

EE 330

Lecture 13

Devices in Semiconductor Processes

- Diodes
- Capacitors
- MOSFETs

Exam 1 Friday Sept 27

- Students may bring 1 page of notes
- HW assignment for week of Sept 23 due on Wed Sept 25 at beginning of class
- No 5:00 p.m extension so solutions can be posted
- Scientific calculators will be provided – no use of any personal electronic devices of any kind
- Those with special accommodation needs, please send me an email message or contact me so arrangements can be made
- Review session – to be determined

Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

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

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

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

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

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

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

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

Identical Expressions for Capacitors

Temperature and Voltage Coefficients

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

VV

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)

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%

Basic Devices and Device Models

- Resistor

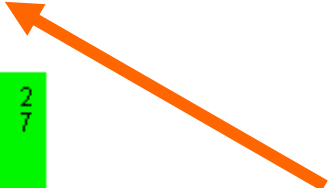
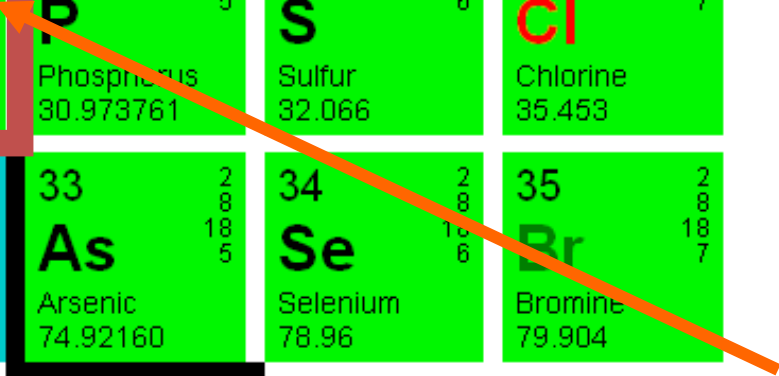
 Diode

- Capacitor
- MOSFET
- BJT

Periodic Table of the Elements

1 IA New Original	2 IIA											18 VIIIA
1 H Hydrogen 1.00794	4 Be Beryllium 9.012182											10 Ne Neon 20.1797
3 Li Lithium 6.941	5 B Boron 10.811											11 Na Sodium 22.98976928
6 C Carbon 12.0107	7 N Nitrogen 14.00643											12 Mg Magnesium 24.304
8 O Oxygen 15.999	9 F Fluorine 18.9984032											13 Al Aluminum 26.9815386
16 S Sulfur 32.06	17 Cl Chlorine 35.45											14 Si Silicon 28.0855
32 Ge Germanium 72.64	33 As Arsenic 74.9216											15 P Phosphorus 30.973762
60 Nd Neodymium 144.24	61 Pm Promethium [144.9127]											16 S Sulfur 32.06
80 Hg Mercury 200.59	81 Tl Thallium 204.3833											17 Cl Chlorine 35.45
110 Ds Darmstadtium [271]	111 Rg Roentgenium [272]											18 Ar Argon 39.948
118 Og Oganesson [294]	119 Uue Ununennium [295]											19 K Potassium 39.0983
120 Uuo Unbinilium [296]	121 Uuh Untrium [297]											20 Ca Calcium 40.078
122 Uuq Unquadium [298]	123 Uub Unbium [299]											21 Sc Scandium 44.955912
124 Uuq Unquadium [299]	125 Uub Unbium [300]											22 Ti Titanium 47.867
126 Uuq Unquadium [301]	127 Uub Unbium [302]											23 V Vanadium 50.9415
128 Uuq Unquadium [303]	129 Uub Unbium [304]											24 Cr Chromium 51.9961
130 Uuq Unquadium [305]	131 Uub Unbium [306]											25 Mn Manganese 54.938045
132 Uuq Unquadium [307]	133 Uub Unbium [308]											26 Fe Iron 55.845
134 Uuq Unquadium [309]	135 Uub Unbium [310]											27 Co Cobalt 58.933195
136 Uuq Unquadium [311]	137 Uub Unbium [312]											28 Ni Nickel 58.6934
138 Uuq Unquadium [313]	139 Uub Unbium [314]											29 Cu Copper 63.546
140 Uuq Unquadium [315]	141 Uub Unbium [316]											30 Zn Zinc 65.38
142 Uuq Unquadium [317]	143 Uub Unbium [318]											31 Ga Gallium 69.723
144 Uuq Unquadium [319]	145 Uub Unbium [320]											32 Ge Germanium 72.64
146 Uuq Unquadium [321]	147 Uub Unbium [322]											33 As Arsenic 74.9216
148 Uuq Unquadium [323]	149 Uub Unbium [324]											34 Se Selenium 78.96
150 Uuq Unquadium [325]	151 Uub Unbium [326]											35 Br Bromine 79.904
152 Uuq Unquadium [327]	153 Uub Unbium [328]											36 Kr Krypton 83.798
154 Uuq Unquadium [329]	155 Uub Unbium [330]											37 Rb Rubidium 85.4678
156 Uuq Unquadium [331]	157 Uub Unbium [332]											38 Sr Strontium 87.62
158 Uuq Unquadium [333]	159 Uub Unbium [334]											39 Y Yttrium 88.90584
160 Uuq Unquadium [335]	161 Uub Unbium [336]											40 Zr Zirconium 91.224
162 Uuq Unquadium [337]	163 Uub Unbium [338]											41 Nb Niobium 92.90638
164 Uuq Unquadium [339]	165 Uub Unbium [340]											42 Mo Molybdenum 95.94
166 Uuq Unquadium [341]	167 Uub Unbium [342]											43 Tc Technetium [98]
168 Uuq Unquadium [343]	169 Uub Unbium [344]											44 Ru Ruthenium 101.07
170 Uuq Unquadium [345]	171 Uub Unbium [346]											45 Rh Rhodium 102.9055
172 Uuq Unquadium [347]	173 Uub Unbium [348]											46 Pd Palladium 106.3678
174 Uuq Unquadium [349]	175 Uub Unbium [350]											47 Ag Silver 107.8682
176 Uuq Unquadium [351]	177 Uub Unbium [352]											48 Cd Cadmium 112.411
178 Uuq Unquadium [353]	179 Uub Unbium [354]											49 In Indium 114.818
180 Uuq Unquadium [355]	181 Uub Unbium [356]											50 Sn Tin 118.710
182 Uuq Unquadium [357]	183 Uub Unbium [358]											51 Sb Antimony 121.757
184 Uuq Unquadium [359]	185 Uub Unbium [360]											52 Te Tellurium 127.6
186 Uuq Unquadium [361]	187 Uub Unbium [362]											53 I Iodine 126.90547
188 Uuq Unquadium [363]	189 Uub Unbium [364]											54 Xe Xenon 131.29
190 Uuq Unquadium [365]	191 Uub Unbium [366]											55 Cs Cesium 132.90545
192 Uuq Unquadium [367]	193 Uub Unbium [368]											56 Ba Barium 137.327
194 Uuq Unquadium [369]	195 Uub Unbium [370]											57 La Lanthanum 138.90547
196 Uuq Unquadium [371]	197 Uub Unbium [372]											58 Ce Cerium 140.12
198 Uuq Unquadium [373]	199 Uub Unbium [374]											59 Pr Praseodymium 140.90766
200 Uuq Unquadium [375]	201 Uub Unbium [376]											60 Nd Neodymium 144.24
202 Uuq Unquadium [377]	203 Uub Unbium [378]											61 Pm Promethium [144.9127]
204 Uuq Unquadium [379]	205 Uub Unbium [380]											62 Sm Samarium 150.36
206 Uuq Unquadium [381]	207 Uub Unbium [382]											63 Eu Europium 151.964
208 Uuq Unquadium [383]	209 Uub Unbium [384]											64 Gd Gadolinium 157.25
210 Uuq Unquadium [385]	211 Uub Unbium [386]											65 Tb Terbium 158.92535
212 Uuq Unquadium [387]	213 Uub Unbium [388]											66 Dy Dysprosium 162.50015
214 Uuq Unquadium [389]	215 Uub Unbium [390]											67 Ho Holmium 164.93033
216 Uuq Unquadium [391]	217 Uub Unbium [392]											68 Er Erbium 167.259
218 Uuq Unquadium [393]	219 Uub Unbium [394]											69 Tm Thulium 168.93032
220 Uuq Unquadium [395]	221 Uub Unbium [396]											70 Yb Ytterbium 173.05468
222 Uuq Unquadium [397]	223 Uub Unbium [398]											71 Lu Lutetium 174.967
224 Uuq Unquadium [399]	225 Uub Unbium [400]											72 Hf Hafnium 178.49
226 Uuq Unquadium [401]	227 Uub Unbium [402]											73 Ta Tantalum 180.94788
228 Uuq Unquadium [403]	229 Uub Unbium [404]											74 W Tungsten 183.84
230 Uuq Unquadium [405]	231 Uub Unbium [406]											75 Re Rhenium 186.207
232 Uuq Unquadium [407]	233 Uub Unbium [408]											76 Os Osmium 190.23
234 Uuq Unquadium [409]	235 Uub Unbium [410]											77 Ir Iridium 192.222
236 Uuq Unquadium [411]	237 Uub Unbium [412]											78 Pt Platinum 195.084
238 Uuq Unquadium [413]	239 Uub Unbium [414]											79 Au Gold 196.96657
240 Uuq Unquadium [415]	241 Uub Unbium [416]											80 Hg Mercury 200.59
242 Uuq Unquadium [417]	243 Uub Unbium [418]											81 Tl Thallium 204.3833
244 Uuq Unquadium [419]	245 Uub Unbium [420]											82 Pb Lead 207.2
246 Uuq Unquadium [421]	247 Uub Unbium [422]											83 Bi Bismuth 208.98039
248 Uuq Unquadium [423]	249 Uub Unbium [424]											84 Po Polonium [209]
250 Uuq Unquadium [425]	251 Uub Unbium [426]											85 At Astatine [210]
252 Uuq Unquadium [427]	253 Uub Unbium [428]											86 Rn Radon [222]
254 Uuq Unquadium [429]	255 Uub Unbium [430]											87 Fr Francium [223]
256 Uuq Unquadium [431]	257 Uub Unbium [432]											88 Ra Radium [226]
258 Uuq Unquadium [433]	259 Uub Unbium [434]											89 to 103
260 Uuq Unquadium [435]	261 Uub Unbium [436]											5 to 16
262 Uuq Unquadium [437]	263 Uub Unbium [438]											17 to 18
264 Uuq Unquadium [439]	265 Uub Unbium [440]											19 to 20
266 Uuq Unquadium [441]	267 Uub Unbium [442]											21 to 22
268 Uuq Unquadium [443]	269 Uub Unbium [444]											23 to 24
270 Uuq Unquadium [445]	271 Uub Unbium [446]											25 to 26
272 Uuq Unquadium [447]	273 Uub Unbium [448]											27 to 28
274 Uuq Unquadium [449]	275 Uub Unbium [450]											29 to 30
276 Uuq Unquadium [451]	277 Uub Unbium [452]											31 to 32
278 Uuq Unquadium [453]	279 Uub Unbium [454]											33 to 34
280 Uuq Unquadium [455]	281 Uub Unbium [456]											35 to 36
282 Uuq Unquadium [457]	283 Uub Unbium [458]											37 to 38
284 Uuq Unquadium [459]	285 Uub Unbium [460]											39 to 40
286 Uuq Unquadium [461]	287 Uub Unbium [462]											41 to 42
288 Uuq Unquadium [463]	289 Uub Unbium [464]											43 to 44
290 Uuq Unquadium [465]	291 Uub Unbium [466]											45 to 46
292 Uuq Unquadium [467]	293 Uub Unbium [468]											47 to 48
294 Uuq Unquadium [469]	295 Uub Unbium [470]											49 to 50
296 Uuq Unquadium [471]	297 Uub Unbium [472]											51 to 52
298 Uuq Unquadium [473]	299 Uub Unbium [474]											53 to 54
300 Uuq Unquadium [475]	301 Uub Unbium [476]											55 to 56
302 Uuq Unquadium [477]	303 Uub Unbium [478]											57 to 58
304 Uuq Unquadium [479]	305 Uub Unbium [480]											59 to 60
306 Uuq Unquadium [481]	307 Uub Unbium [482]											61 to 62
308 Uuq Unquadium [483]	309 Uub Unbium [484]											63 to 64
310 Uuq Unquadium [485]	311 Uub Unbium [486]											65 to 66
312 Uuq Unquadium [487]	313 Uub Unbium [488]											67 to 68
314 Uuq Unquadium [489]	315 Uub Unbium [490]											69 to 70
316 Uuq Unquadium [491]	317 Uub Unbium [492]											71 to 72
318 Uuq Unquadium [493]	319 Uub Unbium [494]											73 to 74
320 Uuq Unquadium [495]	321 Uub Unbium [496]											75 to 76
322 Uuq Unquadium [497]	323 Uub Unbium [498]											77 to 78
324 Uuq Unquadium [499]	325 Uub Unbium [500]											79 to 80
326 Uuq Unquadium [501]	327 Uub Unbium [502]											81 to 82
328 Uuq Unquadium [503]	329 Uub Unbium [504]											83 to 84
330 Uuq Unquadium [505]	331 Uub Unbium [506]											85 to 86
332 Uuq Unquadium [507]	333 Uub Unbium [508]											87 to 88
334 Uuq Unquadium [509]	335 Uub Unbium [510]											89 to 90
336 Uuq Unquadium [511]	337 Uub Unbium [512]											91 to 92
338 Uuq Unquadium [513]	339 Uub Unbium [514]											93 to 94
340 Uuq Unquadium [515]	341 Uub Unbium [516]											95 to 96
342 Uuq Unquadium [517]	343 Uub Unbium [518]											97 to 98
344 Uuq Unquadium [519]	345 Uub Unbium [520]											99 to 100
346 Uuq Unquadium [521]	347 Uub Unbium [522]											101 to 102
348 Uuq Unquadium [523]	349 Uub Unbium [524]											103 to 104
350 Uuq Unquadium [525]	351 Uub Unbium [526]											105 to 106
352 Uuq Unquadium [527]	353 Uub Unbium [528]											107 to 108
354 Uuq Unquadium [529]	355 Uub Unbium [530]											109 to 110
356 Uuq Unquadium [531]	357 Uub Unbium [532]											111 to 112
358 Uuq Unquadium [533]	359 Uub Unbium [534]											113 to 114
360 Uuq Unquadium [535]	361 Uub Unbium [536]											115 to 116
362 Uuq Unquadium [537]	363 Uub Unbium [538]											117 to 118
364 Uuq Unquadium [539]	365 Uub Unbium [540]											119 to 120
366 Uuq Unquadium [541]	367 Uub Unbium [542]											121 to 122
368 Uuq Unquadium [543]	369 Uub Unbium [544]											123 to 124
370 Uuq Unquadium [545]	371 Uub Unbium [546]											125 to 126
372 Uuq Unquadium [547]	373 Uub Unbium [548]											127 to 128
374 Uuq Unquadium [549]	375 Uub Unbium [550]											129 to 130
376 Uuq Unquadium [551]	377 Uub Unbium [552]											131 to 132
378 Uuq Unquadium [553]	379 Uub Unbium [554]											133 to 134
380 Uuq Unquadium [555]	381 Uub Unbium [556]											135 to 136
382 Uuq Unquadium [557]	383 Uub Unbium [558]											137 to 138
384 Uuq Unquadium [559]	385 Uub Unbium [560]											139 to 140
386 Uuq Unquadium [561]	387 Uub Unbium [562]											141 to 142
388 Uuq Unquadium [563]	389 Uub Unbium [564]											143 to 144
390 Uuq Unquadium [565]	391 Uub Unbium [566]											145 to 146
392 Uuq Unquadium [567]	393 Uub Unbium [568]											147 to 148
394 Uuq Unquadium [569]	395 Uub Unbium [570]											149 to 150
396 Uuq Unquadium [571]	397 Uub Unbium [572]											151 to 152
398 Uuq Unquadium [573]	399 Uub Unbium [574]											153 to 154
400 Uuq Unquadium [575]	401 Uub Unbium [576]											155 to 156
402 Uuq Unquadium [577]	403 Uub Unbium [578]											157 to 158
404 Uuq Unquadium [579]	405 Uub Unbium [580]											159 to 160
406 Uuq Unquadium [581]	407 Uub Unbium [582]											161 to 162
408 Uuq Unquadium [583]	409 Uub Unbium [584]											163 to 164
410 Uuq Unquadium [585]	411 Uub Unbium [586]											165 to 166
412 Uuq Unquadium [587]	413 Uub Unbium [588]											167 to 168
414 Uuq Unquadium [589]	415 Uub Unbium [590]											169 to 170
416 Uuq Unquadium [591]	417 Uub Unbium [592]											171 to 172
418 Uuq Unquadium [593]	419 Uub Unbium [594]											173 to 174
420 Uuq Unquadium [595]	421 Uub Unbium [596]											175 to 17

