EE 330
Lecture 13

Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFETs

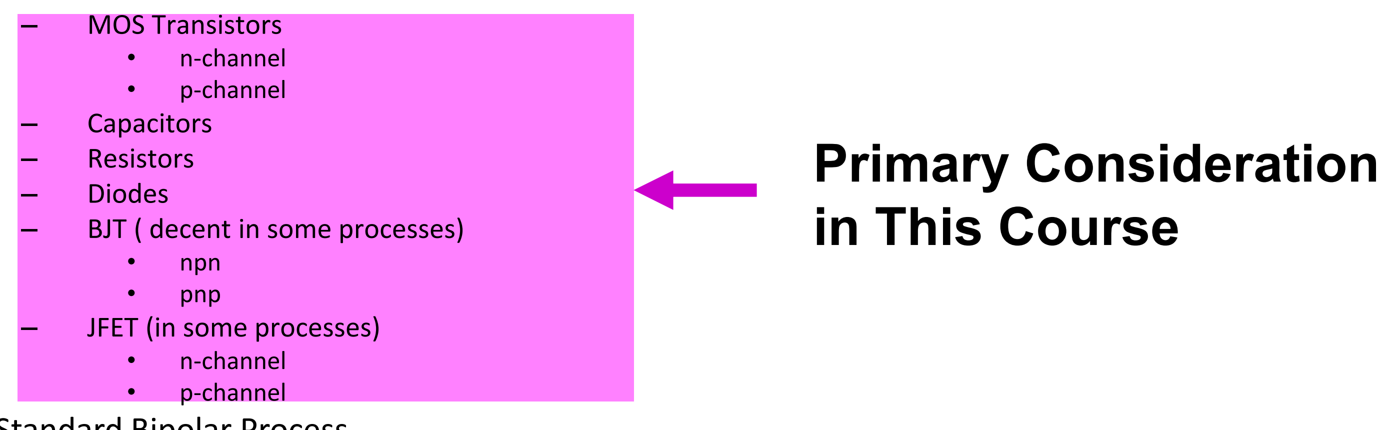
Exam Schedule for Fall 2022

Exam 1	Friday Sept 23
Exam 2	Friday Oct 21
Exam 3	Friday Nov 13
Final	Tuesday Dec 13 12:00 – 2:00 p.m.

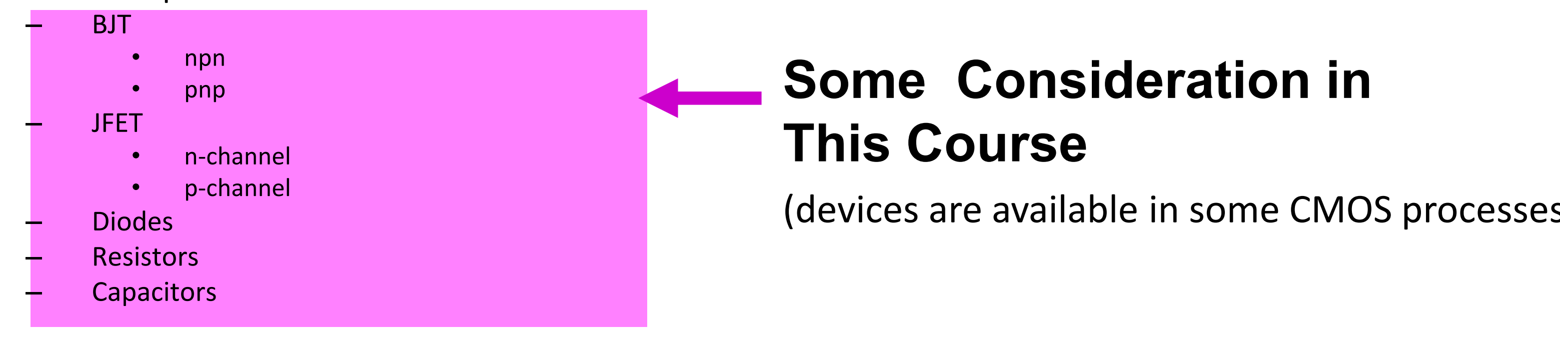
Review from last lecture

Basic Devices

- Standard CMOS Process



- Standard Bipolar Process



- 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

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

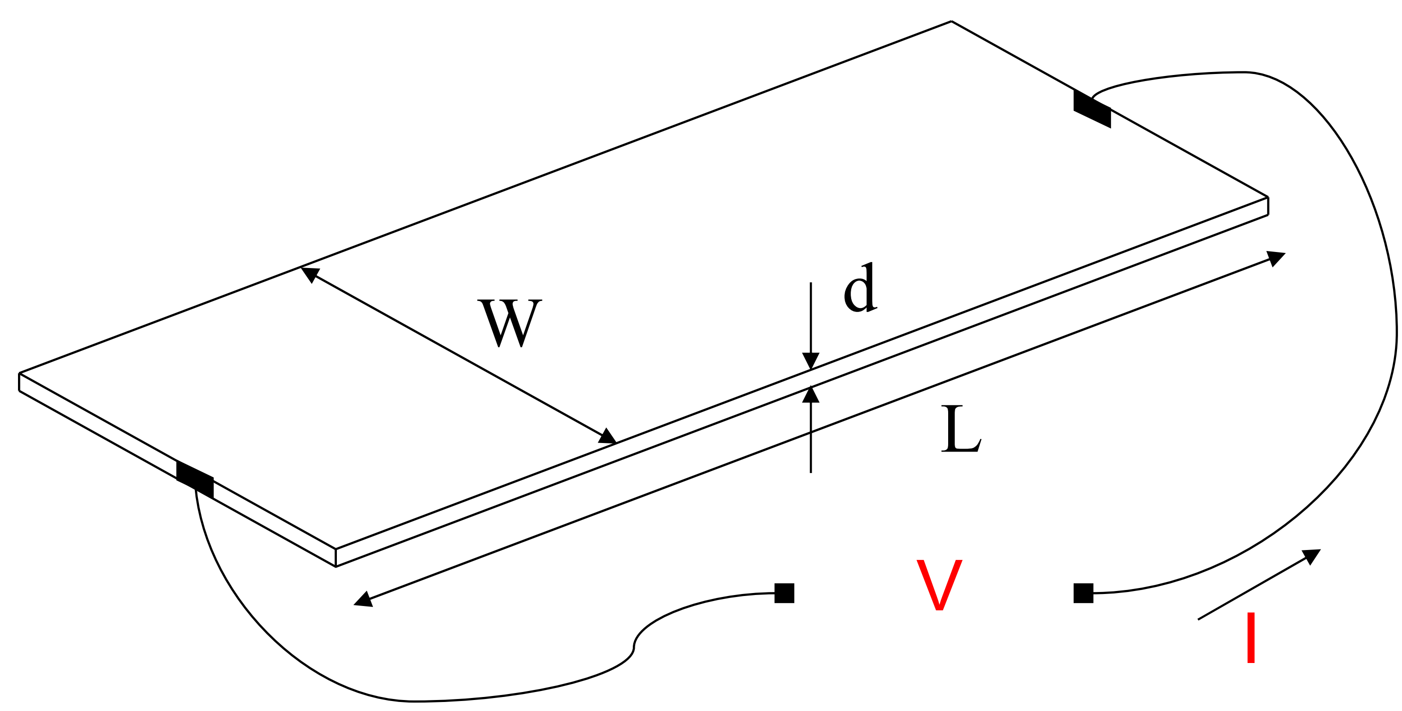
Resistors were discussed when considering interconnects so will only be briefly reviewed here

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

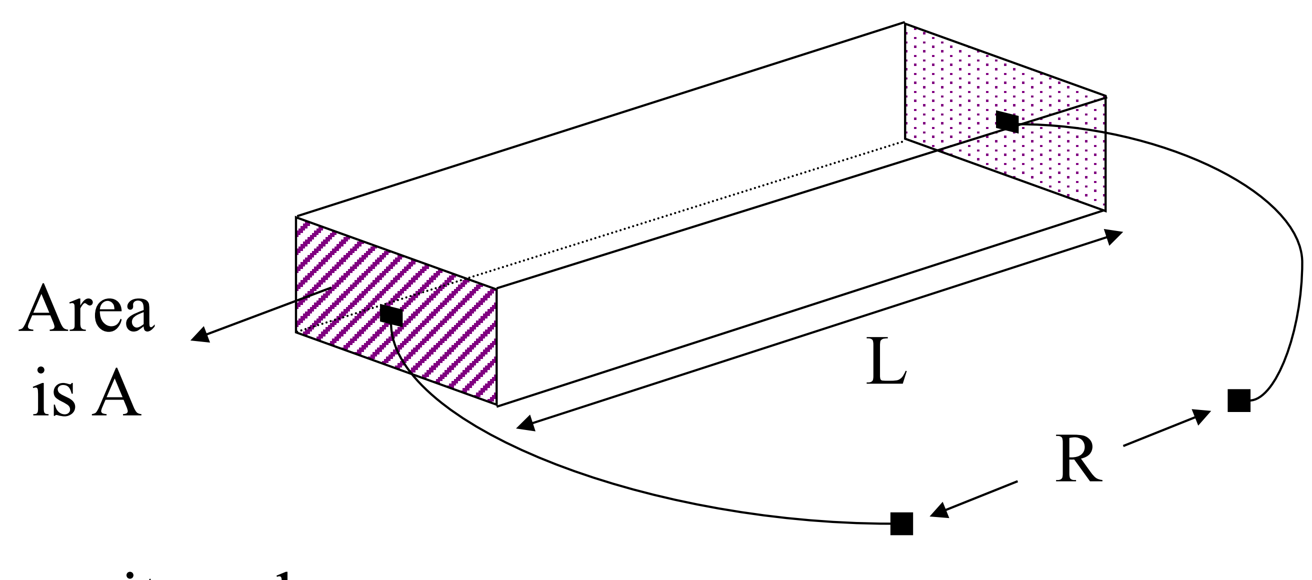


Model:

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

Resistivity

- Volumetric measure of conduction capability of a material

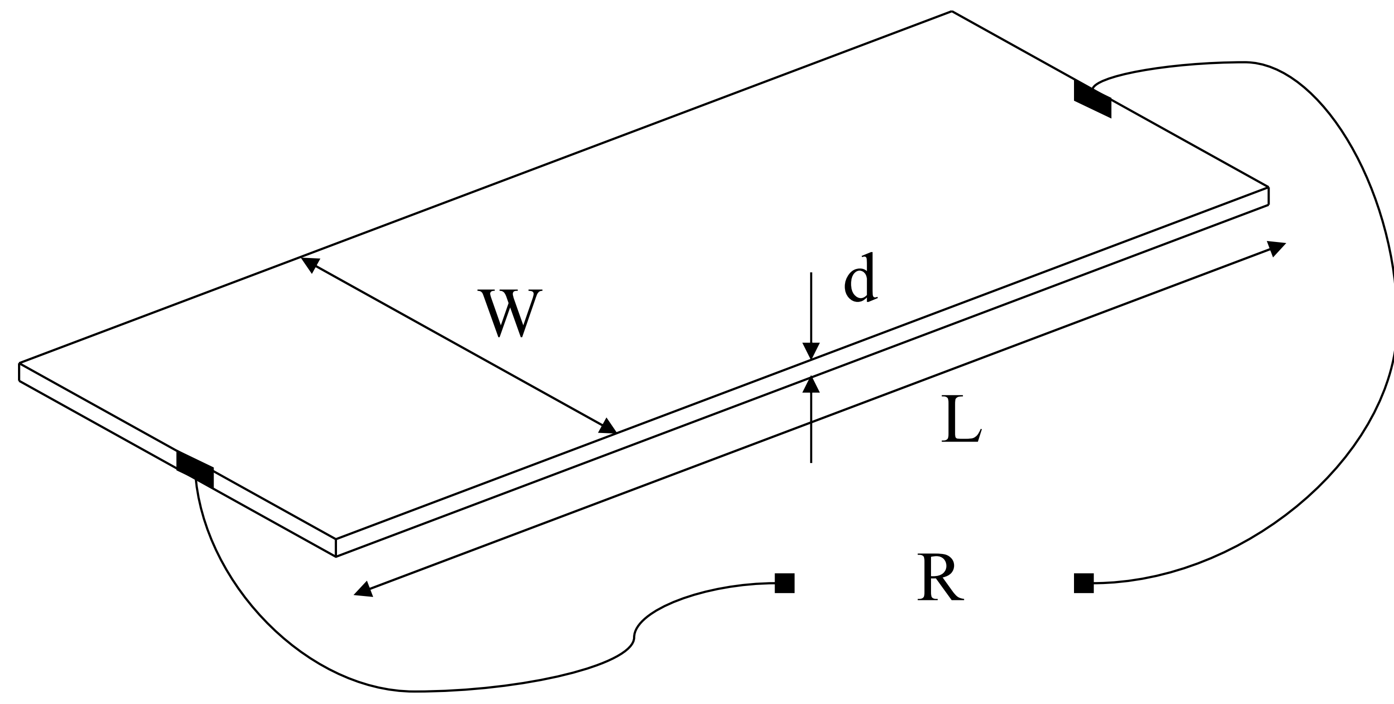


units : ohm cm

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

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

Sheet Resistance



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

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

Relationship between ρ and R

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

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

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

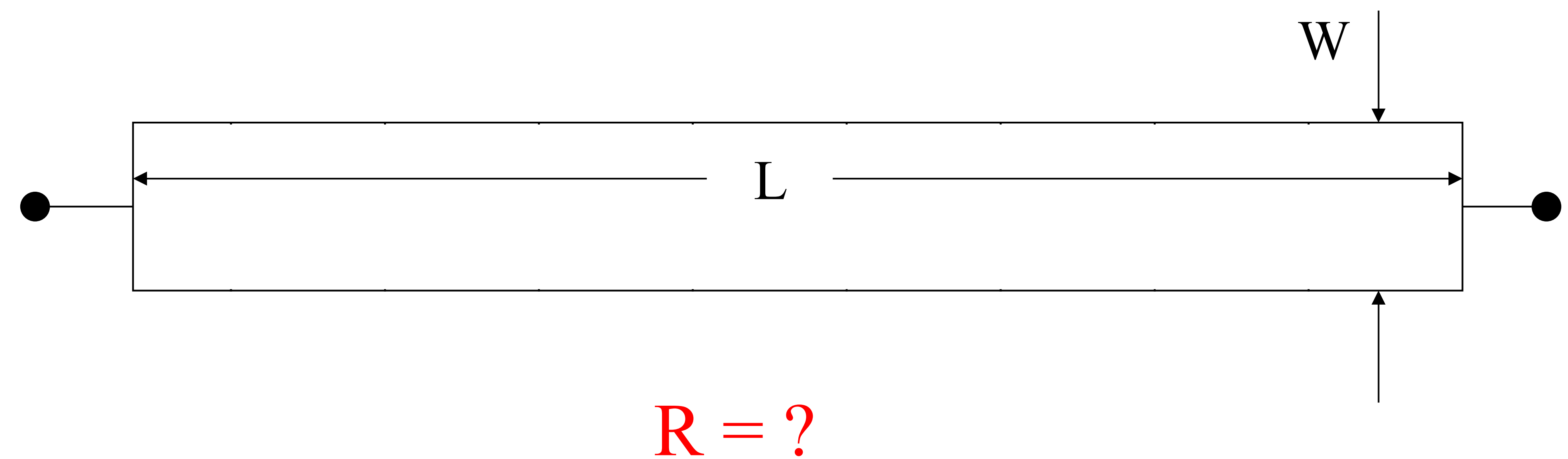
$$A = W \times d$$

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

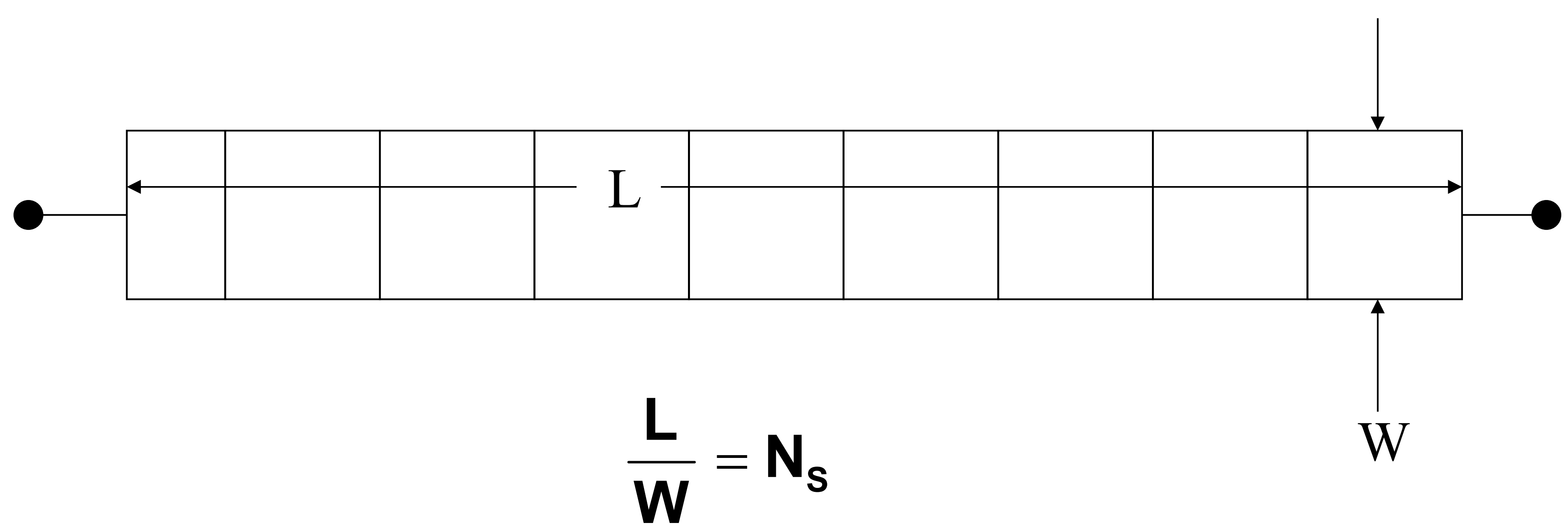
Number of squares, N_S, often used instead of L / W in determining resistance of film resistors

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

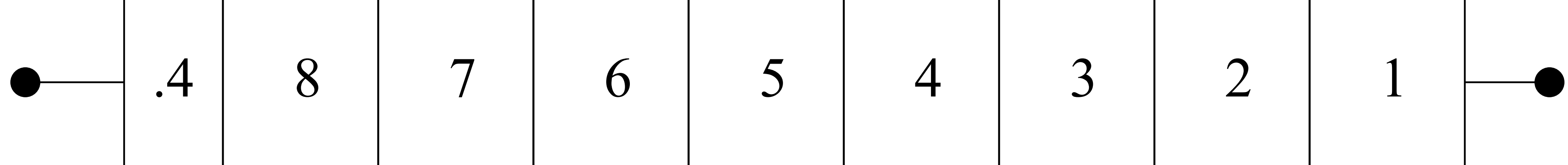
Example 1



Example 1

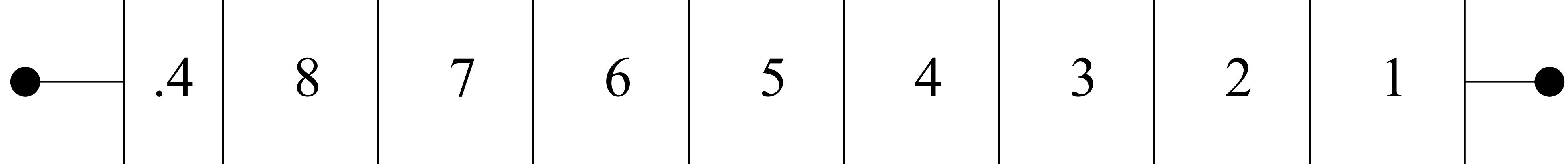


Example 1



R = ?

Example 1

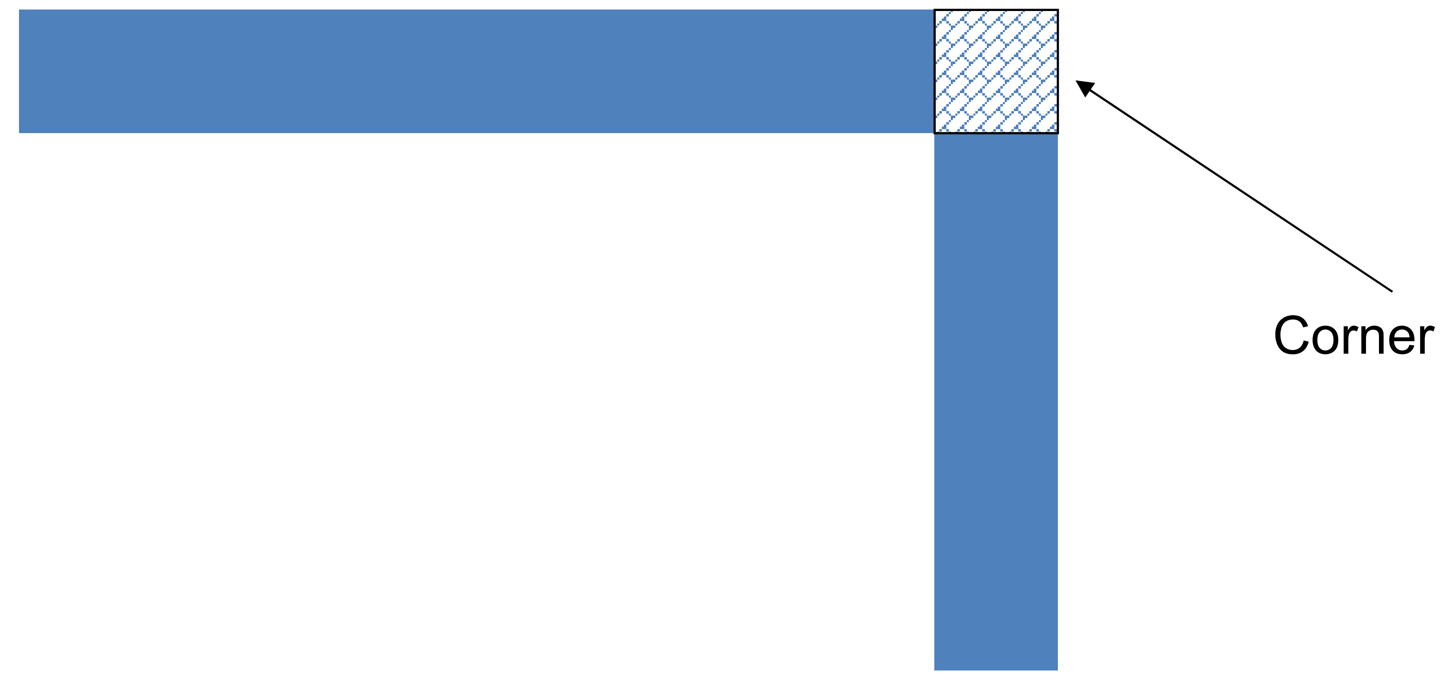


R = ?

N_S=8.4

R = R (8.4)

