Physics 160
Lecture 5

R. Johnson

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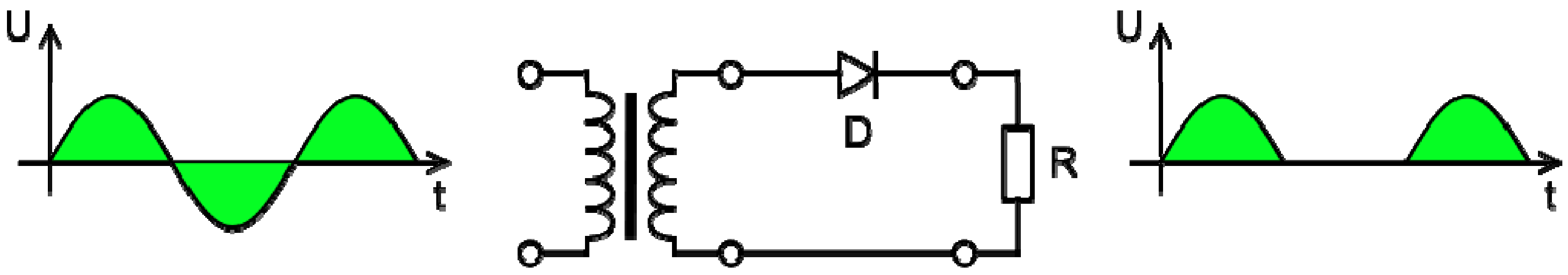
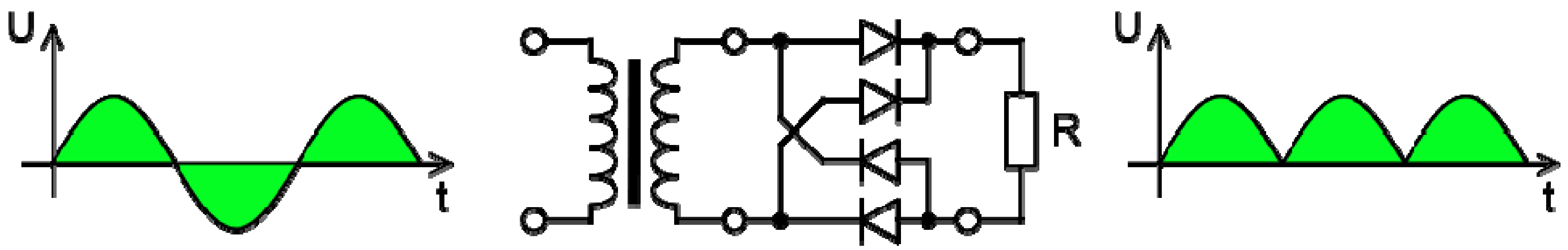
Diode Rectifiers

Half Wave



Full Wave

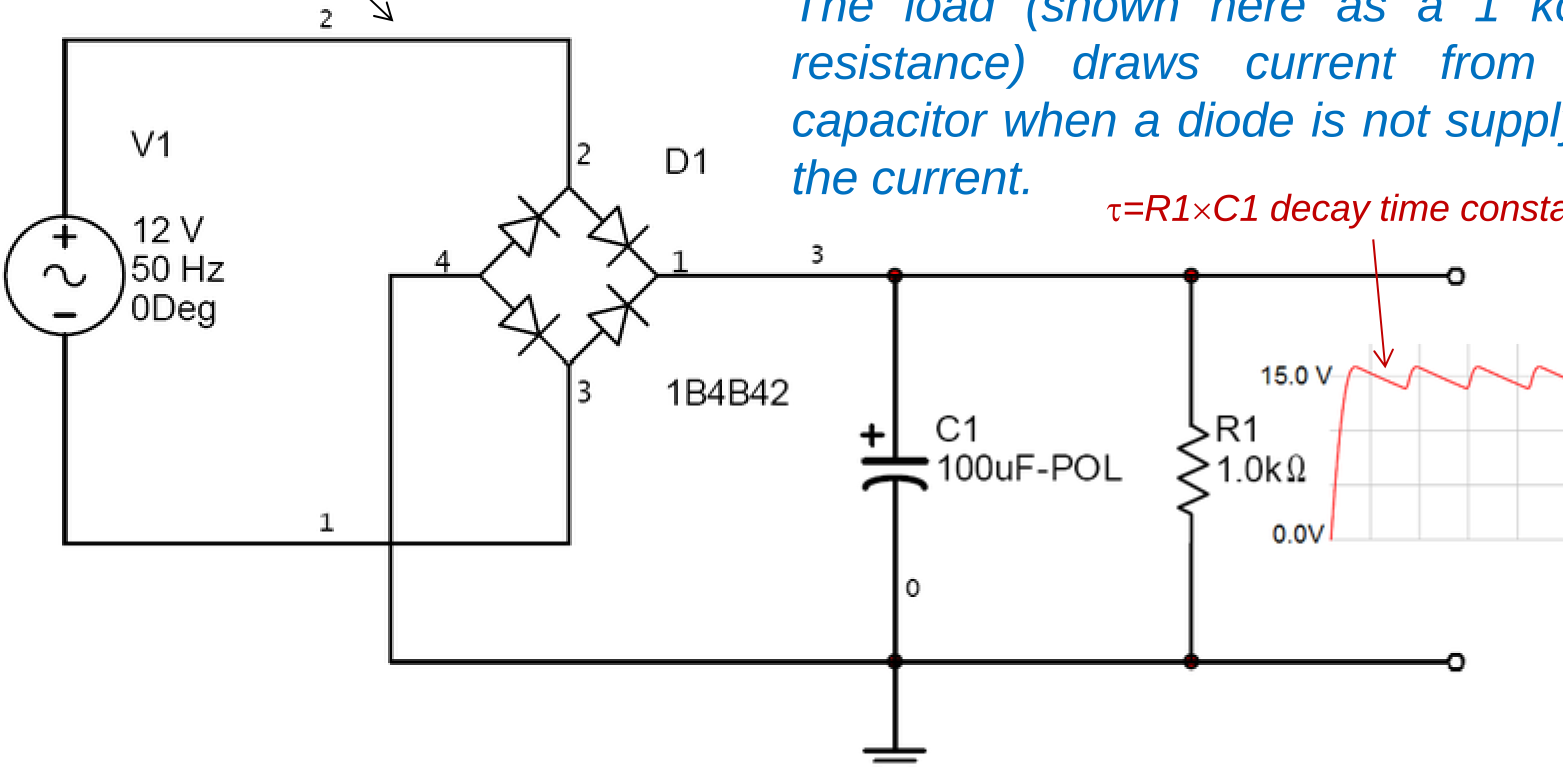


Output Smoothing

Note that there is no ground connection on this side of the rectifier!

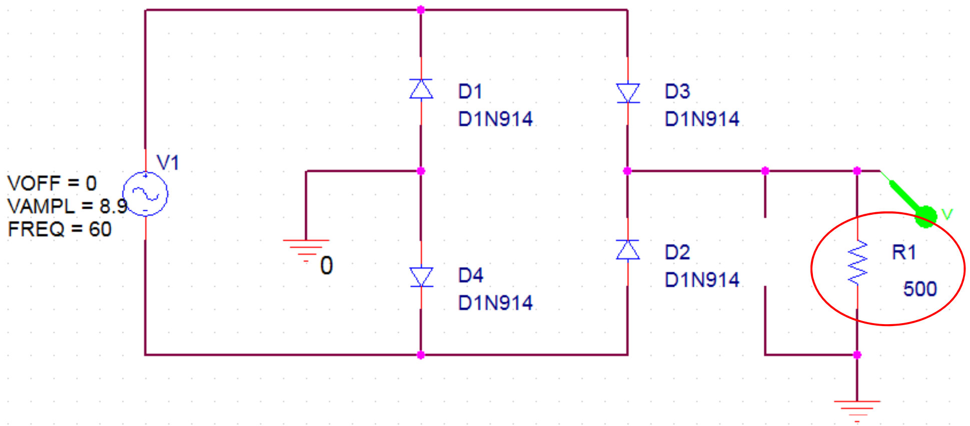
The load (shown here as a 1 kohm resistance) draws current from the capacitor when a diode is not supplying the current.

