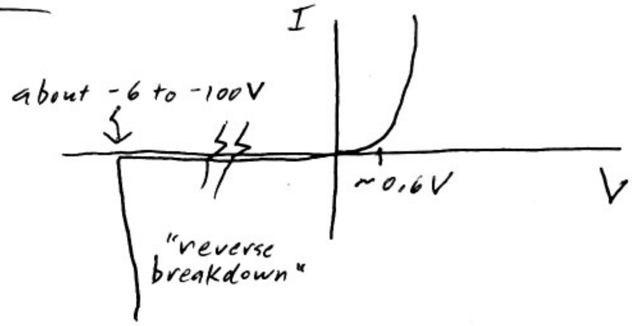
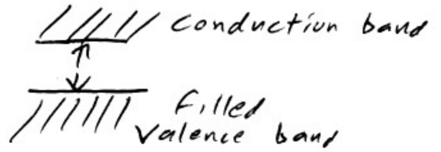
Diodes



For Si (Ge, GaAs similar) there is a bandgap $\gtrsim kT$:

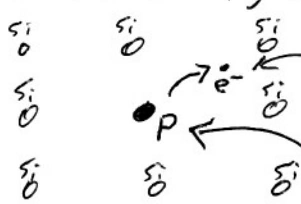


$\frac{kT}{e} \cong 0.025\,V$ at room temp.

There are just a few thermal conduction electrons, $\sim 10^{16}\ m^{-3}$ at room temp.

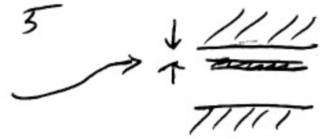
Things change drastically if trace impurities are added:

n-type: Add P, As, or Sb dopant, valence 5

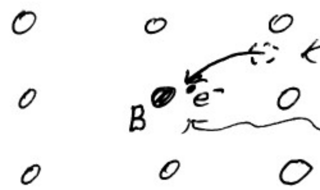


little energy is required to liberate the extra electron

immobile (+) ion, "donor", fixed in lattice



p-type: Add B, valence 3, or similar



The "hole" can move freely if the electron is attached to the

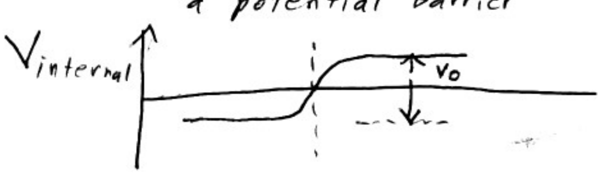
Immobile (−) ion or "acceptor"

So in effect, p-type charge carriers are (+).

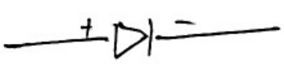
Diode junction

depletion region builds a potential barrier

Holes and electrons recombine at boundary until the potential inhibits further net motion.



For Si, $V_0 \sim 0.5\,V$ (on the order of the bandgap)

Symbol 

Equilibrium: Let N_p = hole density, N_e = electron density

For holes on n side, no barrier, but very few holes are available. For holes on p side, fraction able to cross is given by a Boltzmann factor,

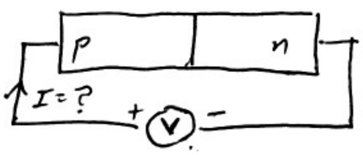
$$e^{-eV_0/k_BT} \qquad (k_BT \sim \tfrac{1}{40}\,\text{eV at } 300\text{K})$$

So in equilibrium,

$$N_p\,(n\text{ side}) = N_p\,(p\text{ side})\, e^{-eV_0/k_BT}$$

Likewise, $N_e\,(p\text{ side}) = N_e\,(n\text{ side})\, e^{-eV_0/k_BT}$

Externally biased diode



V will appear across depletion region, reducing potential to $V_0 - V$ (or increasing, if V is (−)).