Corners in Film Resistors

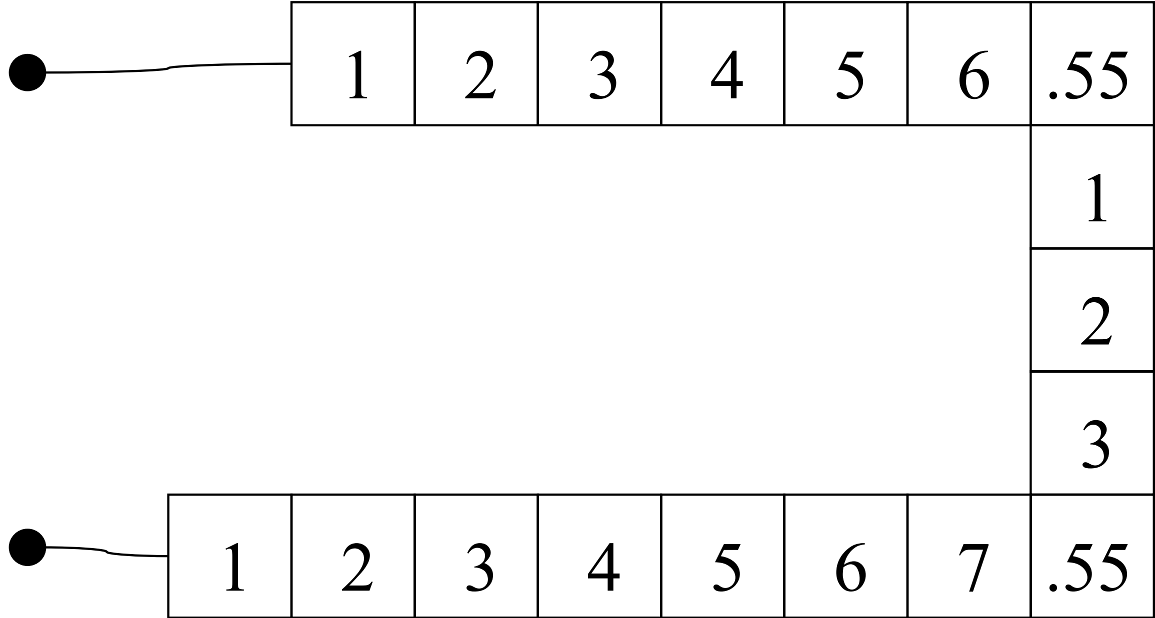


Rule of Thumb: .55 squares for each corner

Example 2

Determine R if $R = 100\ \Omega$ /

Example 2



N_S=17.1

R = (17.1) R

R = 1710 Ω

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

Resistivity and Temperature Coefficient at 20 C

Material	Resistivity ρ (ohm m)		Temperature coefficient α per degree C	Conductivity σ x 10^7 /Ωm	Ref
Silver	1.59	$x10^{-8}$	.0038	6.29	3
Copper	1.68	$x10^{-8}$	.00386	5.95	3
Copper, annealed	1.72	$x10^{-8}$	.00393	5.81	2
Aluminum	2.65	$x10^{-8}$	.00429	3.77	1
Tungsten	5.6	$x10^{-8}$	.0045	1.79	1
Iron	9.71	$x10^{-8}$	.00651	1.03	1
Platinum	10.6	$x10^{-8}$	.003927	0.943	1
Manganin	48.2	$x10^{-8}$	.000002	0.207	1
Lead	22	$x10^{-8}$	...	0.45	1
Mercury	98	$x10^{-8}$	.0009	0.10	1
Nichrome (Ni,Fe,Cr alloy)	100	$x10^{-8}$	.0004	0.10	1
Constantan	49	$x10^{-8}$	...	0.20	1
Carbon* (graphite)	3-60	$x10^{-5}$	-.0005	...	1
Germanium*	1-500	$x10^{-3}$	-.05	...	1
Silicon*	0.1-60	...	-.07	...	1
Glass	1-10000	$x10^{9}$	...	...	1
Quartz (fused)	7.5	$x10^{17}$	...	...	1
Hard rubber	1-100	$x10^{13}$	...	...	1

hyperphysics.phy-astr.gsu.edu/hbase/Tables/rstiv.html

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

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

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

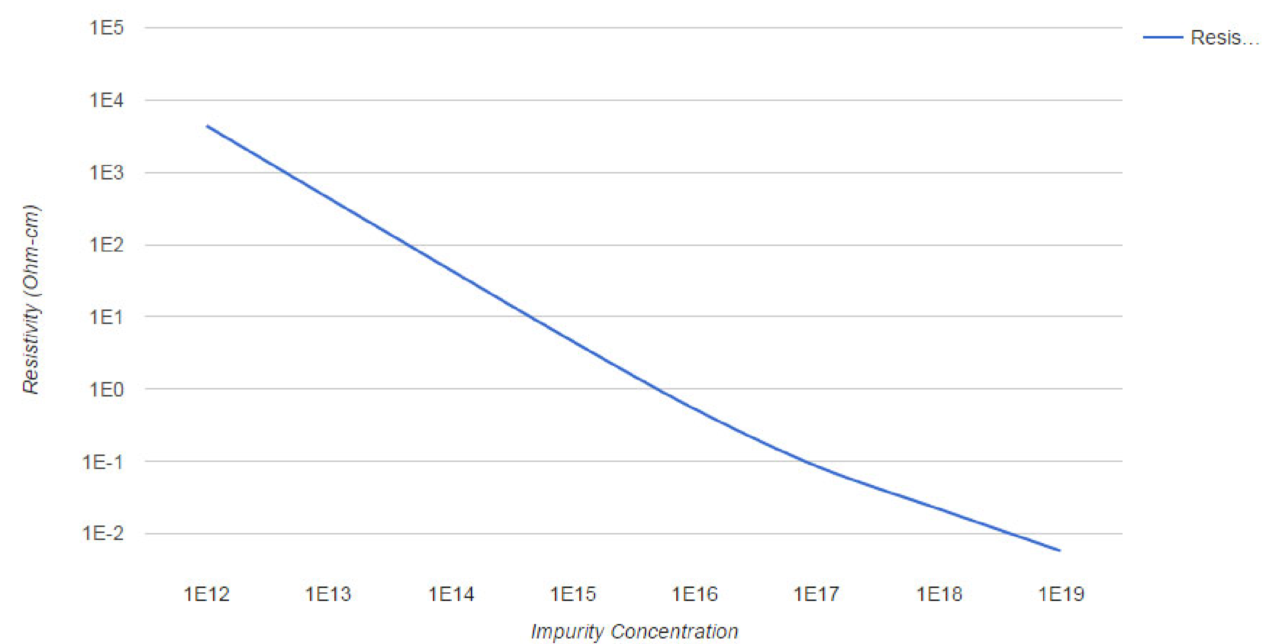
Impurity Concentration: 1e15 (cm^{-3})

[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 (selected)
- Phosphorus

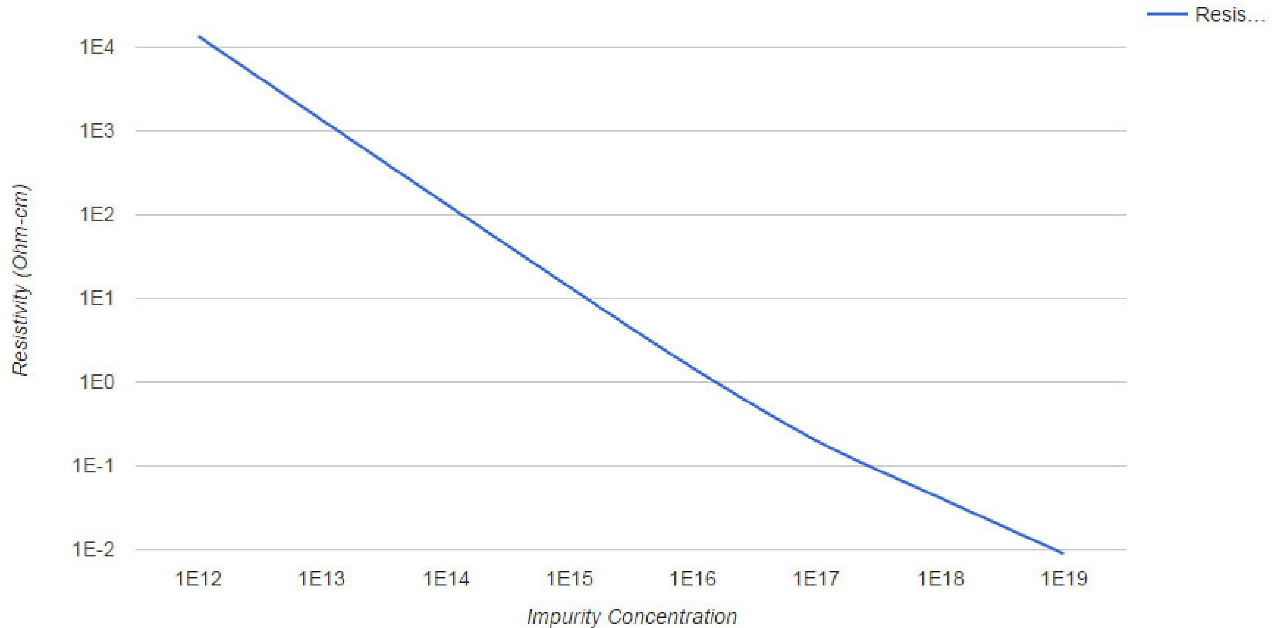
Impurity Concentration: 1e15 (cm^{-3})

Calculate | Export to CSV

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

Resistivity: 13.511075765839905 [Ω-cm]

Calculations are for a silicon substrate.



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

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

Dopant:
- ○ Arsenic
- ○ Boron
- ◉ Phosphorus

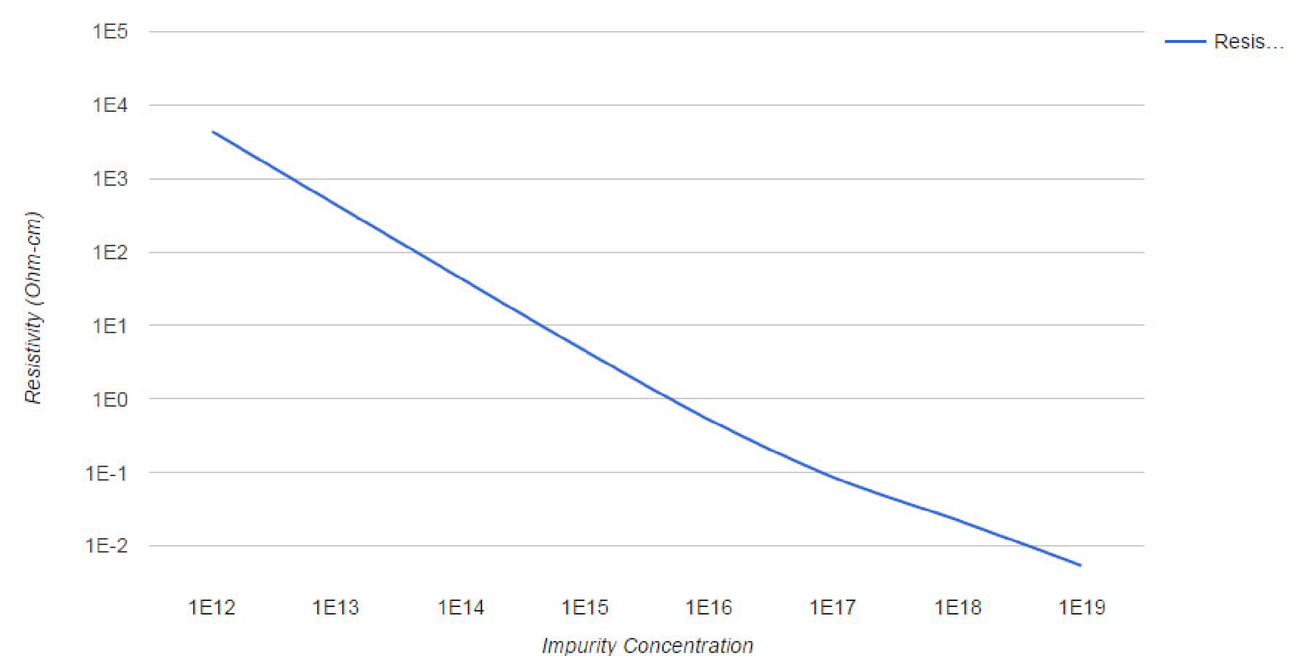
Impurity Concentration: 1e15 (cm^{-3})

[Calculate] [Export to CSV]

Mobility: 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:

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

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,

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

Identical Expressions for Capacitors

Voltage Coefficients

Used for indicating voltage sensitivity of resistors & capacitors

For a resistor:

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

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,

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

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 $\Omega/\square$	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	-

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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 Ω/□	0.4%	1500 ppm/°C	200 ppm/V
N^+ Diffused resistor (non-silicide)	50–80 Ω/□	0.4%	1500 ppm/°C	200 ppm/V
N^+ Poly resistor (non-silicide)	300 Ω/□	2%	−2000 ppm/°C	100 ppm/V
P^+ Poly resistor (non-silicide)	300 Ω/□	0.5%	−500 ppm/°C	100 ppm/V
P^- Poly resistor (non-silicide)	1000 Ω/□	0.5%	−1000 ppm/°C	100 ppm/V
n-well resistor	1–2 kΩ/□		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-semi-conductor 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/°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

RESISTORS

MOS Resistors - Source/Drain Resistor

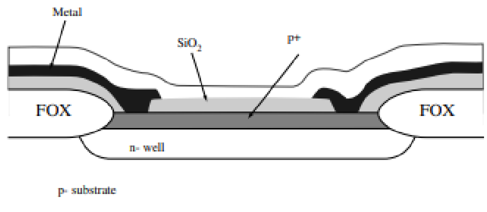

Fig. 2.5-16

Diffusion:

10-100 ohms/square
Absolute accuracy = ±35%
Relative accuracy=2% (5µm), 0.2% (50µm)
Temperature coefficient = +1500 ppm/°C
Voltage coefficient ≈ 200 ppm/V

Ion Implanted:

500-2000 ohms/square
Absolute accuracy = ±15%
Relative accuracy=2% (5µm), 0.15% (50µn
Temperature coefficient = +400 ppm/°C
Voltage coefficient ≈ 800 ppm/V

N-well Resistor

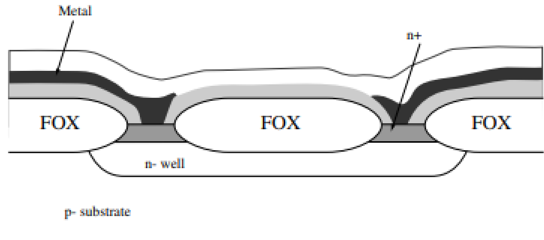

Fig. 2.5-18

1000-5000 ohms/square
Absolute accuracy = ±40%
Relative accuracy ≈ 5%
Temperature coefficient = 4000 ppm/°C
Voltage coefficient is large ≈ 8000 ppm/V
Comments:

- Good when large values of resistance are needed.
- Parasitics are large and resistance is voltage dependent

Polysilicon Resistor

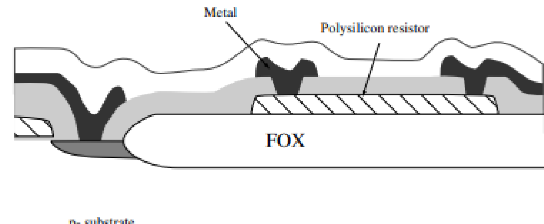

Fig. 2.5-17

30-100 ohms/square (unshielded)
100-500 ohms/square (shielded)
Absolute accuracy = ±30%
Relative accuracy = 2% (5 µm)
Temperature coefficient = 500-1000 ppm/°C
Voltage coefficient ≈ 100 ppm/V
Comments:

- Used for fuzzes and laser trimming
- Good general resistor with low parasitics

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Allen is probably missing the sign on the TCR of poly resistors as they likely have negative TCRs

Temperature-Dependent Characteristics of Polysilicon and Diffused Resistors

Hung-Ming Chuang, Kong-Beng Thei, Sheng-Fu Tsai, and Wen-Chau Liu

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 5, MAY 2003 1413

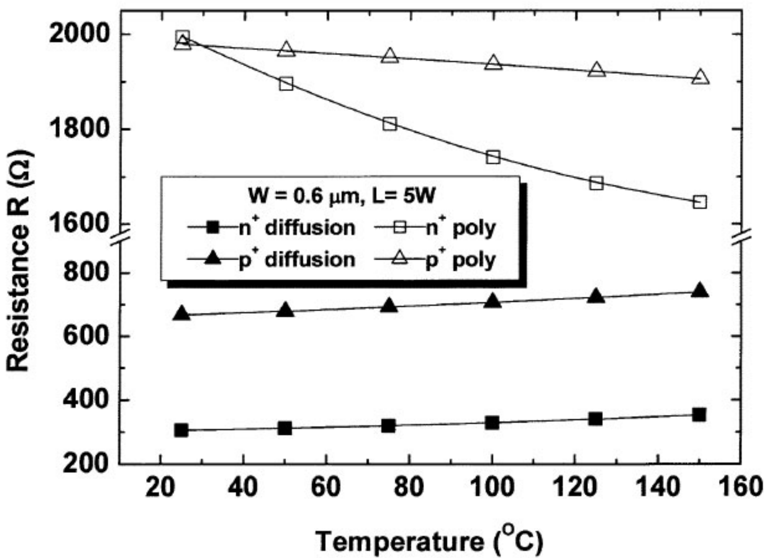


Fig. 1. Total resistances R of polysilicon and diffused resistors with $W = 0.6\ \mu$m and $L = 5$ W versus temperature.

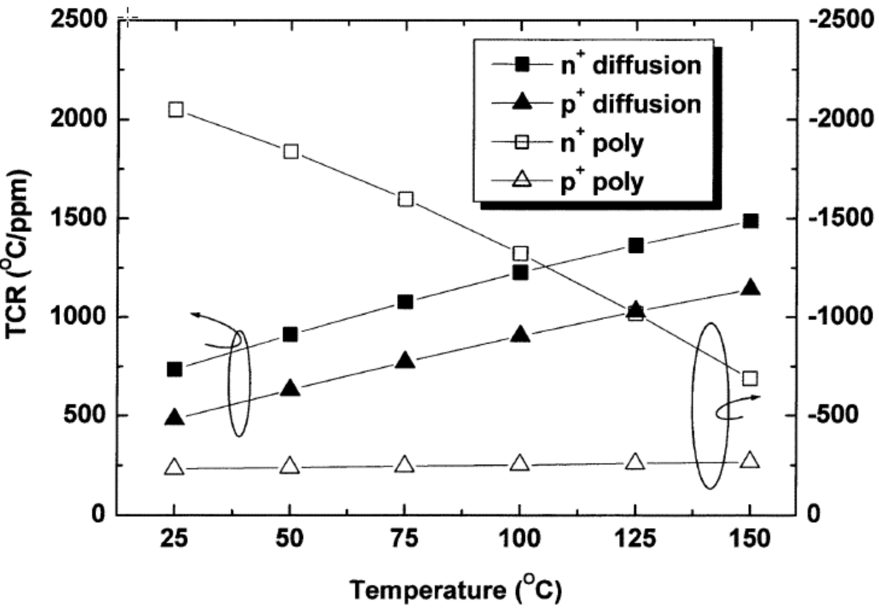
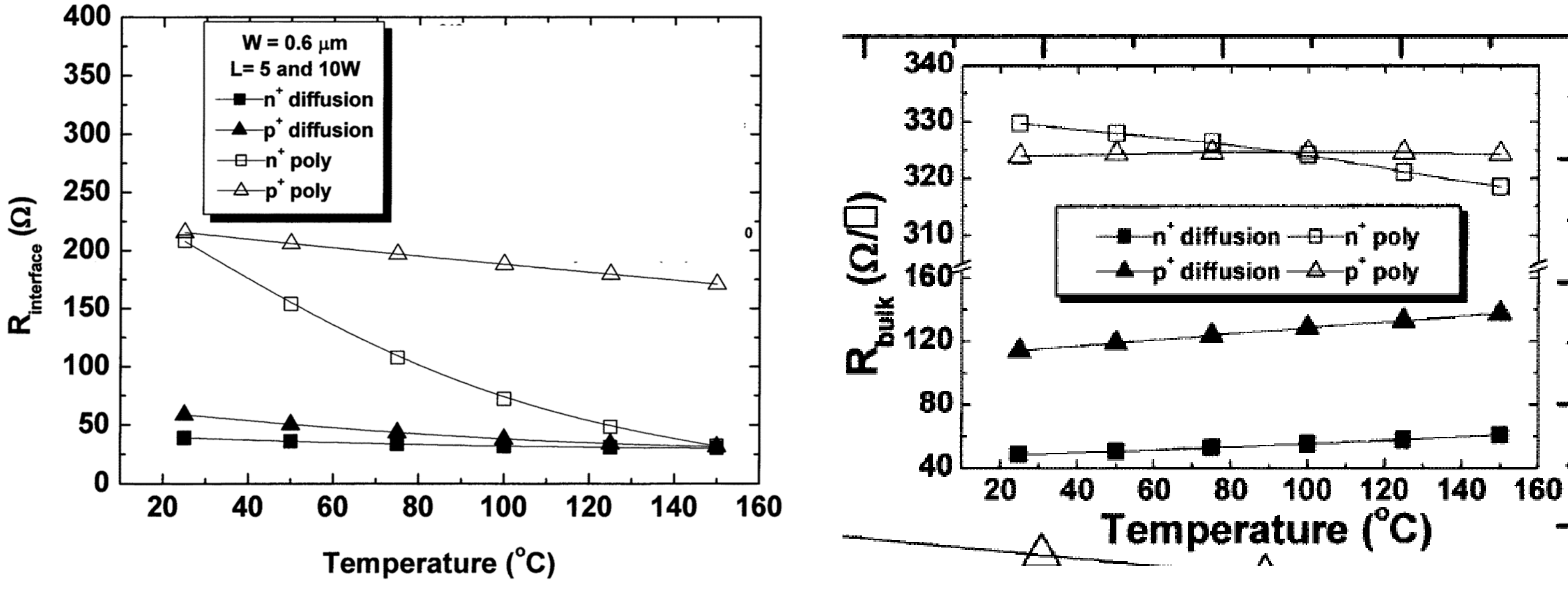


Fig. 2. TCR values of polysilicon and diffused resistors with $W = 0.6\ \mu$m and $L = 5$ W.

Temperature-Dependent Characteristics of Polysilicon and Diffused Resistors

Hung-Ming Chuang, Kong-Beng Thei, Sheng-Fu Tsai, and Wen-Chau Liu



R_{BULK} is the body of the Poly resistors

concentration and RTA temperature, the TCR values can be precisely controlled. Yet, in view of the throughput, resistors are generally doped with source/drain implantation or LDD implantation if higher resistivity is required. Also, the RTA temperature is mainly determined

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%

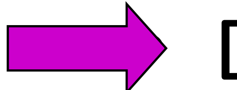
Did not need $R(T_1)$ to answer this question !