τ=R1×C1 decay time constant



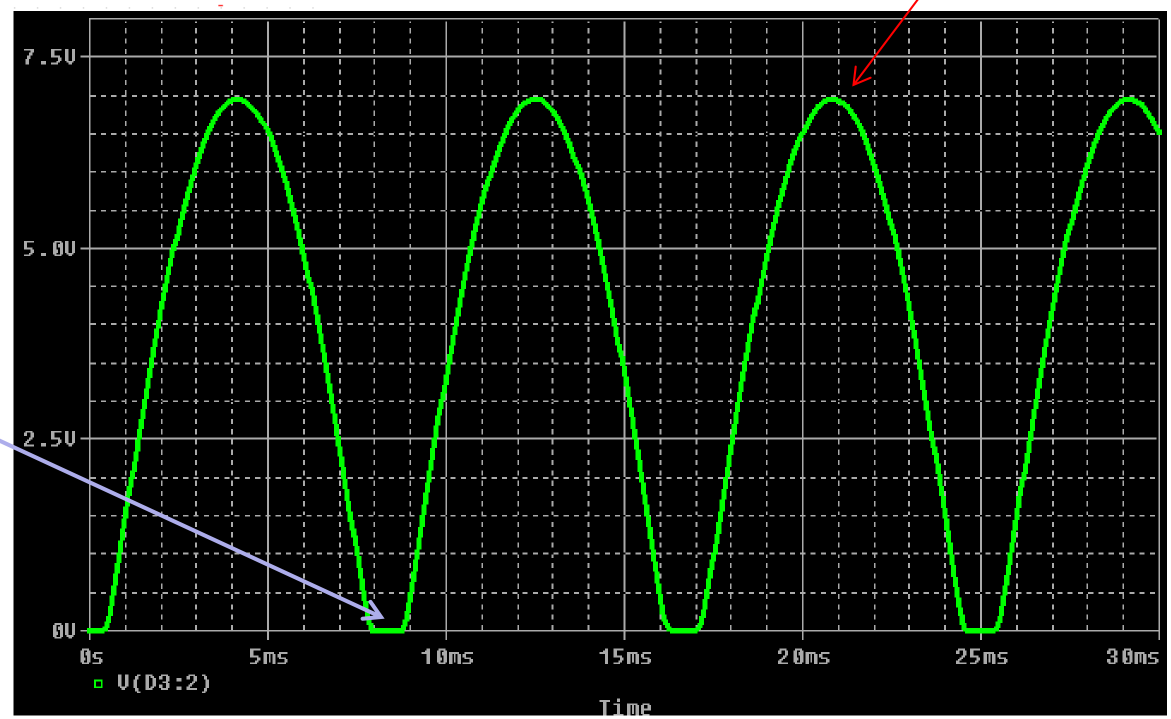
- *If R1 is small (high load; i.e. high current), then C1 must be large in order for the time constant to be long enough to minimize the ripple.*
- *Later in the quarter we will see how to improve on this using active voltage regulators to eliminate ripple and hold the output voltage constant even with a changing load.*

Spice Simulation of the Rectifier



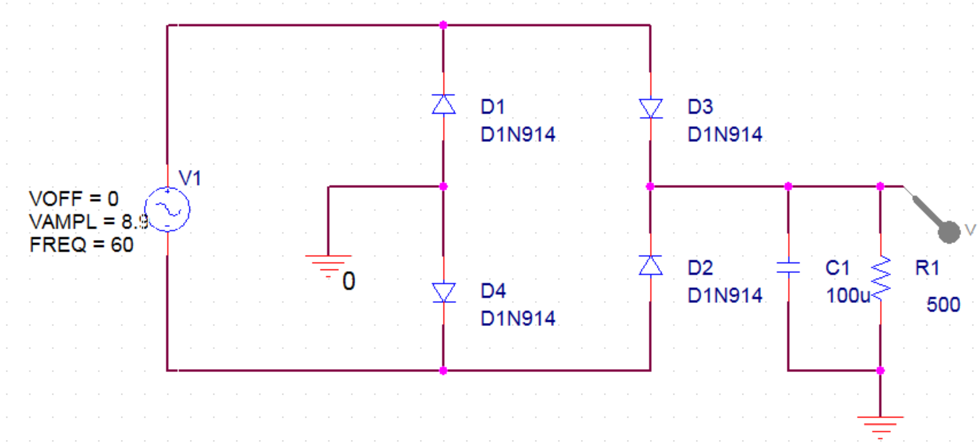
500 ohm load resistance

Output peak is two diode drops less than the input peak.



This region of zero output is where no diode is conducting, because of the 2-diode drops (about 1.4 V) needed to flow current through the two diodes in series.

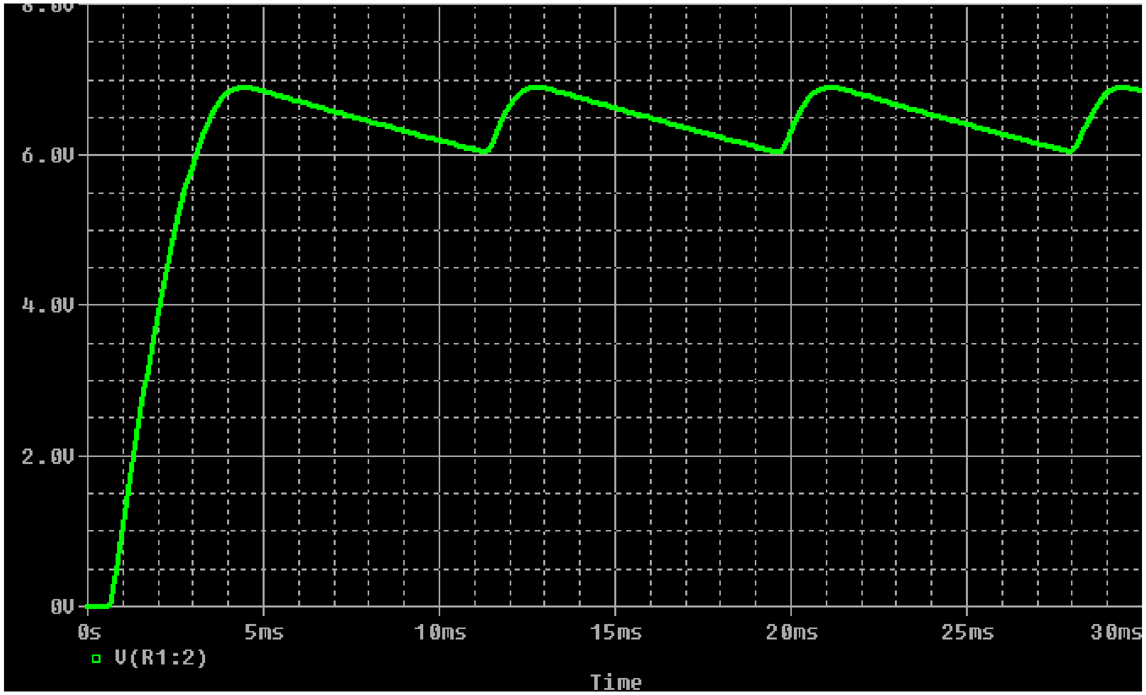
Rectifier With Filtering



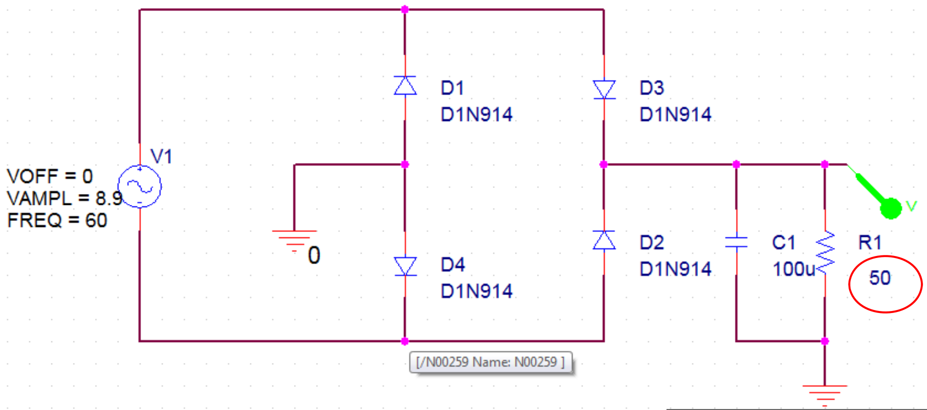
$$I = \frac{dQ}{dt} = \frac{V}{R_L}$$

$$\Delta Q = C\Delta V \approx \frac{V}{R_L}\Delta t$$

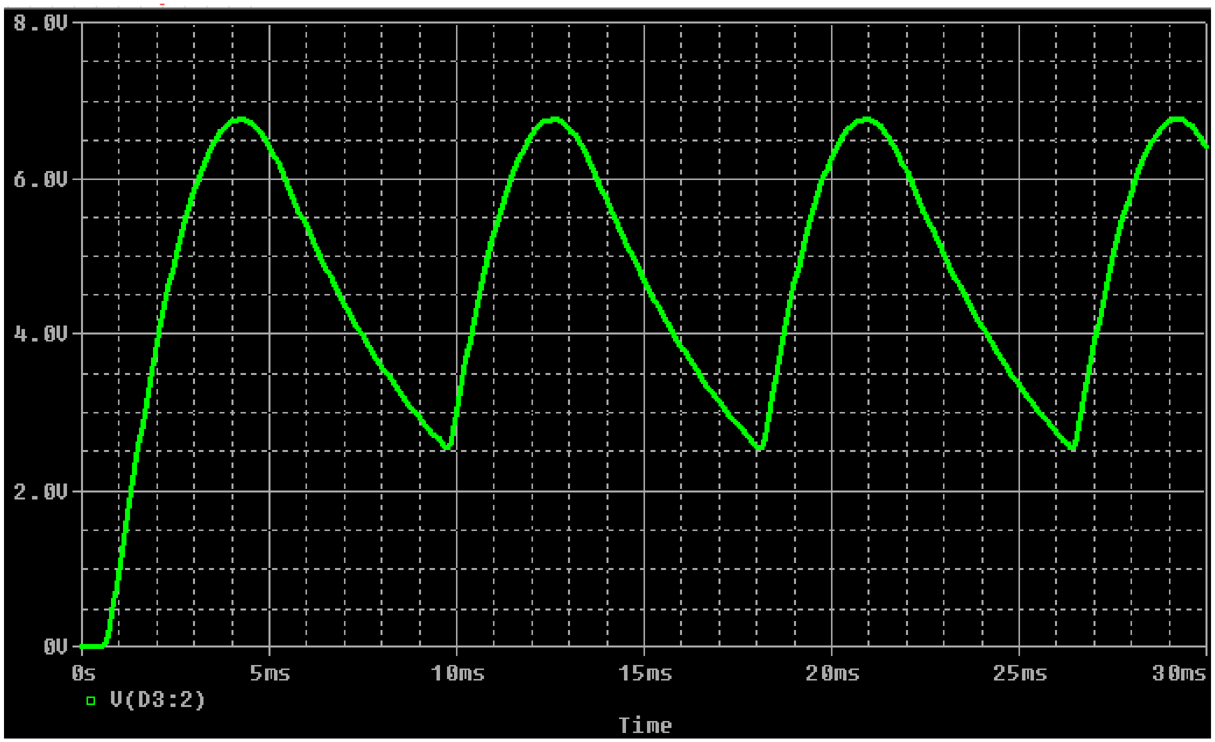
$$\frac{\Delta V}{V} \approx \frac{\Delta t}{\tau}$$



