

EE 330

Lecture 13

Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFETs

Photo courtesy of the director of the National Institute of Health (NIH)



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 February 18

Format: Open-Book, Open Notes

Exam will be posted at 8:00 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 5 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 5-hour open interval of the exam except from the course instructor who will be responding to email messages from 8:00 a.m. to 9:30 a.m. on the date of the exam.

Special Accommodations

For anyone with approved special accommodations, the 5-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 February 14 if alternative accommodations are requested.

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

**Primary Consideration
in This Course**

- Niche Devices
 - Photodetectors
 - MESFET
 - 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

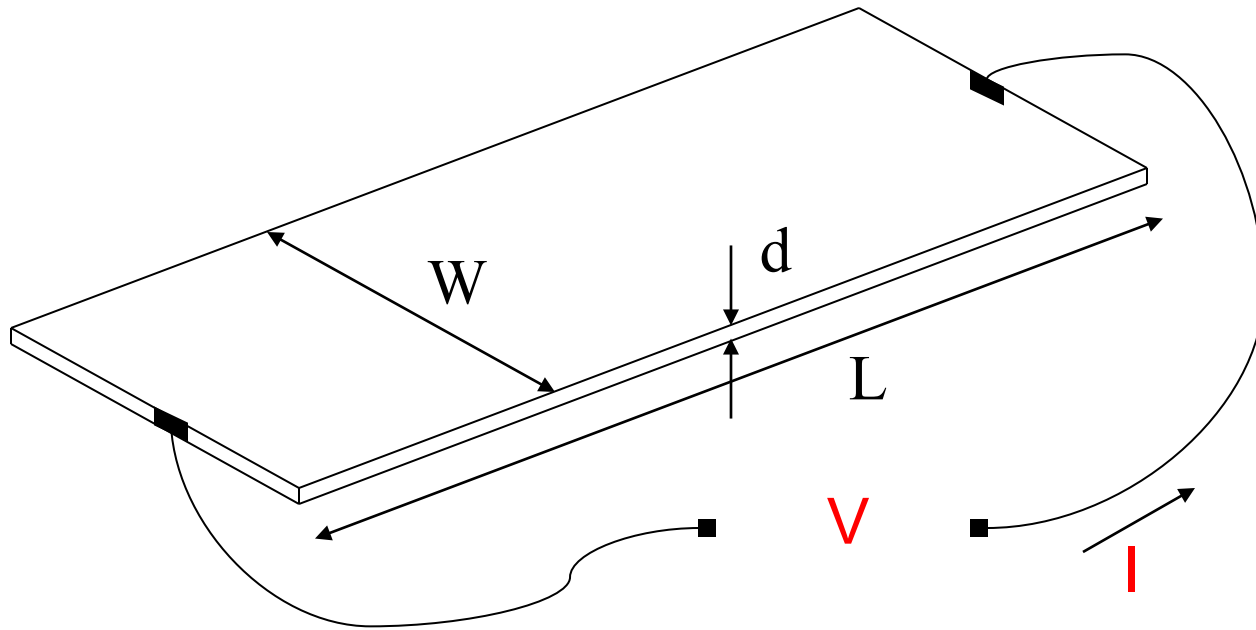
Resistors

- 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

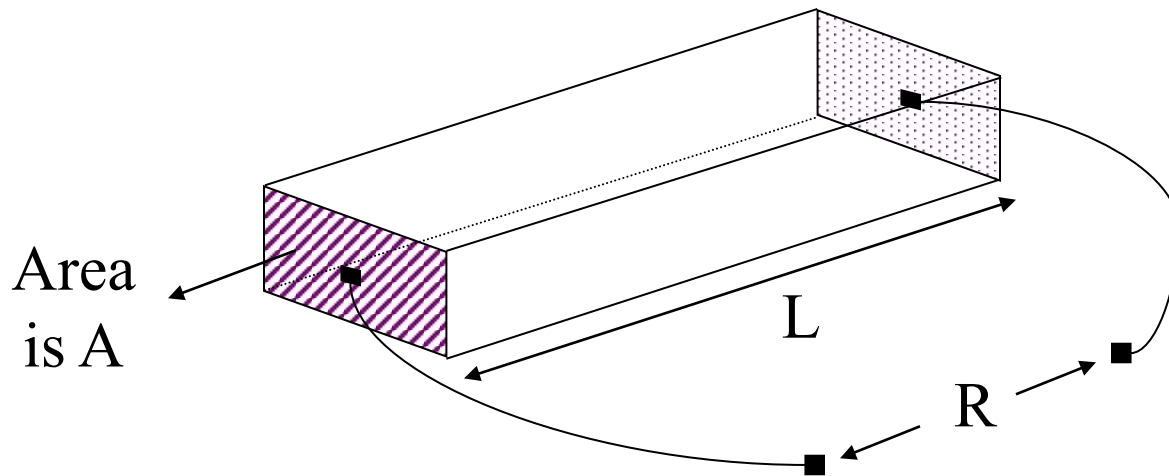


Model:

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

Resistivity

- Volumetric measure of conduction capability of a material



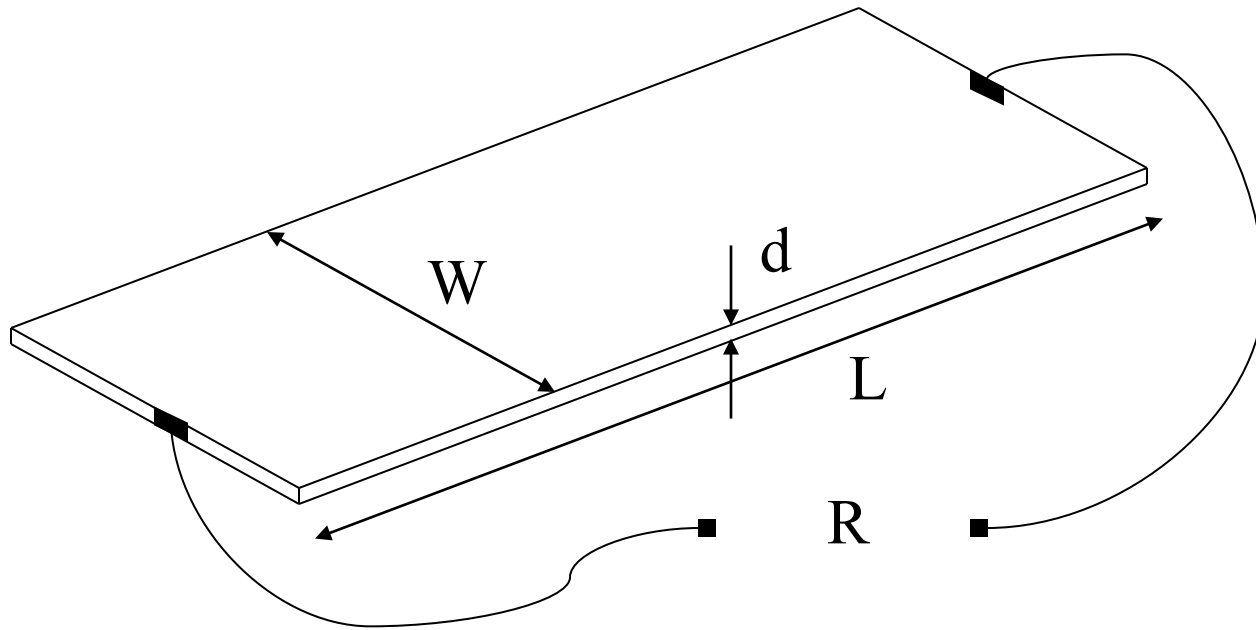
Area
is A

units : ohm cm

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

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

Sheet Resistance



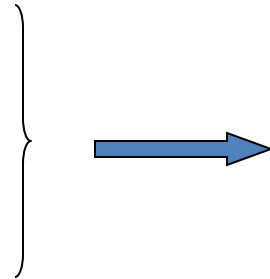
$$R_{\square} = \frac{RW}{L} \quad (\text{for } d \ll w, d \ll L) \quad \text{units : ohms / } \square$$