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

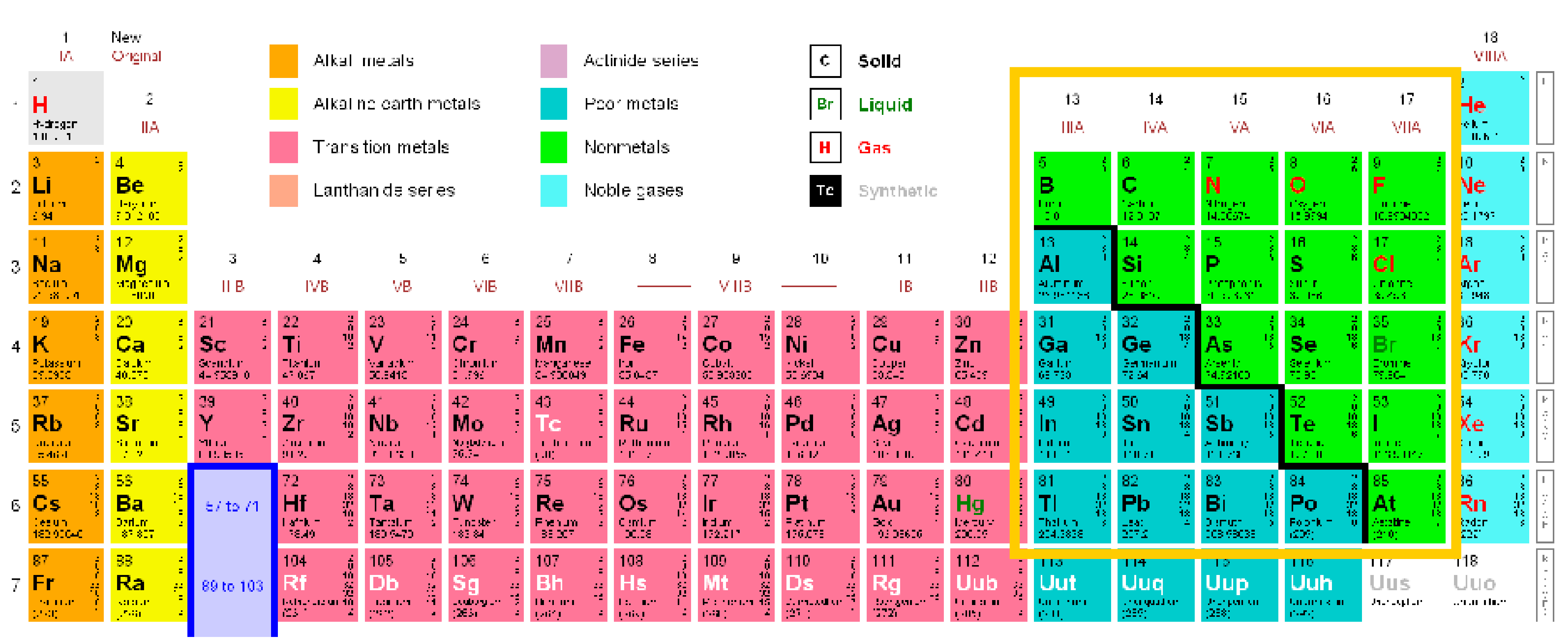
- Resistor



Diode

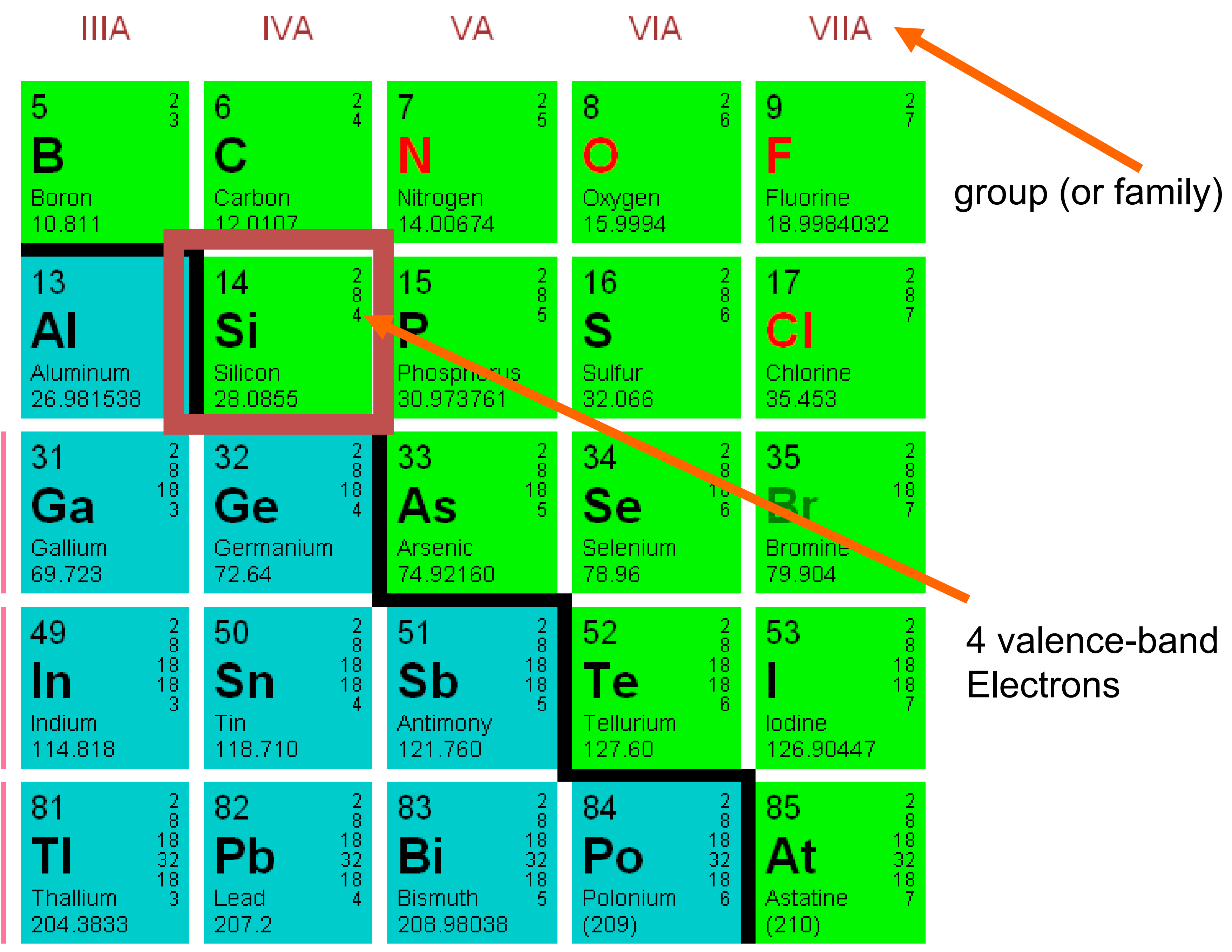
- Capacitor
- MOSFET
- BJT

Periodic Table of the Elements

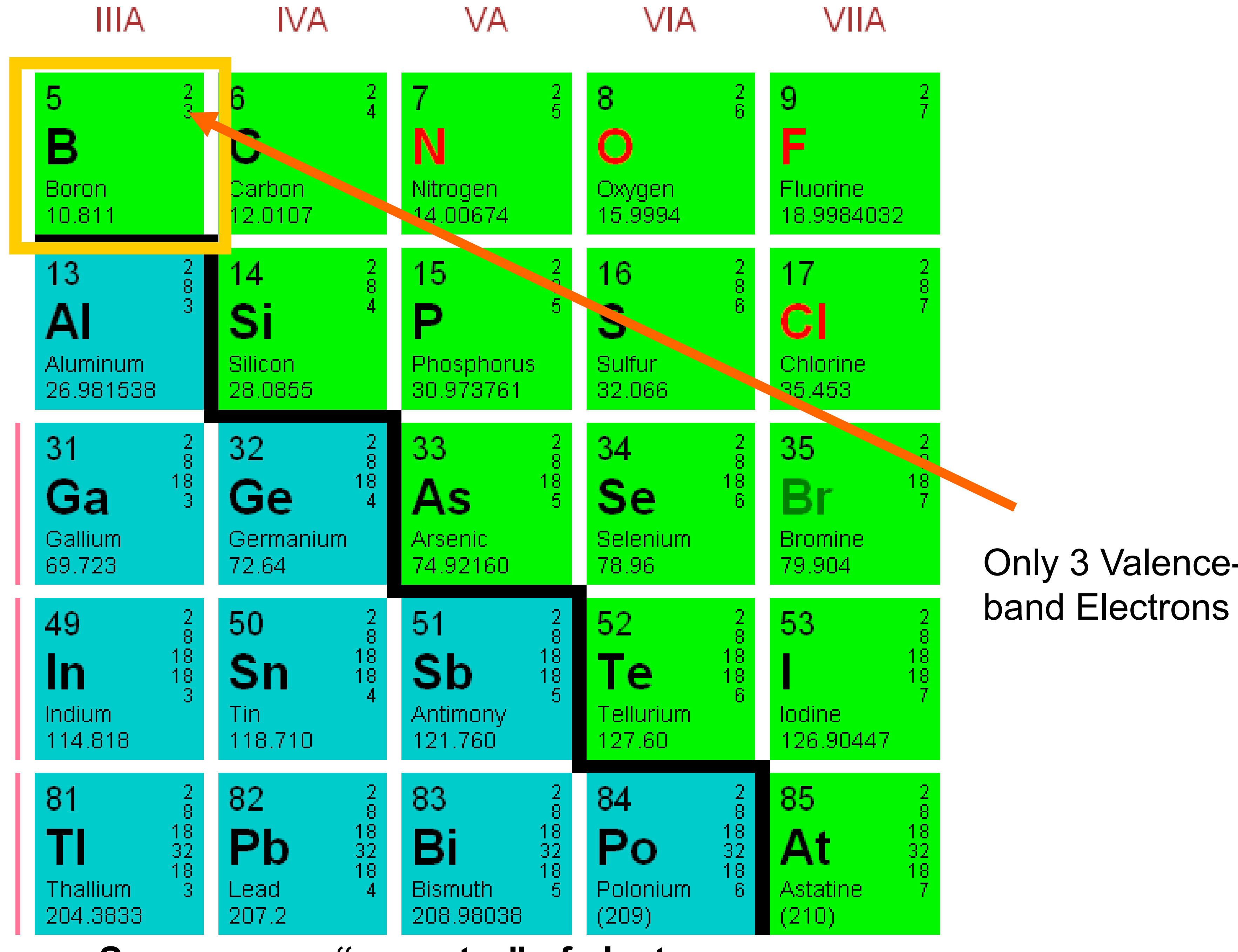


http://www.dayah.com/periodic/Images/periodic%20table.png

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)



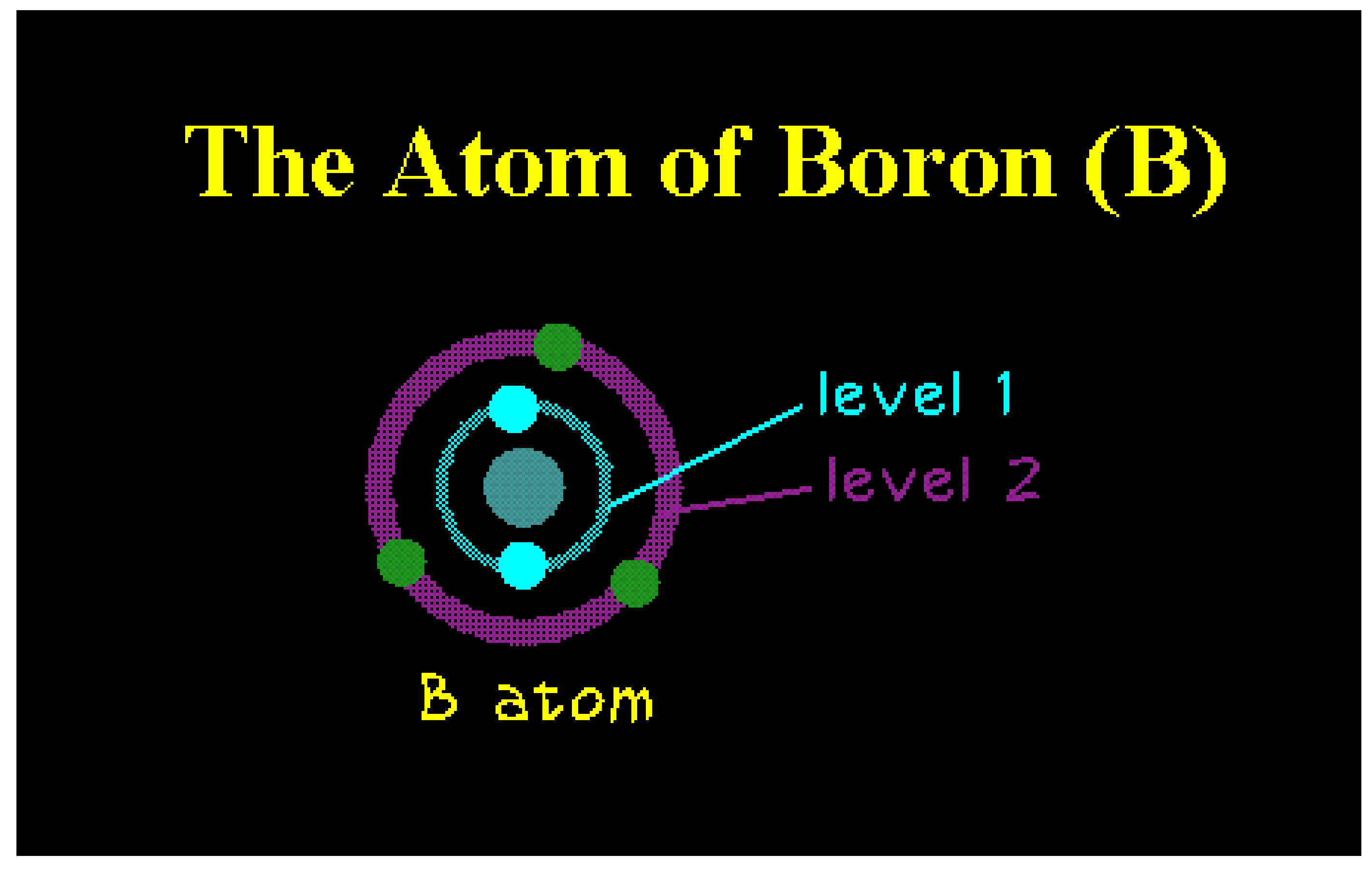
All elements in group IV have 4 valence-band electrons