With Too Much Load

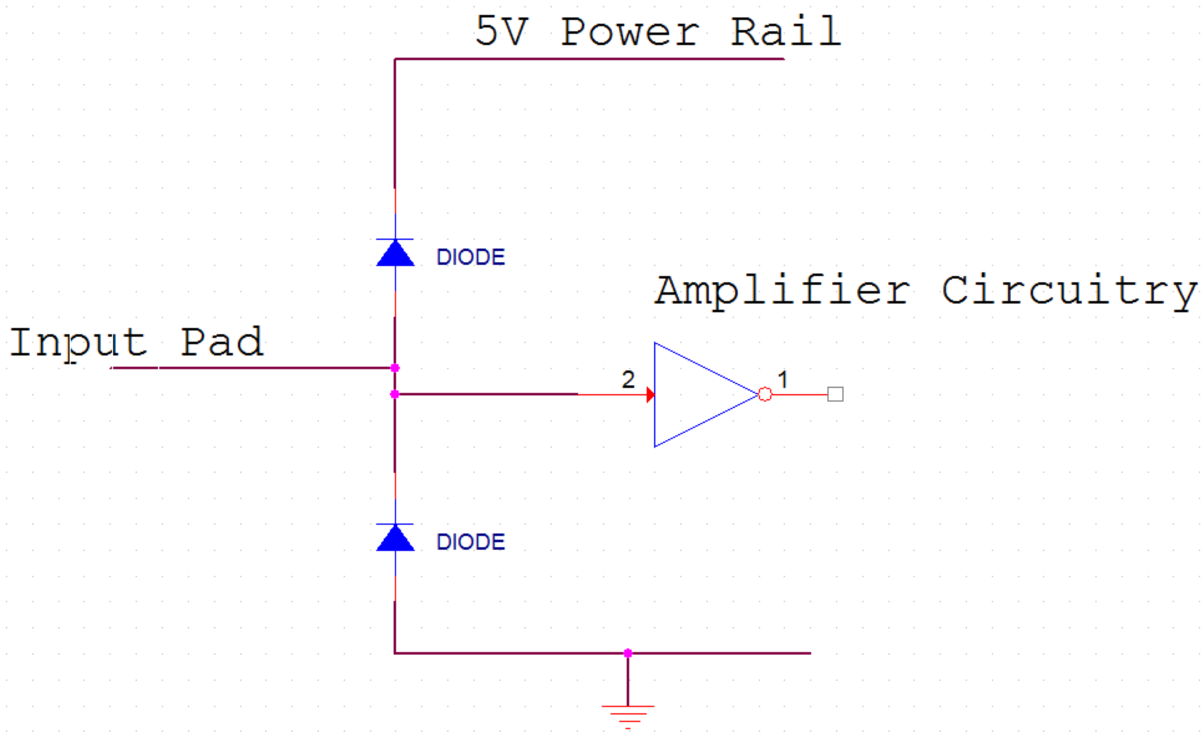


I decrease the load resistance by a factor of 10 to draw 10 times more current. Then the ripple becomes unacceptably large.

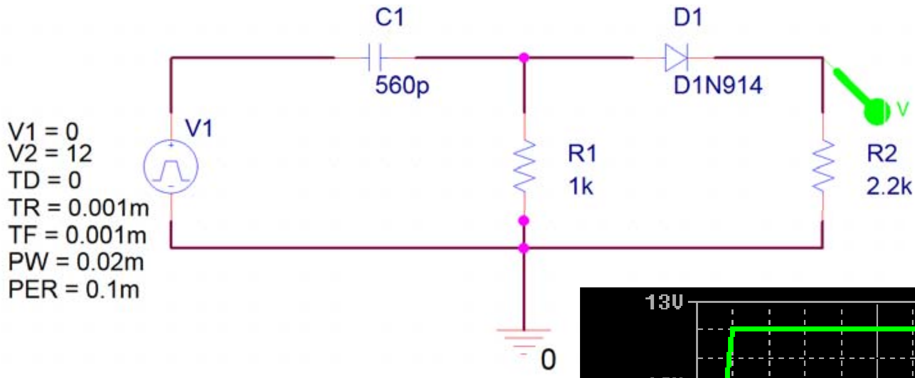


Voltage Clamp

Common Example: protecting circuitry in an IC from external voltage spikes (e.g. electrostatic discharge) on the input pads or pins.

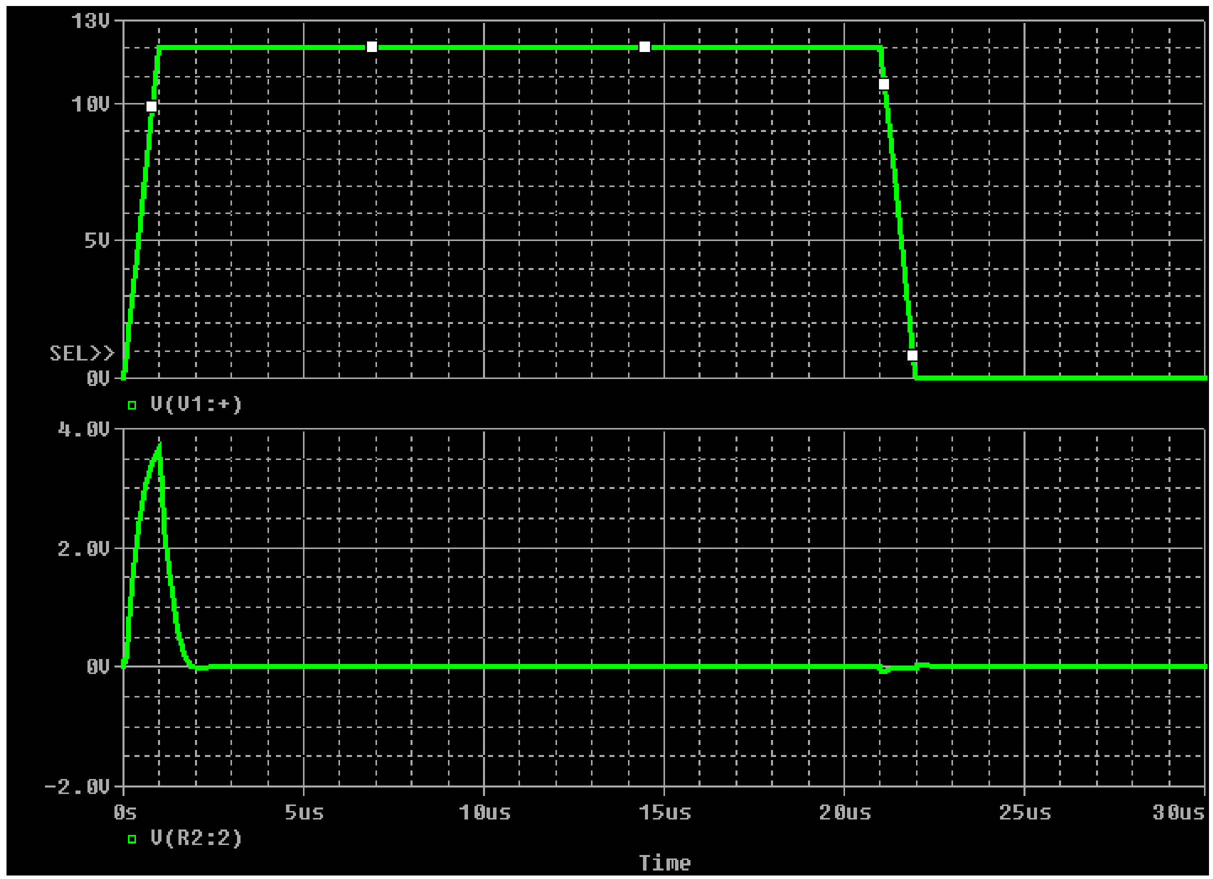


Rectified "Differentiator"

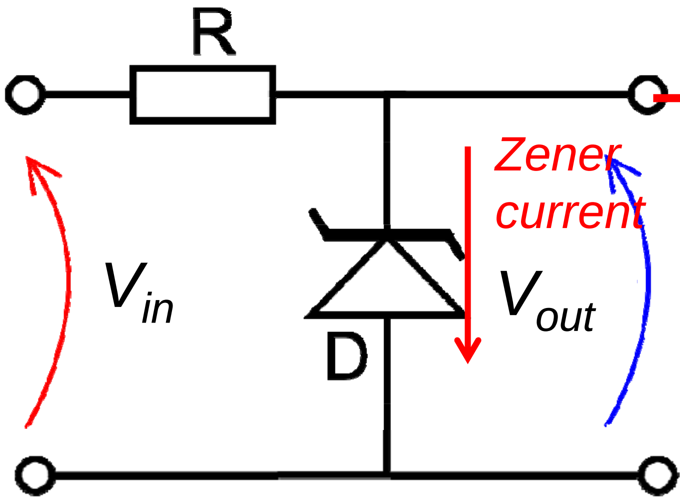


One of the lab projects for this week.

