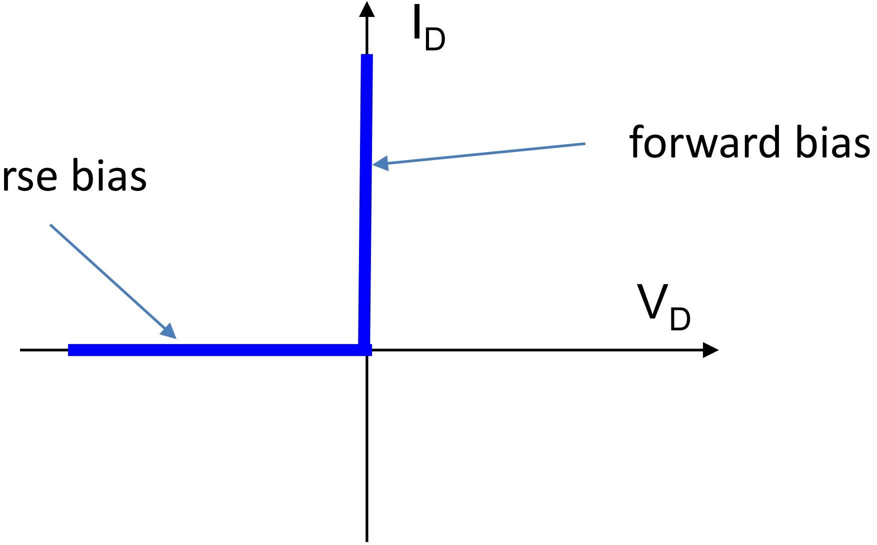


Simple model often referred to as the “Ideal” diode model

pn Junctions

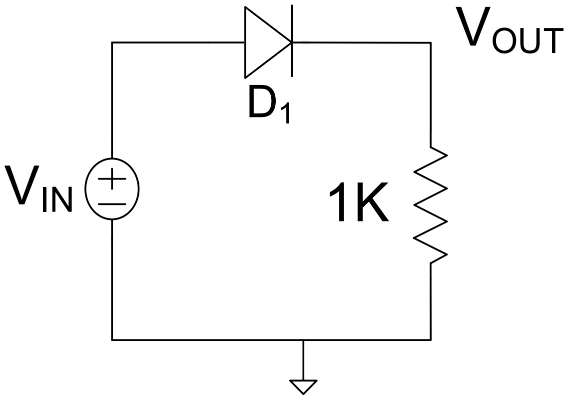


Simple Diode Model:



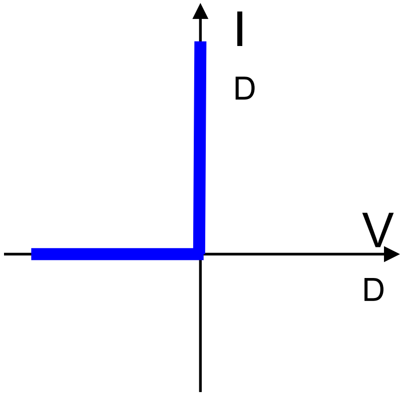
pn junction serves as a “rectifier” passing current in one direction and blocking it in the other direction

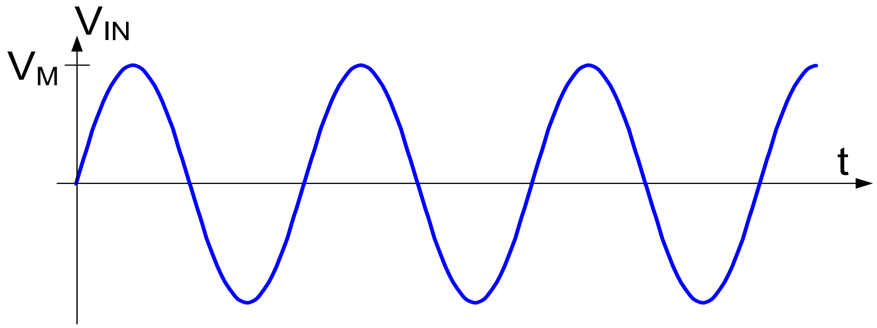
Rectifier Application:

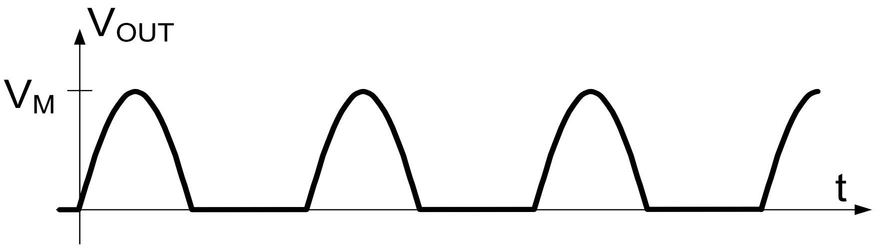


$V_{IN}=V_M\sin\omega t$

Simple Diode Model:





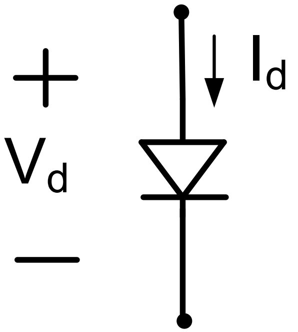


Analysis based upon “passing current” in one direction and “ blocking current” in the other direction

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:



Diode Equation

$$I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$$

I_S and n are model parameters

What is V_t at room temp?

V_t is about 26mV at room temp

I_S in the 10fA to 100fA range

I_S proportional to junction area

$$V_t = \frac{kT}{q}$$

$k= 1.380\,64852 \times 10^{-23} JK^{-1}$

$q = -1.60217662\times10^{-19}$ C

$k/q=8.62\times 10^{-5}$ VK^{-1}

n typically about 1

Diode equation due to William Shockley, inventor of BJT

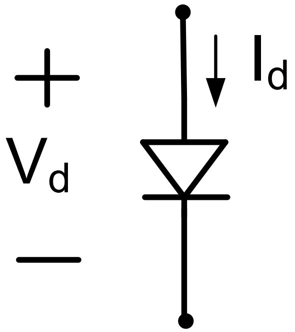
In 1919, William Henry Eccles coined the term ***diode***

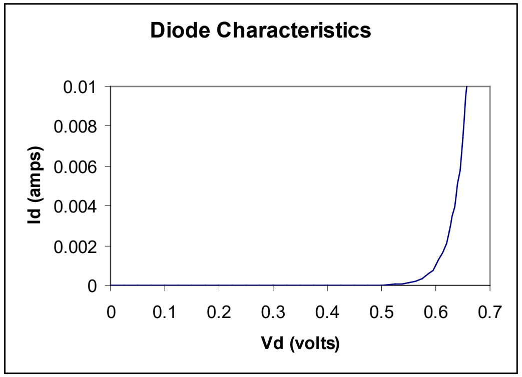
In 1940, Russell Ohl “stumbled upon” the p-n junction diode

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:





Diode Characteristics

I_S in 10fA -100fA range (for signal diodes)

n typically about 1

$$V_t = \frac{kT}{q}$$

$k/q = 8.62 \times 10^{-5}\ \mathrm{VK}^{-1}$

V_t is about 26mV at room temp

Diode Equation $$I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$$

Simplification of Diode Equation:

Under reverse bias ($V_d<0$), $I_D \cong -I_S$

Under forward bias ($V_d>0$), $I_D = I_S e^{\frac{V_d}{nV_t}}$

Simplification essentially identical model except for V_d very close to 0

Diode Equation or forward bias simplification are unwieldy to work with analytically

Stay Safe and Stay Healthy !

End of Lecture 13