EE 330
Lecture 13

Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFETs

As a courtesy to fellow classmates, TAs, and the instructor

Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status

Exam 1 Schedule

Exam 1 will be given on Friday September 23

Format: Open-Book, Open Notes

Exam will be posted at 9:00 a.m. on the class WEB site and will be due at 1:00 p.m. as a .pdf upload on CANVAS

It will be structured to be a 50-minute closed-book closed-notes exam but administered as an open-book, open-notes exam with a 4 hour open interval so reserving the normal lecture period for taking the exam should provide adequate time

Honor System Expected

It is expected that this exam be an individual effort and that students should not have input in **any form** from **anyone else** during the 4-hour open interval of the exam except from the course instructor who will be responding to email messages from 11:00 a.m. to 1:00 p.m. on the date of the exam.

Special Accommodations

For anyone with approved special accommodations, the 4-hour open interval should cover extra time allocations but if for any reason this does not meet special accommodation expectations, please contact the instructor by Monday Sept. 14 if alternative accommodations are requested.

Review from last lecture

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

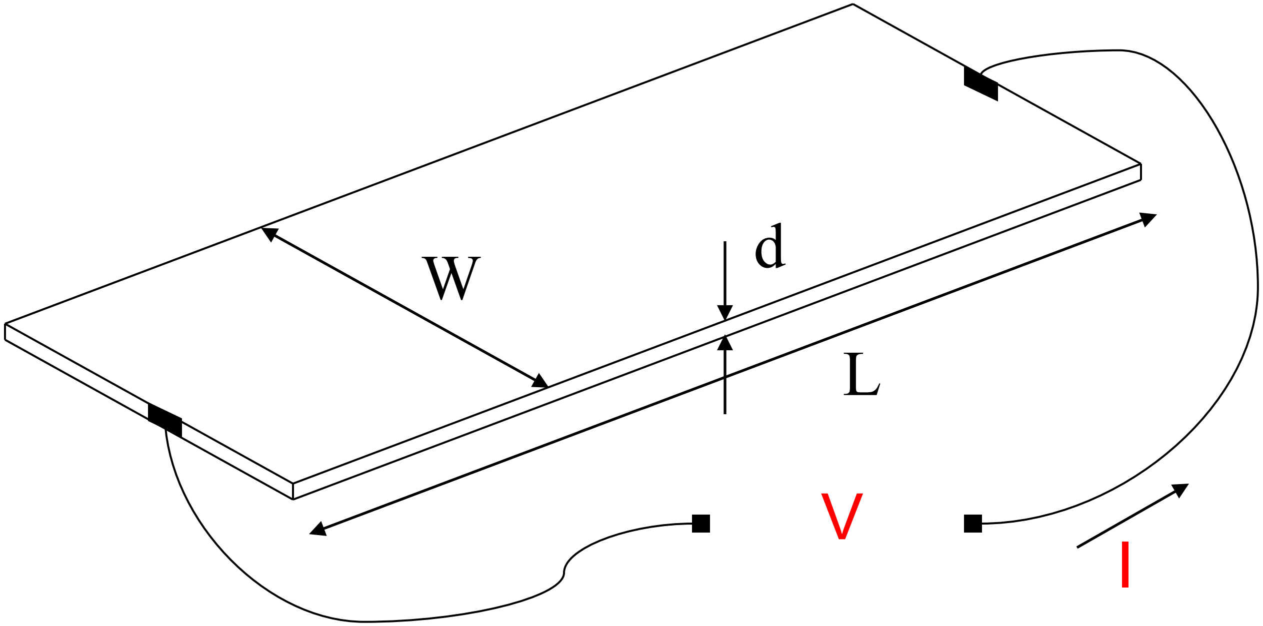
Resistors were discussed when considering interconnects so will only be briefly reviewed here

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

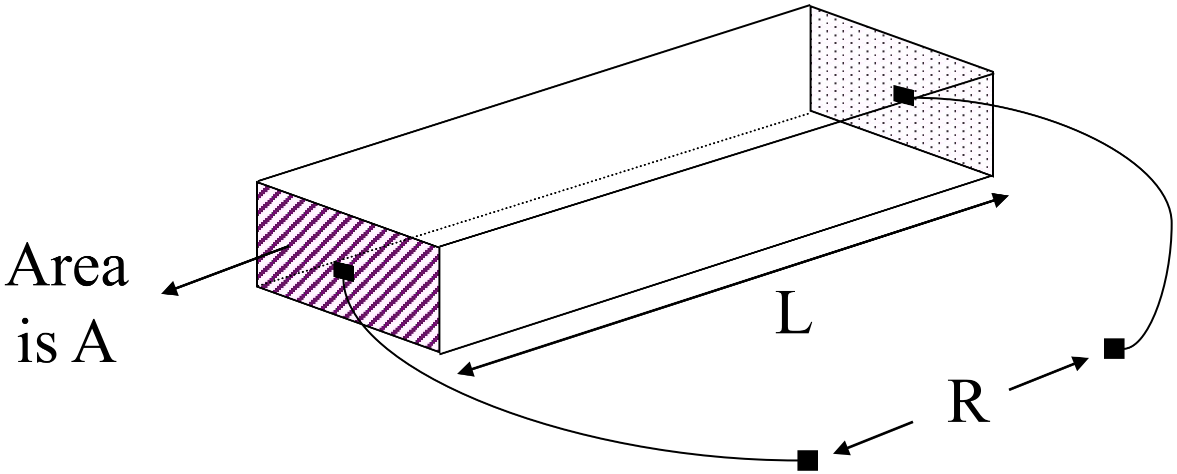


Model:

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

Resistivity

- Volumetric measure of conduction capability of a material

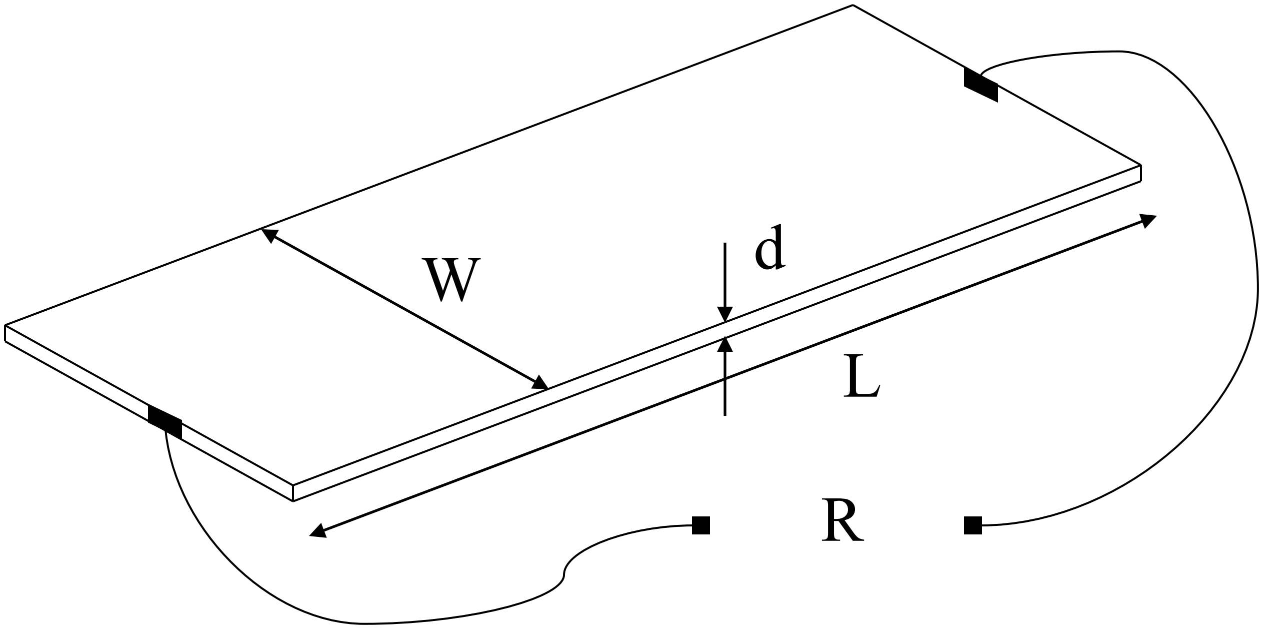


$$\rho = \frac{AR}{L}$$

for homogeneous material,
ρ ⊥ 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 $R_\square$

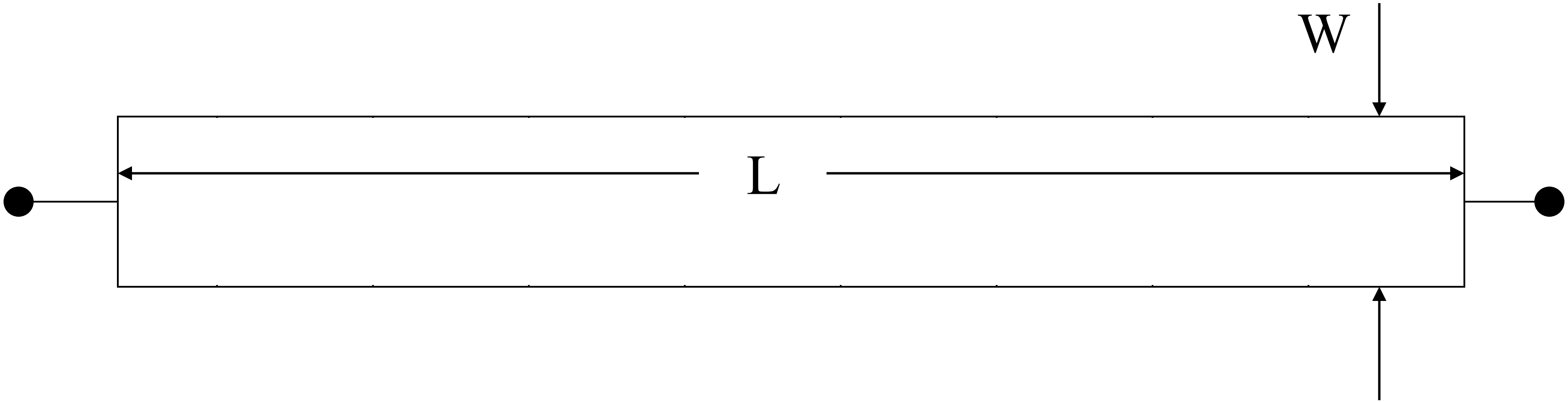
$$\left.\begin{array}{l} R_\square = \dfrac{RW}{L} \\[2ex] \rho = \dfrac{AR}{L} \end{array}\right\} \longrightarrow \begin{array}{l} \rho = \dfrac{A}{W} R_\square \\[2ex] A = W \times d \end{array}$$