- *We see only the positive approximate "derivative" at the output.*
- *This won't work if the 2.2k resistor is removed. Why?*
- *What are the charge and discharge paths for the capacitor charge?*



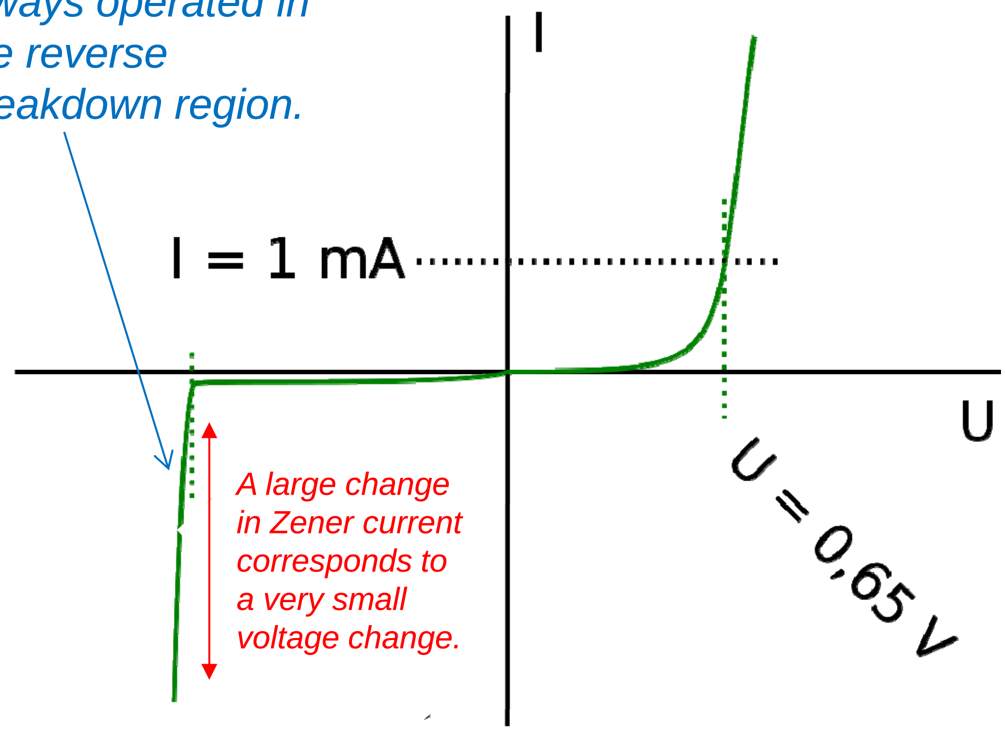
Zener Voltage Reference



Output current

Why is the resistor R necessary?

The Zener is always operated in the reverse breakdown region.

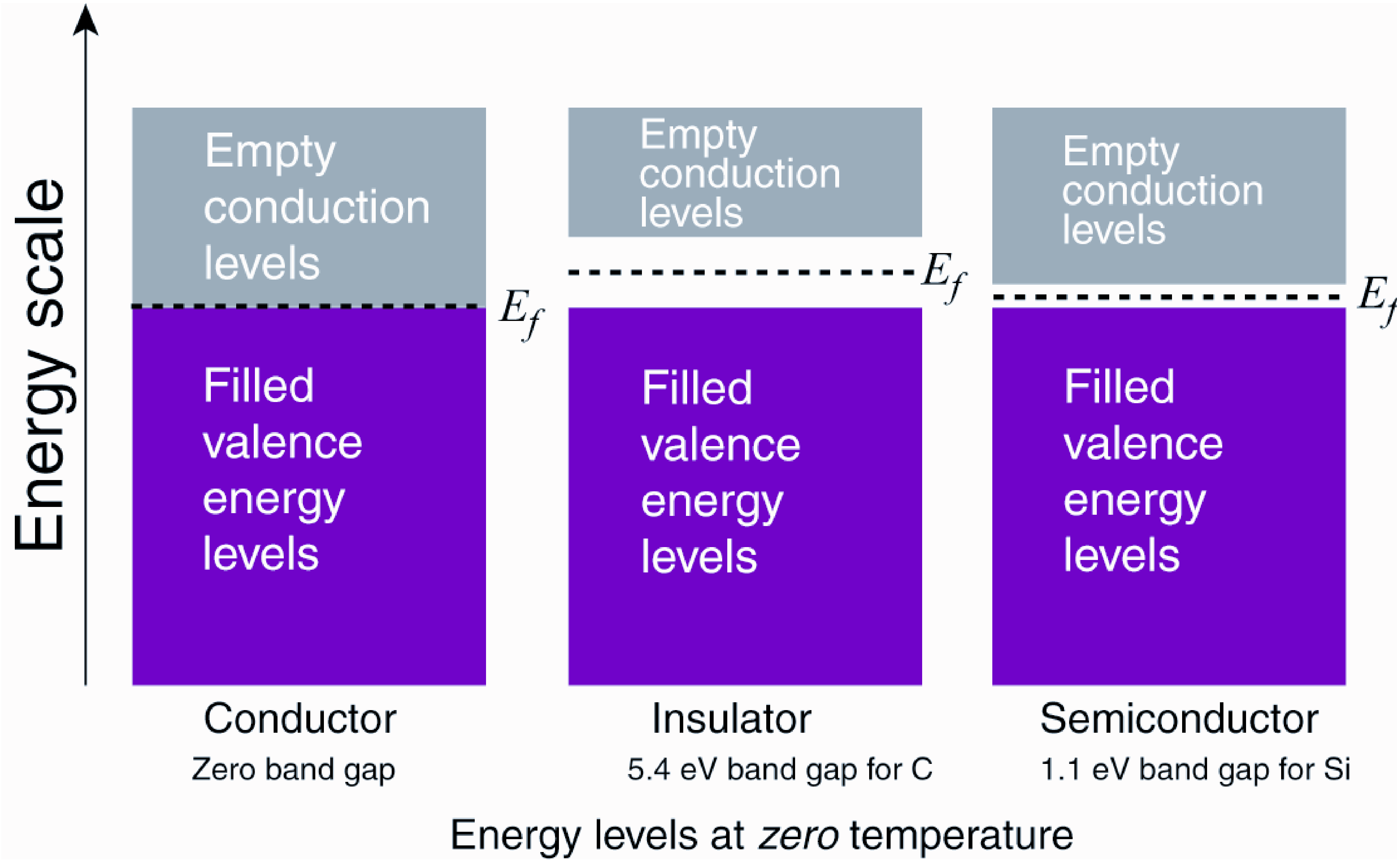


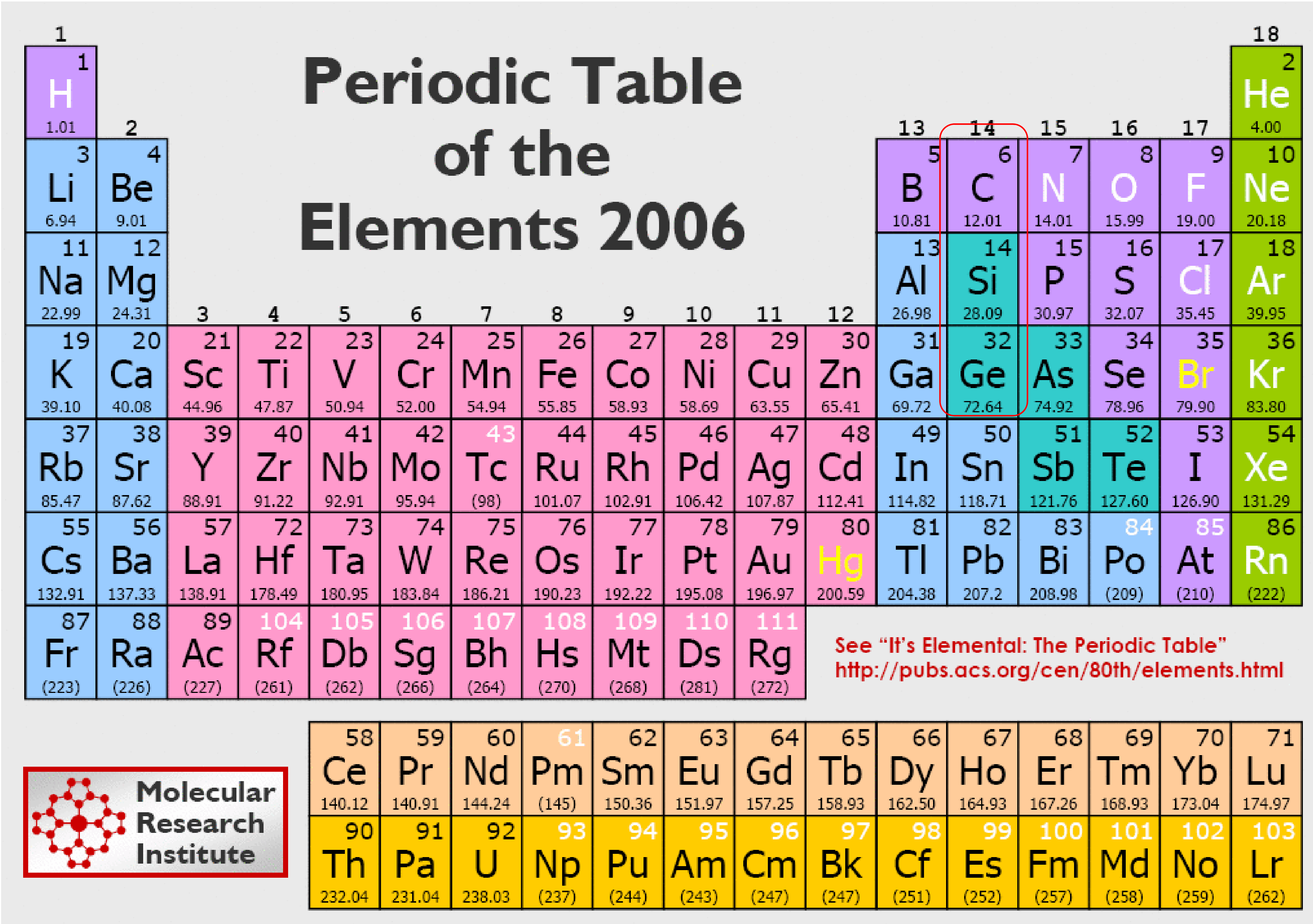
As long as the Zener reverse current is not close to zero, then Vout is close to the Zener breakdown voltage over a wide range of output current.