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	 4 valence-band Electrons
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)	

All elements in group IV have 4 valence-band electrons

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

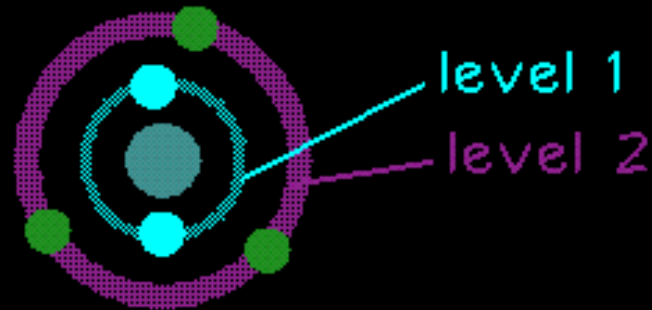
Only 3 Valence-band Electrons

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)



B atom

<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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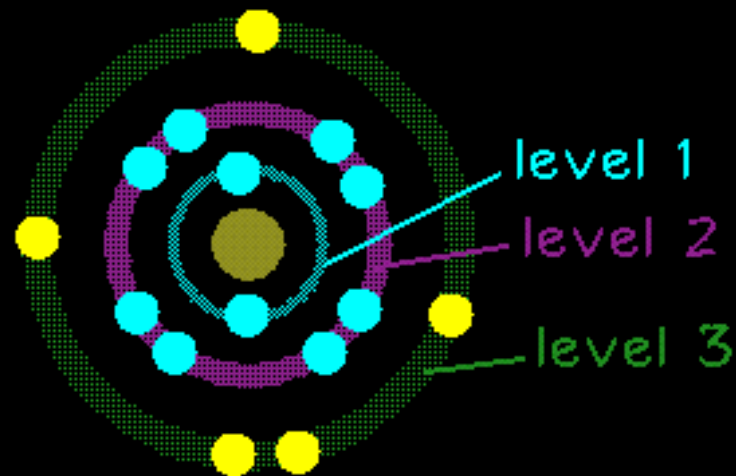
Five Valence-band Electrons

Serves as an “donor” of electrons

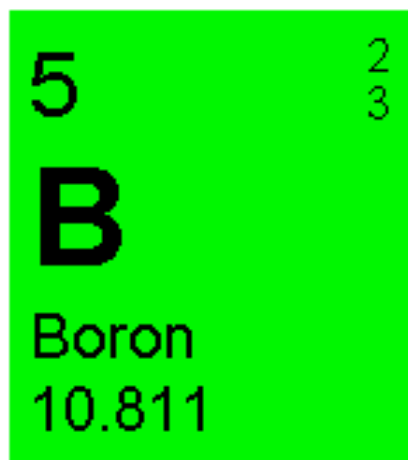
Acts as an n-type impurity when used as a silicon dopant

All elements in group V have 5 valence-band electrons

The Atom of Phosphorus (P)



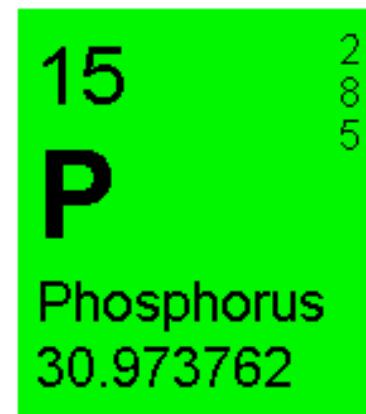
P atom



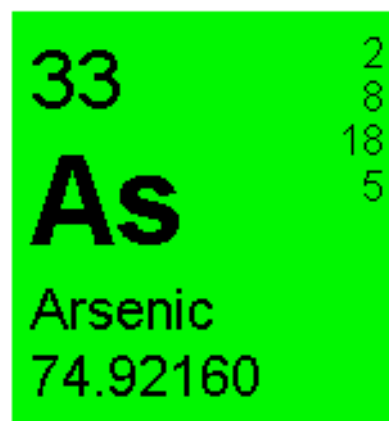
$1s^2 2s^2 2p^1$



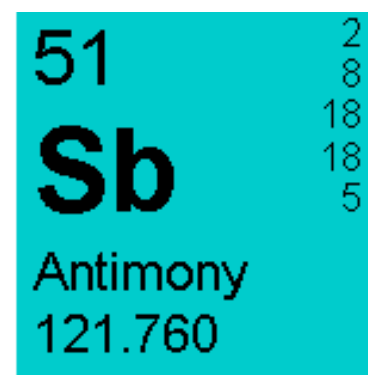
$[\text{Ne}]3s^2 3p^2$



$[\text{Ne}]3s^2 3p^3$



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



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

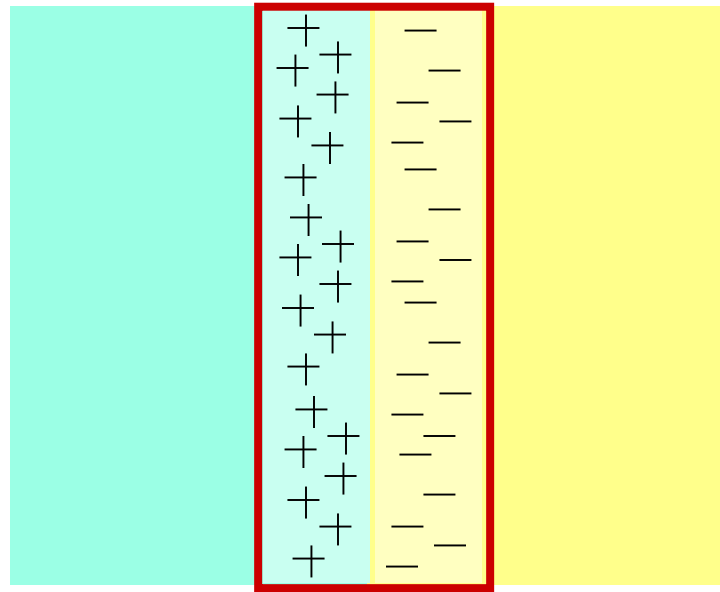
Silicon Dopants in Semiconductor Processes

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)