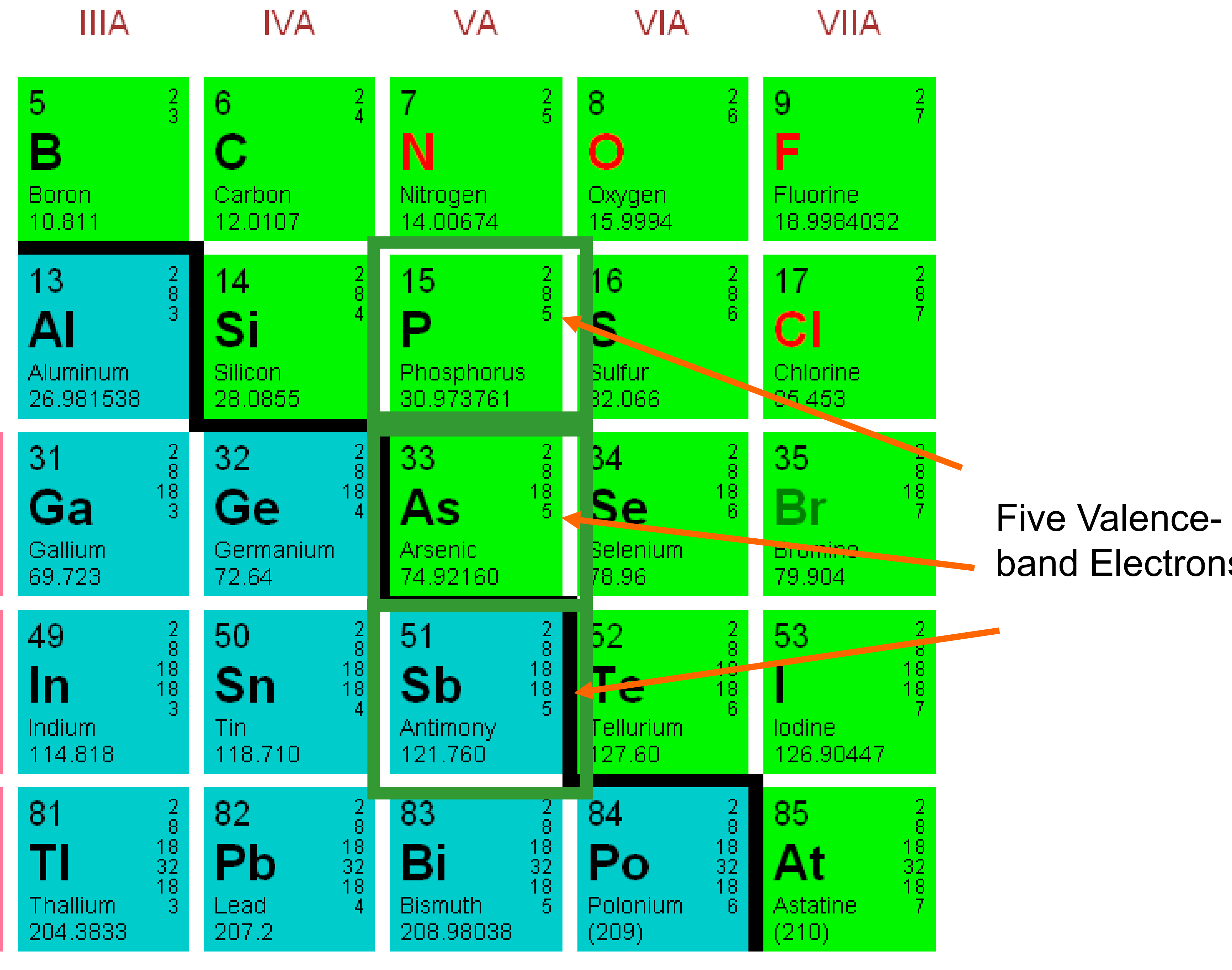
Serves as an “acceptor” of electrons

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

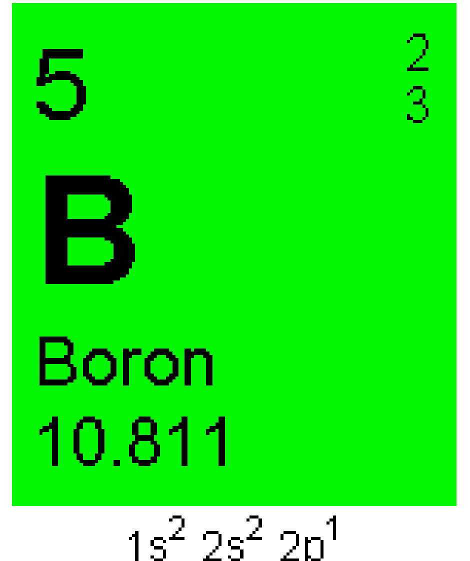
The Atom of Phosphorus (P)

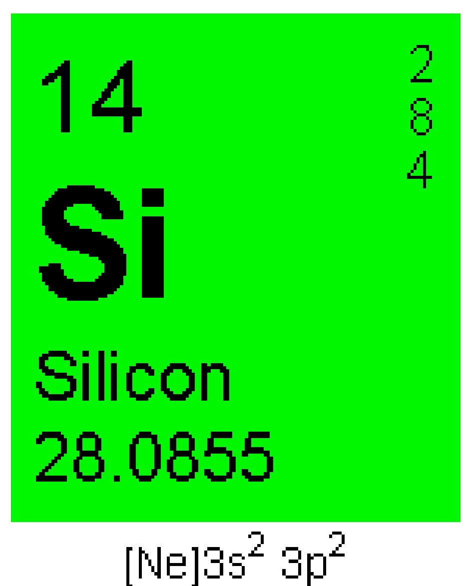
level 1

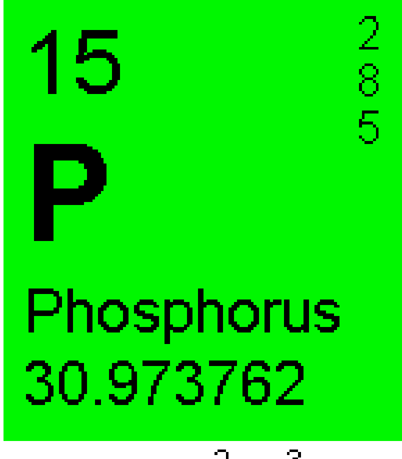
level 2

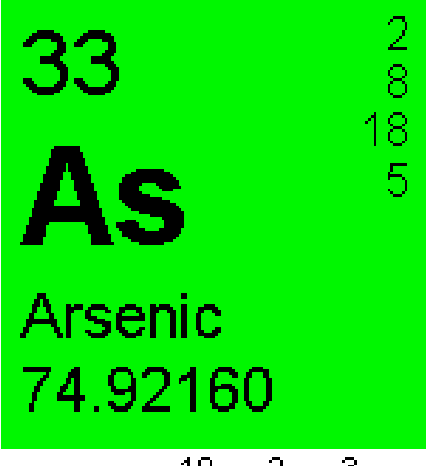
level 3

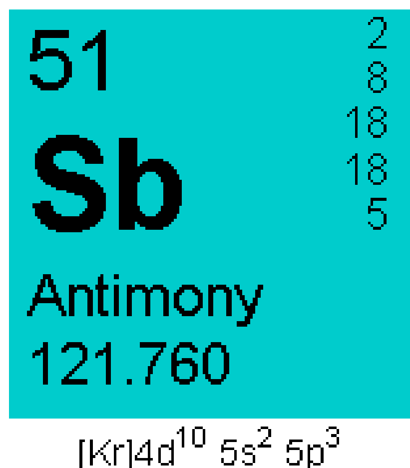
P atom


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


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

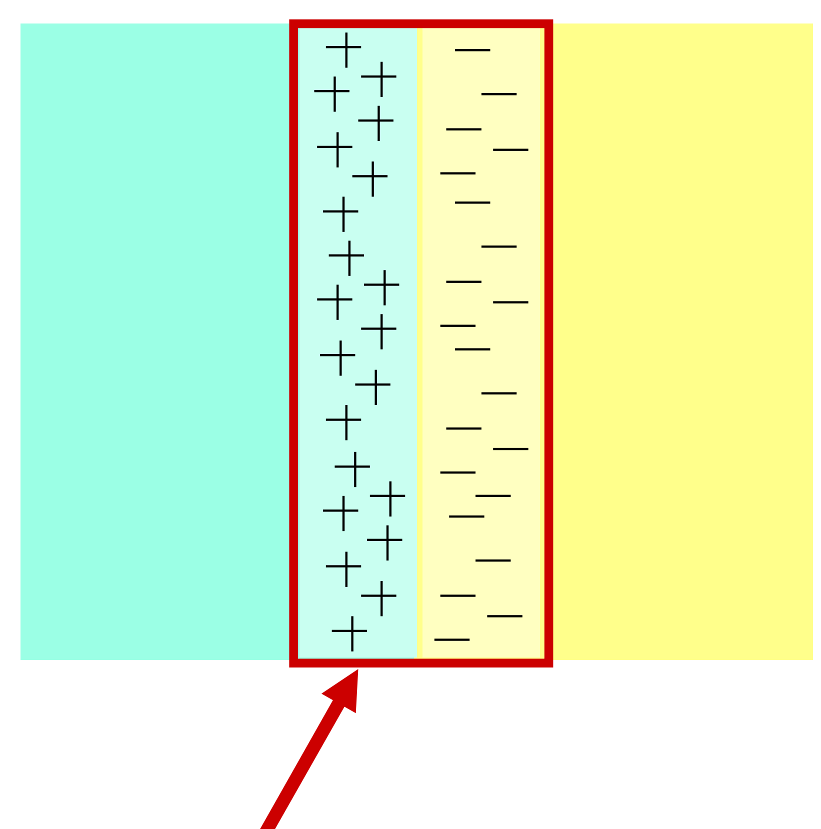
Silicon Dopants in Semiconductor Processes

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)

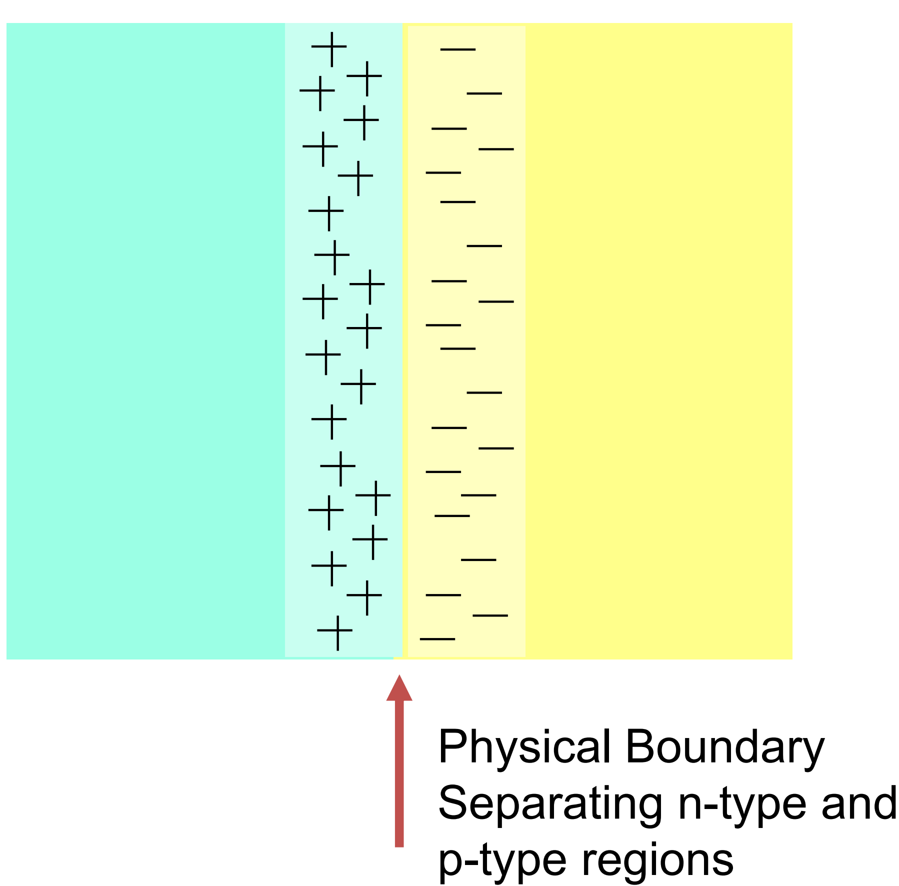
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



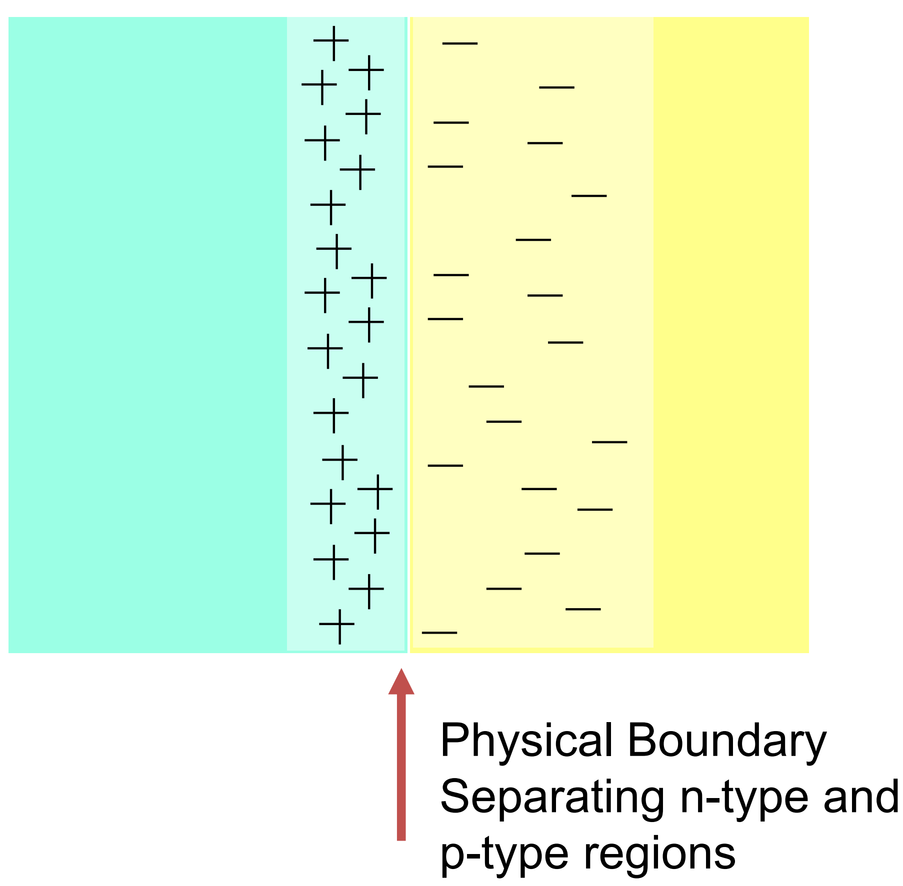
Depletion region created that is ionized but void of carriers