Semiconductors

- *Pure silicon conductivity ("intrinsic"):*
  - *Cu conductivity: ~6×10^{5} S/cm (S=siemens=1/ohm)*
  - *Si conductivity: ~3×10^{-6} S/cm (but impossible to get this pure)*
  - *C (diamond) conductivity: ~10^{-16} S/cm (pure, undoped)*
- *Conductor: No energy gap between the "valence" energy levels ("bands") and the "conduction" energy levels ("bands").*
  - *Electrons near the Fermi level are easily moved into slightly higher unoccupied energy levels where they are free to move.*
- *Insulator: Large energy gap between filled "valence bands" and unoccupied "conduction bands."*
  - *Normal temperatures are extremely unlikely to excite an electron into the conduction band where it would be free to move.*
- *Semiconductor: band structure essentially the same as that of an insulator, but with a small "band gap" of energy not too much greater than ~kT at room temperature.*
  - *A small but significant number of electrons are excited into the conduction band at room temperature.*

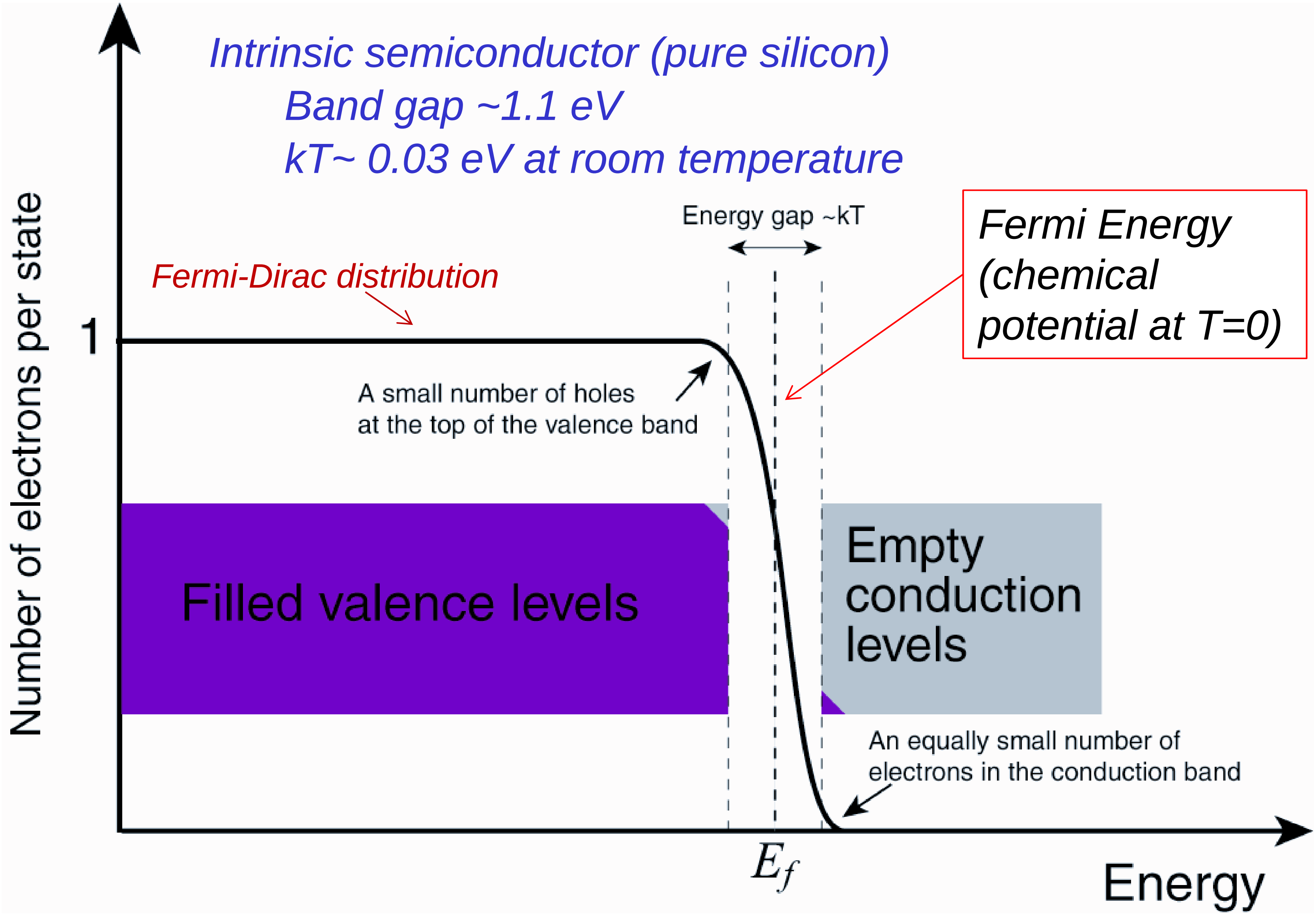
Energy Bands



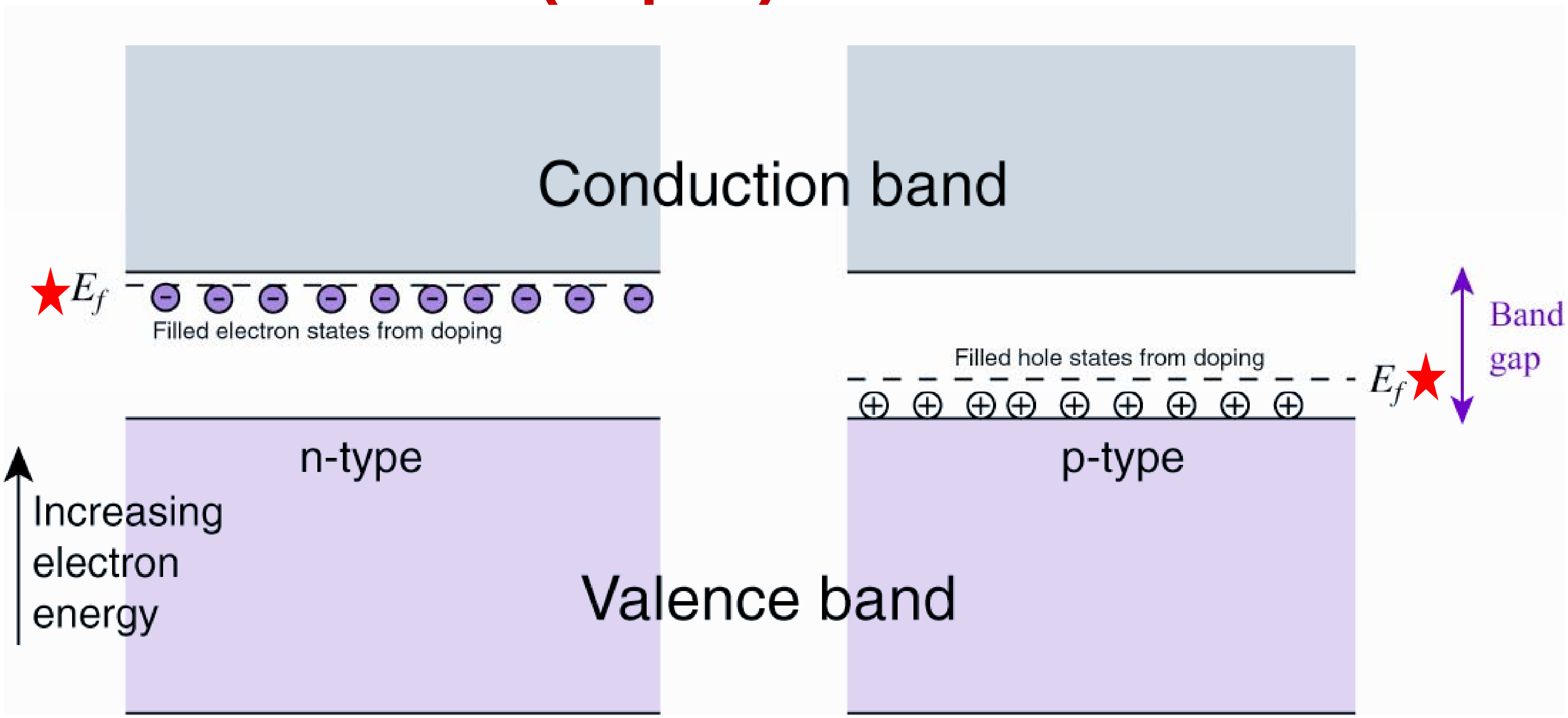


Periodic Table of the Elements 2006
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
1 H 1.01
2 He 4.00
3 Li 6.94
4 Be 9.01
5 B 10.81
6 C 12.01
7 N 14.01
8 O 15.99
9 F 19.00
10 Ne 20.18
11 Na 22.99
12 Mg 24.31
13 Al 26.98
14 Si 28.09
15 P 30.97
16 S 32.07
17 Cl 35.45
18 Ar 39.95
19 K 39.10
20 Ca 40.08
21 Sc 44.96
22 Ti 47.87
23 V 50.94
24 Cr 52.00
25 Mn 54.94
26 Fe 55.85
27 Co 58.93
28 Ni 58.69
29 Cu 63.55
30 Zn 65.41
31 Ga 69.72
32 Ge 72.64
33 As 74.92
34 Se 78.96
35 Br 79.90
36 Kr 83.80
37 Rb 85.47
38 Sr 87.62
39 Y 88.91
40 Zr 91.22
41 Nb 92.91
42 Mo 95.94
43 Tc (98)
44 Ru 101.07
45 Rh 102.91
46 Pd 106.42
47 Ag 107.87
48 Cd 112.41
49 In 114.82
50 Sn 118.71
51 Sb 121.76
52 Te 127.60
53 I 126.90
54 Xe 131.29
55 Cs 132.91
56 Ba 137.33
57 La 138.91
72 Hf 178.49
73 Ta 180.95
74 W 183.84
75 Re 186.21
76 Os 190.23
77 Ir 192.22
78 Pt 195.08
79 Au 196.97
80 Hg 200.59
81 Tl 204.38
82 Pb 207.2
83 Bi 208.98
84 Po (209)
85 At (210)
86 Rn (222)
87 Fr (223)
88 Ra (226)
89 Ac (227)
104 Rf (261)
105 Db (262)
106 Sg (266)
107 Bh (264)