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

Relationship between ρ and R_{\square}

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

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



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

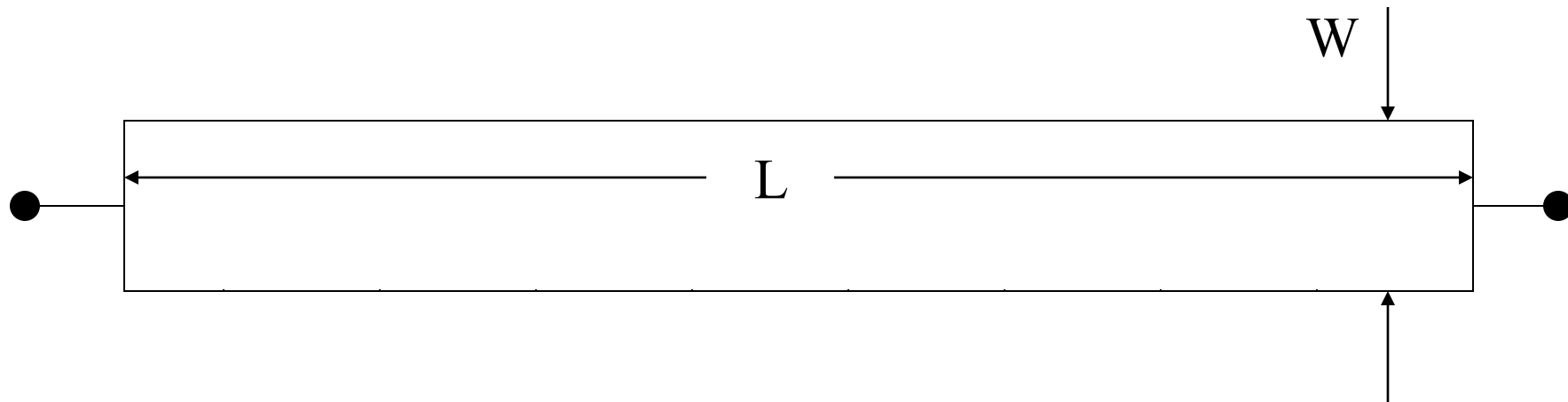
$$A = W \times d$$

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

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

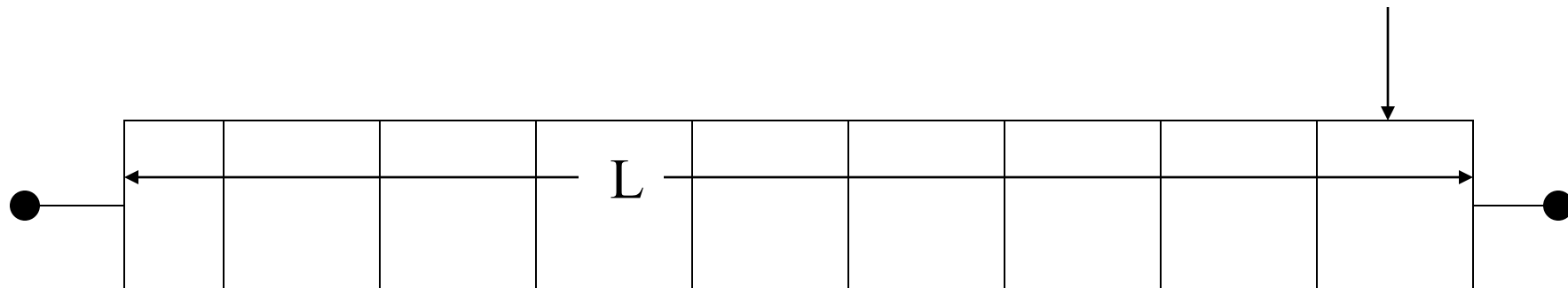
$$R = R_{\square} N_s$$

Example 1



$$R = ?$$

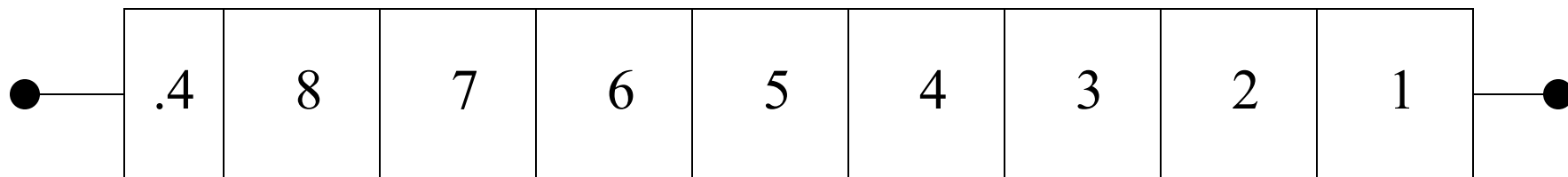
Example 1



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

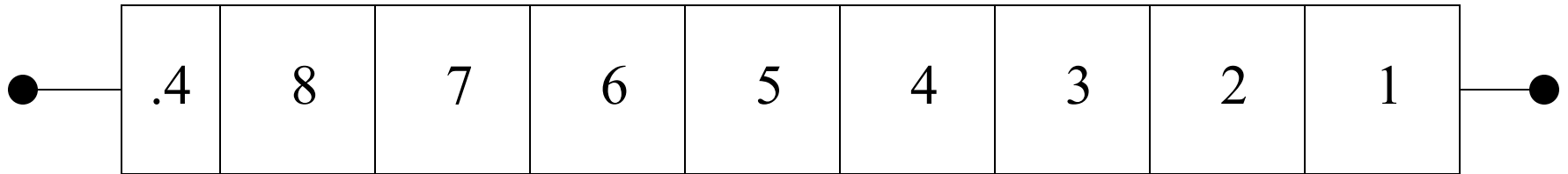
W

Example 1



$R = ?$

Example 1

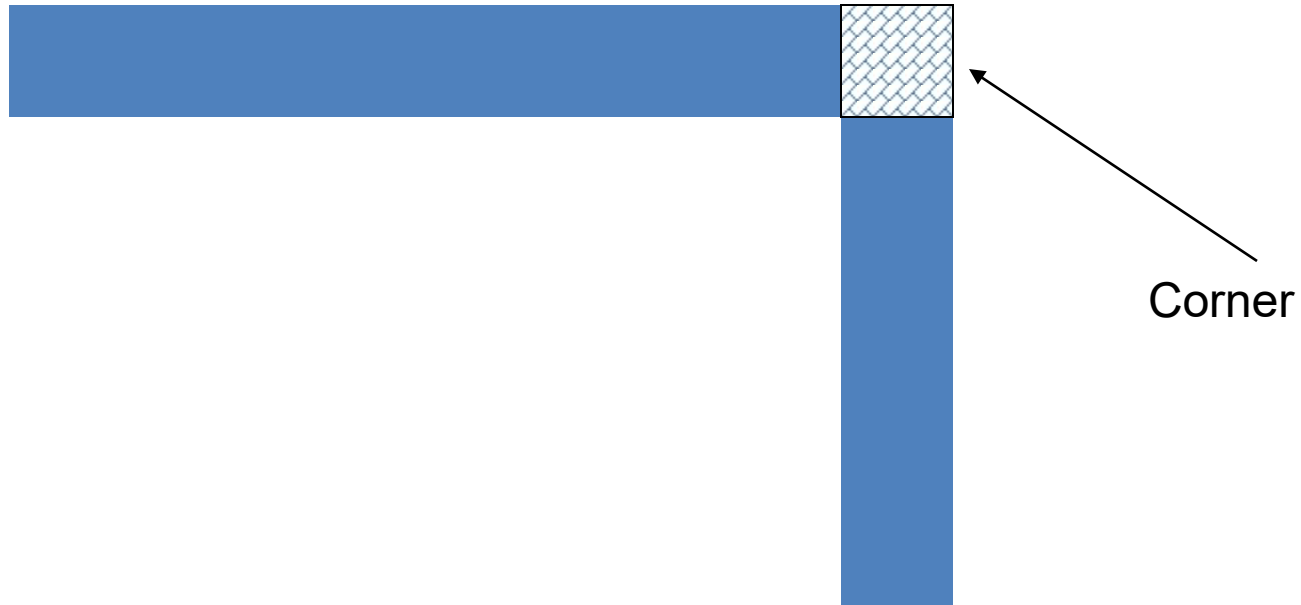


$$R = ?$$

$$N_S = 8.4$$