pn Junctions



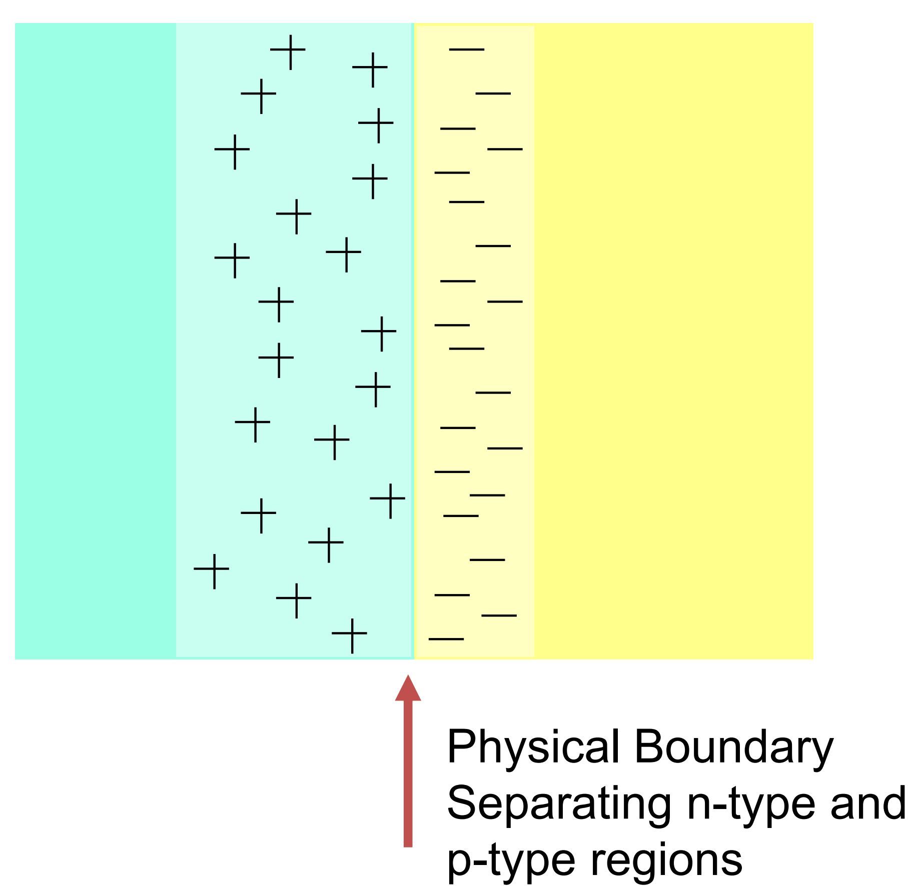
If doping levels identical, depletion region extends equally into n-type and p-type regions

pn Junctions



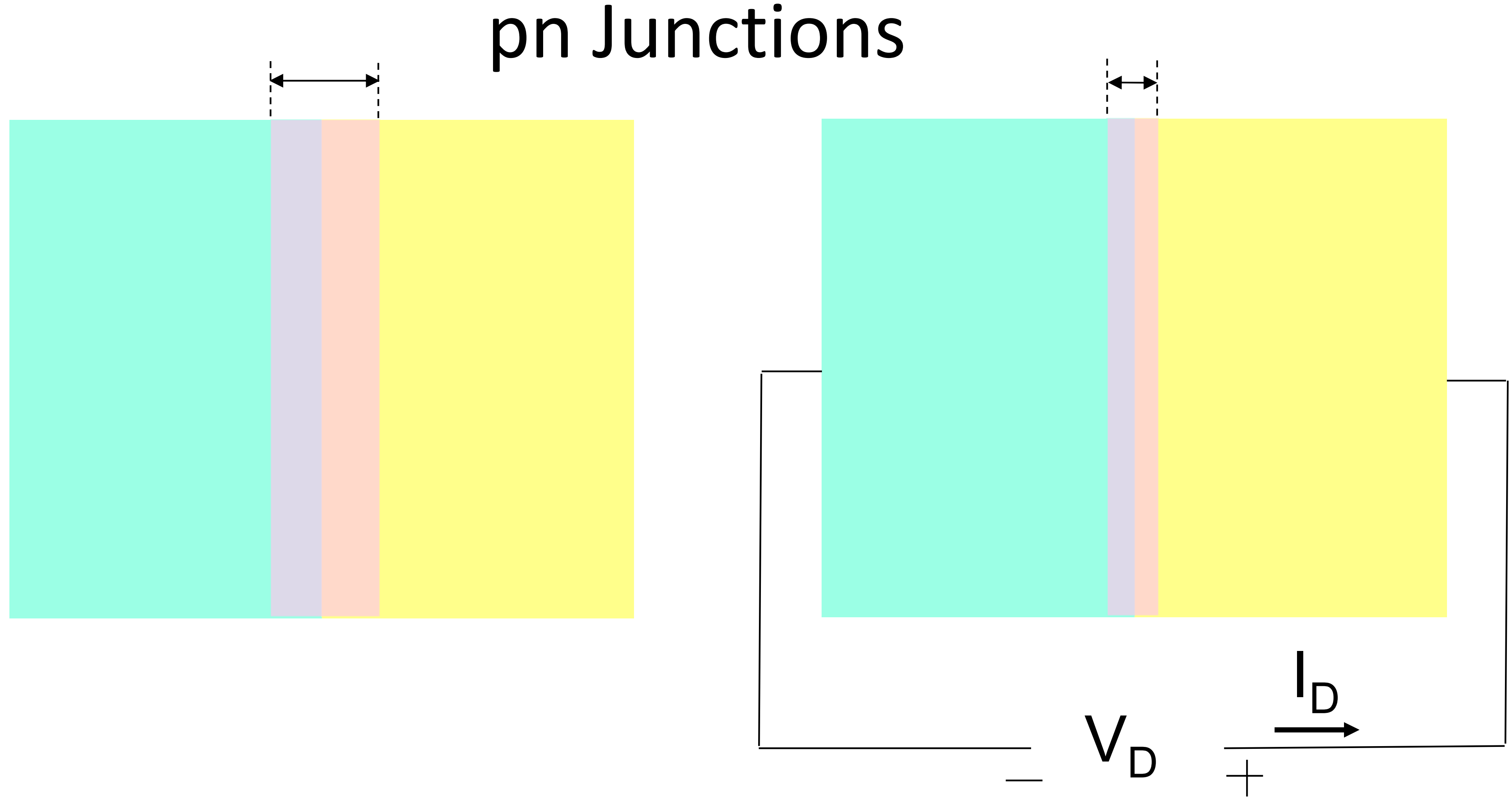
Extends farther into p-type region if p-doping lower than n-doping

pn Junctions



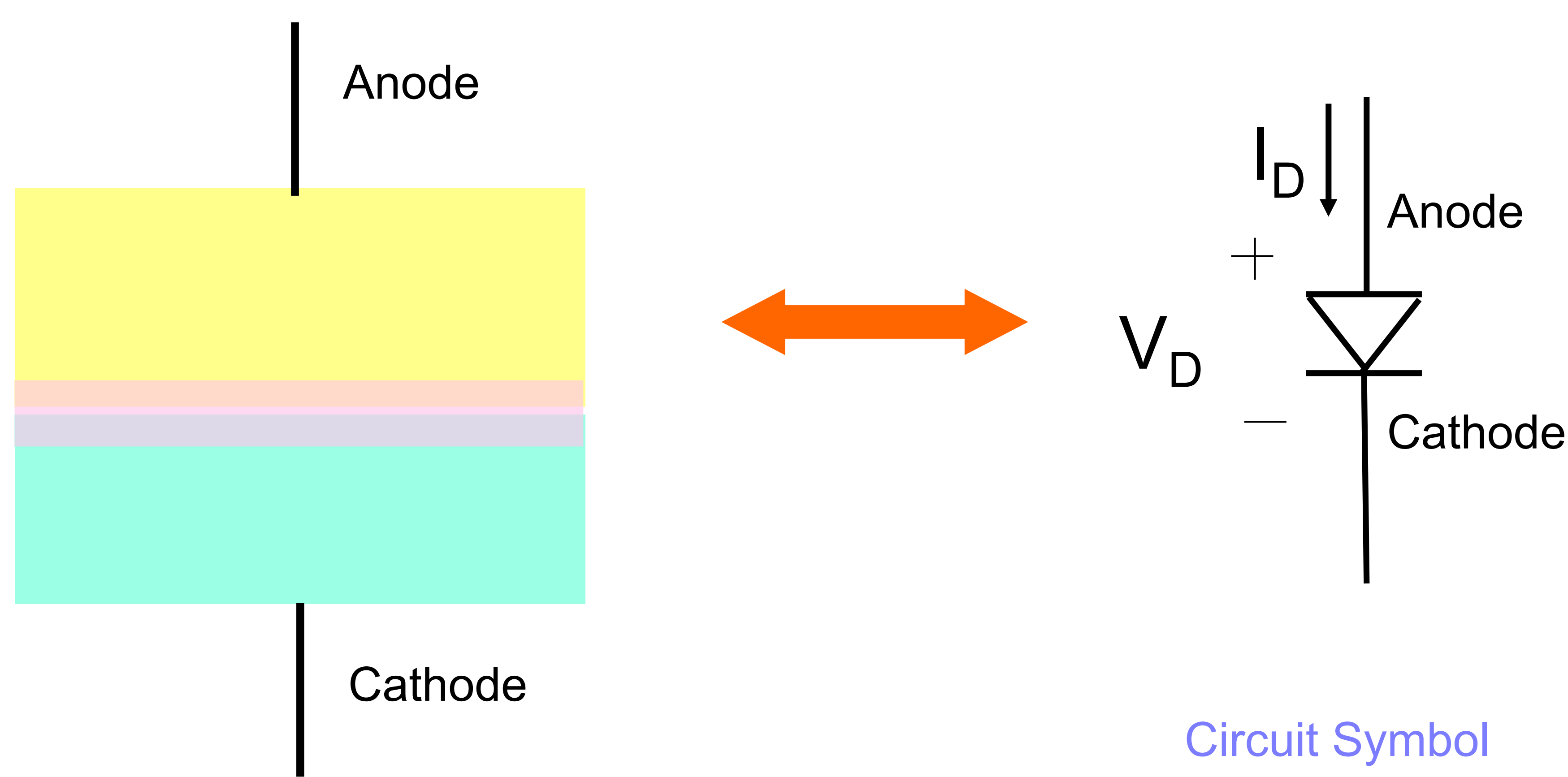
Extends farther into n-type region if n-doping lower than p-doping

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



From Chapter 4 Page 92 of:

Modern Semiconductor Devices for Integrated Circuits by Chenming C. Hu (Apr 1, 2009)

The voltage differential, φ_{bi}, is called the **built-in potential**. A built-in potential is present at the interface of any two dissimilar materials. We are usually unaware of them because they are difficult to detect directly. For example, if one tries to measure the built-in potential, φ_{bi}, by connecting the PN junction to a voltmeter, no voltage will be registered because the net sum of the built-in potentials at the PN junction, the semiconductor–metal contacts, the metal to wire contacts, etc., in any closed loop is zero (see the sidebar, "Hot-Point Probe, Thermoelectric Generator and Cooler," in Sec. 2.1). However, the built-in voltage and field are as real as the voltage and field that one may apply by connecting a battery to a bar of semiconductor. For example, electrons and holes are accelerated by the built-in electric field exactly as was discussed in Chapter 2.

Can the built-in potential be measured directly?