108 Hs (270)
109 Mt (268)
110 Ds (281)
111 Rg (272)
See "It's Elemental: The Periodic Table"
http://pubs.acs.org/cen/80th/elements.html
58 Ce 140.12
59 Pr 140.91
60 Nd 144.24
61 Pm (145)
62 Sm 150.36
63 Eu 151.97
64 Gd 157.25
65 Tb 158.93
66 Dy 162.50
67 Ho 164.93
68 Er 167.26
69 Tm 168.93
70 Yb 173.04
71 Lu 174.97
90 Th 232.04
91 Pa 231.04
92 U 238.03
93 Np (237)
94 Pu (244)
95 Am (243)
96 Cm (247)
97 Bk (247)
98 Cf (251)
99 Es (252)
100 Fm (257)
101 Md (258)
102 No (259)
103 Lr (262)
Molecular Research Institute

Non-Zero Temperature



Extrinsic (doped) Semiconductors



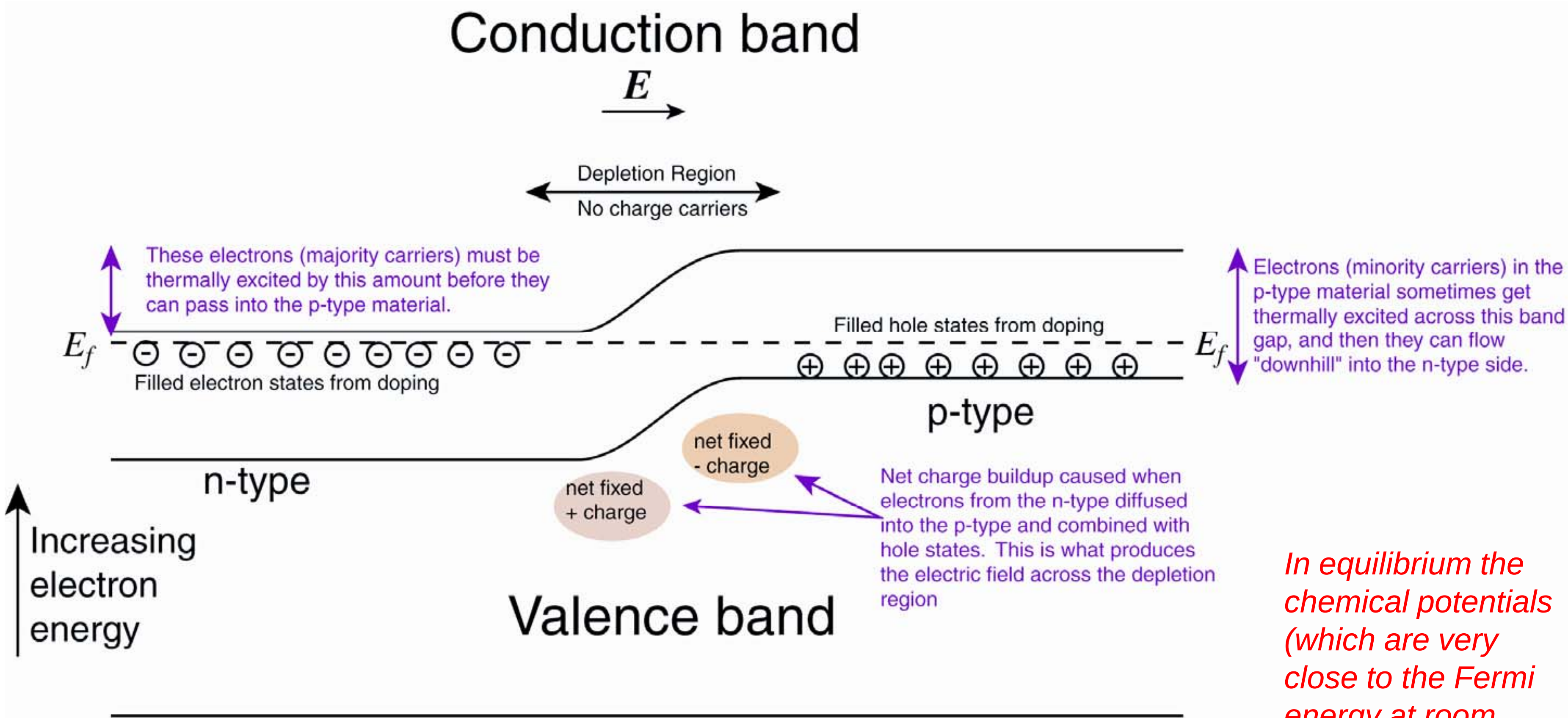
- *Add a tiny bit of phosphorus to the silicon (n-type doped silicon):*
  - *New states are produced just below the conduction band*
  - *Electrons on those states easily get excited into the conduction band*
- *Add a tiny bit of boron to the silicon (p-type doped silicon):*
  - *Holes at the top of the valence band can conduct*

PN Junction

What happens if we bring an N-type semiconductor into very close contact with a P-type semiconductor?

- *Some electrons in the N-type material move into the P-type material to fill in some of the holes.*
- *This movement of charge builds up an electric field.*
- *Eventually the electric field prevents any more net movement of charge.*
  - *At that point the system is in equilibrium.*
  - *Then the chemical potentials match between the P and N type materials.*
  - *There is a thin charge-free "depletion region" at the junction where the electric field is established.*

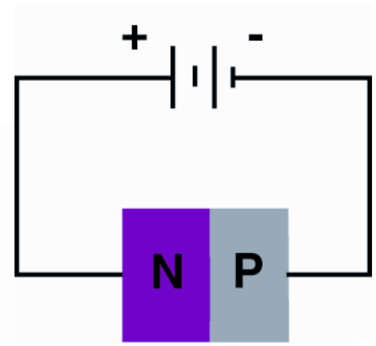
PN Junction in Equilibrium



Unbiased PN junction at equilibrium. The Fermi energy matches between P and N sides. Small thermally excited electron currents flow in both directions across the junction, as indicated. However, small thermally excited hole currents also flow across the junction in both directions. The net current of electrons and of holes is zero in equilibrium.

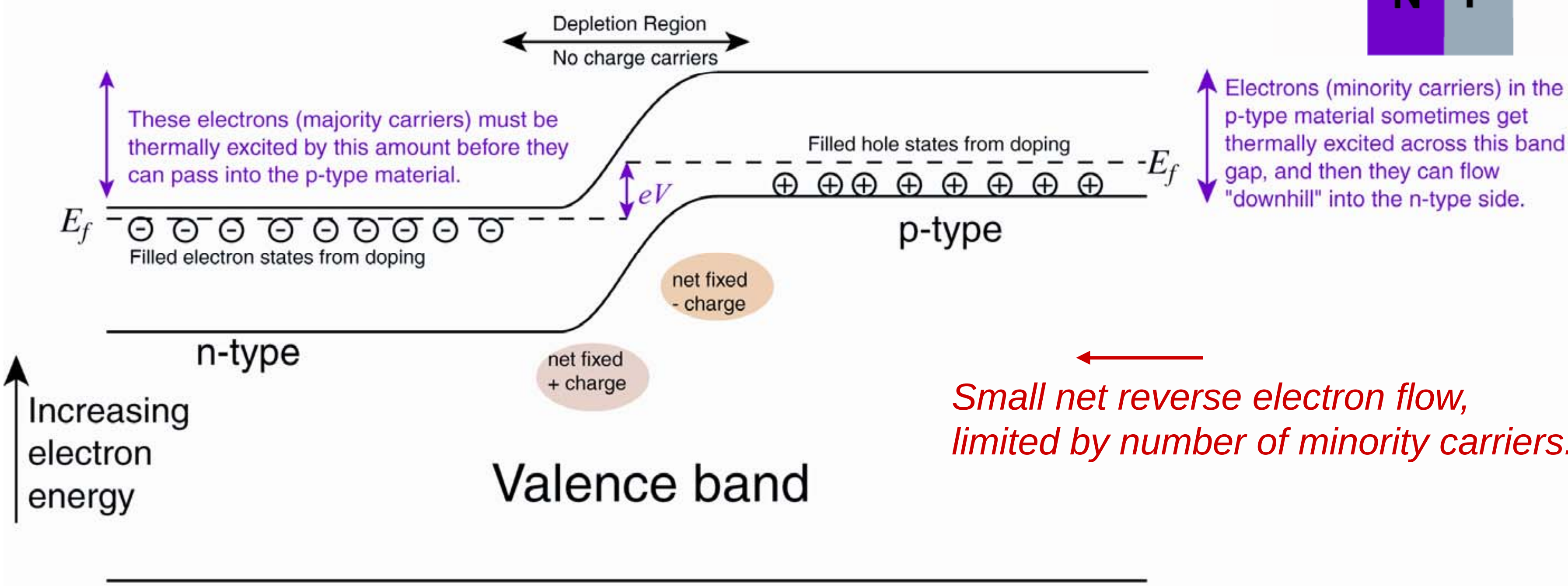
In equilibrium the chemical potentials (which are very close to the Fermi energy at room temperature) must match between the two substances.