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

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

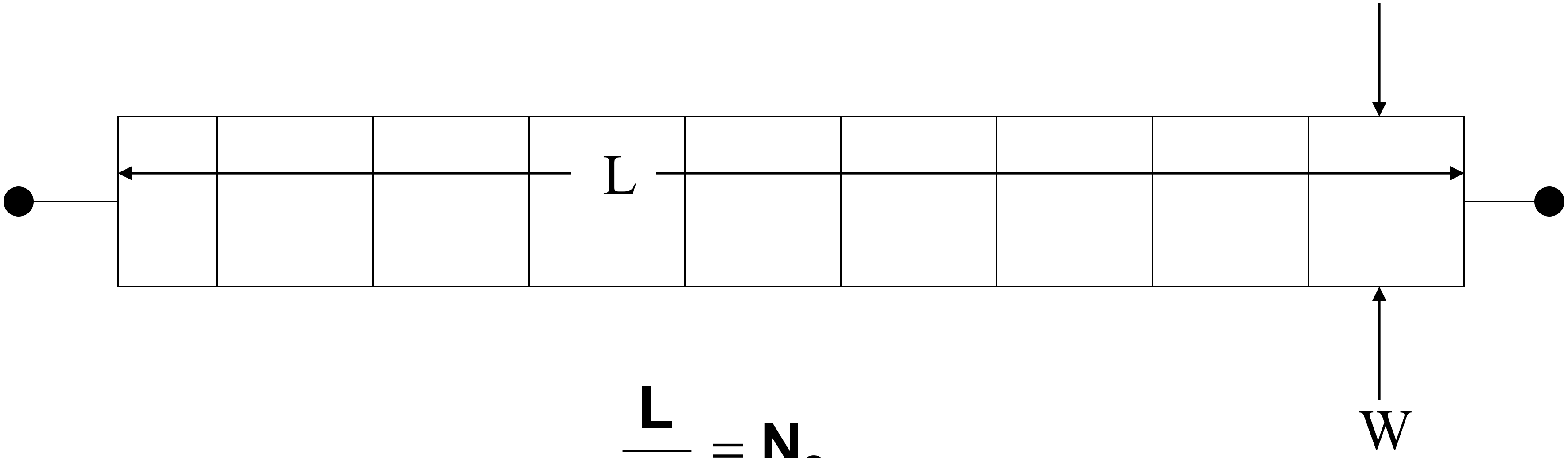
$$R = R_\square N_S$$

Example 1



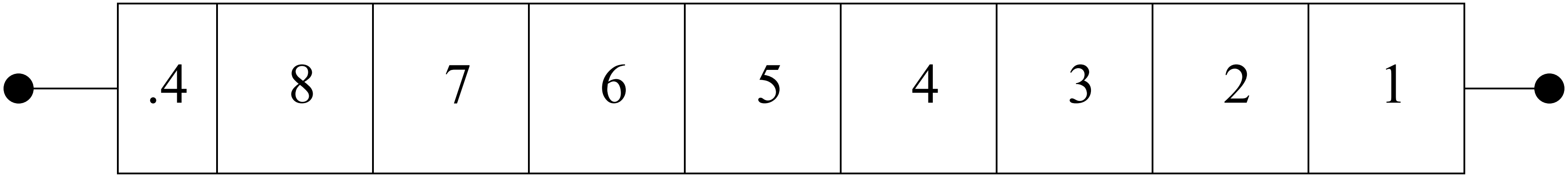
$R = ?$

Example 1



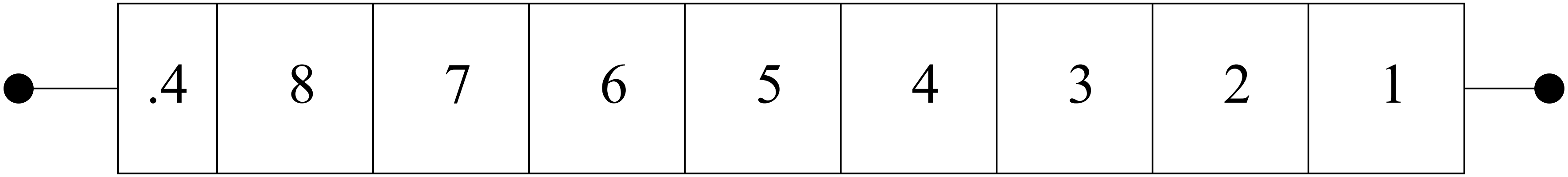
$$\frac{\mathbf{L}}{\mathbf{W}} = \mathbf{N_S}$$

Example 1



R = ?

Example 1

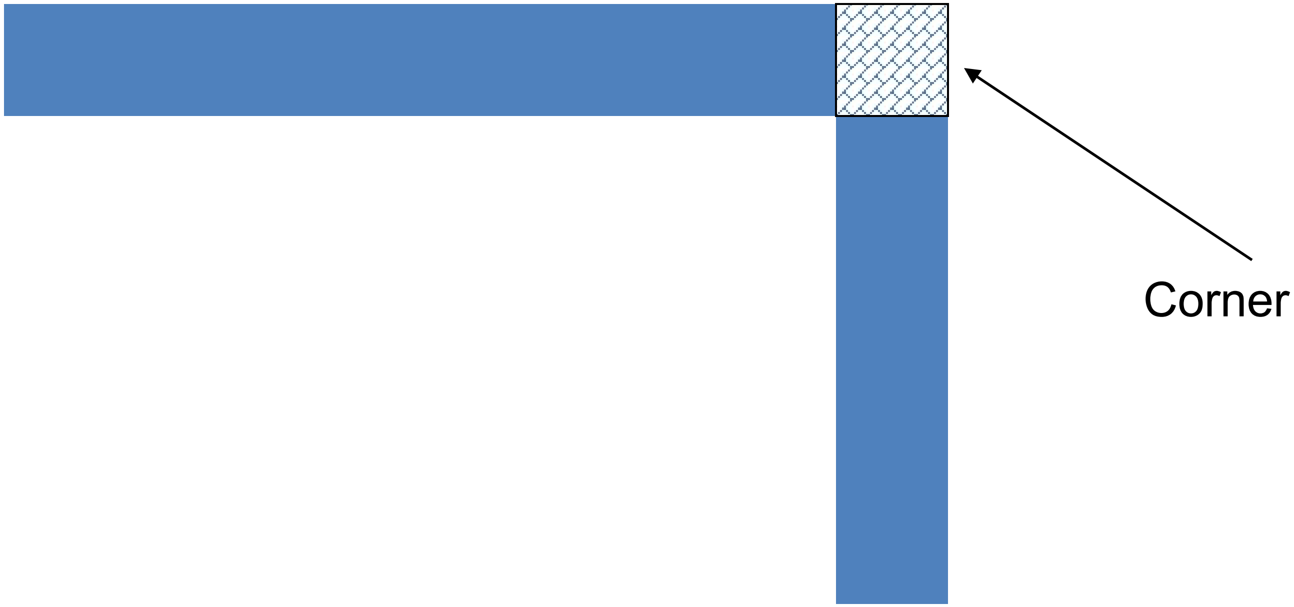


R = ?

$N_S = 8.4$

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

Corners in Film Resistors

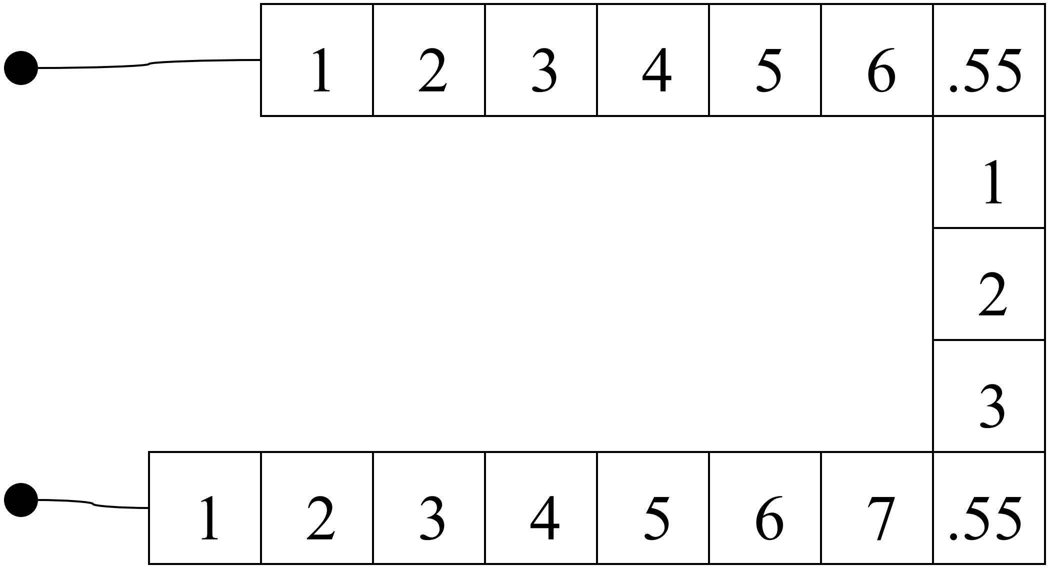


Rule of Thumb: .55 squares for each corner

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*-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})

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:

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

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

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

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:

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

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

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

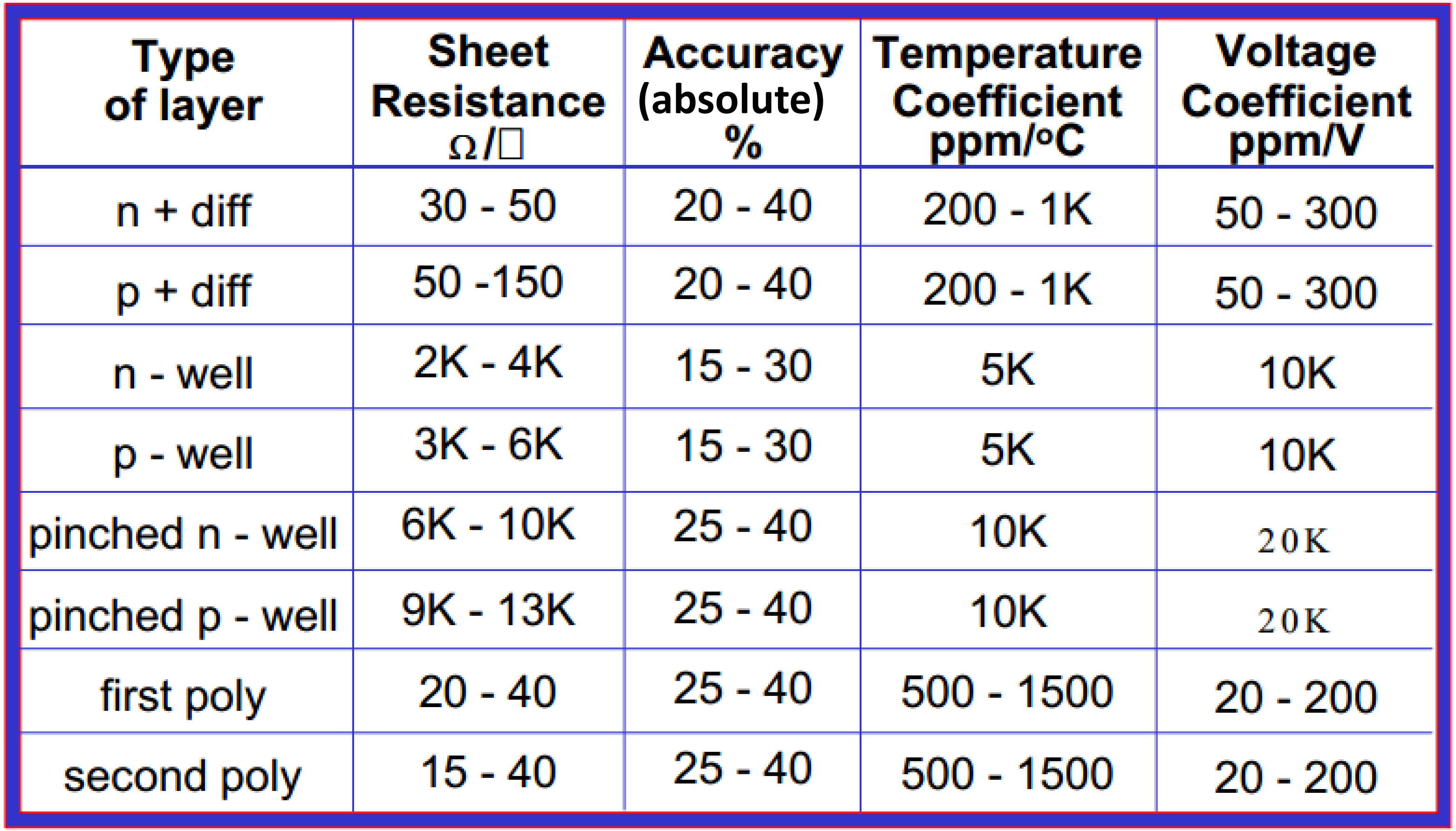
It follows that If VCR*(V_2-V_1) is small,

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

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	-

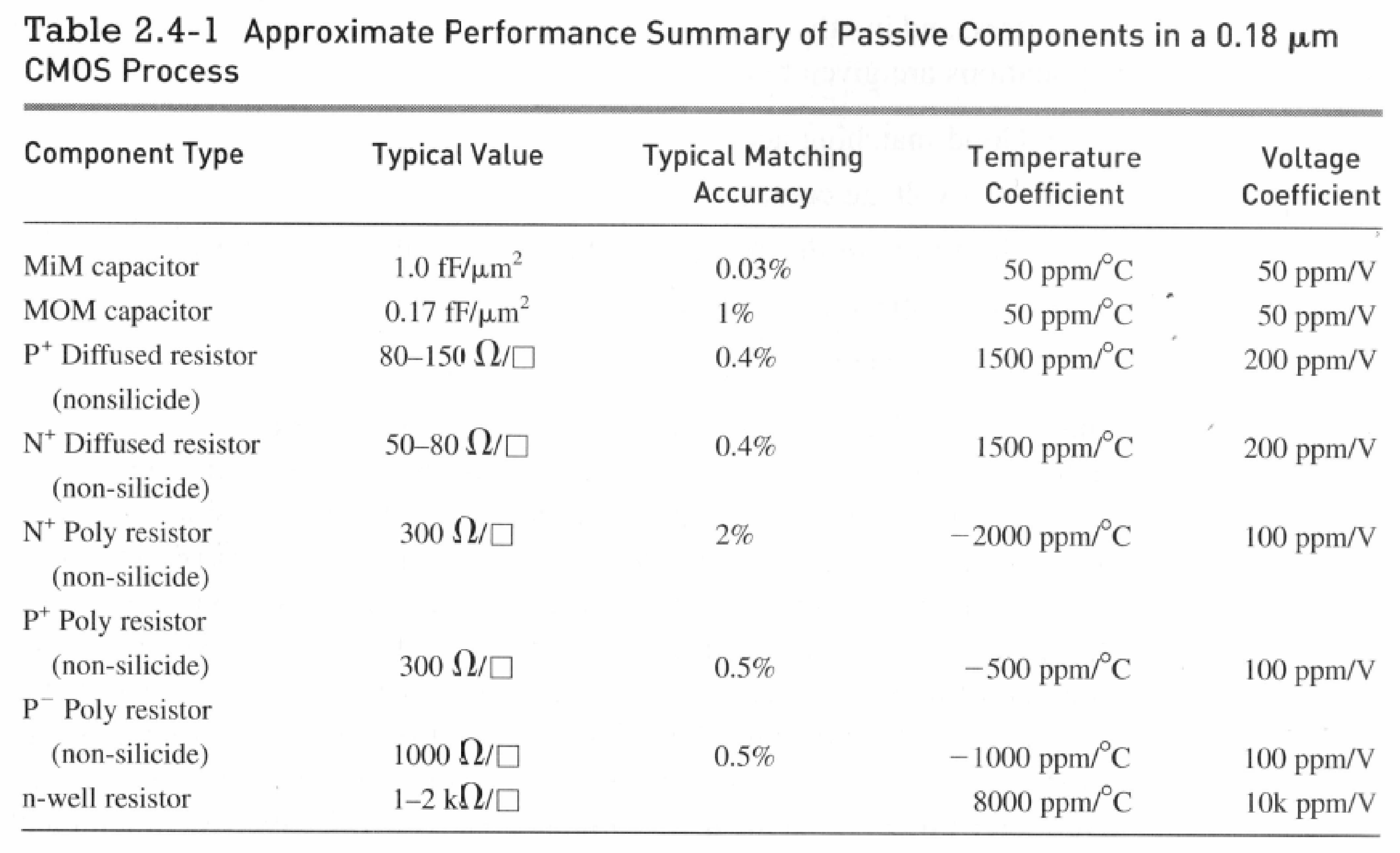
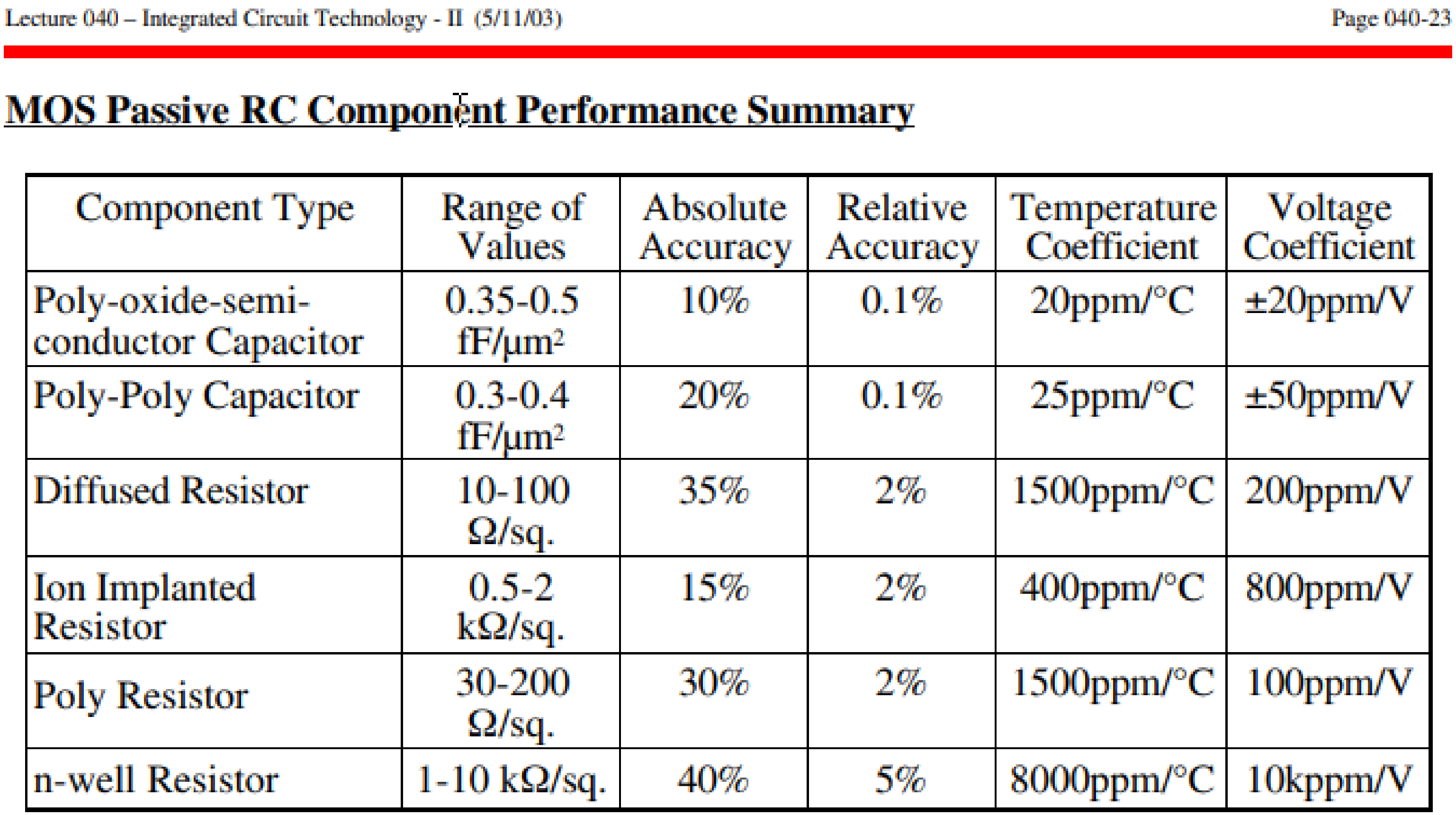