Net flow of e^- from n side is now

$$I_e \propto \underbrace{N_e\,(n\text{ side})}_{\text{still } \simeq N_e\,(p\text{ side})\, e^{eV_0/k_BT}} e^{-e(V_0-V)/k_BT} - N_e\,(p\text{ side})$$

$$= \underbrace{C\,N_e\,(p\text{ side})}_{\equiv I_{e0},\ \text{electron saturation current}} \left(e^{eV/k_BT} - 1\right)$$

So $I_e = I_{e0}\left(e^{eV/k_BT} - 1\right)$

Similarly, $I_p = I_{p0}\left(e^{eV/k_BT} - 1\right)$, so altogether,

$$I \cong I_0\left(e^{eV/k_BT} - 1\right).$$ Also OK for reverse bias!

A slightly modified version works better,

$$\boxed{I_{diode} \simeq I_0\left(e^{\frac{eV}{nk_BT}} - 1\right)}$$

Here n is between 1 and 2, and accounts for recombination and other device-dependent effects.

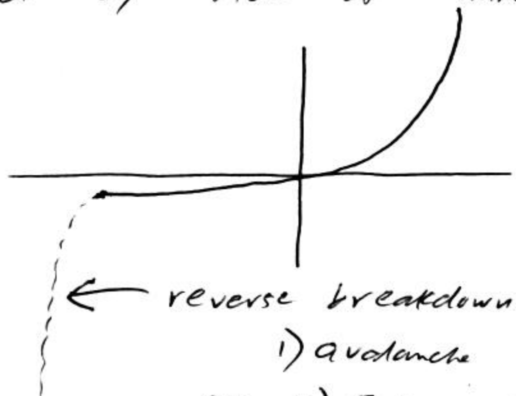
This works well unless V is so negative that reverse avalanche breakdown occurs (failure!) or, in special "Zener diodes", a sharp breakdown is reached due to quantum tunneling. These are used as voltage references.

where $\frac{e}{kT} \cong \frac{1}{.025V}$ as before assuming $T \sim 300K$.

and I_0 = "reverse saturation current", typ. ~ 1μA or less.

and n contains device physics; it's about 1-2.

I_0 is set by flow of "minority" carriers.



← reverse breakdown occurs by
1) avalanche breakdown
or 2) Zener breakdown -- direct breakage of covalent bonds by E field at junction.

Normally causes destruction, but used intentionally for "zener diodes."

Ratings:

Important ones are -- 1) PIV (peak inverse voltage) or V_R (max)
2) max. fwd current or I_F
3) Reverse leakage I_R (max) (goes up 6.2% / °C !)

Small-signal:
1N914: (or 1N4148) V_R (max) = 75 V
I_F = 10 mA max (cont.), at $V_F = 0.75V$
I_R (max) = 5 μA at 100°C and V_R

Typ. rectifier:
1N4007: V_R (max) = 1000 V
I_F = 1000 mA (cont.), at $V_F = 0.9V$
I_R (max) = 50 μA

Note: 1N400x is much slower than 1N914.
General rule (of thumb): when "conducting", $\Delta V \sim 0.6V$ for Si diodes.