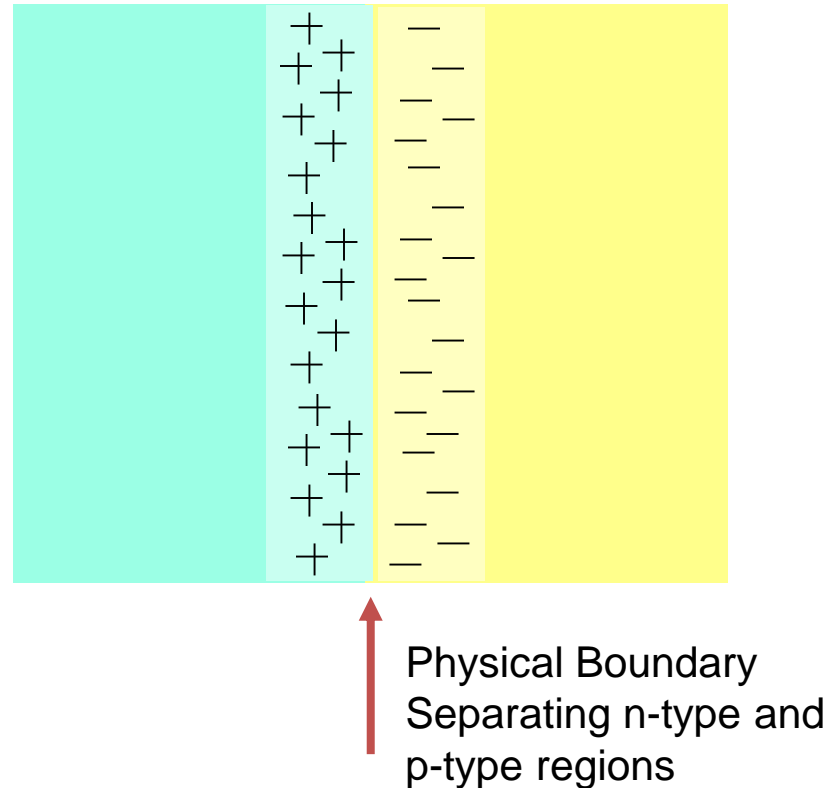
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



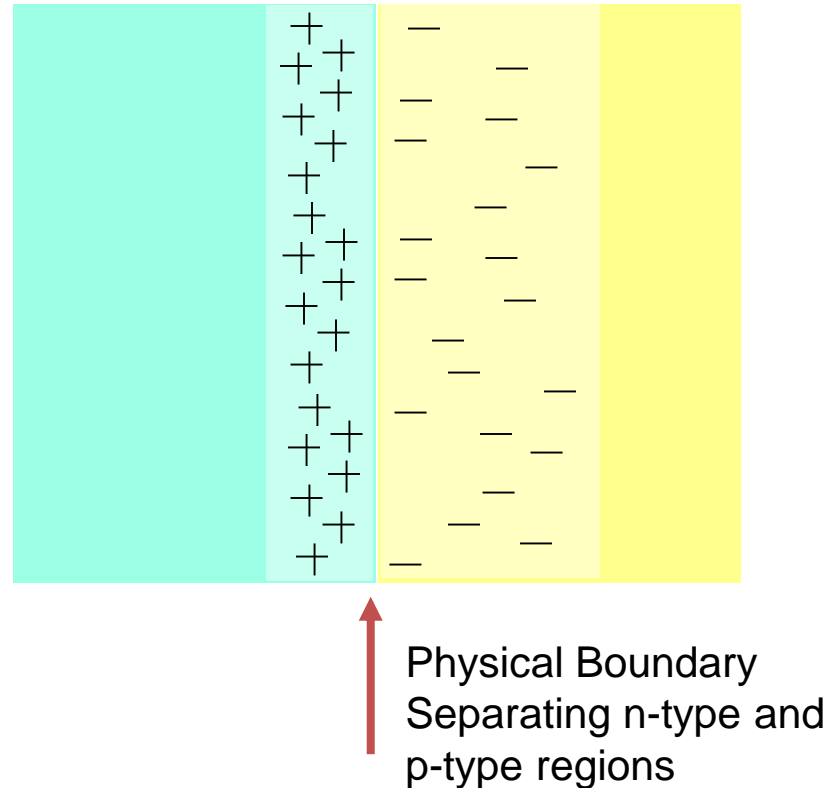
Depletion region created that is ionized but void of carriers

pn Junctions



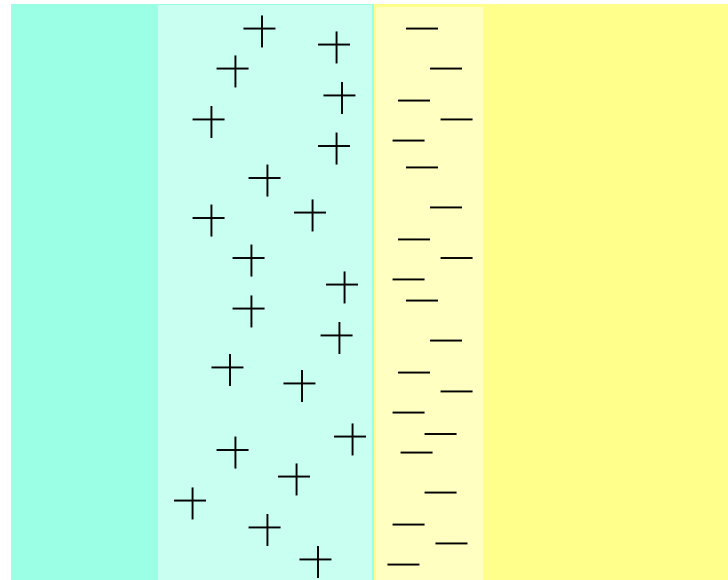
If doping levels identical, depletion region extends equally into n-type and p-type regions

pn Junctions



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

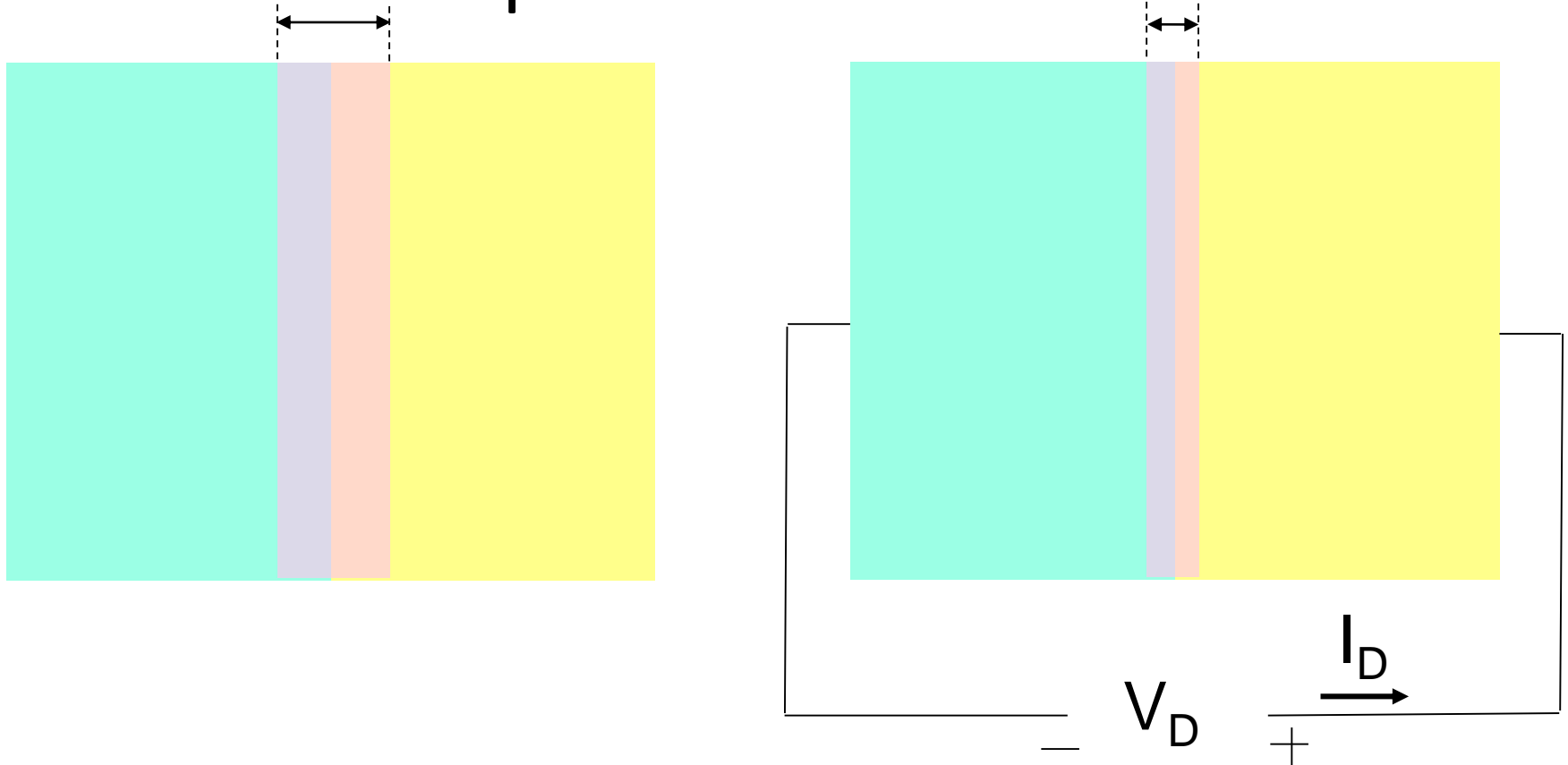
pn Junctions



Physical Boundary
Separating n-type and
p-type regions

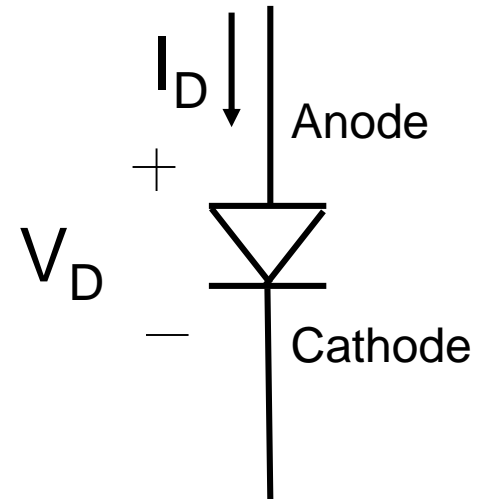
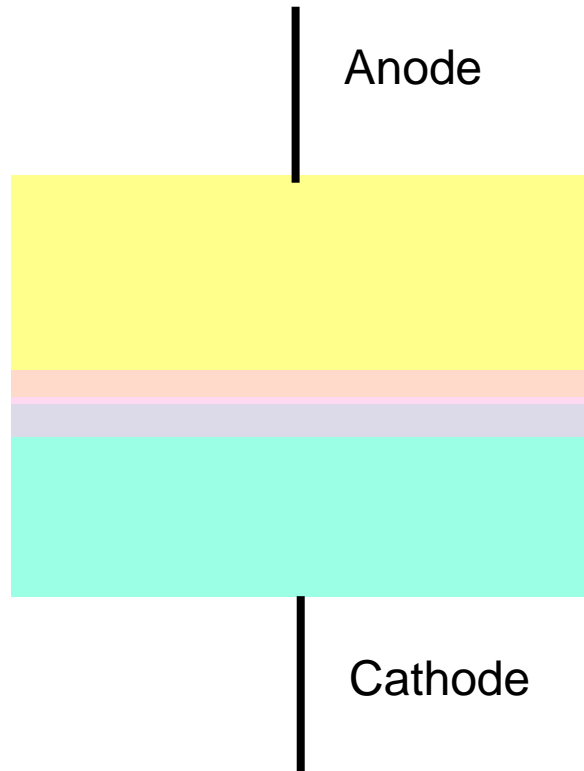
Extends farther into n-type region if n-doping lower
than p-doping