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

Corners in Film Resistors



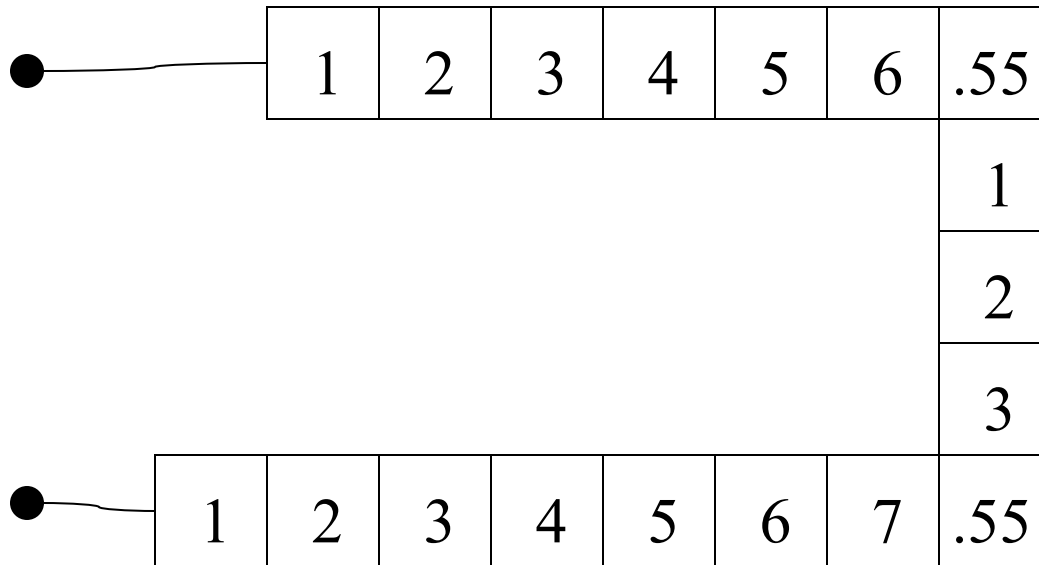
Rule of Thumb: .55 squares for each corner

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: $1.7E-6 \Omega\text{cm}$
- Al: $2.7E-6 \Omega\text{cm}$
- Gold: $2.4E-6 \Omega\text{cm}$
- Platinum: $1.1E-5 \Omega\text{cm}$
- Polysilicon: $1E-2$ to $1E4 \Omega\text{cm}^*$
- n-Si: typically $.25$ to $5 \Omega\text{cm}^*$ (but larger range possible)
- intrinsic Si: $2.5E5 \Omega\text{cm}$
- SiO_2 : $E14 \Omega\text{cm}$

* But fixed in a given process

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

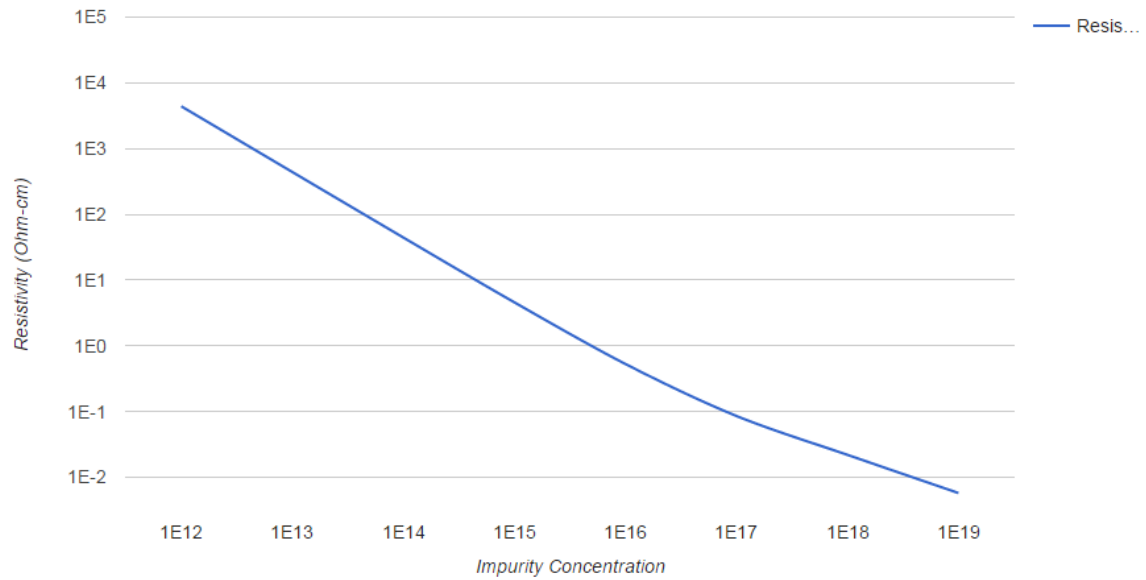
Dopant: Arsenic Boron Phosphorus

Impurity Concentration: (cm⁻³)

Mobility: [cm²/V-s]

Resistivity: [Ω-cm]

Calculations are for a silicon substrate.