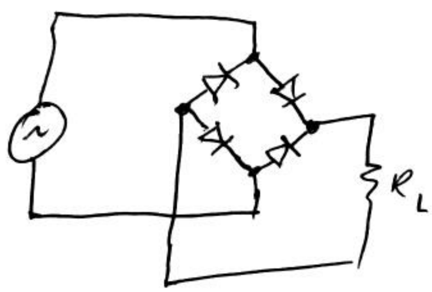
Still OK: ~~network~~ Kirchoff's laws

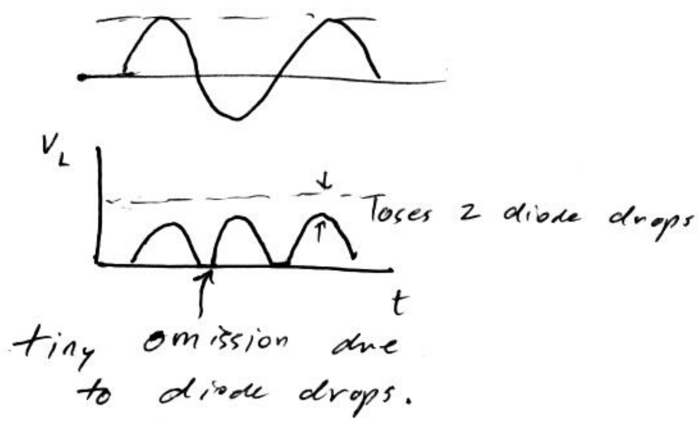
Not OK: { Ohm's law (assumes linearity)
Thevenin's theorem (assumes both linearity & superposition princ.)

Applications :

1) Rectification :

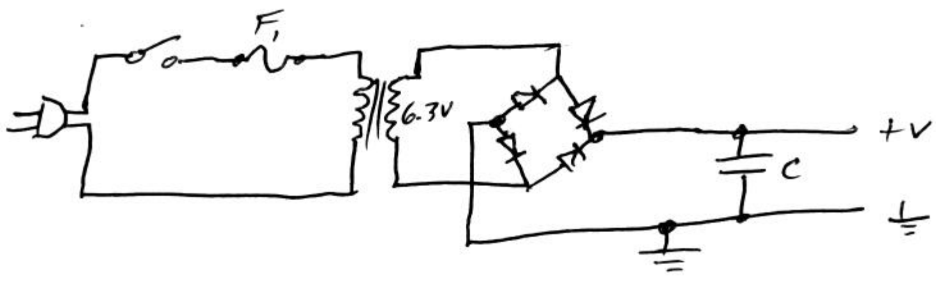
a) half - wave

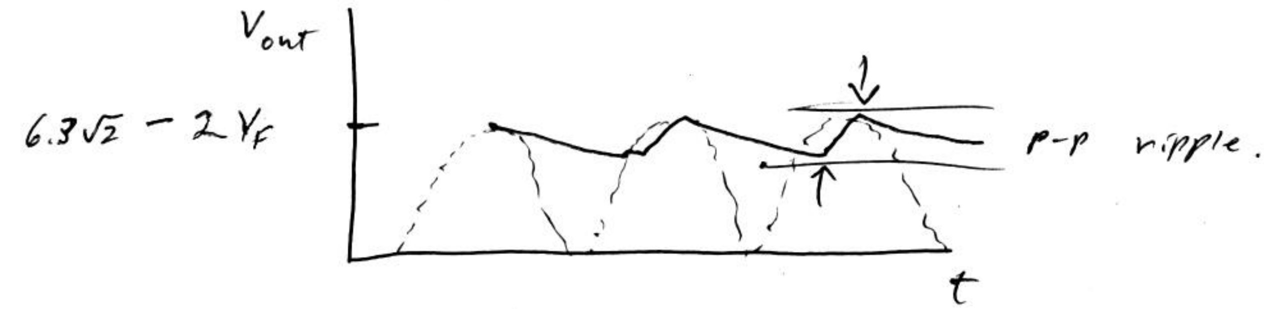




b) full - wave

Simple power supply :





Estimate ripple: Look at limit of small ripple –
Assume $I_{load} \simeq$ constant, and that C discharges for full half-cycle, $\Delta t = \frac{1}{2f}$