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

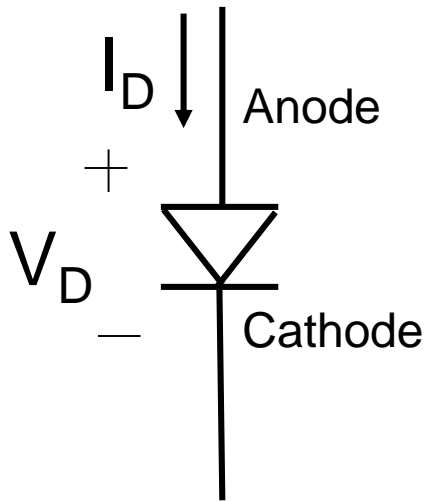


Circuit Symbol

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:

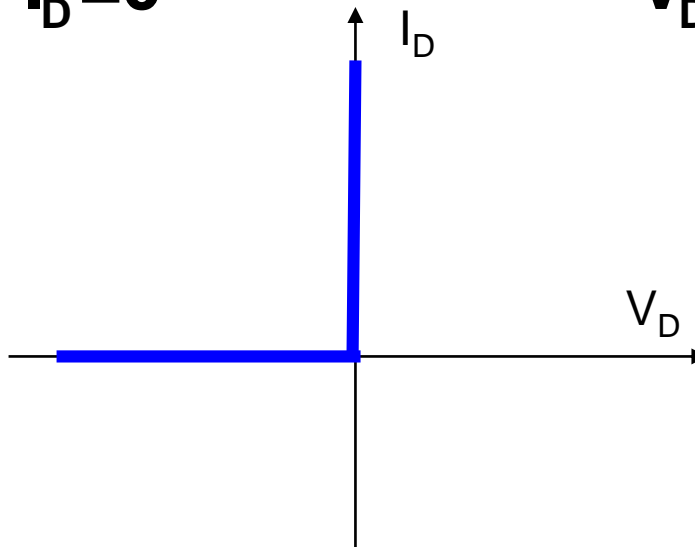


$$V_D = 0$$

$$I_D = 0$$

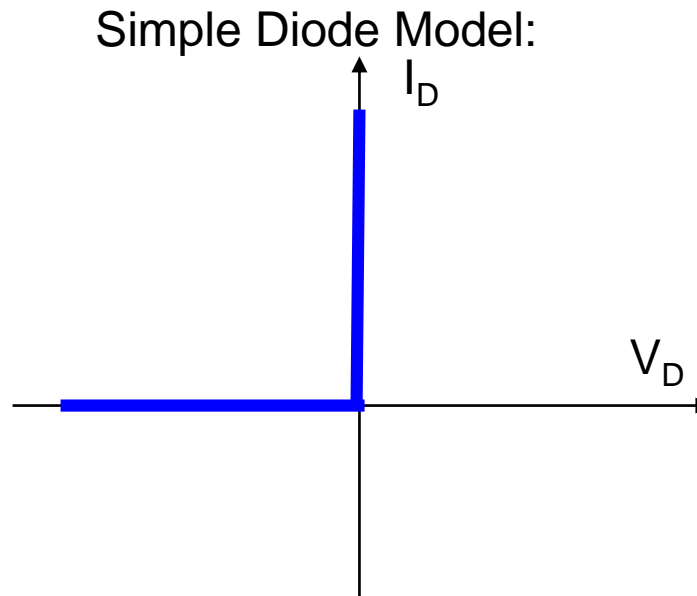
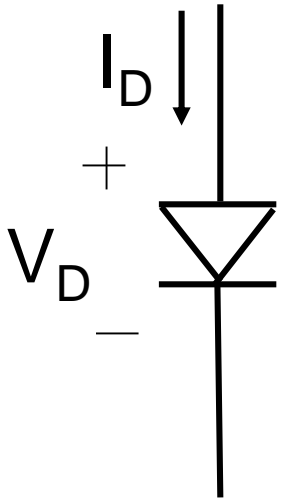
$$I_D > 0$$

$$V_D < 0$$



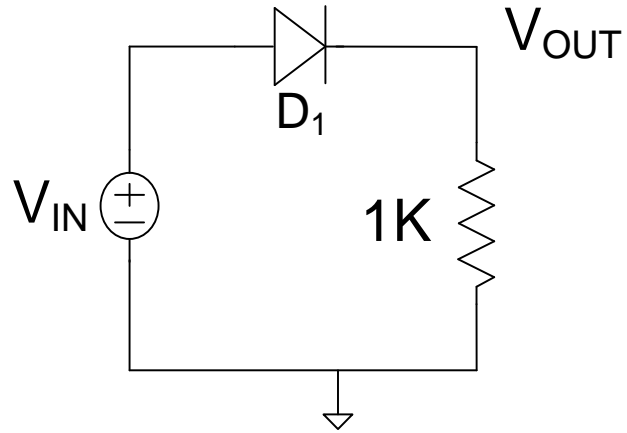
Simple model often referred to as the "Ideal" diode model

pn Junctions

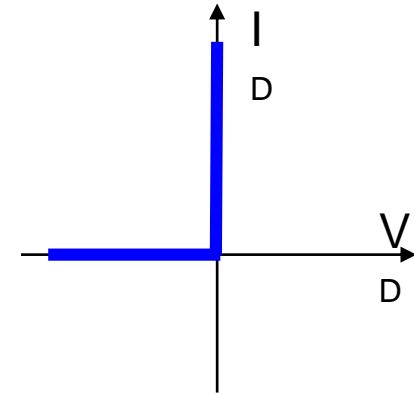


pn junction serves as a “rectifier” passing current in one direction and blocking it in the other direction

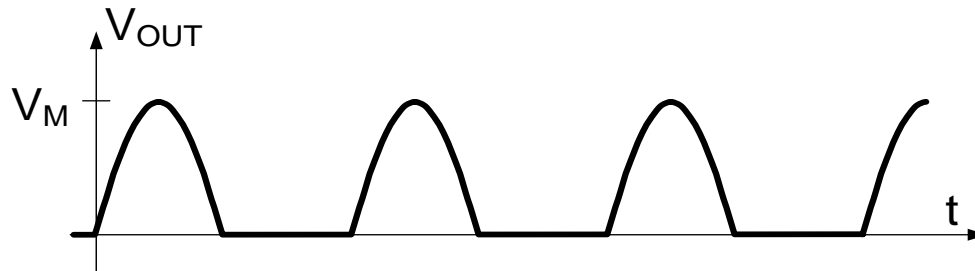
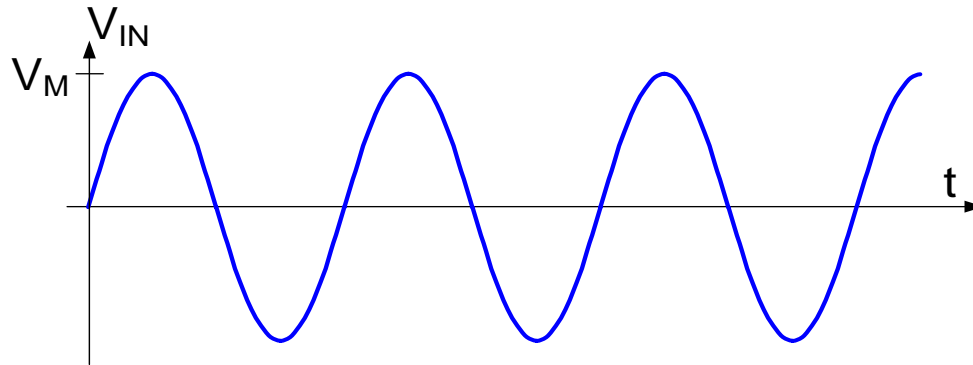
Rectifier Application:



Simple Diode Model:



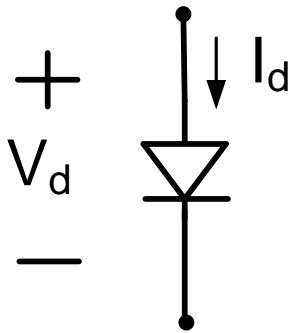
$$V_{IN} = V_M \sin \omega t$$



I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:



Diode Equation

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

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

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

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

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

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

Diode equation due to William Shockley, inventor of BJT

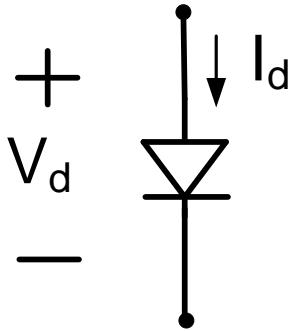
In 1919, [William Henry Eccles](#) coined the term **diode**

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

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:

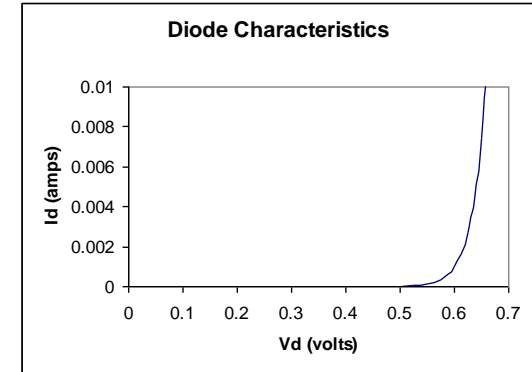


Diode Equation
$$I_D = I_S \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

Simplification of Diode Equation:

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

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



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

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

$$k = 1.380\,6504(24) \times 10^{-23} \text{ JK}^{-1}$$

$$q = -1.602176487(40) \times 10^{-19} \text{ C}$$

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

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 is unwieldy to work with analytically

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:

Diode Equation

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

I_S often in the 10fA to 100fA range
 I_S proportional to junction area

V_t is about 26mV at room temp

Simplification of Diode Equation:

Under reverse bias, $I_D \cong -I_S$

Under forward bias, $I_D = I_S e^{\frac{V_d}{V_t}}$

How much error is introduced using the simplification for $V_d > 0.5V$?

$$\varepsilon = \frac{I_S \left(e^{\frac{V_d}{V_t}} - 1 \right) - I_S e^{\frac{V_d}{V_t}}}{I_S \left(e^{\frac{V_d}{V_t}} - 1 \right)} \quad \varepsilon < \frac{1}{e^{\frac{0.5}{0.026}}} = 4.4 \bullet 10^{-9}$$

How much error is introduced using the simplification for $V_d < -0.5V$?