Table 2.4-1 Approximate Performance Summary of Passive Components in a 0.18 μm CMOS Process

Component Type	Typical Value	Typical Matching Accuracy	Temperature Coefficient	Voltage Coefficient
MiM capacitor	1.0 fF/μm^2	0.03%	50 ppm/°C	50 ppm/V
MOM capacitor	0.17 fF/μm^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 k$\Omega/\square$		8000 ppm/°C	10k ppm/V

From Allen Holberg   Third Edition



MOS Passive RC Component Performance Summary

Component Type	Range of Values	Absolute Accuracy	Relative Accuracy	Temperature Coefficient	Voltage Coefficient
Poly-oxide-semiconductor Capacitor	0.35-0.5 fF/μm²	10%	0.1%	20ppm/°C	±20ppm/V
Poly-Poly Capacitor	0.3-0.4 fF/μm²	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/^oC] @ T = 25 ^oC	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

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

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

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

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

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

Thus the resistor increases by 4.5%

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

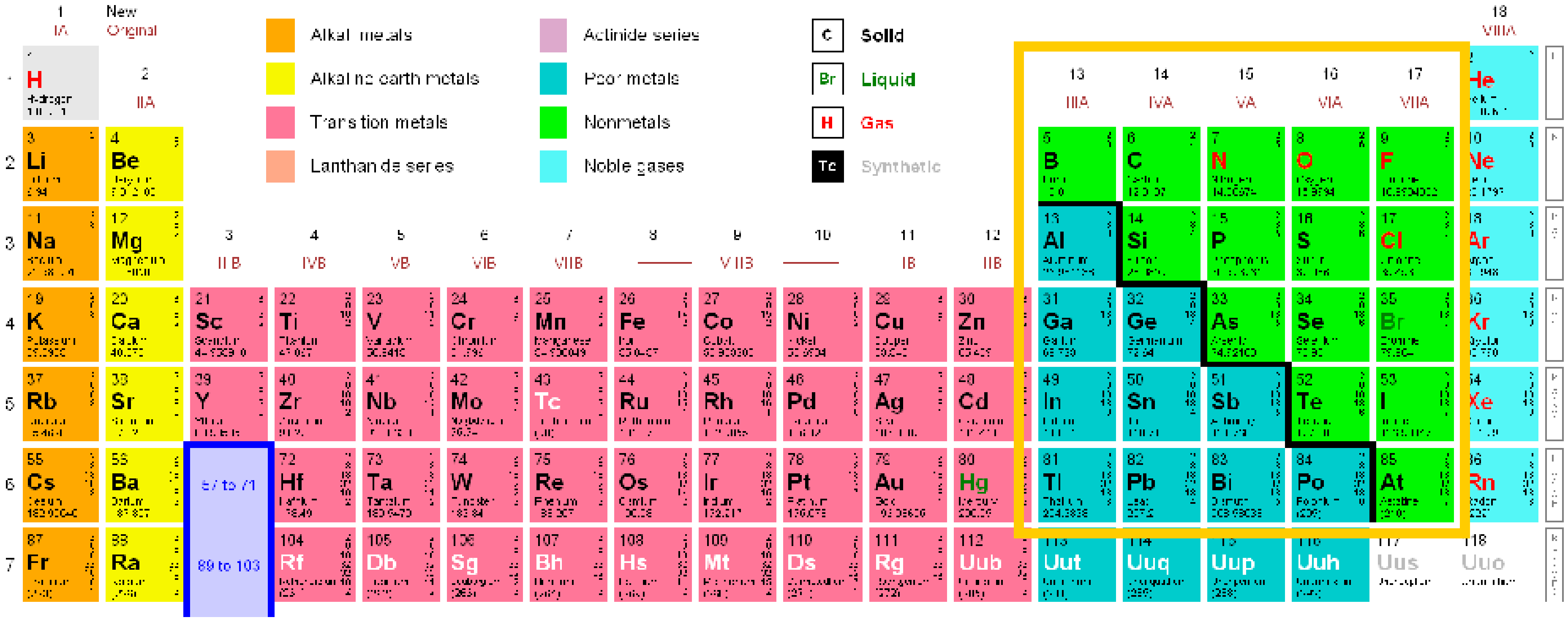
What is $R(T_1)$ as stated in this example ? 5K?

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

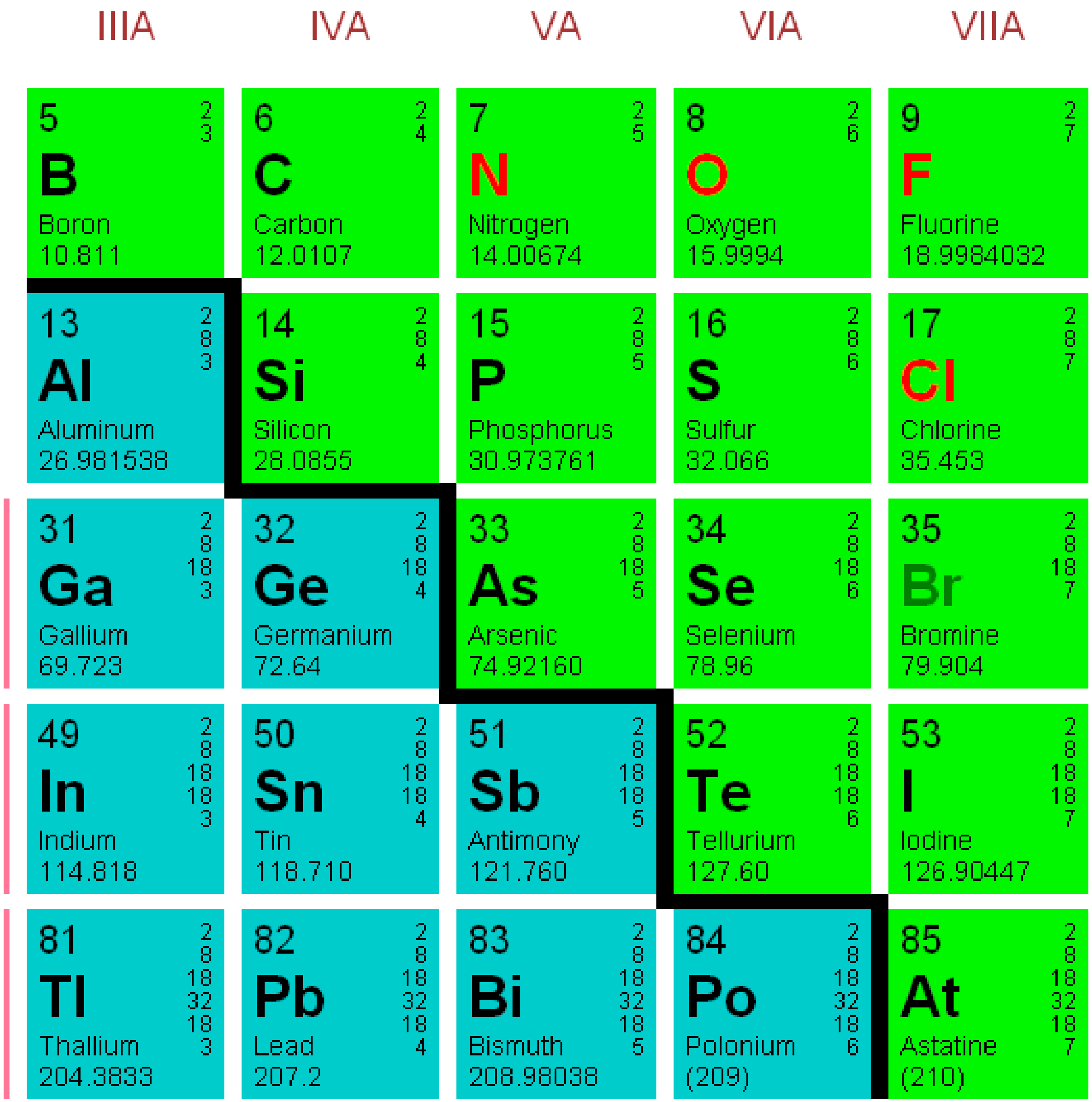


Alkali metals
Alkaline earth metals
Transition metals
Lanthanide series
Actinide series
Poor metals
Nonmetals
Noble gases