PN Junction in Reverse Bias



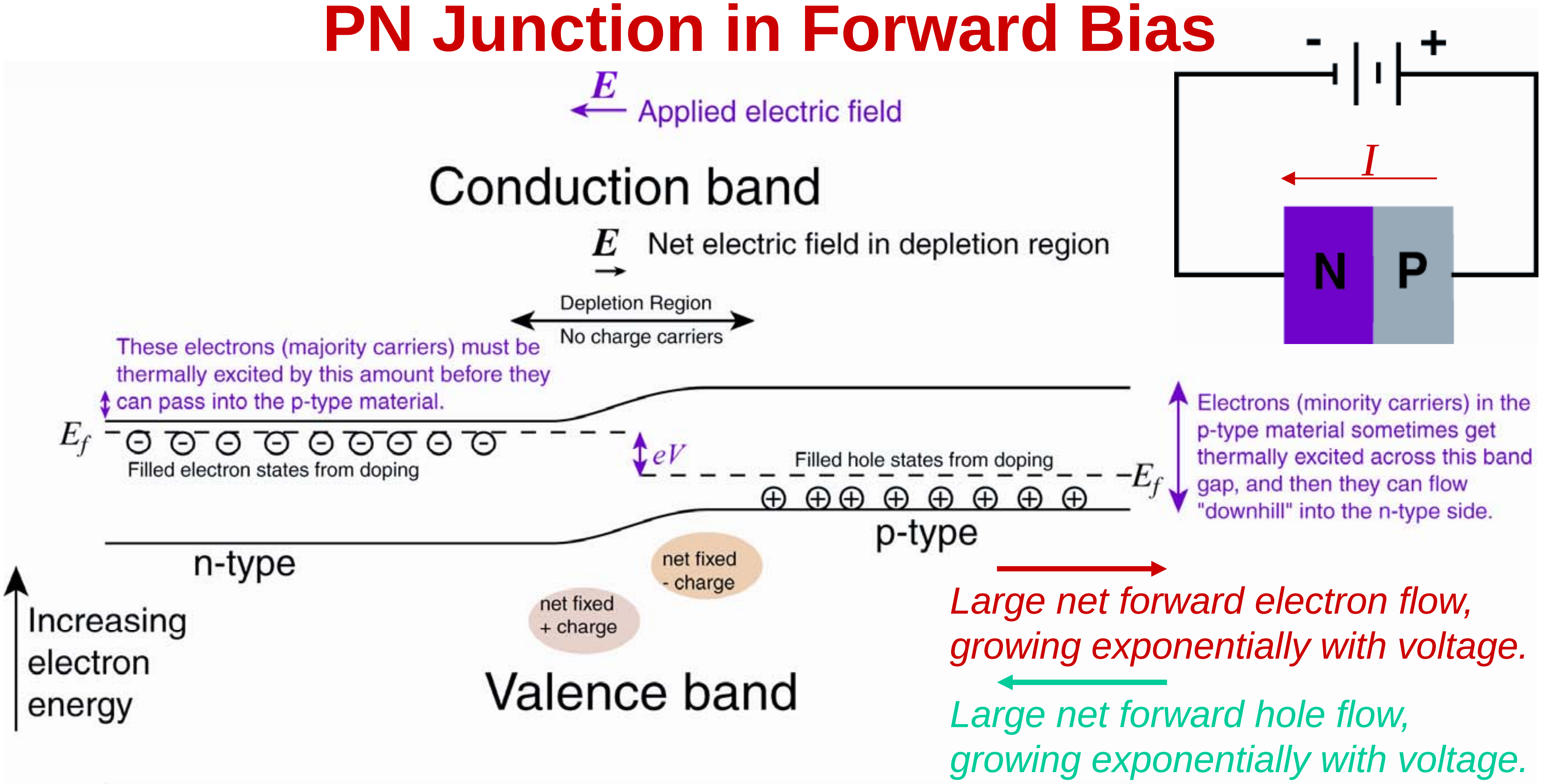
Conduction band

E



PN junction under reverse bias of potential V. The system is no longer in equilibrium, and the Fermi levels are shifted between P and N by an energy eV. The energy barrier is that much higher now, so the electron majority current flowing from left to right is greatly decreased, while the electron minority current flowing from right to left is unchanged, but is still small because of the limited number of thermally excited electrons in the P type material. Equivalent statements hold for the hole currents. The net result is a very small current in the direction of the applied field (but one that is exponentially sensitive to temperature).

PN Junction in Forward Bias



Large net forward electron flow, growing exponentially with voltage.

Large net forward hole flow, growing exponentially with voltage.

PN junction under forward bias. It is no longer in equilibrium, and the Fermi levels are shifted between the P and N sides. Since the barrier is lower, the electrons on the N side do not have to be thermally excited by much in order to make it over the barrier. Therefore, the electron current from left to right is exponentially increased, while the electron current from right to left is unchanged. Equivalent statements hold for the hole currents. Hence there is a net positive current flowing in the direction of the applied field (from P to N), which depends exponentially on V.

Diode Review

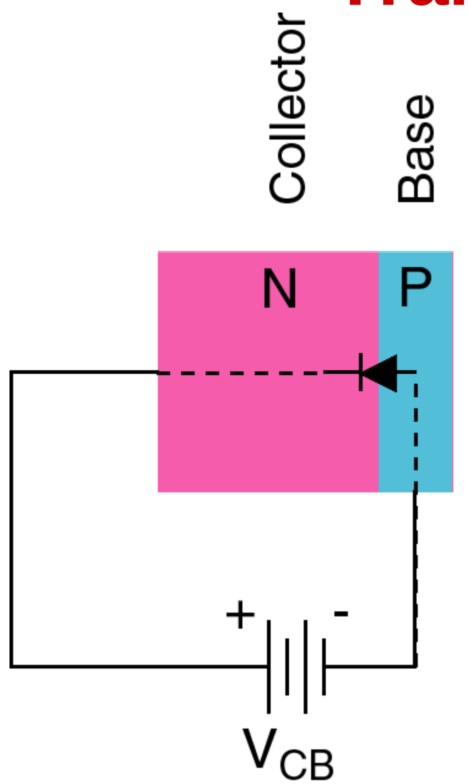
- *A diode conducts in the forward direction because*
  1. *the external potential V lowers the potential barrier between the N and P doped silicon by an amount eV,*
  2. *and as a result, there are exponentially more electrons on the N side with thermal energy fluctuating high enough to get over the barrier.*
- *It conducts only a tiny current in the reverse direction because, independent of V, there are few electrons in the p-type material to conduct current (and few holes in the n-type material).*
- *Therefore, the dependence of current on voltage will be*

$$I = I_0\left(e^{eV/kT} - 1\right)$$

Follows from the Boltzmann factor related to the population of the conduction band.

- *where I_0 is the tiny reverse current (which itself depends exponentially on temperature but not on V).*

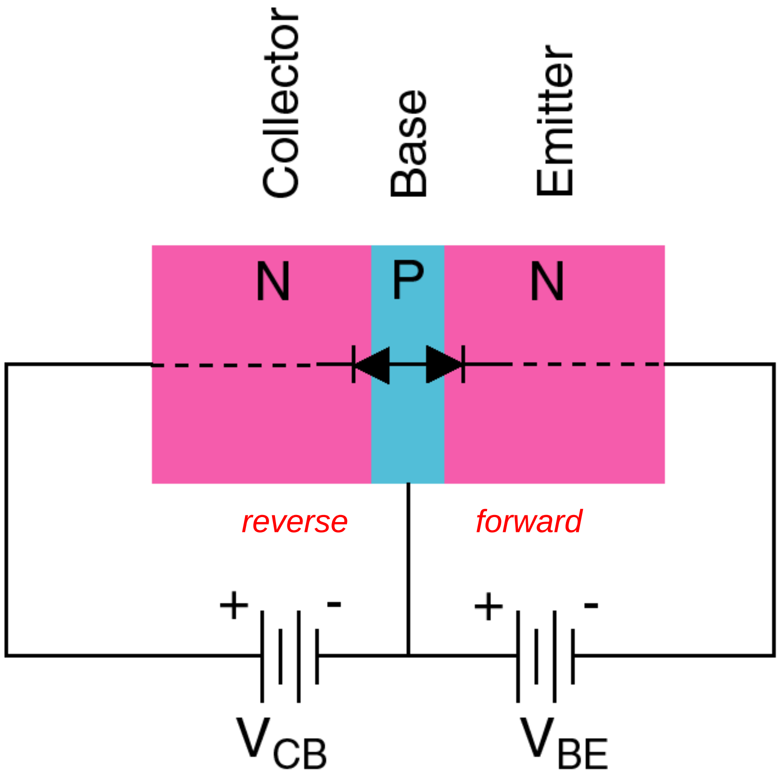
Transistor Prelude



Reverse biased diode. Only a tiny current flows, due to lack of conduction electrons in the base.