$$\varepsilon < e^{\frac{-0.5}{0.026}} = 4.4 \bullet 10^{-9}$$

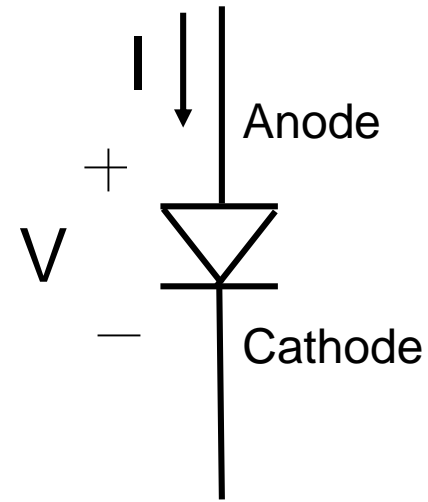
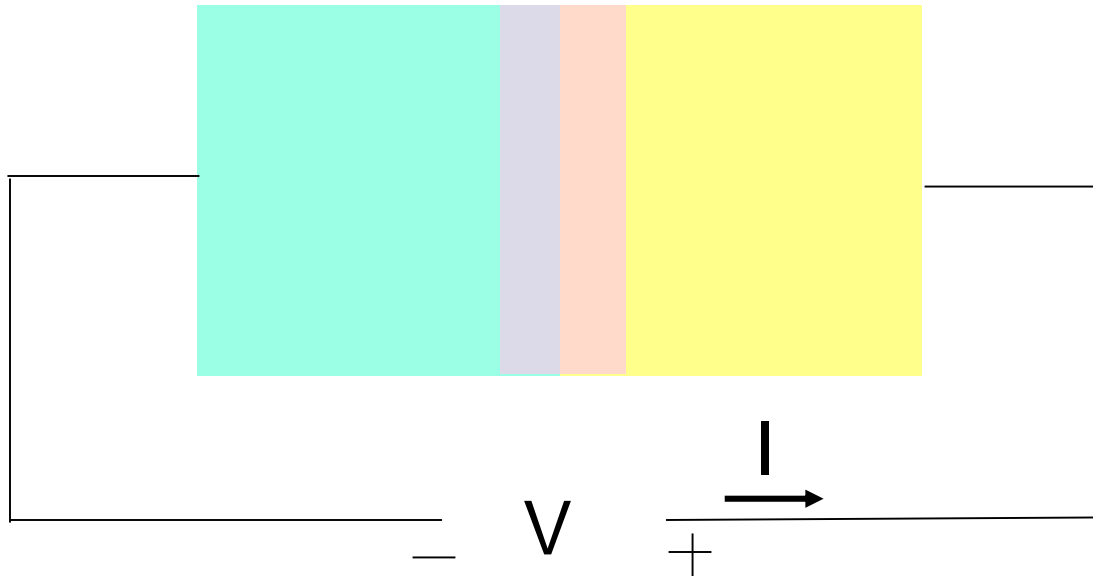
Simplification almost never introduces any significant error

Will you impress your colleagues or your boss if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$?



Will your colleagues or your boss be unimpressed if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$?

pn Junctions



Diode Equation:
(good enough for most applications)

$$I = \begin{cases} J_s A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

Note: $I_s = J_s A$

J_s = Sat Current Density (in the $1\text{aA}/\text{u}^2$ to $1\text{fA}/\text{u}^2$ range)

A = Junction Cross Section Area

$V_T = kT/q$ ($k/q = 1.381 \times 10^{-23} \text{V} \cdot \text{C} / ^\circ\text{K} / 1.6 \times 10^{-19} \text{C} = 8.62 \times 10^{-5} \text{V} / ^\circ\text{K}$)

n is approximately 1

pn Junctions

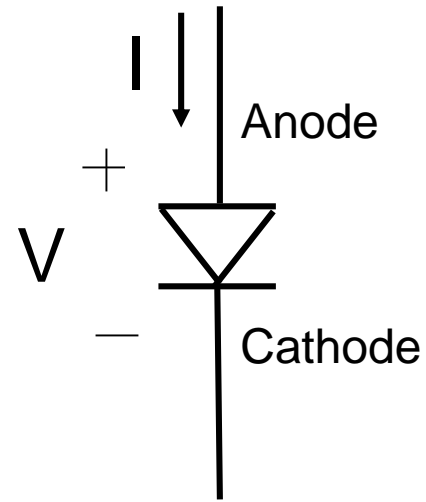
Diode Equation:
$$I = \begin{cases} J_s A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

J_s is strongly temperature dependent

With $n=1$, for $V>0$,

$$I(T) = \left(J_{SX} \left[T^m e^{\frac{-V_{G0}}{V_t}} \right] \right) A e^{\frac{V_D}{V_t}}$$

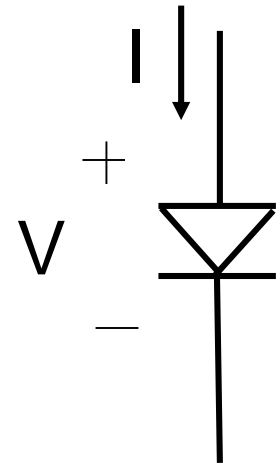
Typical values for key parameters: $J_{SX}=0.5\text{A}/\mu^2$, $V_{G0}=1.17\text{V}$, $m=2.3$



pn Junctions

Example:

$$I(T) = \left(J_{SX} \left[T^m e^{\frac{-V_{G0}}{V_t}} \right] \right) A e^{\frac{V_D}{V_t}}$$



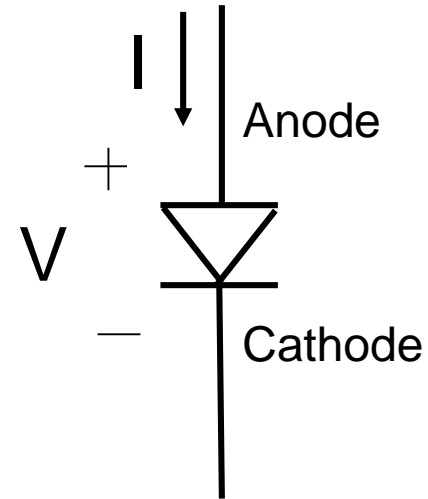
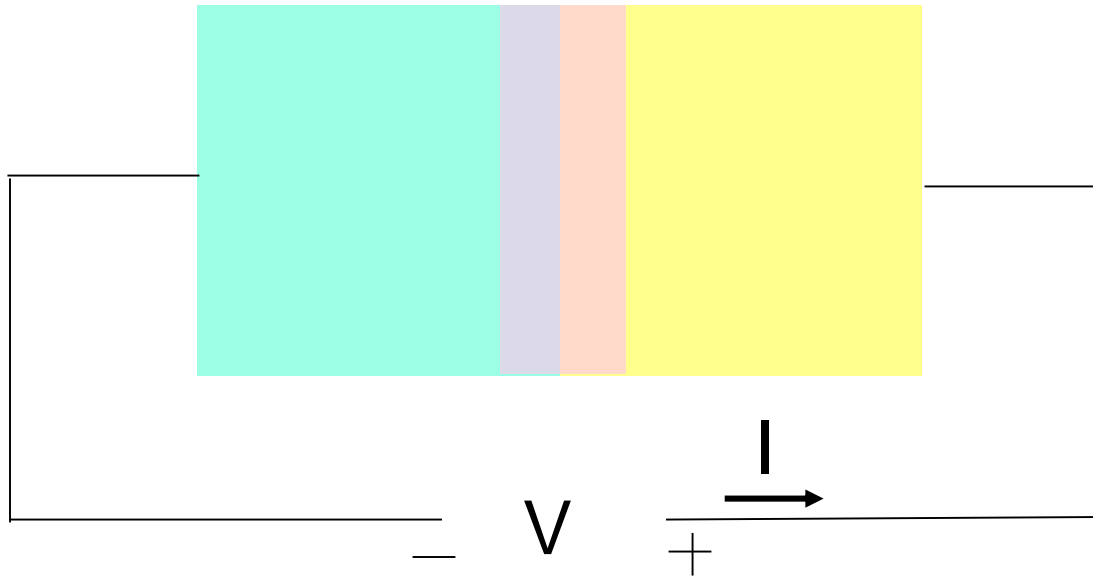
What percent change in I_S will occur for a 1°C change in temperature at room temperature?

$$\frac{\Delta I_S}{I_S} = \frac{\left(J_{SX} \left[T_2^m e^{\frac{-V_{G0}}{V_t(T_2)}} \right] \right) A e^{\frac{V_D}{V_t}} - \left(J_{SX} \left[T_1^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right] \right) A e^{\frac{-V_{G0}}{V_t(T_2)}}}{\left(J_{SX} \left[T_1^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right] \right) A e^{\frac{-V_{G0}}{V_t(T_2)}}} = \frac{\left(\left[T_2^m e^{\frac{-V_{G0}}{V_t(T_2)}} \right] \right) - \left(\left[T_1^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right] \right)}{\left(\left[T_1^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right] \right)}$$

$$\frac{\Delta I_S}{I_S} = \frac{(1.240 \times 10^{-15}) - (1.025 \times 10^{-15})}{(1.025 \times 10^{-15})} 100\% = 21\%$$

- Attempts to measure I_S in our laboratories can result in large errors !
- Most circuits whose performance depends upon precise value for I_S are not practical

pn Junctions

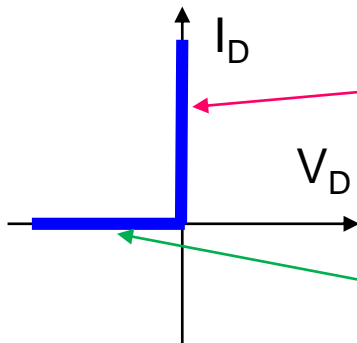


Diode Equation:
(good enough for most applications)

$$I = \begin{cases} J_s A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

$$I_s = J_s A$$

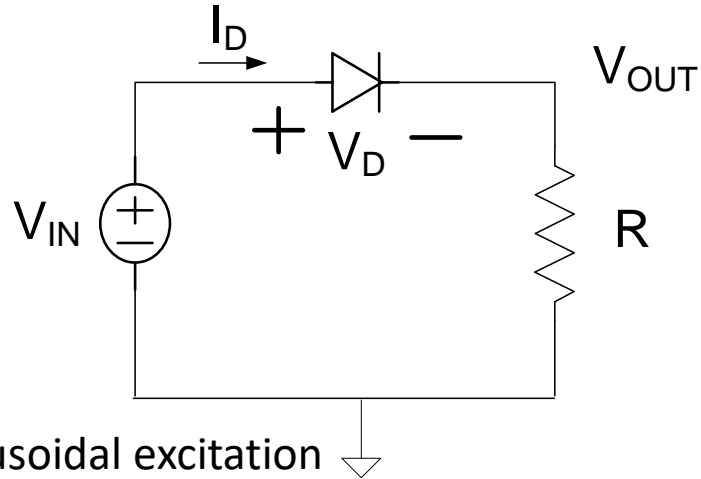
Simple Diode Model:



Often termed the “conducting” or “ON” state

Often termed the “nonconducting” or “OFF” state

Consider again the basic rectifier circuit



- Previously considered sinusoidal excitation
- Previously gave “qualitative” analysis
- **Rigorous analysis method is essential**

$$V_{OUT} = ?$$

Analysis of Nonlinear Circuits

(Circuits with one or more nonlinear devices)

What analysis tools or methods can be used?

KCL ?

Nodal Analysis ?

KVL?

Mesh Analysis ?

~~Superposition?~~

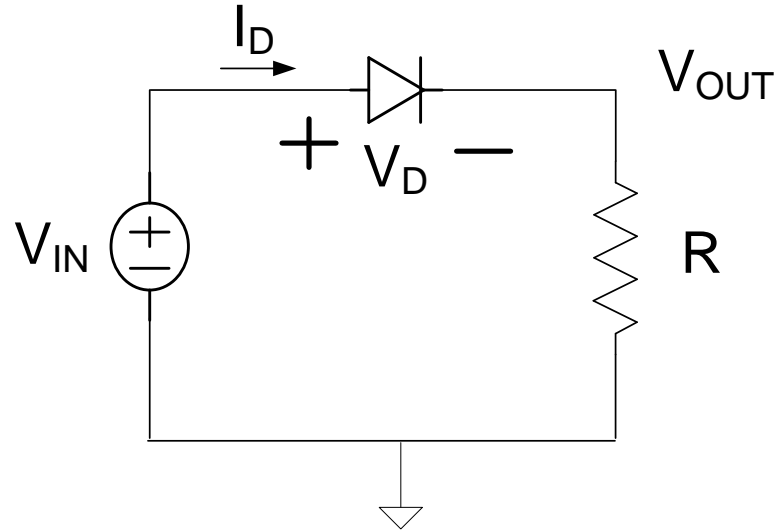
Two-Port Subcircuits ?