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

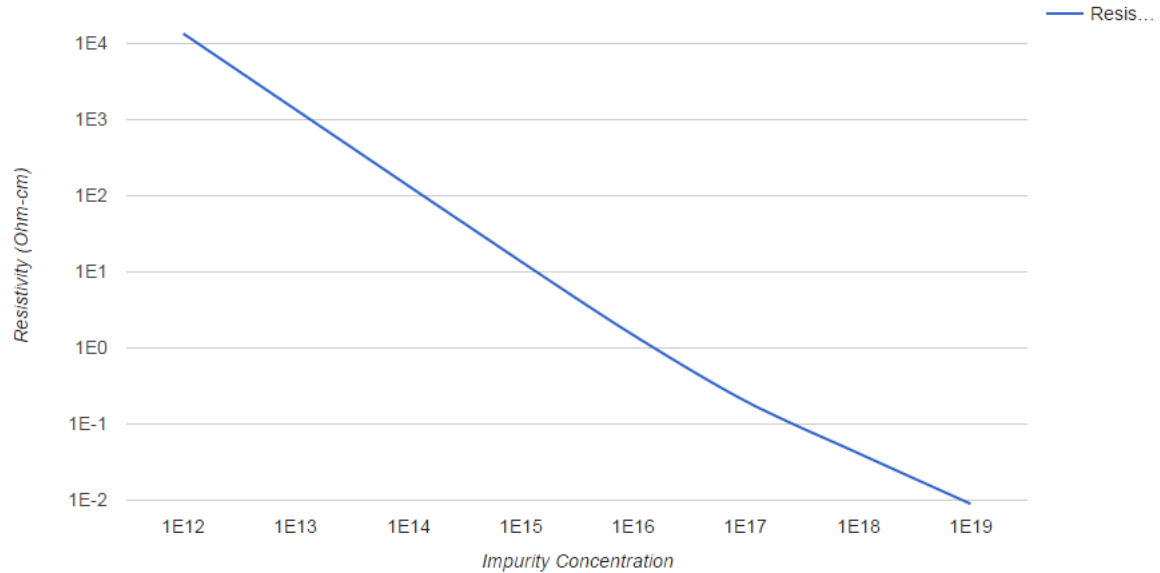
Dopant: Arsenic Boron Phosphorus

Impurity Concentration: (cm⁻³)

Mobility: [cm²/V-s]

Resistivity: [Ω -cm]

Calculations are for a silicon substrate.



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

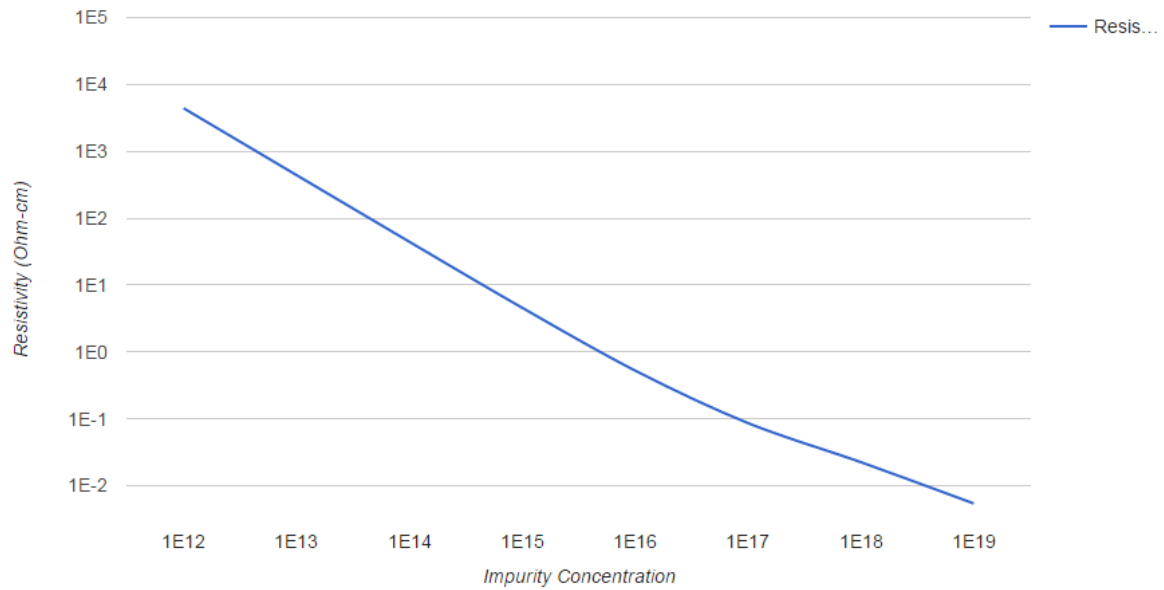
Dopant: Arsenic Boron Phosphorus

Impurity Concentration: (cm⁻³)

Mobility: [cm²/V-s]

Resistivity: [Ω-cm]

Calculations are for a silicon substrate.



Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

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

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

$$R(T_2) = R(T_1) e^{\frac{T_2 - T_1}{10^6} \text{TCR}} \quad \text{If } x \text{ is small, } e^x \cong 1 + x$$

It follows that if $\text{TCR} \cdot (T_2 - T_1)$ 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:

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

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

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

It follows that if $\mathbf{VCR * (V_2 - V_1)}$ is small,

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

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

V V

Type of layer	Sheet Resistance Ω/\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)

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/ $^{\circ}\text{C}$	$\pm 20\text{ppm/V}$
Poly-Poly Capacitor	0.3-0.4 fF/ μm^2	20%	0.1%	25ppm/ $^{\circ}\text{C}$	$\pm 50\text{ppm/V}$
Metal-Metal Capacitor	0.1-1 fF/ μm^2	10%	0.6%	-40ppm/ $^{\circ}\text{C}$	$\pm 1\text{ppm/V}$
Diffused Resistor	10-100 $\Omega/\text{sq.}$	35%	2%	1500ppm/ $^{\circ}\text{C}$	200ppm/V
Ion Implanted Resistor	0.5-2 k $\Omega/\text{sq.}$	15%	2%	400ppm/ $^{\circ}\text{C}$	800ppm/V
Poly Resistor	30-200 $\Omega/\text{sq.}$	30%	2%	1500ppm/ $^{\circ}\text{C}$	100ppm/V
<i>n</i> -well Resistor	1-10 k $\Omega/\text{sq.}$	40%	5%	8000ppm/ $^{\circ}\text{C}$	10kppm/V
Top Metal Resistor	30 m $\Omega/\text{sq.}$	15%	2%	4000ppm/ $^{\circ}\text{C}$	-
Lower Metal Resistor	70 m $\Omega/\text{sq.}$	28%	3%	4000ppm/ $^{\circ}\text{C}$	-

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/ $^\circ\text{C}$	50 ppm/V
MOM capacitor	0.17 fF/ μm^2	1%	50 ppm/ $^\circ\text{C}$	50 ppm/V
P ⁺ Diffused resistor (nonsilicide)	80–150 Ω/\square	0.4%	1500 ppm/ $^\circ\text{C}$	200 ppm/V
N ⁺ Diffused resistor (non-silicide)	50–80 Ω/\square	0.4%	1500 ppm/ $^\circ\text{C}$	200 ppm/V
N ⁺ Poly resistor (non-silicide)	300 Ω/\square	2%	–2000 ppm/ $^\circ\text{C}$	100 ppm/V
P ⁺ Poly resistor (non-silicide)	300 Ω/\square	0.5%	–500 ppm/ $^\circ\text{C}$	100 ppm/V
P [–] Poly resistor (non-silicide)	1000 Ω/\square	0.5%	–1000 ppm/ $^\circ\text{C}$	100 ppm/V
n-well resistor	1–2 k Ω/\square		8000 ppm/ $^\circ\text{C}$	10k ppm/V