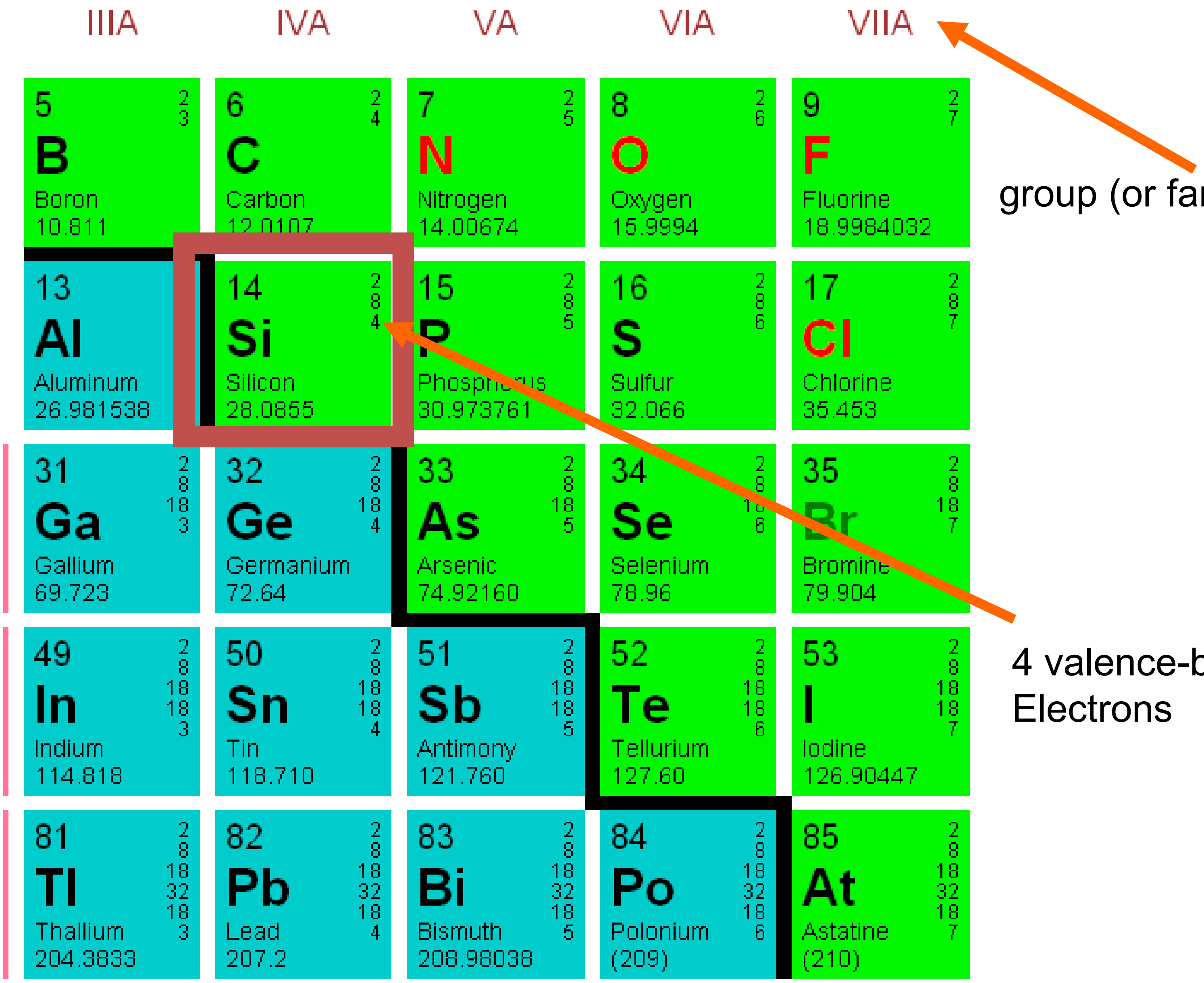
C Solid
Br Liquid
H Gas
Tc Synthetic

	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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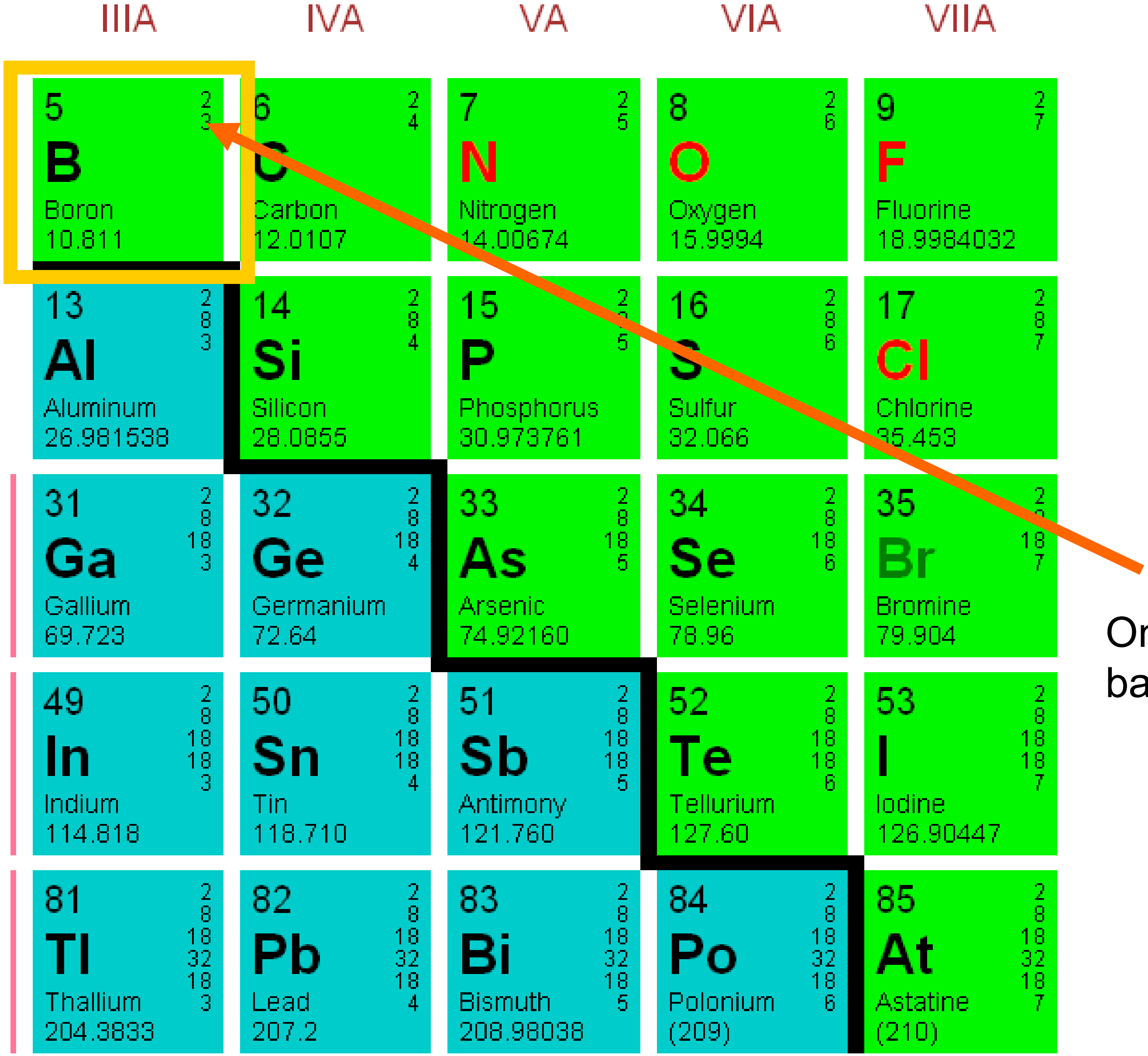
group (or family)

4 valence-band Electrons

All elements in group IV have 4 valence-band electrons



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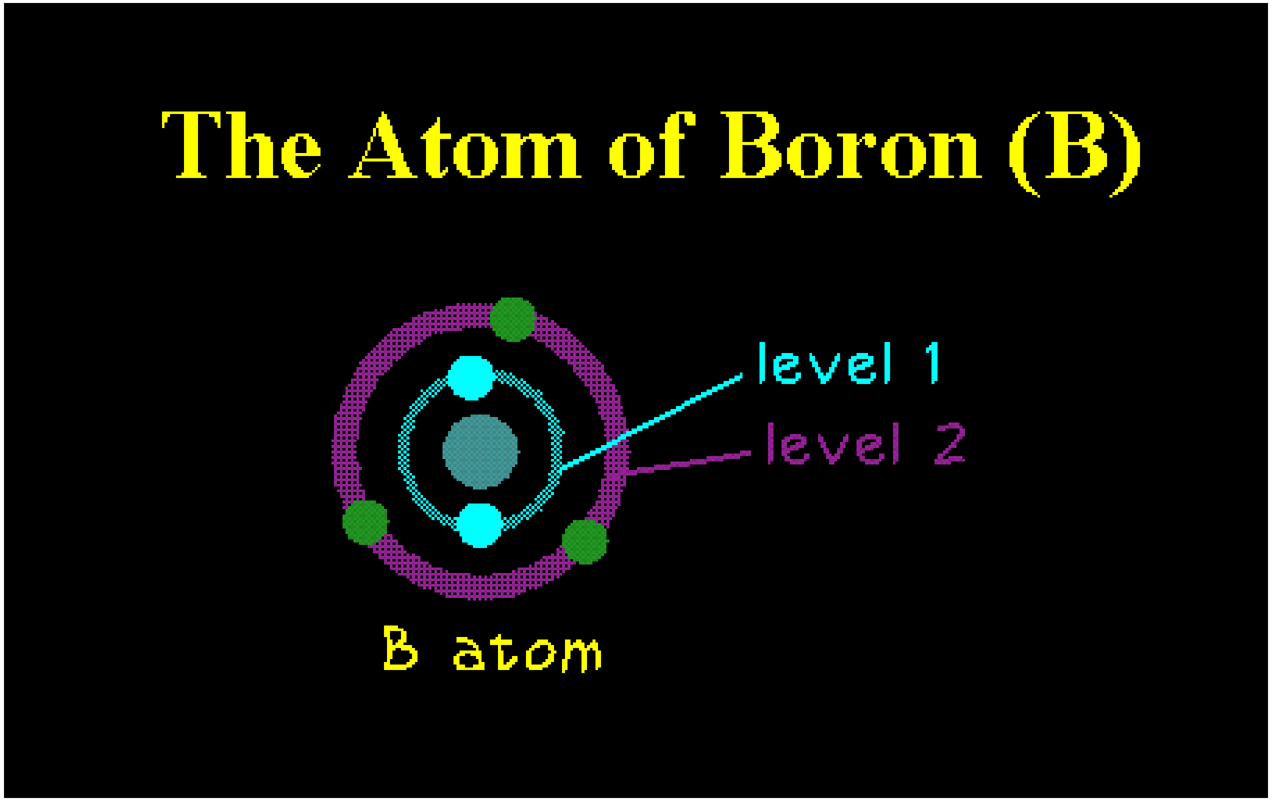
Only 3 Valence-band Electrons