~~Voltage Divider ?~~

~~Current Divider?~~

~~Thevenin and Norton Equivalent Circuits?~~

Consider again the basic rectifier circuit



$$\left. \begin{aligned} V_{IN} &= V_D + I_D R \\ V_{OUT} &= I_D R \\ I_D &= I_S \left(e^{\frac{V_D}{V_t}} - 1 \right) \end{aligned} \right\} \quad V_{OUT} = I_S R \left(e^{\frac{V_{IN} - V_{OUT}}{V_t}} - 1 \right)$$

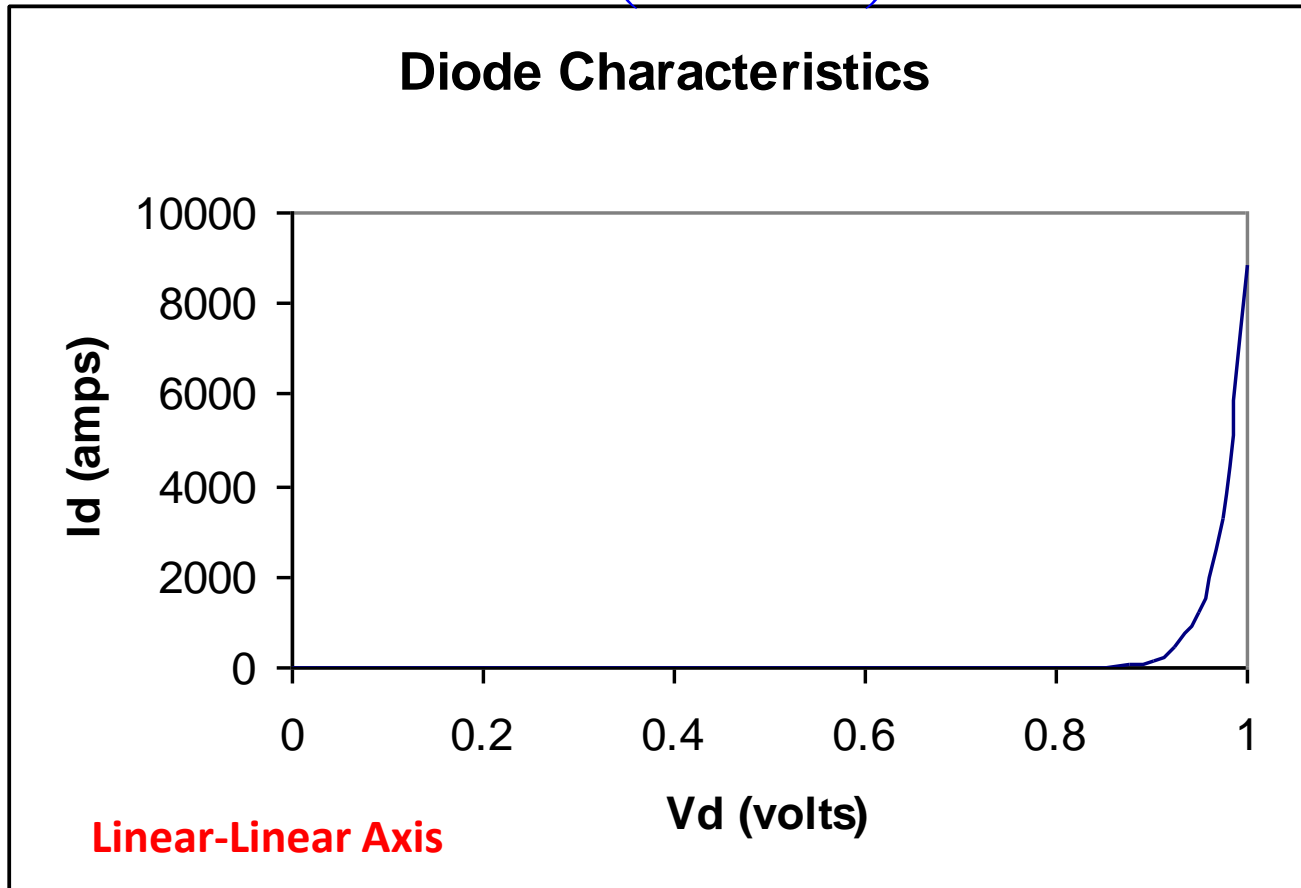
Even the simplest diode circuit does not have a closed-form solution when diode equation is used to model the diode !!

Due to the nonlinear nature of the diode equation

Simplifications are essential if analytical results are to be obtained

Lets study the diode equation a little further

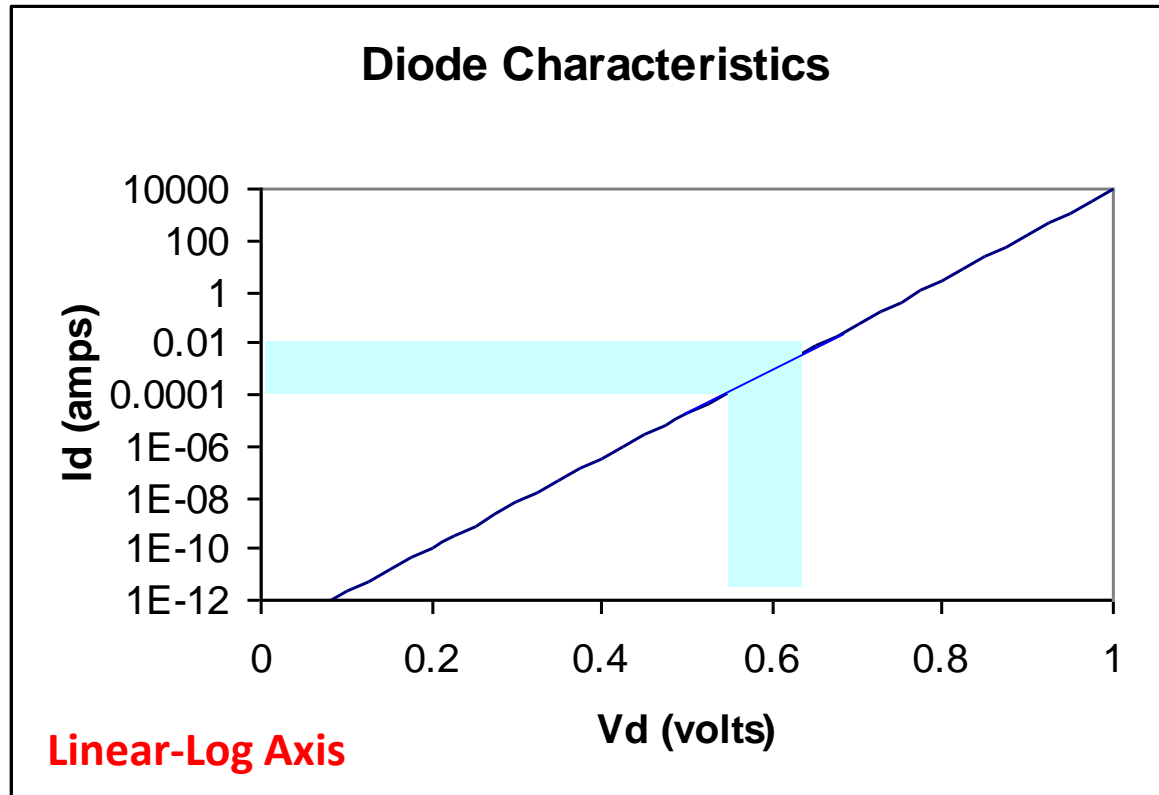
$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$



Power Dissipation Becomes Destructive if $V_d > 0.85V$ (actually less)