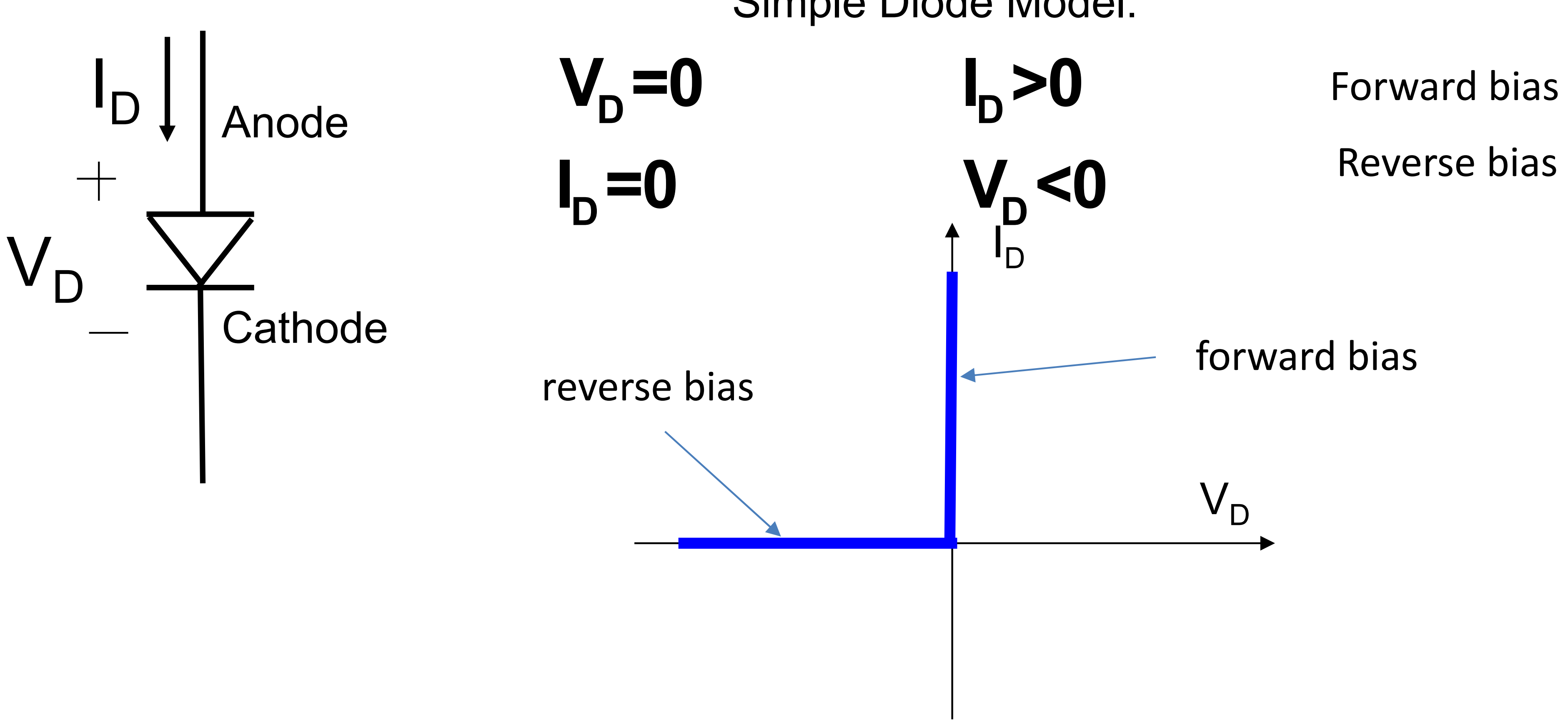
A built-in potential or contact potential is developed whenever two dissimilar materials are brought in contact. The two materials may be p-type and n-type regions of the same semiconductor, or a metal and a semiconductor. In all such cases, as the Fermi levels of the two materials in contact should align, the built-in potential (in Volts) is equal to the difference in the positions of the Fermi level (in eV) of the two materials when they were isolated, or in other words to the difference in their work functions. Now if we are to measure the contact potential, we have to connect a voltmeter, which requires that metal contacts be provided at both p- and n-ends of the junction. We now have three junctions, namely metal–p-semiconductor, p-n junction, and n-semiconductor–metal junctions, in series. The voltmeter will measure the sum of the three contact potentials. If $q\phi_m$, $q\phi_n$, and $q\phi_p$ are the work functions of the metal, n-semiconductor, and p-semiconductor respectively, the voltmeter reading will be equal to

$$V = \frac{(q\phi_m - q\phi_p) + (q\phi_p - q\phi_n) + (q\phi_n - q\phi_m)}{q} = 0$$

Thus, it is observed that the built-in potential cannot be measured by simply connecting a voltmeter across the junction as the sum of the contact potentials between metal and semiconductor exactly compensates the built-in potential of the p-n junction.

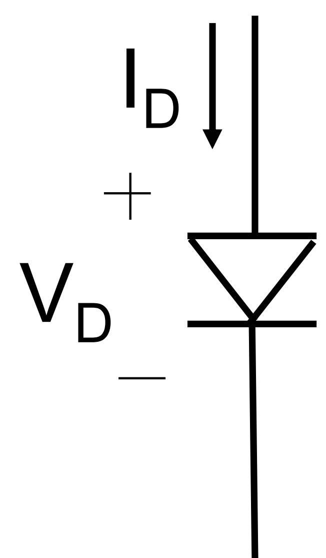
pn Junctions

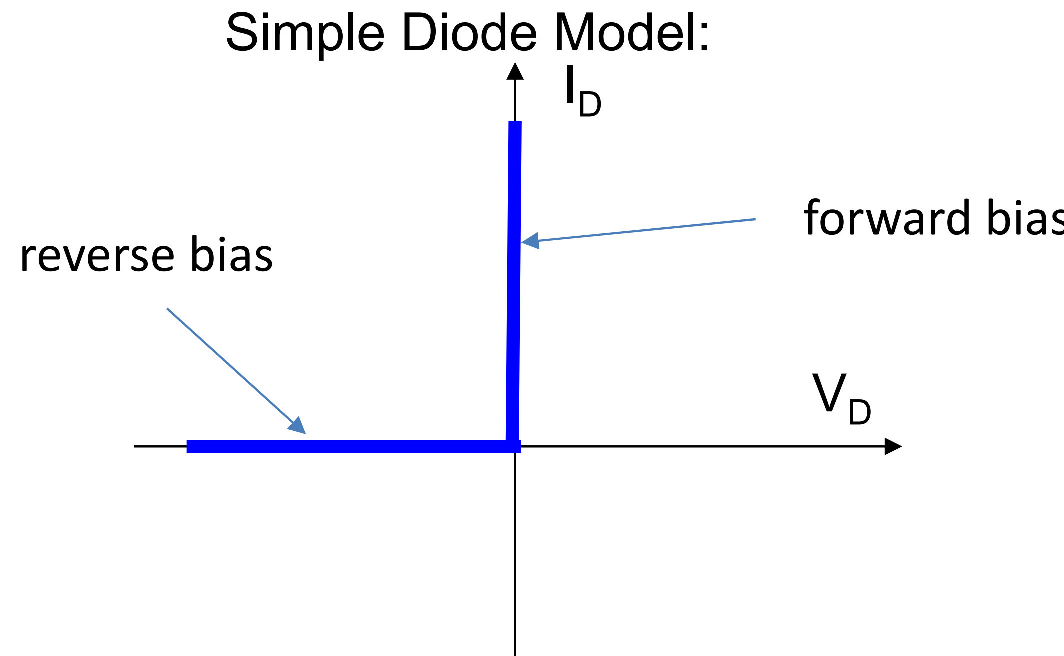
- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases



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

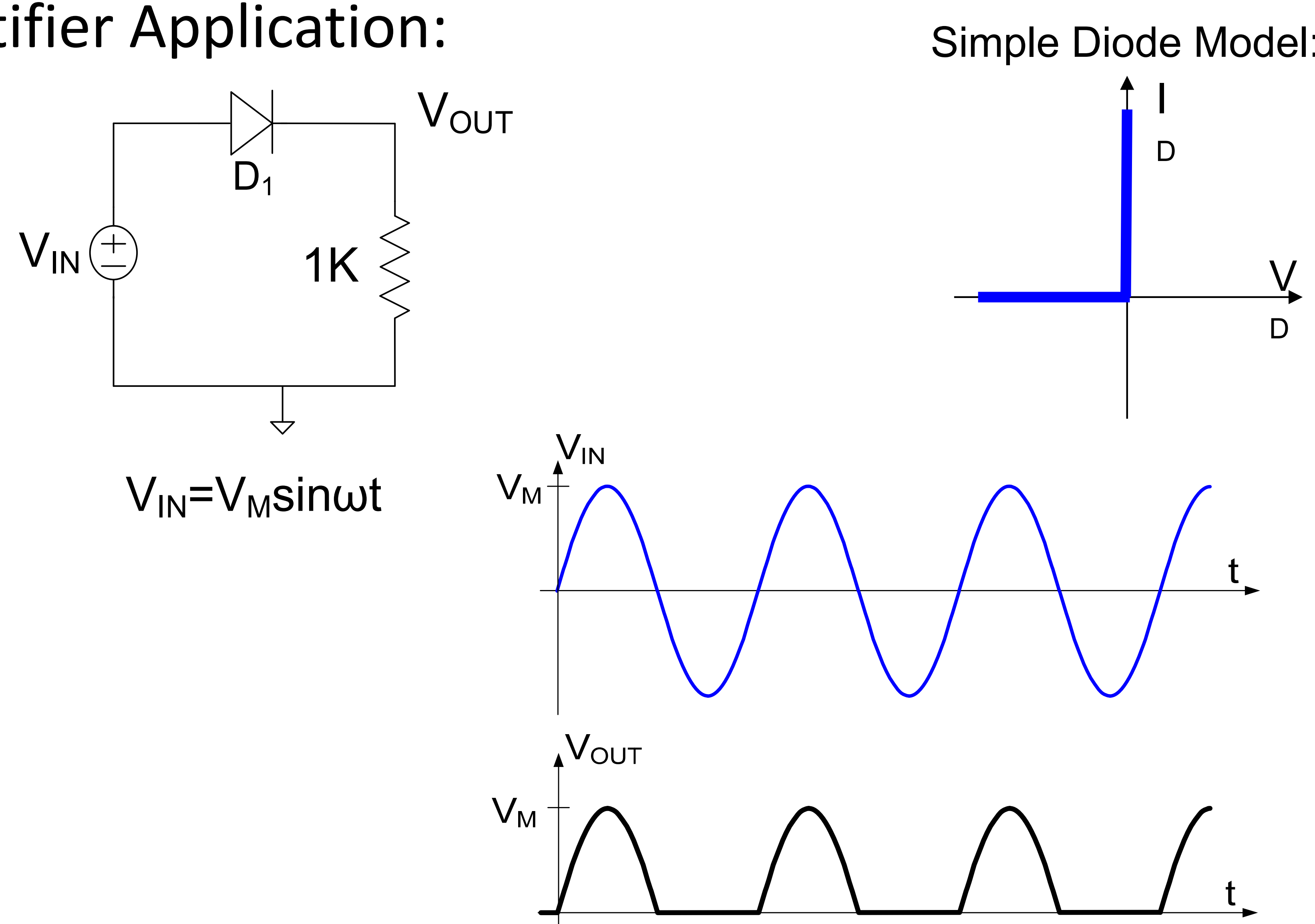
pn Junctions





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

Rectifier Application:

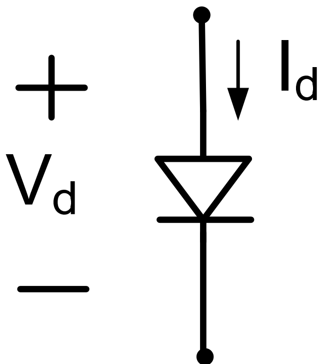


Analysis based upon “passing current” in one direction and “ blocking current” in the other direction

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:



I_S in the 10fA to 100fA range

I_S proportional to junction area

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

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

Diode Equation

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

$q = -1.60217662 \times 10^{-19}$ C

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

n typically about 1

I_S and n are model parameters

Diode equation due to William Shockley, inventor of BJT

What is V_t at room temp?

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

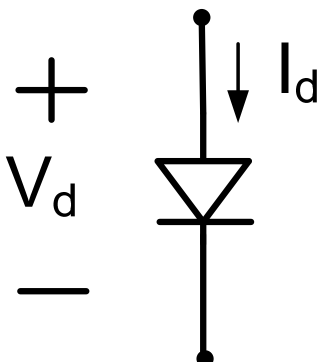
V_t is about 26mV at room temp

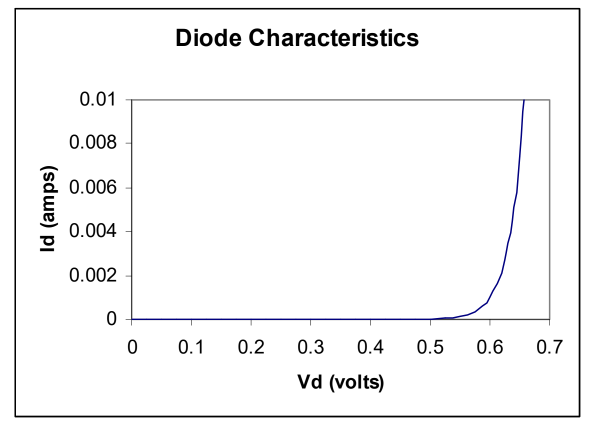
In 1940, Russell Ohl “stumbled upon” the p-n junction diode

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

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

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

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