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/ μm^2	10%	0.1%	20ppm/ $^{\circ}\text{C}$	± 20 ppm/V
Poly-Poly Capacitor	0.3-0.4 fF/ μm^2	20%	0.1%	25ppm/ $^{\circ}\text{C}$	± 50 ppm/V
Diffused Resistor	10-100 $\Omega/\text{sq.}$	35%	2%	1500ppm/ $^{\circ}\text{C}$	200ppm/V
Ion Implanted Resistor	0.5-2 k $\Omega/\text{sq.}$	15%	2%	400ppm/ $^{\circ}\text{C}$	800ppm/V
Poly Resistor	30-200 $\Omega/\text{sq.}$	30%	2%	1500ppm/ $^{\circ}\text{C}$	100ppm/V
n-well Resistor	1-10 k $\Omega/\text{sq.}$	40%	5%	8000ppm/ $^{\circ}\text{C}$	10kppm/V

2

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

Lingkai Kong

EECS240

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

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

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

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

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

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

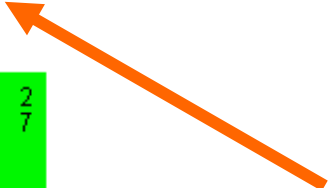
- BJT

Periodic Table of the Elements

1 IA	New Original												13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794	2 He Helium 4.002602											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00642	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 19.99244	
3 Li Lithium 6.941	4 Be Beryllium 9.01224	3 II B	4 IV B	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 Al Aluminum 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.905848	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.3675	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29	
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.96657	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 209	85 At Astatine 209	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89 to 103		104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Uub Ununbium 285	113 Uut Ununtrium 288	114 Uuq Ununquadium 289	115 Uup Ununpentium 288	116 Uuh Ununhexium 289	117 Uus Ununseptium 289	118 Uuo Ununoctium 289

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

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

IIIA	IVA	VA	VIA	VIIA	
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	 group (or family)
13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.453	
31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	
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4 valence-band Electrons

All elements in group IV have 4 valence-band electrons

IIIA	IVA	VA	VIA	VIIA
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032
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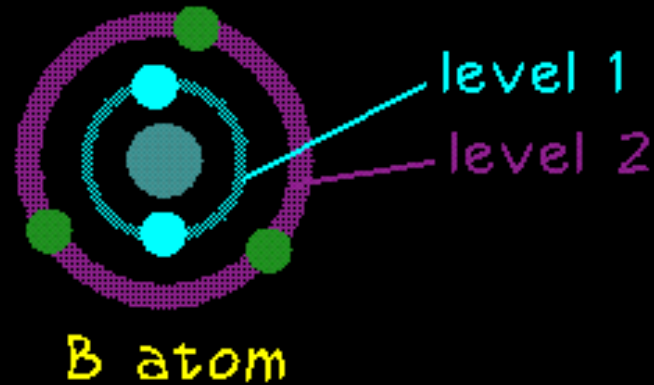
Only 3 Valence-band Electrons

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

The Atom of Boron (B)



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

IIIA	IVA	VA	VIA	VIIA
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032
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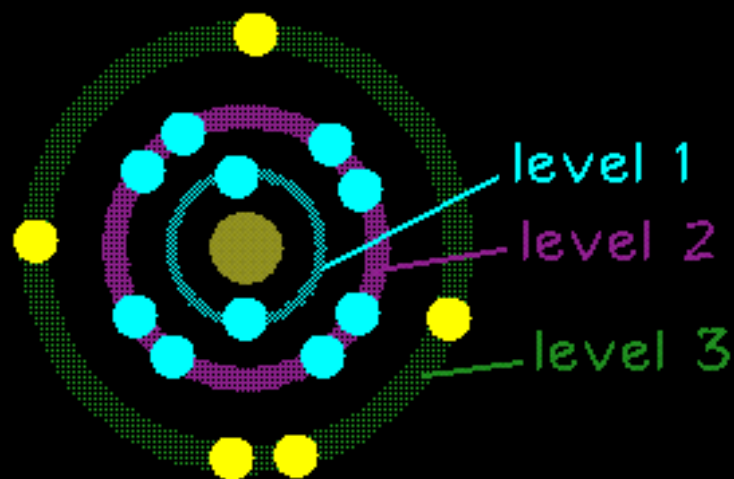
Five Valence-band Electrons

Serves as an “donor” of electrons

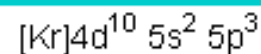
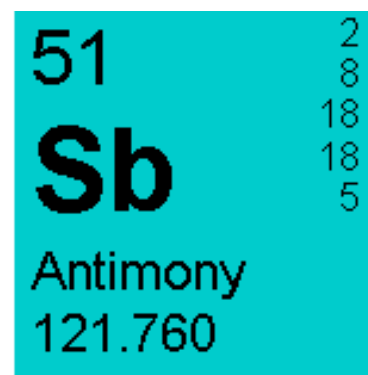
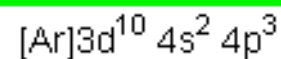
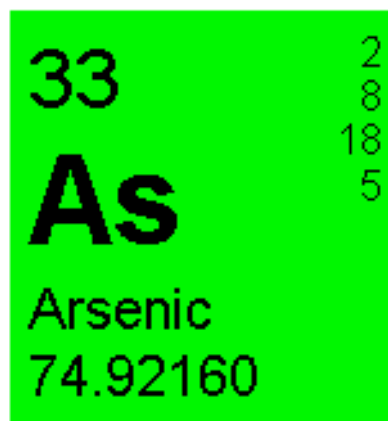
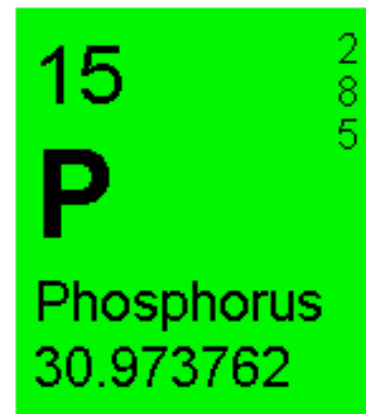
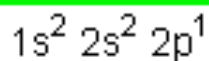
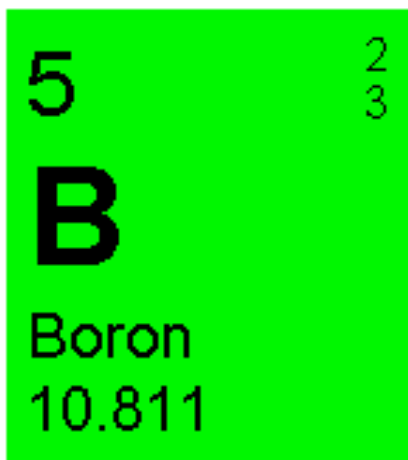
Acts as an n-type impurity when used as a silicon dopant

All elements in group V have 5 valence-band electrons

The Atom of Phosphorus (P)



P atom



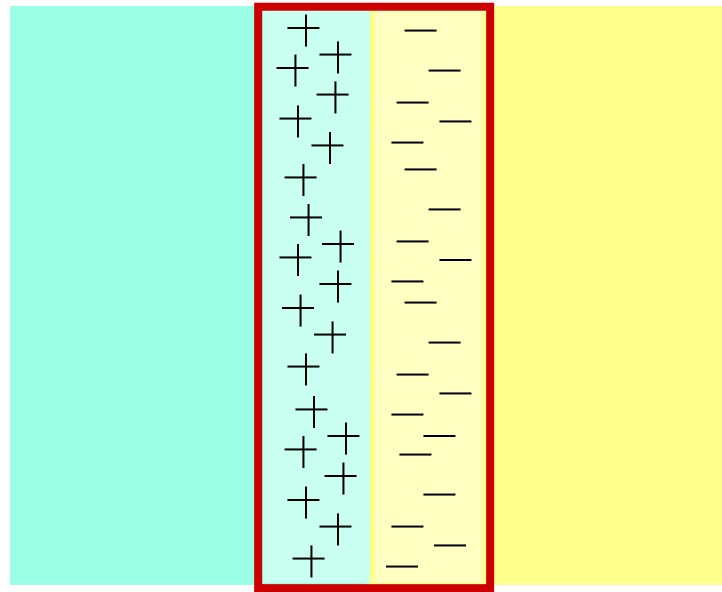
Silicon Dopants in Semiconductor Processes