Lets study the diode equation a little further

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

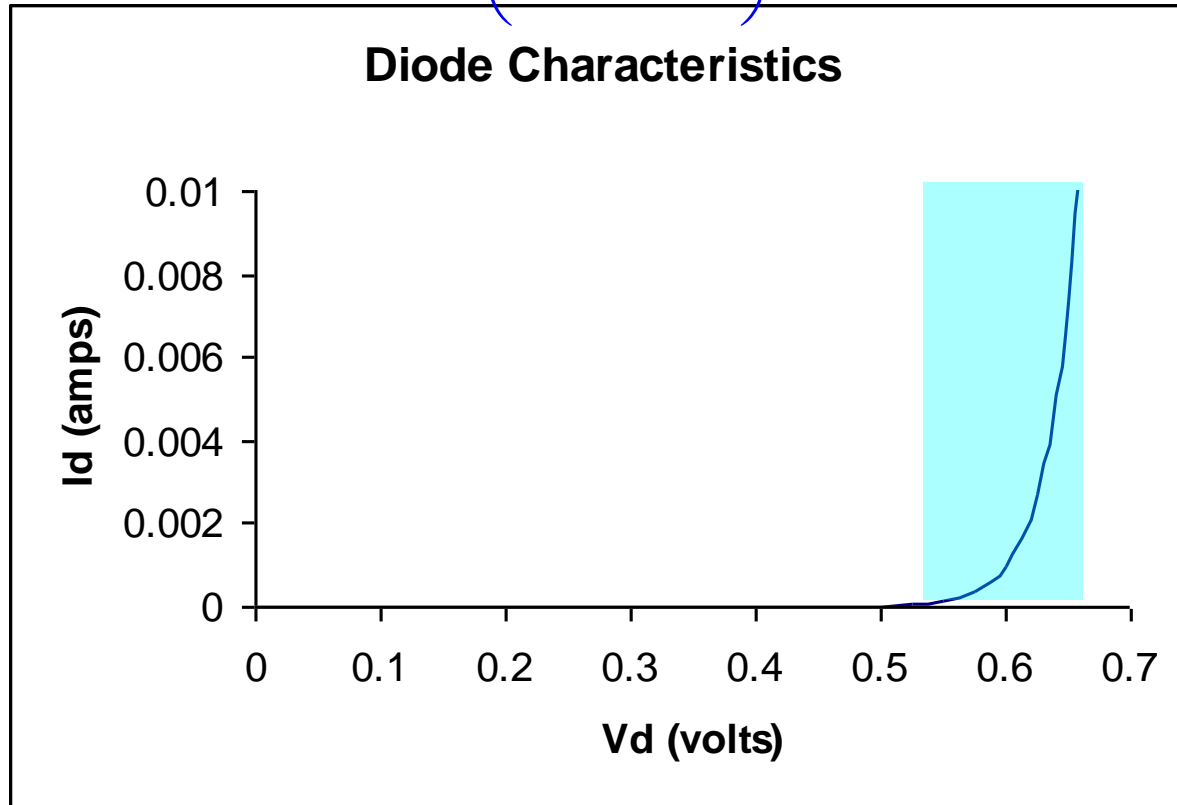


For two decades of current change, V_d is close to 0.6V

This is the most useful conducting current range for many applications

Lets study the diode equation a little further

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$



For two decades of current change, V_d is close to 0.6V

This is the most useful current range when conducting for many applications

Lets study the diode equation a little further

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

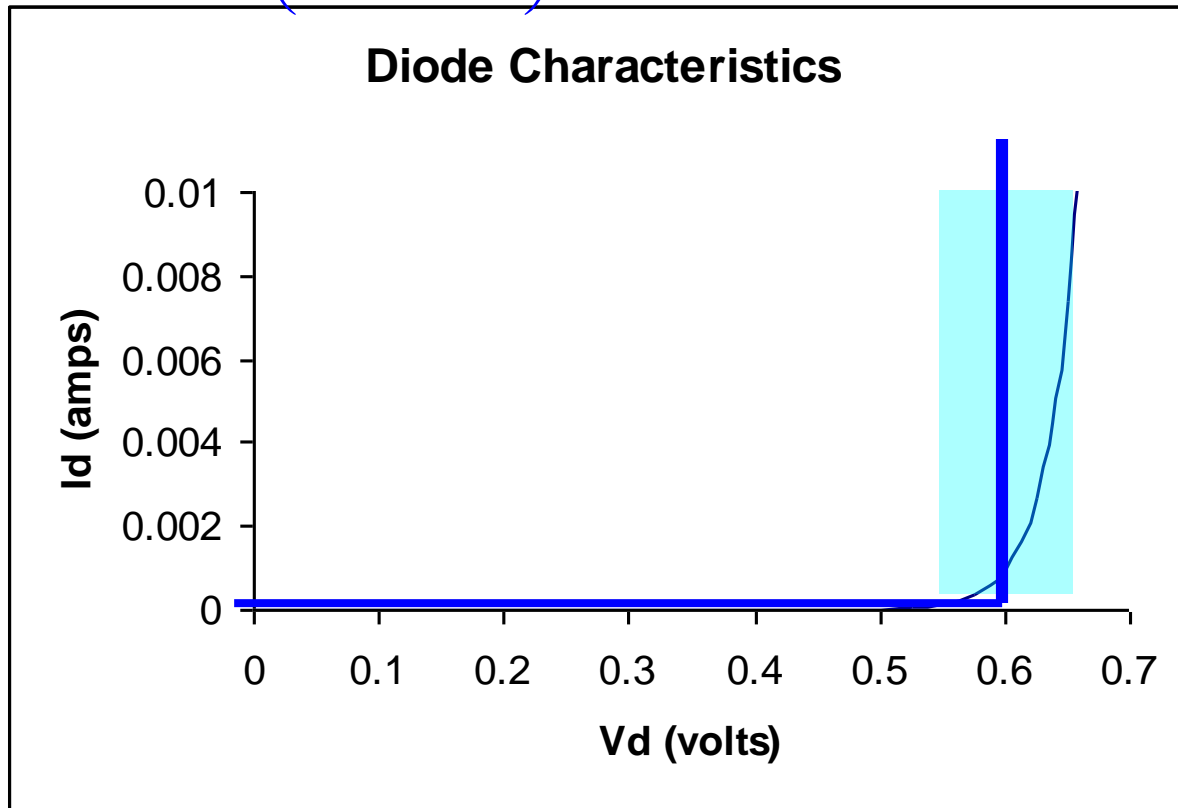


$$I_d = 0$$

$$V_d = 0.6V$$

$$V_d < 0.6V$$

$$I_d > 0$$

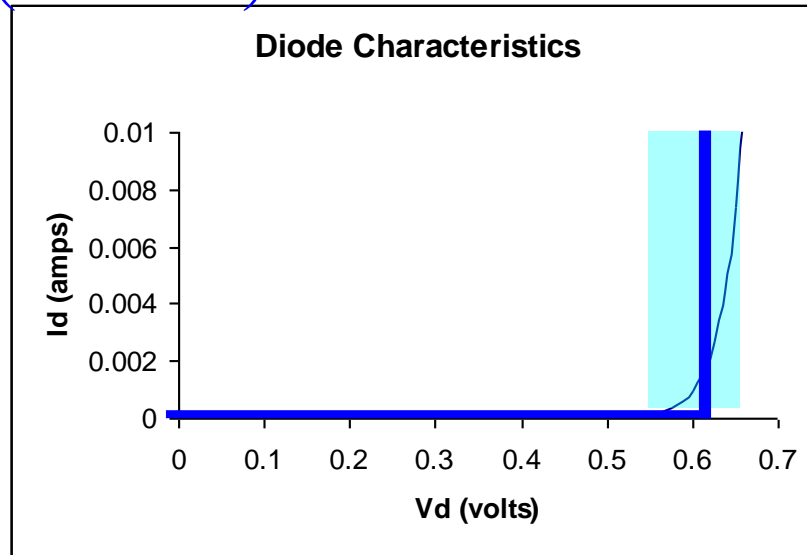


Widely Used Piecewise Linear Model

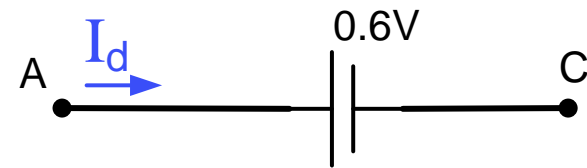
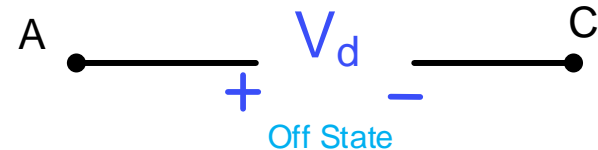
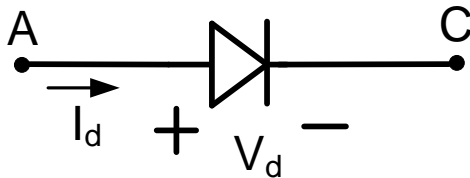
Lets study the diode equation a little further

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

$$\begin{aligned} I_d &= 0 & V_d < 0.6V \\ V_d &= 0.6V & I_d > 0 \end{aligned}$$

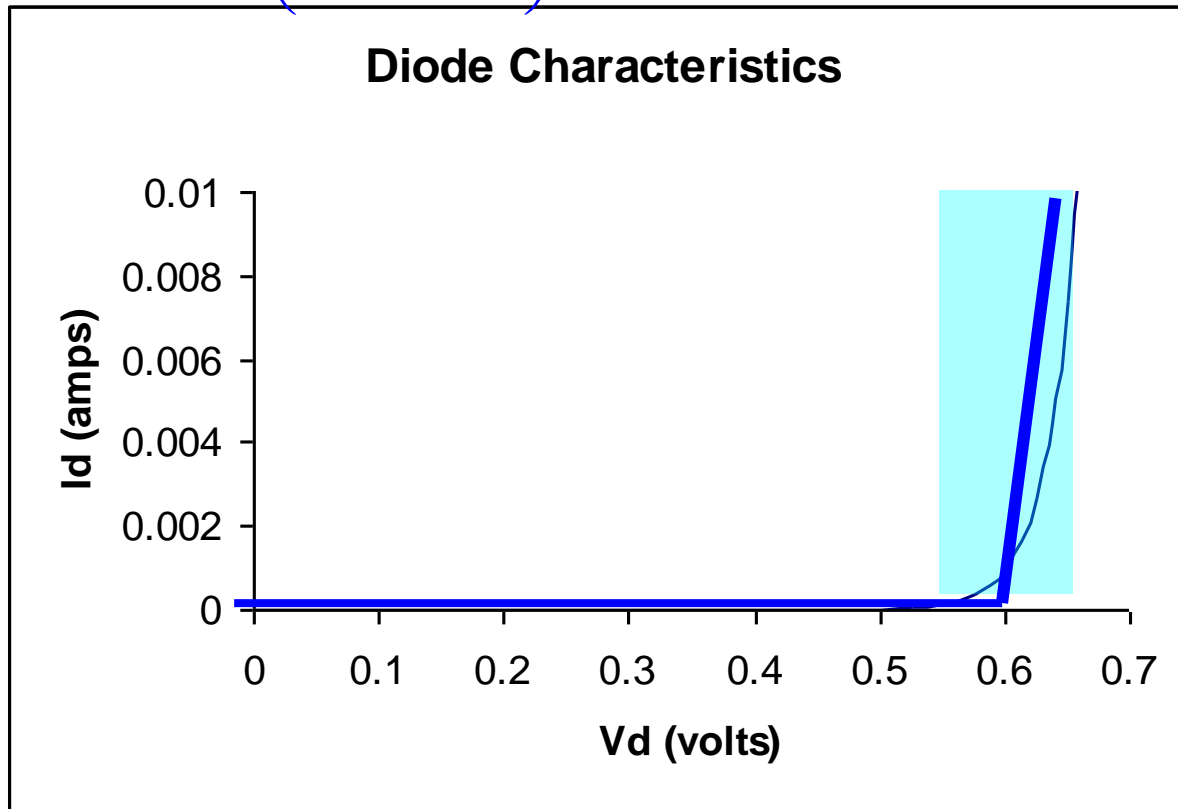


Equivalent Circuit



Lets study the diode equation a little further

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$



Better model in “ON” state though often not needed

Includes Diode “ON” resistance

Lets study the diode equation a little further

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

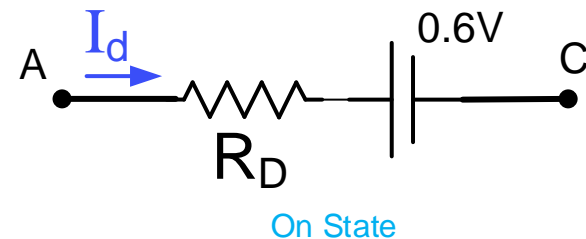
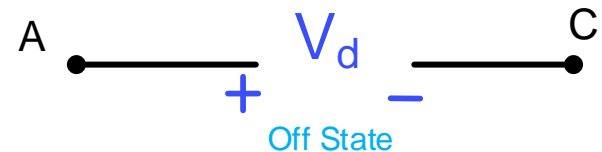
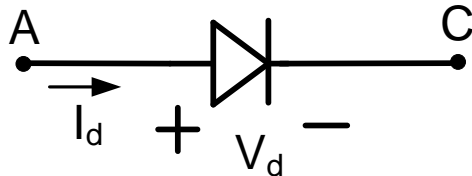
Piecewise Linear Model with Diode Resistance

$$I_d = 0 \quad \text{if } V_d < 0.6V$$

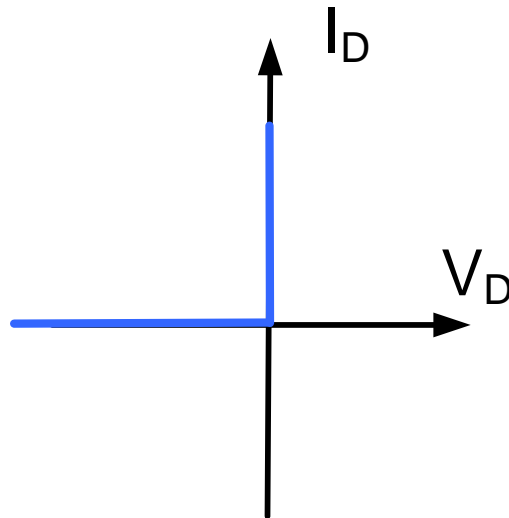
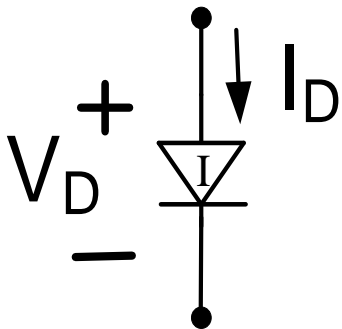
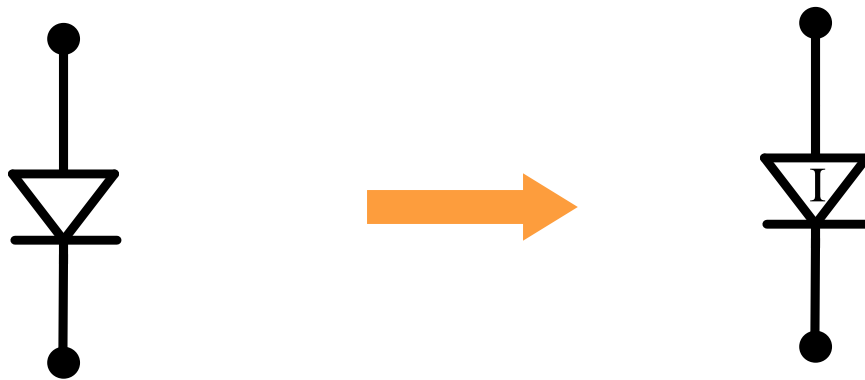
$$V_d = 0.6V + I_d R_D \quad \text{if } I_d > 0$$