- *But, if we could inject electrons into the base somehow, they would easily fall “downhill” into the collector, making a flow of current far greater than the normal tiny reverse current.*

Transistor Action (NPN)

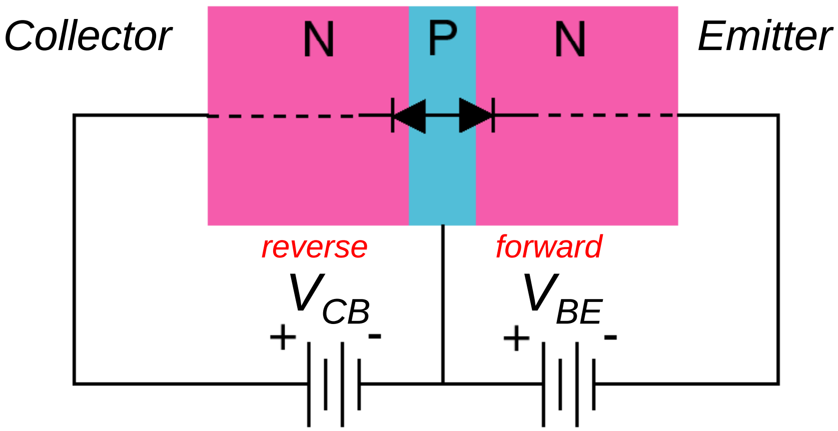


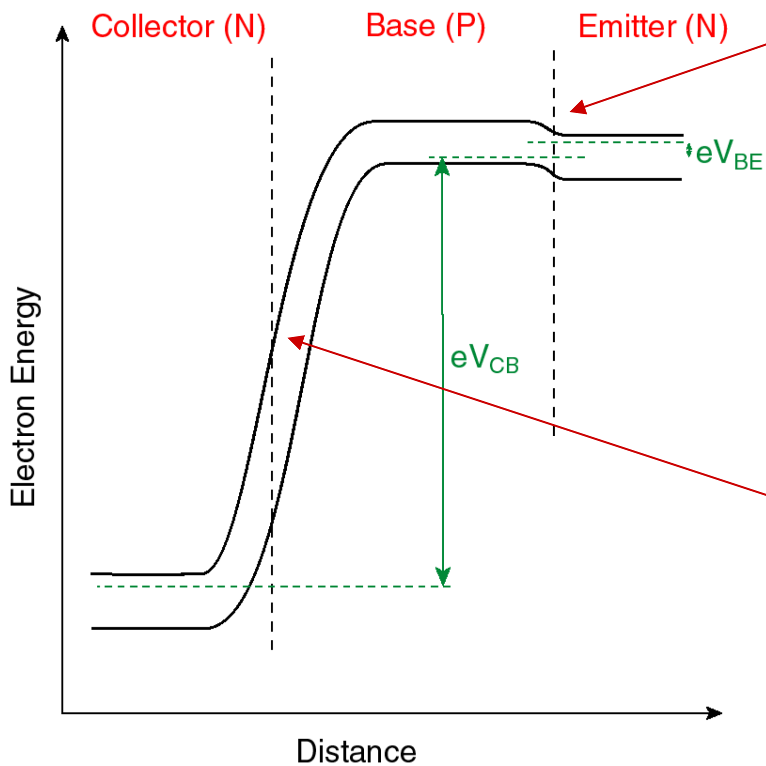
The base should be very thin and lightly doped:

- *Most injected electrons diffuse across to the collector.*
- *Few electrons recombine.*
- *Very few holes flowing from base to emitter.*

- *Attach a second PN junction and forward bias it.*
- *The voltage V_{BE} controls the barrier height between base and emitter.*
- *Raising V_{BE} lowers the barrier, allowing electrons to flood into the base from the emitter.*
- *The base is very thin, so most of those electrons quickly diffuse to the collector junction, where they fall "downhill" into the collector.*
- *Only a few percent of the electrons flow to the base electrode.*

Transistor Action (NPN)





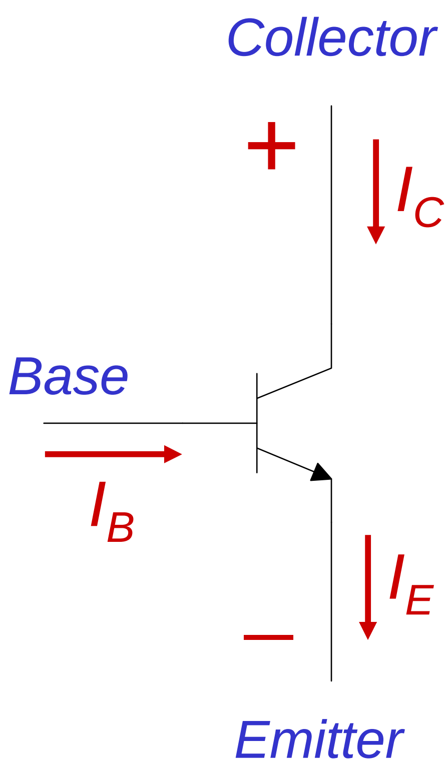
The emitter-base voltage controls the height of this barrier, thus controlling the "injection" of electrons into the base.

*Note that the "output" **current** is controlled by the "input" **voltage**.*

"Transconductance": $g_m = \dfrac{\Delta I_{\text{out}}}{\Delta V_{\text{in}}}$

The vast majority (>99%) of the electrons injected into the Base diffuse to the Collector-Base junction and accelerate into the Collector.

NPN Transistor Basic "Rules"

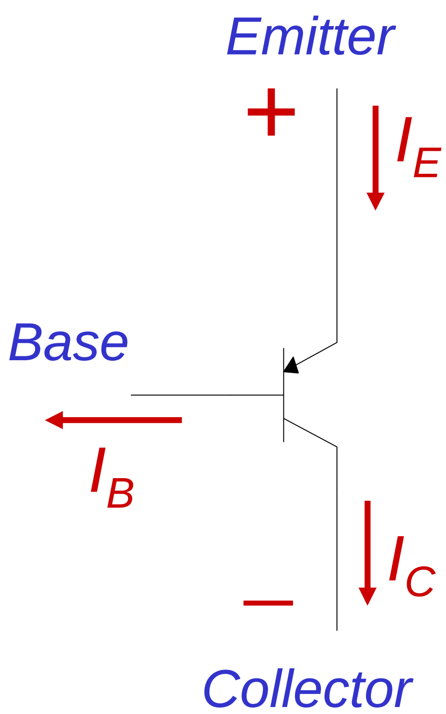


- *The collector is more positive than the emitter (by at least a few tenths of a volt at "saturation," but usually much more).*
- *The base-emitter junction is forward biased, with the base about 1 diode drop (~0.6 to 0.7 V) higher than the emitter during normal operation (for currents of a few mA).*
- *The base-collector junction is normally reverse biased during operation.*
- *Since most of the electrons injected into the base go to the collector, not the emitter, then*

$$I_C = \beta I_B$$

with β >>1, typically ~50 to ~250.

PNP Transistor Basic "Rules"



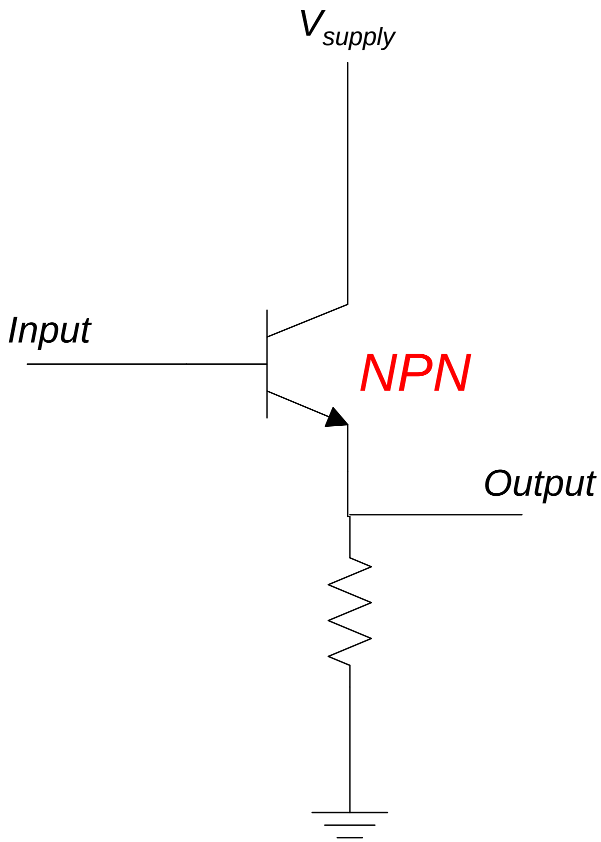
- *The collector is less positive than the emitter (by at least a few tenths of a volt at "saturation," but usually much more).*
- *The base-emitter junction is forward biased, with the base about 1 diode drop (~0.6 V) less than the emitter during normal operation.*
- *The base-collector junction is normally reverse biased during operation.*

- *Since most of the holes injected into the base go to the collector, not the emitter, then*

$$I_C = \beta I_B$$

with β >>1, typically ~50 to ~250.

NPN Emitter Follower



- $V_{out}=V_{in}$ *minus 1 diode drop*
- *Current gain; no voltage gain*
  - *Hi input impedance*
  - *Low output impedance*
  - *Power gain!*
- *Bias voltage and current*
  - $I_E=V_E/R$, typically a few mA in our circuits
  - $I_C \cong I_E$
  - $I_B \cong I_E/100$ Allowance *must* be made to provide this small base current!

Of course, an emitter follower can also be made with a PNP transistor.