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)

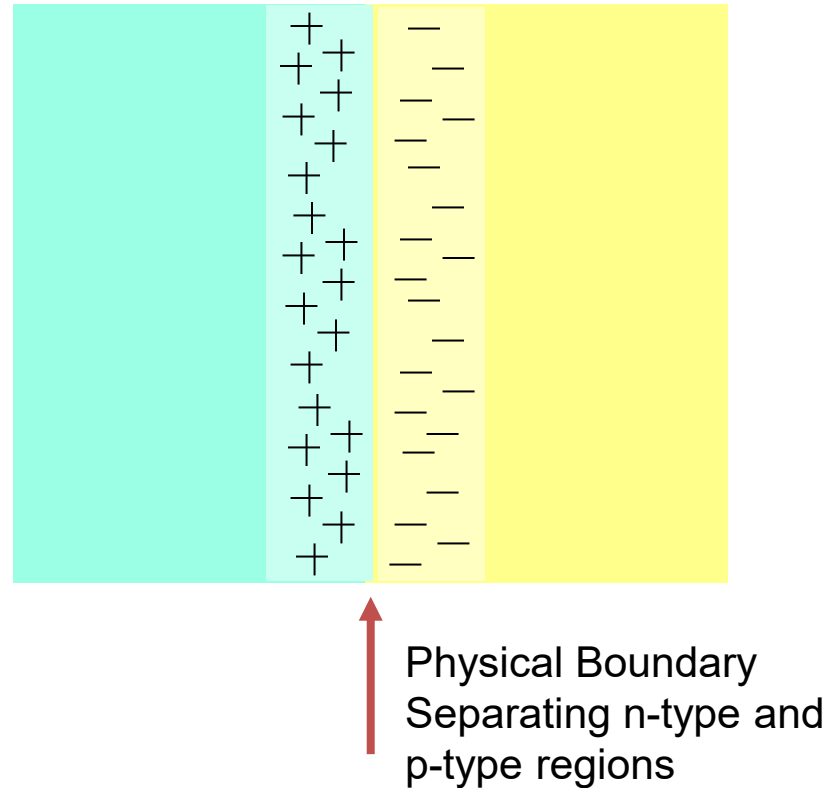
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



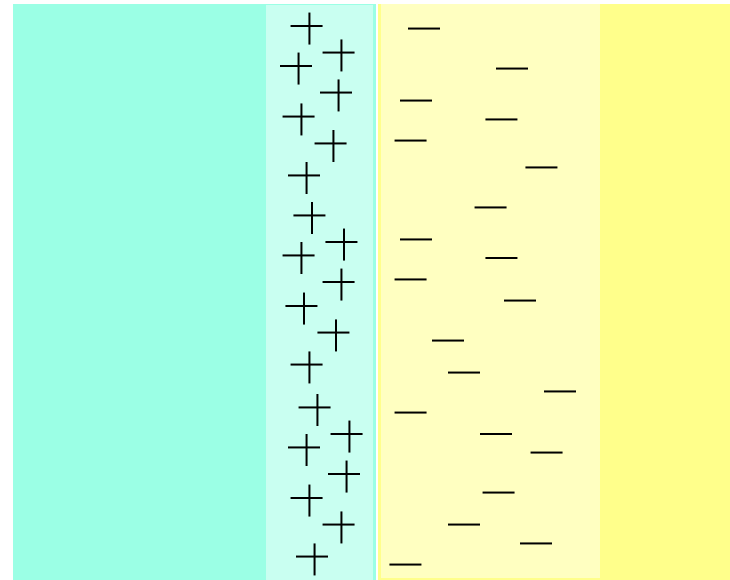
Depletion region created that is ionized but void of carriers

pn Junctions



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

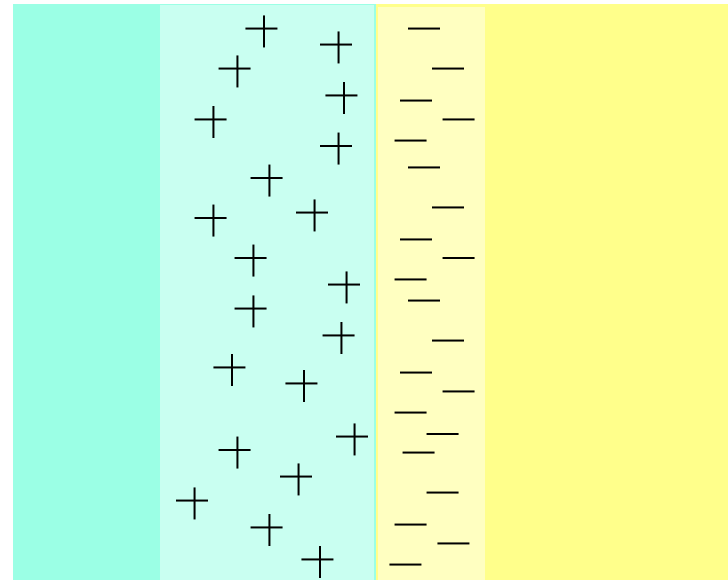
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