(R_D is rather small: often in the 20Ω to 100Ω range):

Equivalent Circuit

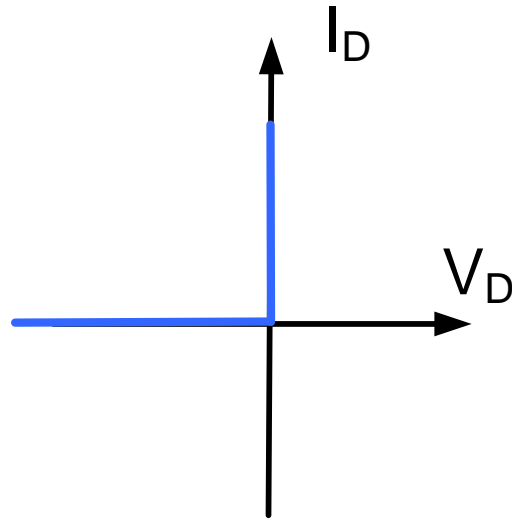


The Ideal Diode



$$\begin{aligned} I_D &= 0 & \text{if } V_D \leq 0 \\ V_D &= 0 & \text{if } I_D > 0 \end{aligned}$$

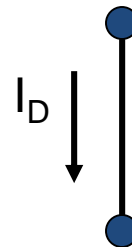
The Ideal Diode



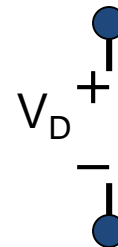
$$\begin{aligned} I_D &= 0 & \text{if } V_D &\leq 0 & \text{"OFF"} \\ V_D &= 0 & \text{if } I_D &> 0 & \text{"ON"} \end{aligned}$$



"ON"



"OFF"

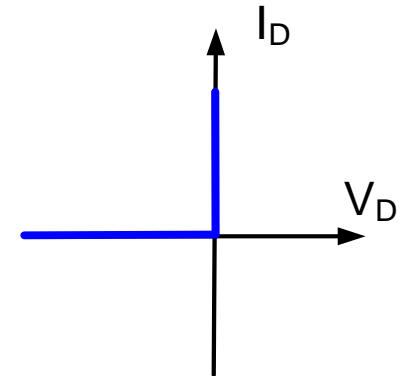
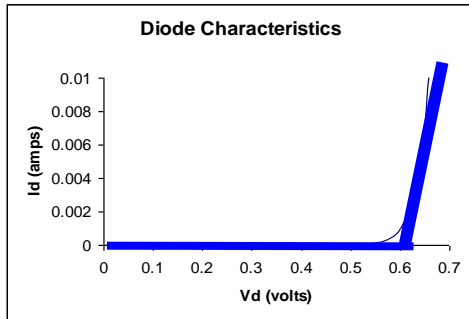
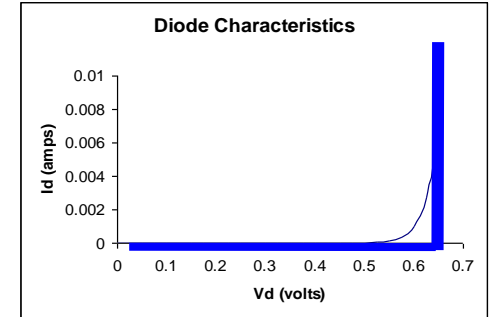
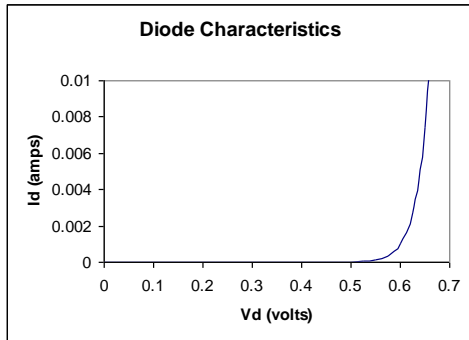


Valid for

$$I_D > 0$$

$$V_D \leq 0$$

Diode Models



Which model should be used?

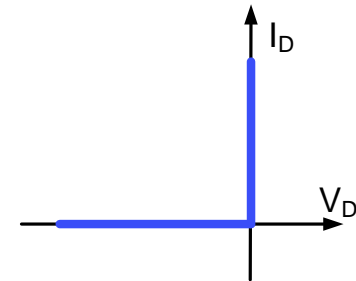
The simplest model that will give acceptable results in the analysis of a circuit

Diode Model Summary

Piecewise Linear Models

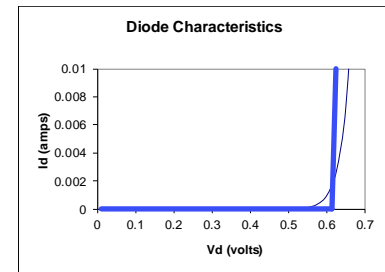
$$I_d = 0 \quad \text{if } V_d < 0$$

$$V_d = 0 \quad \text{if } I_d > 0$$



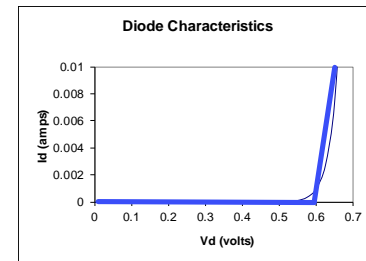
$$I_d = 0 \quad \text{if } V_d < 0.6V$$

$$V_d = 0.6V \quad \text{if } I_d > 0$$



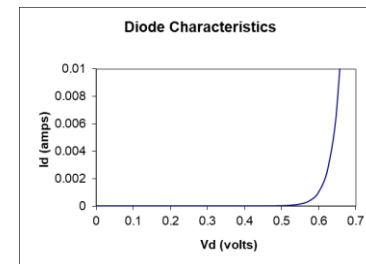
$$I_d = 0 \quad \text{if } V_d < 0.6$$

$$V_d = 0.6 + I_d R_d \quad \text{if } I_d > 0$$



Diode Equation

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$



Diode Model Summary

Piecewise Linear Models

$$I_d = 0 \quad \text{if } V_d < 0$$

$$V_d = 0 \quad \text{if } I_d > 0$$

$$I_d = 0 \quad \text{if } V_d < 0.6V$$

$$V_d = 0.6V \quad \text{if } I_d > 0$$

$$I_d = 0 \quad \text{if } V_d < 0.6$$

$$V_d = 0.6 + I_d R_d \quad \text{if } I_d > 0$$

Diode Equation

$$I_d = I_s \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

When is the ideal model adequate?

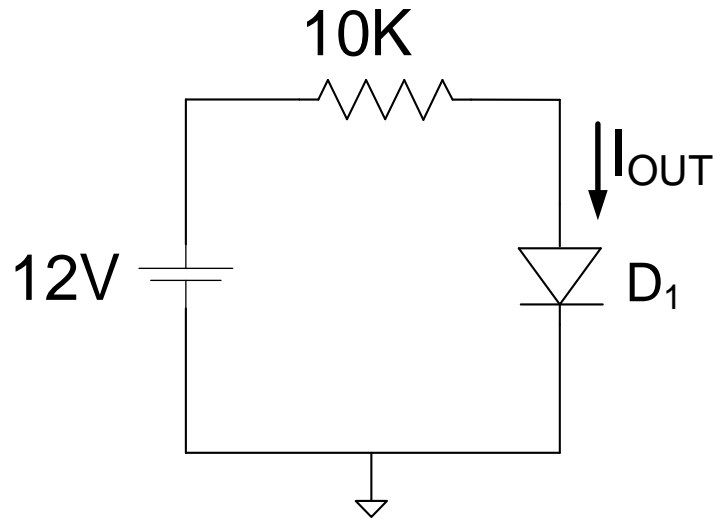
When it doesn't make much difference whether $V_d = 0V$ or $V_d = 0.6V$

When is the second piecewise-linear model adequate?

When it doesn't make much difference whether $V_d = 0.6V$ or $V_d = 0.7V$

Example:

Determine I_{OUT} for the following circuit



Solution:

Strategy:

1. Assume PWL model with $V_D=0.6V$, $R_D=0$
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2 (verify the “if” condition in model)

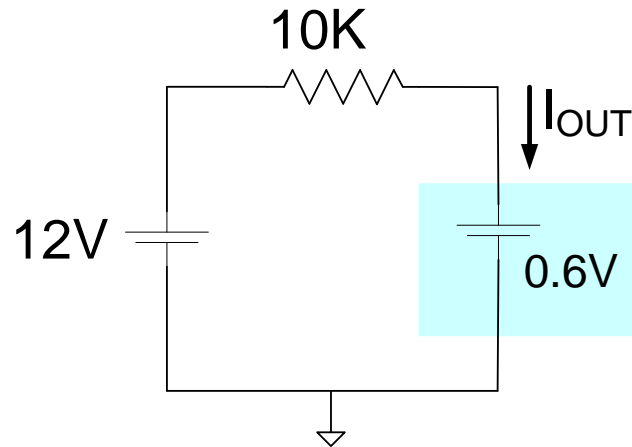
Select
Model

5. Assume PWL with $V_D=0.7V$
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6 (verify the “if” condition in model)
9. Show difference between results using these two models is small
10. If difference is not small, must use a different model

Validate
Model

Solution:

1. Assume PWL model with $V_D=0.6V$, $R_D=0$
2. Guess state of diode (ON)



3. Analyze circuit with model

$$I_{OUT} = \frac{12V - 0.6V}{10K} = 1.14mA$$

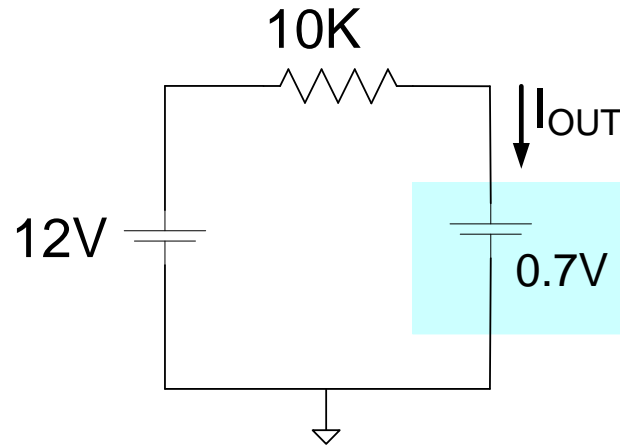
4. Validate state of guess in step 2

To validate state, must show $I_D > 0$

$$I_D = I_{OUT} = 1.14mA > 0$$

Solution:

5. Assume PWL model with $V_D=0.7V$, $R_D=0$
6. Guess state of diode (ON)



7. Analyze circuit with model

$$I_{OUT} = \frac{12V - 0.7V}{10K} = 1.13mA$$

8. Validate state of guess in step 6

To validate state, must show $I_D > 0$

$$I_D = I_{OUT} = 1.13mA > 0$$

Solution:

9. Show difference between results using these two models is small

$$I_{\text{OUT}}=1.14\text{mA} \text{ and } I_{\text{OUT}}=1.13 \text{ mA} \quad \text{are close}$$

Thus, can conclude

$$I_{\text{OUT}} \cong 1.14\text{mA}$$

End of Lecture 13