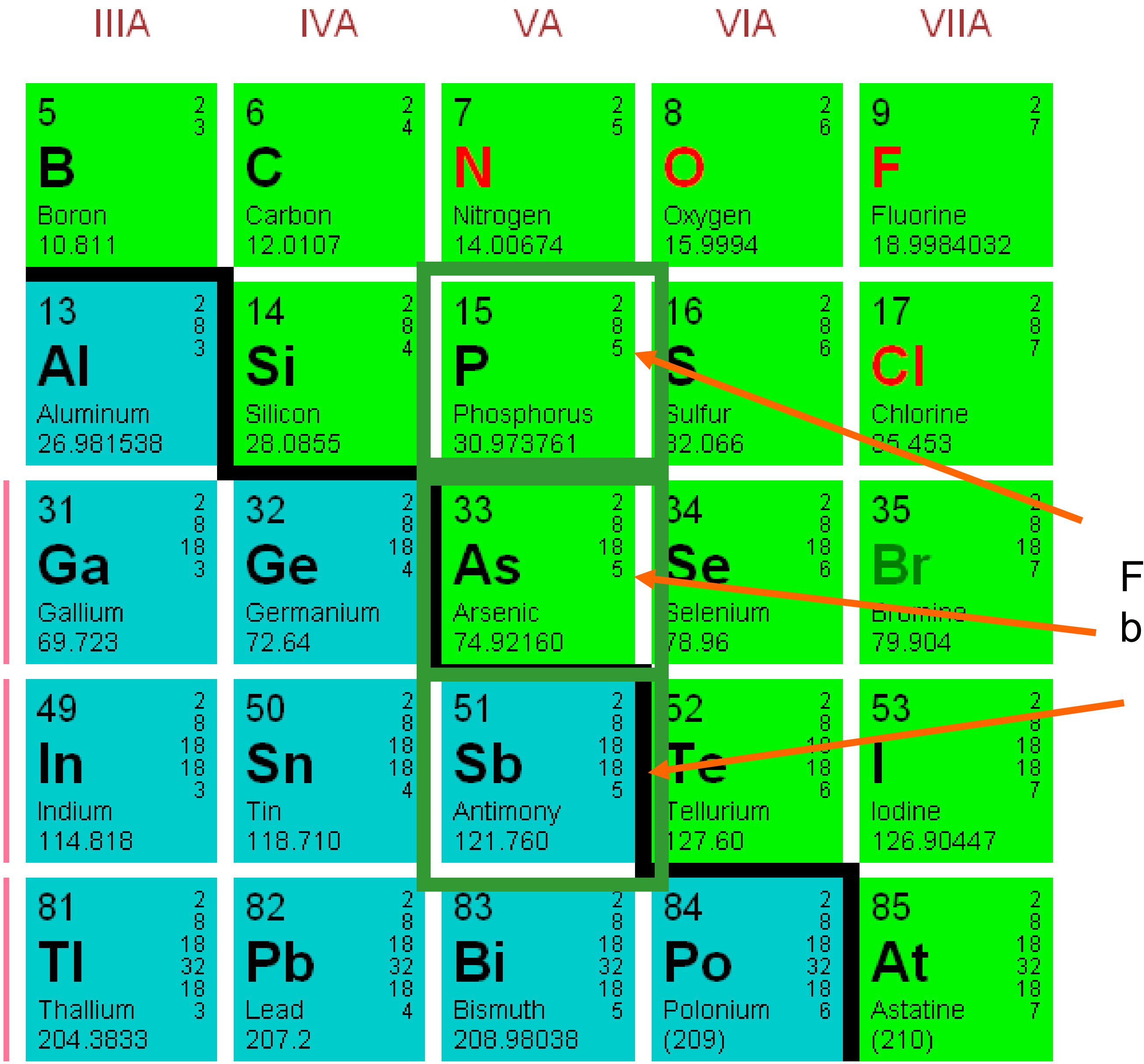
Serves as an “acceptor” of electrons

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



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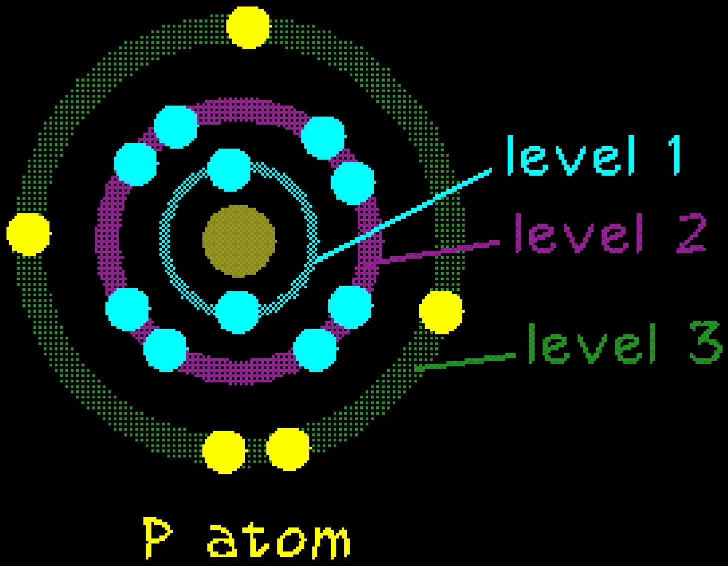
Five Valence-band Electrons

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)



5
2
3
B
Boron
10.811

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

14
2
8
4
Si
Silicon
28.0855

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

15
2
8
5
P
Phosphorus
30.973762

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

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

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

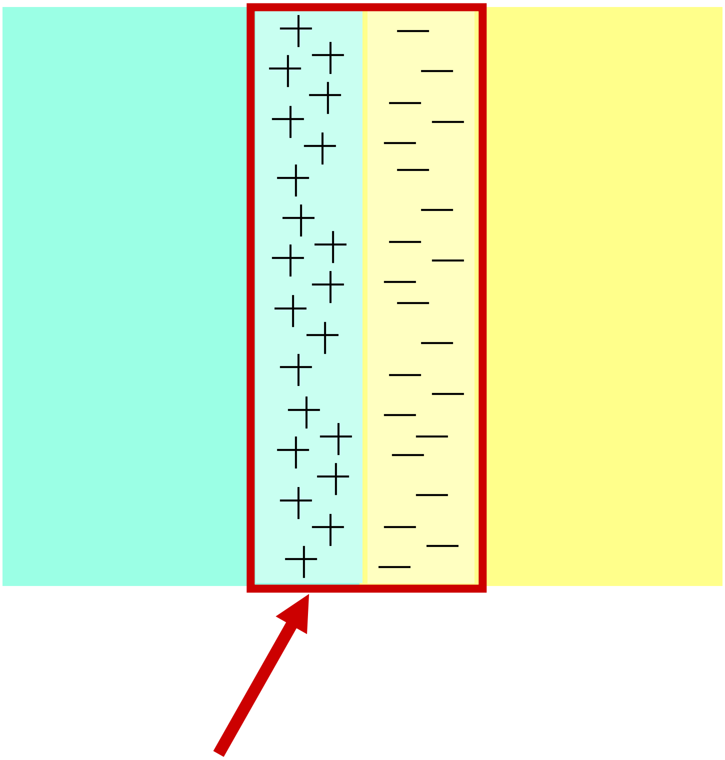
Silicon Dopants in Semiconductor Processes

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)

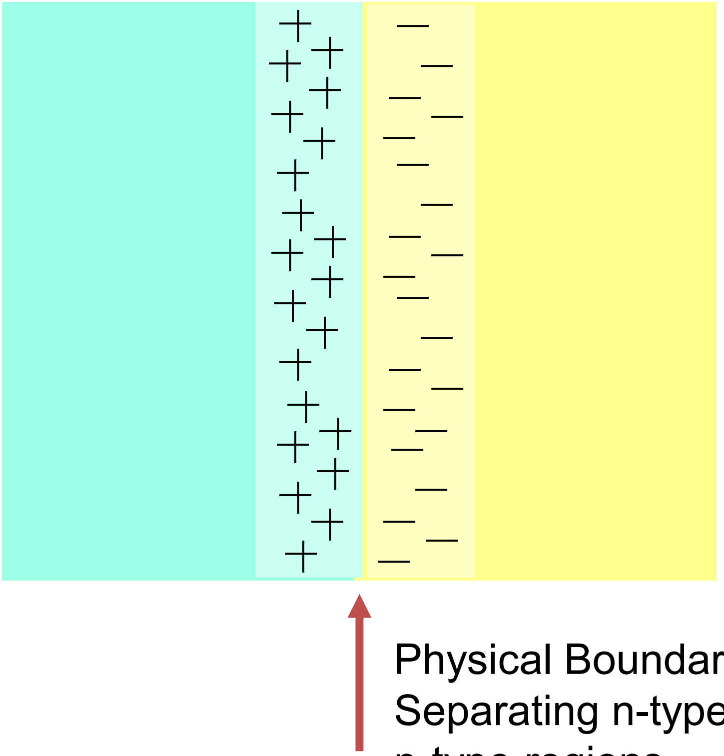
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