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

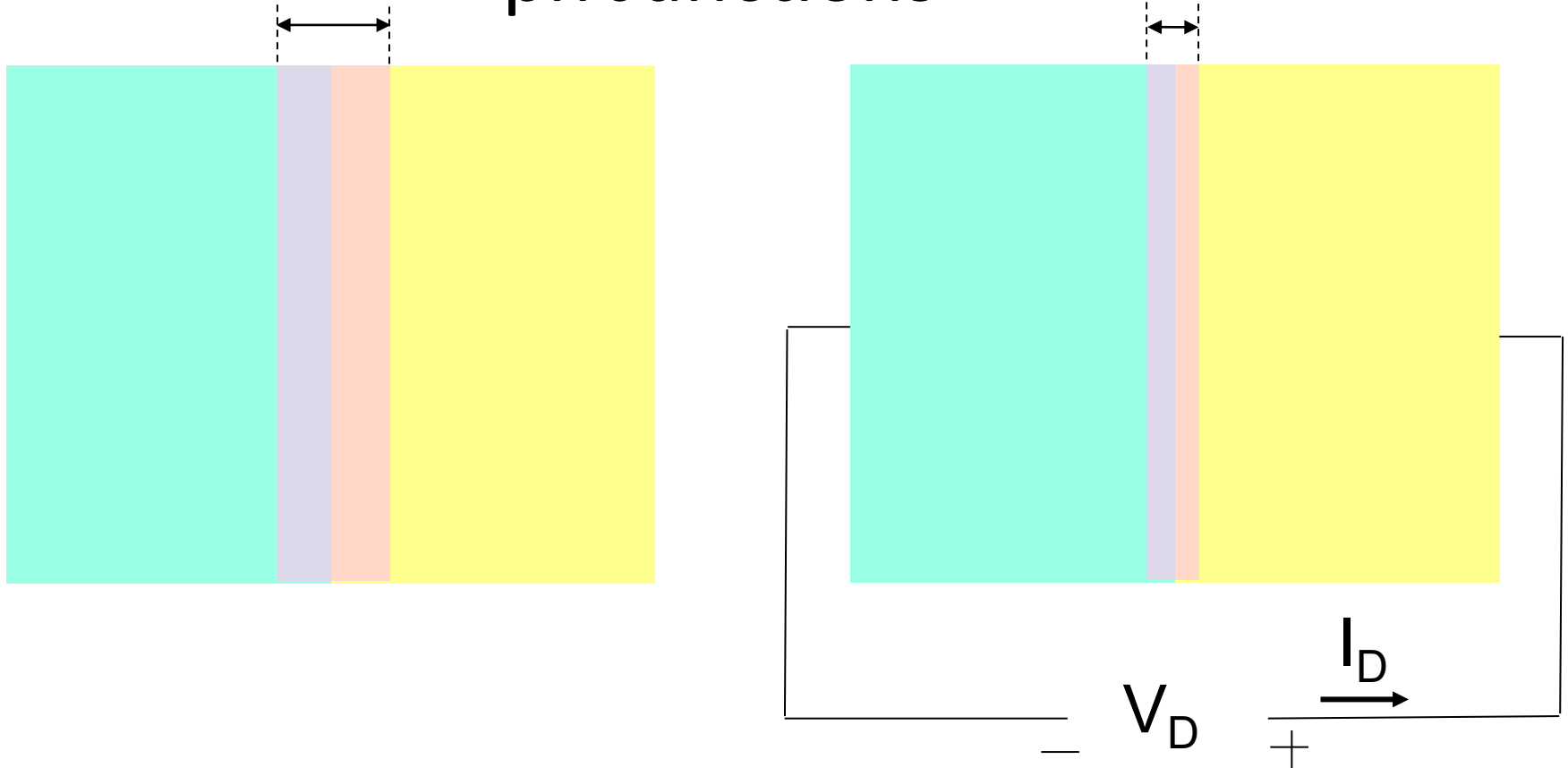
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

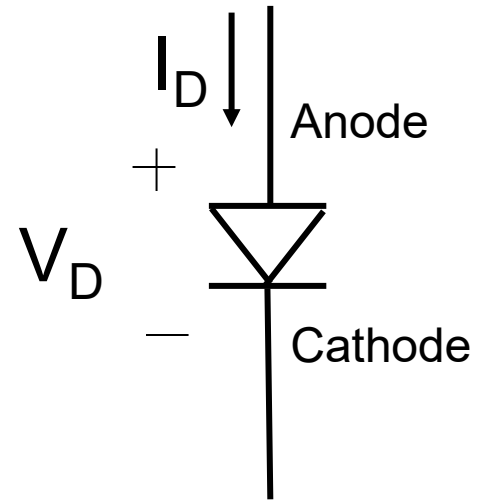
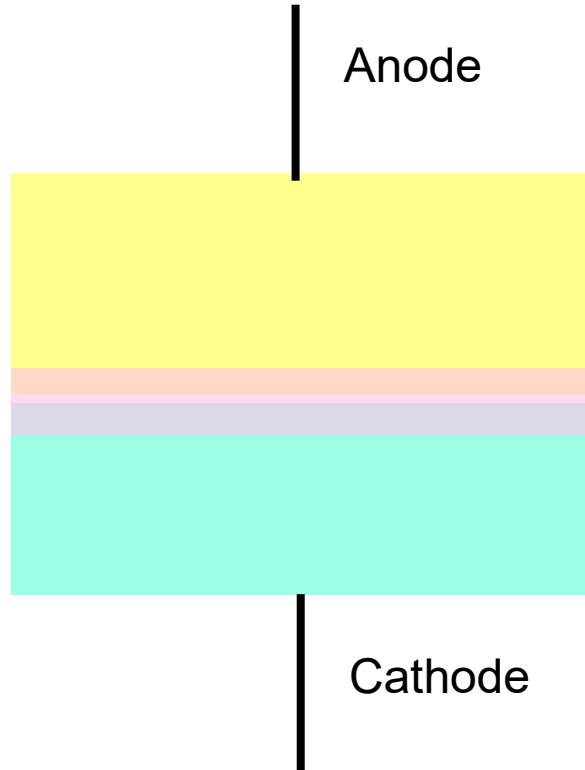
Extends farther into n-type region if n-doping lower
than p-doping

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 reverse bias

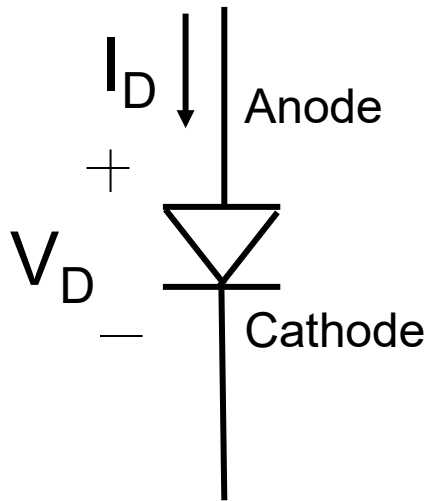
pn Junctions



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:

$$V_D = 0$$

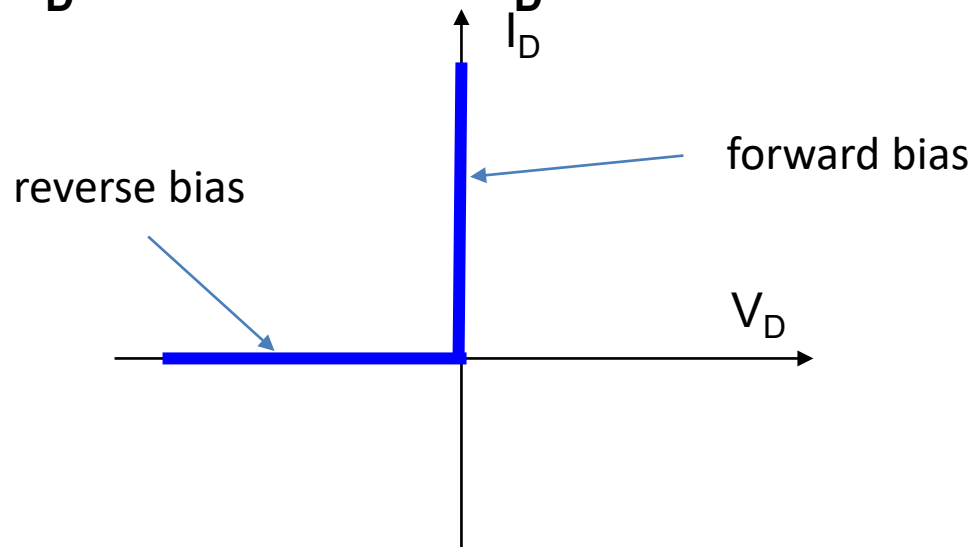
$$I_D = 0$$

$$I_D > 0$$

$$V_D < 0$$

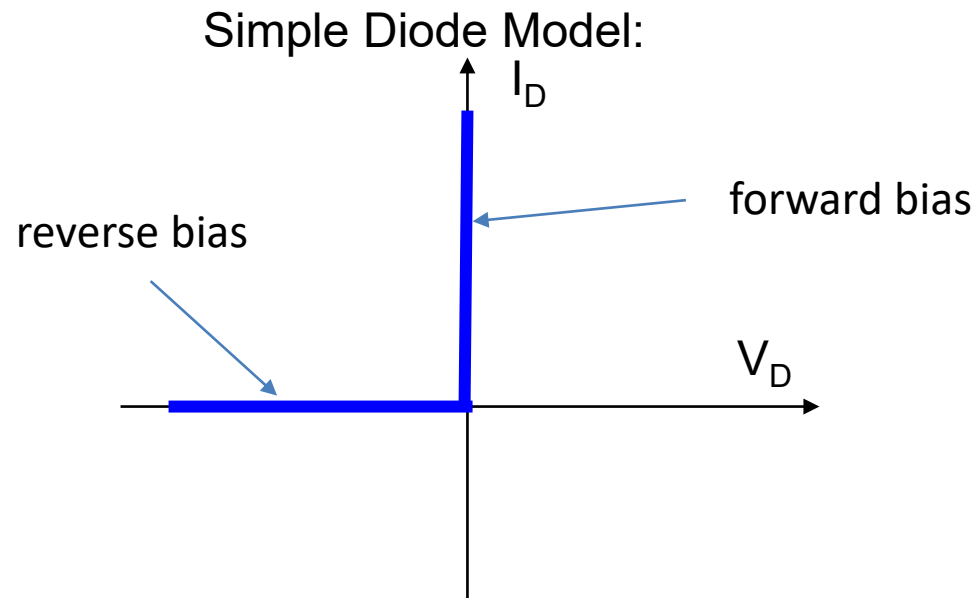
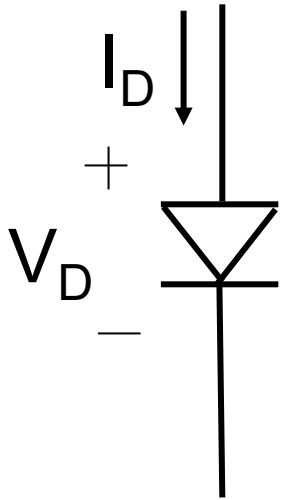
Forward bias

Reverse bias



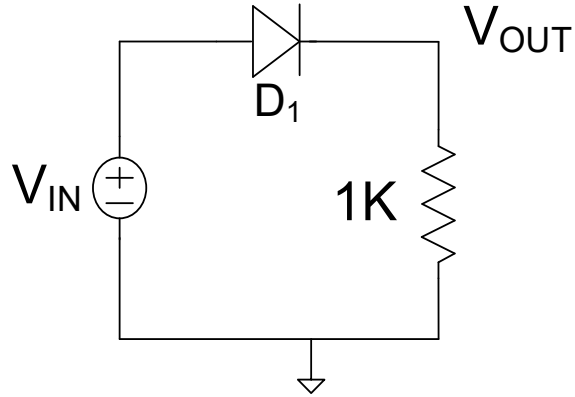
Simple model often referred to as the "Ideal" diode model

pn Junctions



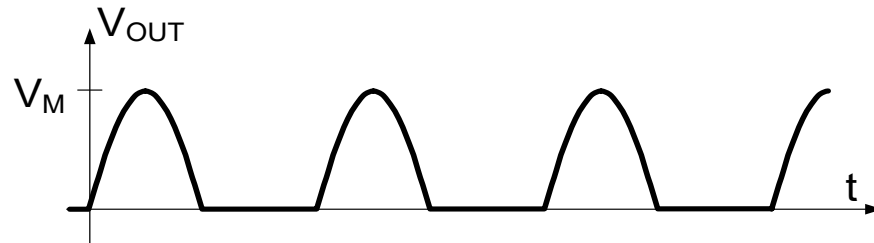
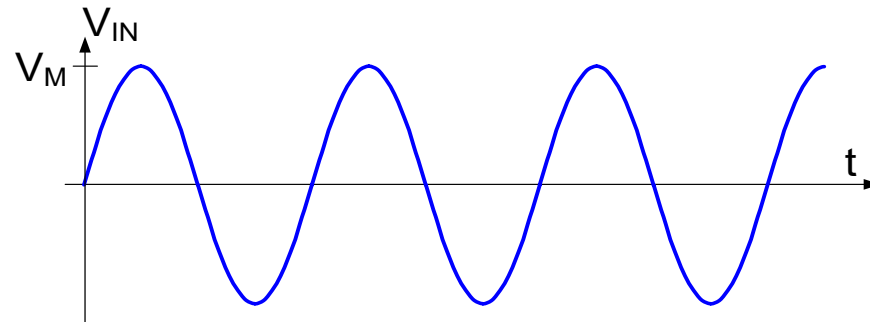
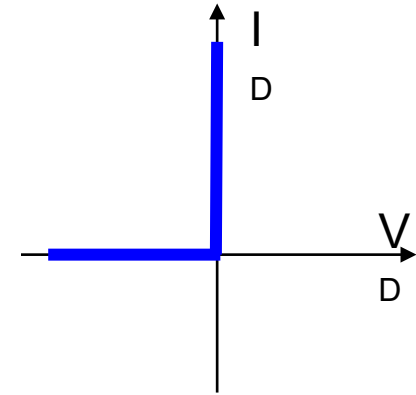
pn junction serves as a “rectifier” passing current in one direction and blocking it in the other direction

Rectifier Application:



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

Simple Diode Model:

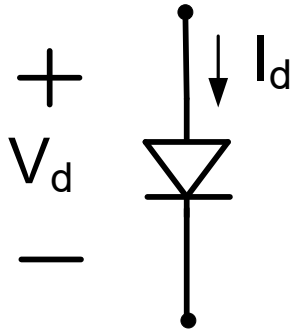


Analysis based upon “passing current” in one direction and “blocking current” in the other direction

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:



I_S in the 10fA to 100fA range

I_S proportional to junction area

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

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

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

$$q = -1.60217662 \times 10^{-19} \text{ C}$$
$$k/q = 8.62 \times 10^{-5} \text{ VK}^{-1}$$

n typically about 1

Diode equation due to William Shockley, inventor of BJT

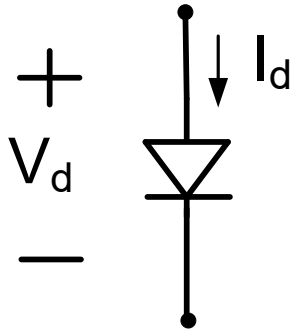
In 1919, [William Henry Eccles](#) coined the term **diode**

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

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:

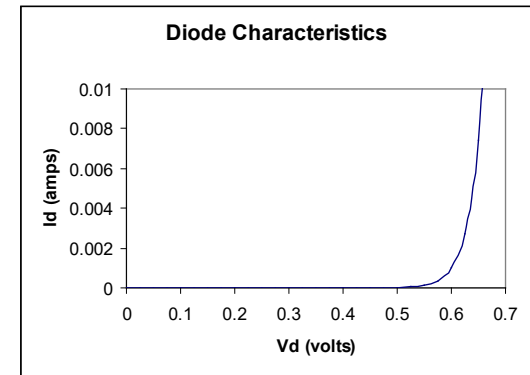


Diode Equation
$$I_D = I_S \left(e^{\frac{V_d}{nV_t}} - 1 \right)$$

Simplification of Diode Equation:

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

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



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

n typically about 1

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

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

V_t is about 26mV at room temp

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