Depletion region created that is ionized but void of carriers

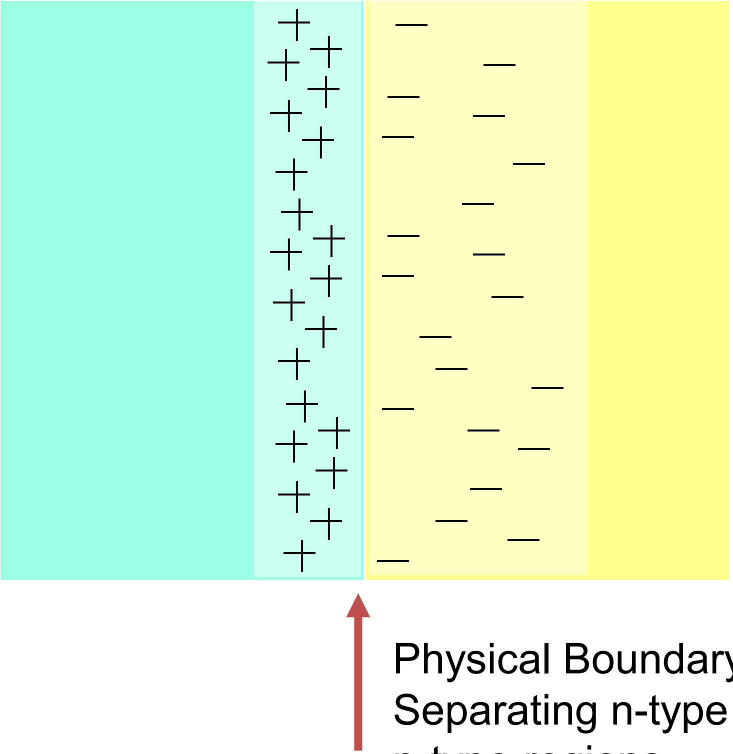
pn Junctions



Physical Boundary Separating n-type and p-type regions

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

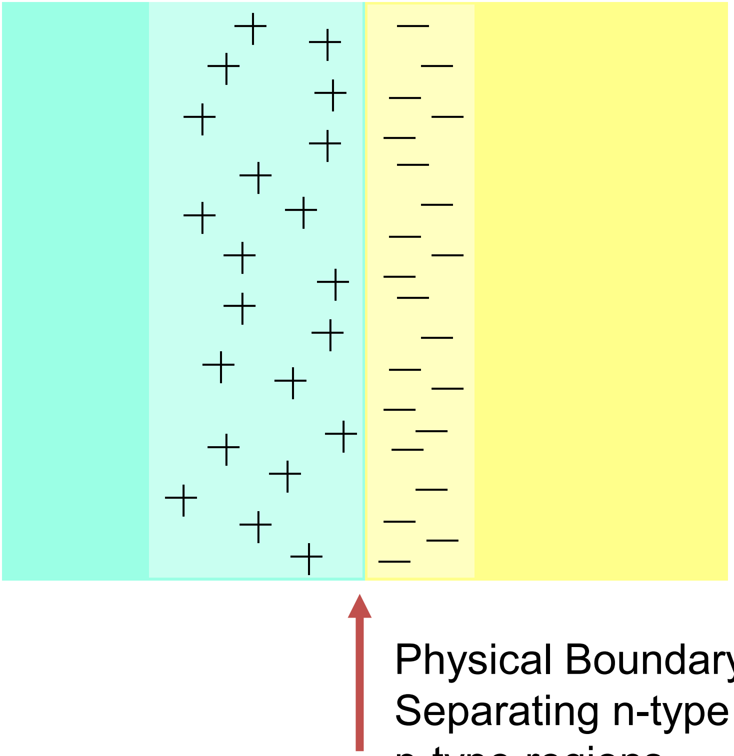
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

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

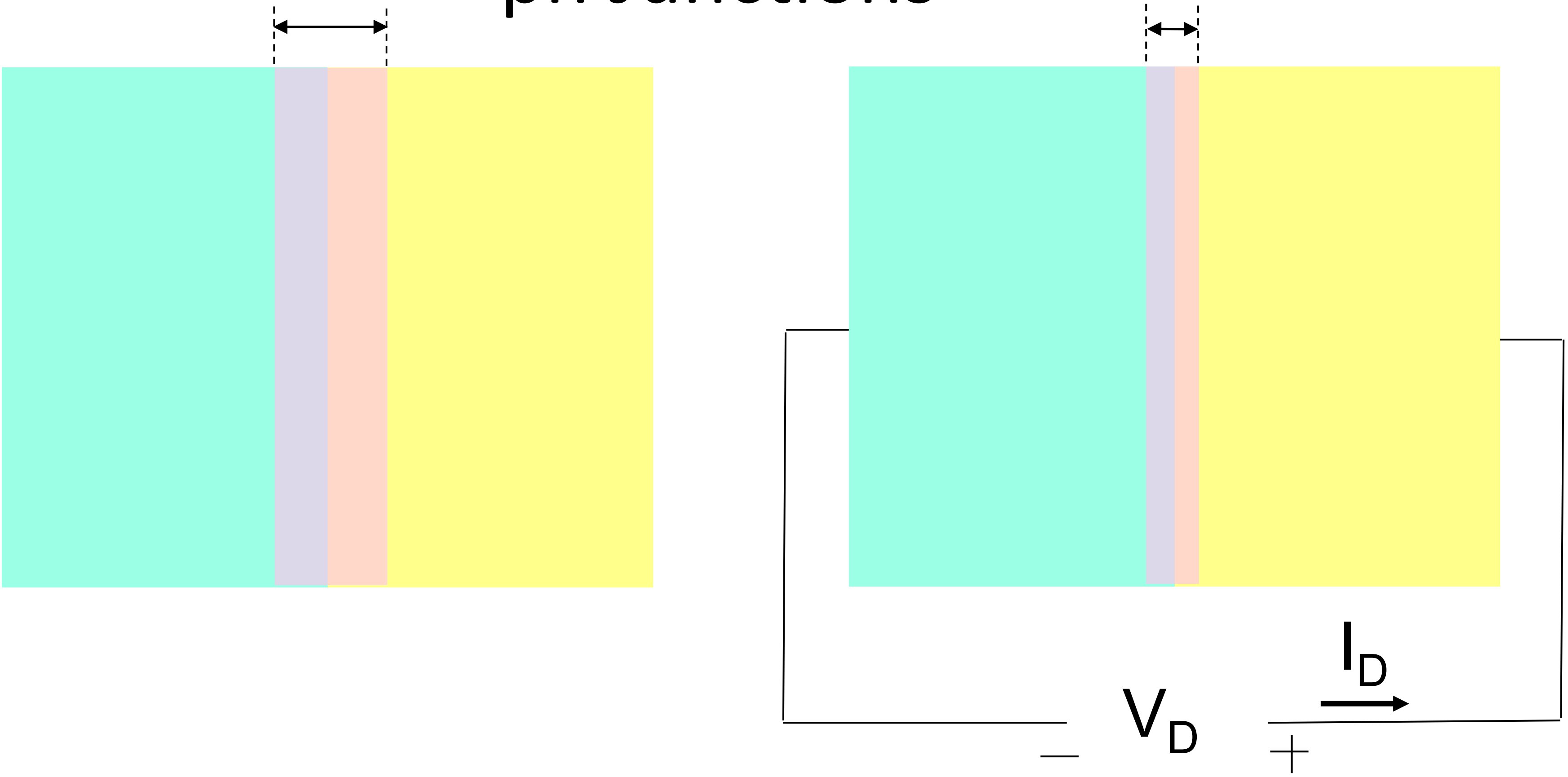
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

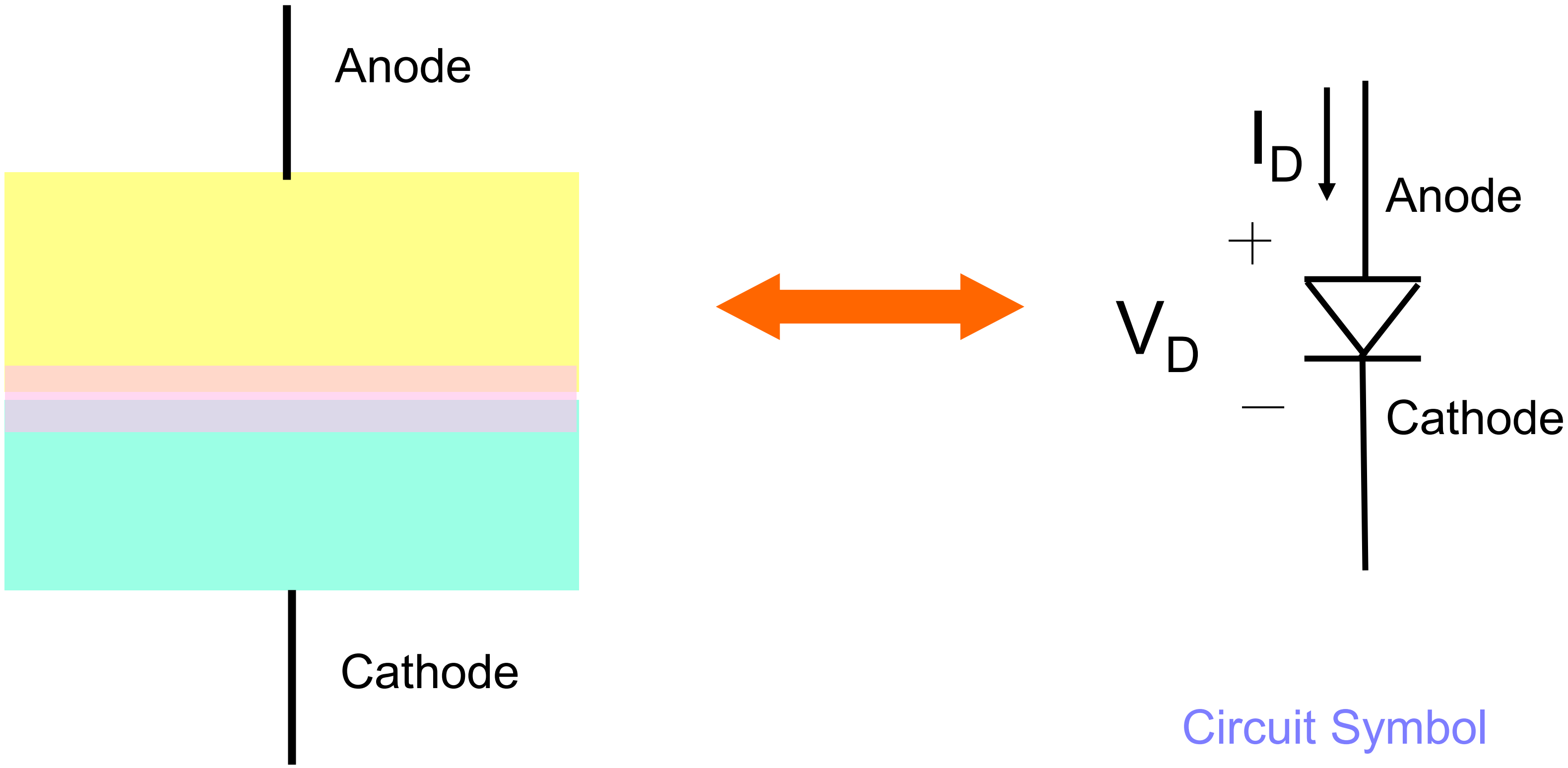
Extends farther into n-type region if n-doping lower than p-doping

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 very rapidly as forward bias increases
- Current is very small under revere bias

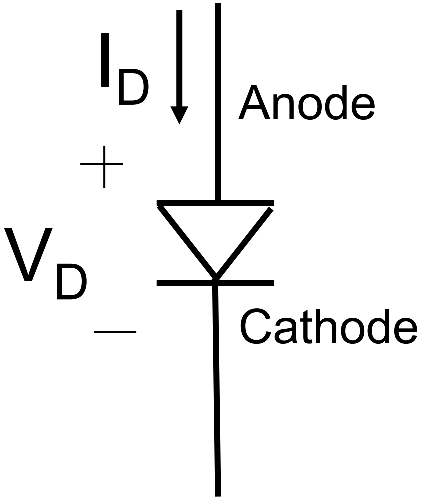
pn Junctions



Circuit Symbol

pn Junctions

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



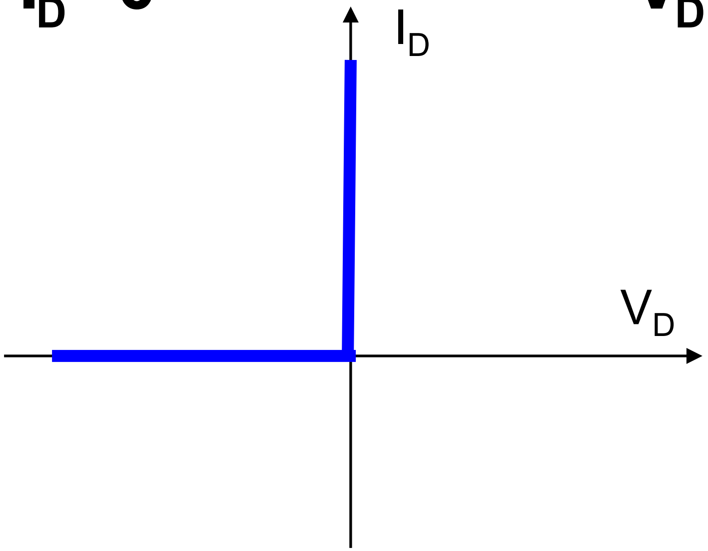
Simple Diode Model:

$V_D = 0$

$I_D = 0$

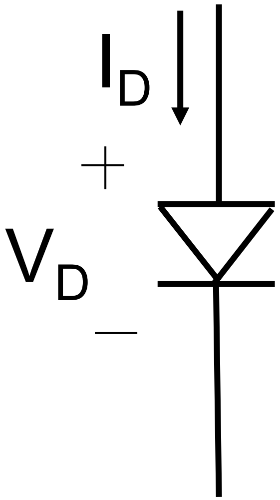
$I_D > 0$

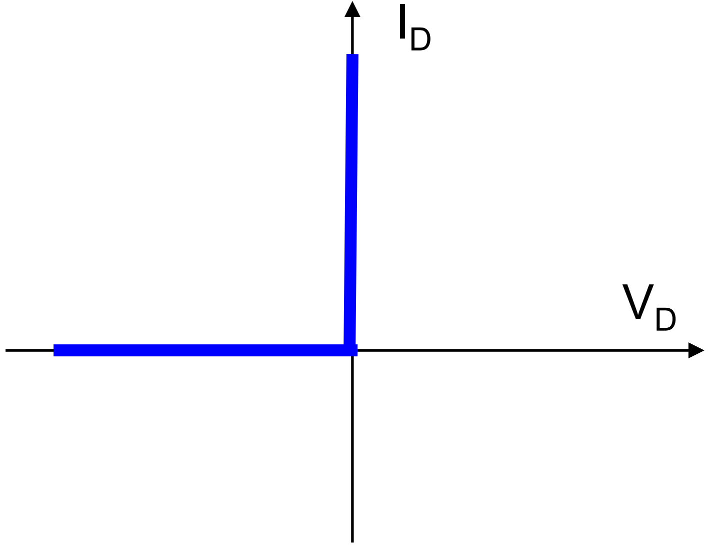
$V_D < 0$



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

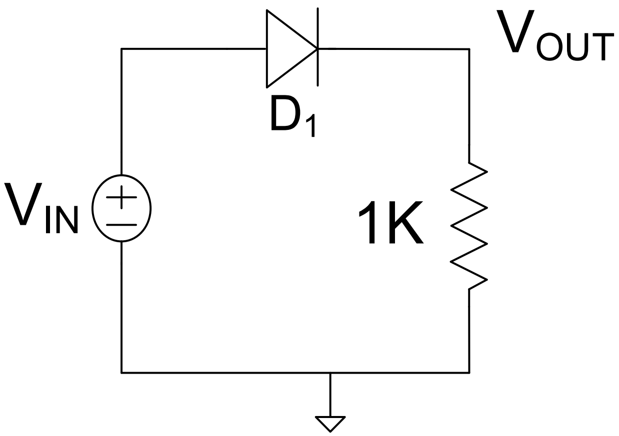
pn Junctions



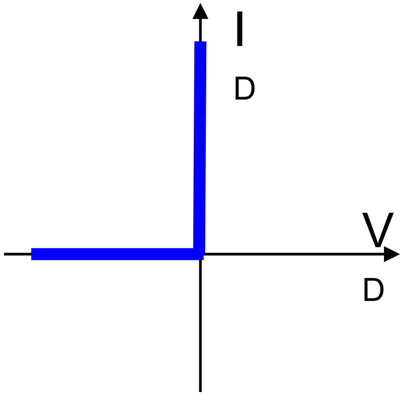

Simple Diode Model:

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

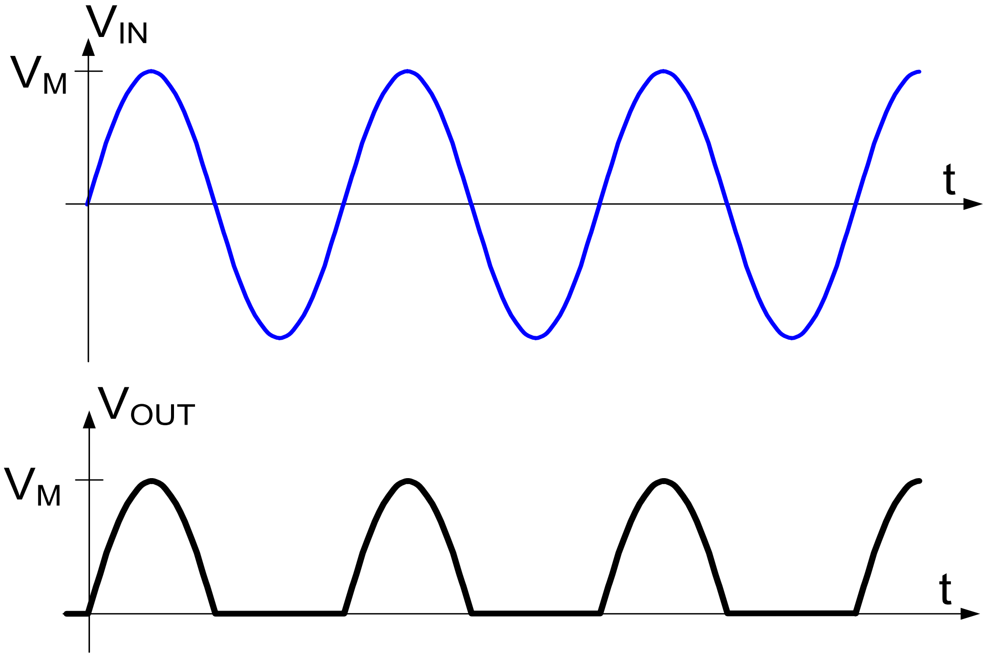
Rectifier Application:



Simple Diode Model:



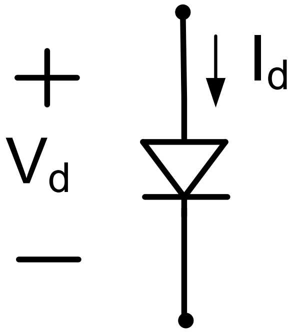
$V_{IN} = V_M \sin\omega t$



I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:



I_S in the 10fA to 100fA range

I_S proportional to junction area

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

k= 1.380 64852 × 10^{-23} JK^{-1}

q = −1.60217662× 10^{-19} C
k/q=8.62× 10^{-5} VK^{-1}

Diode Equation

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

n typically about 1

What is V_t at room temp?

V_t is about 26mV at room temp

Diode equation due to William Shockley, inventor of BJT

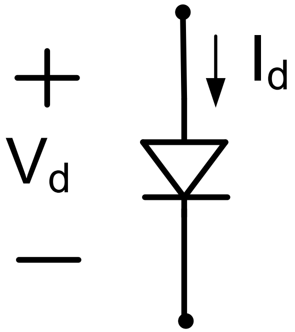
In 1919, William Henry Eccles coined the term ***diode***

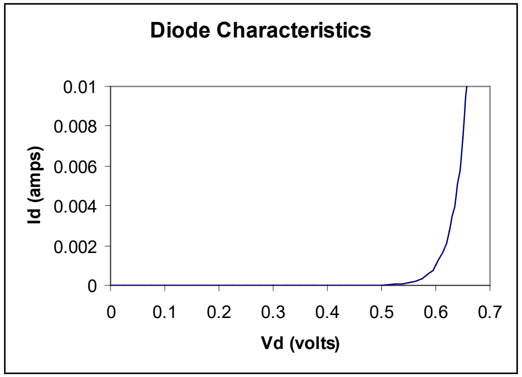
In 1940, Russell Ohl “stumbled upon” the p-n junction diode

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:





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 is unwieldy to work with analytically

Stay Safe and Stay Healthy !

End of Lecture 13