Then $\Delta V = \frac{Q}{C} = \frac{I_L \Delta t}{C} = \frac{I_{Load}}{2fC}$

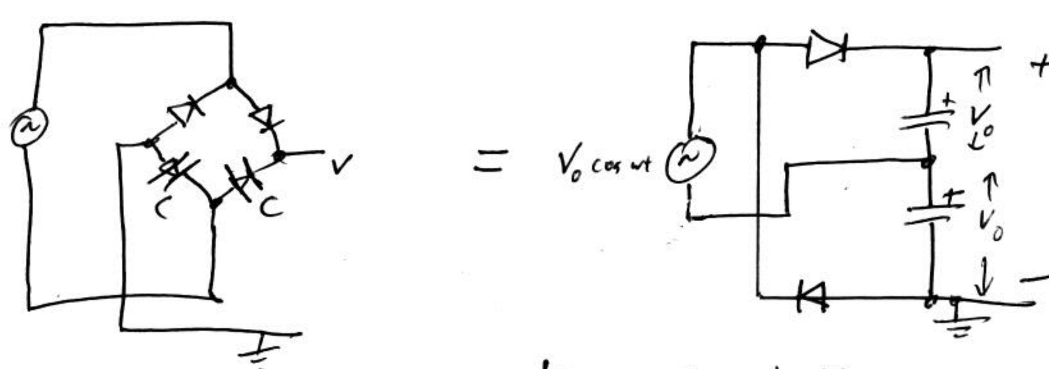
(This overestimates real ripple.)

Ex: $100\,\mu F$, $I = 100\,mA$, $60\,Hz$

$$\Rightarrow \frac{.1}{2(60)(10^{-4})} = 8.3\ V \quad (!)$$

So we need at least $1000\,\mu F$ to do at all well, here.
Apart from using huge capacitors (and xformers!), a good solution is to add <u>regulators</u> and series inductors, called "chokes."
Increasing f also an option -- used by <u>switching</u> power supplies.

2) Variant: voltage doubler:

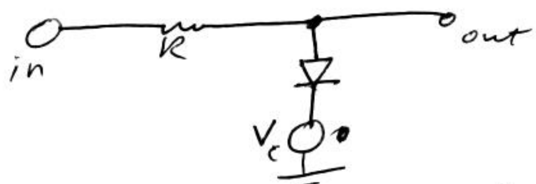


like 2 half-wave rectifiers in series.

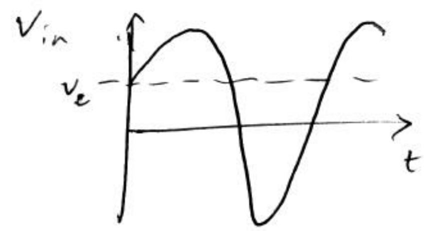
Can extend for tripler, etc.

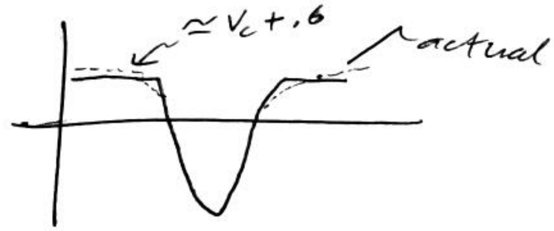
Diode clamps & limiters:

Basic clamp:



yes



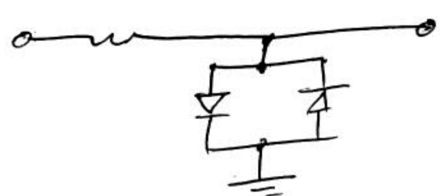


Want a perfect clamp? Use an op amp!

Uses:
1) protection (e.g. in IC's)
2) prevent overmodulation (radio, etc.)
3) limit swing in servos, etc., prevent latching.

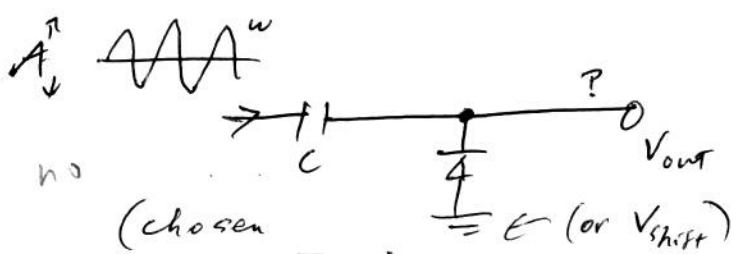
Symmetric limiter:

no



Also good for ampl. protection!

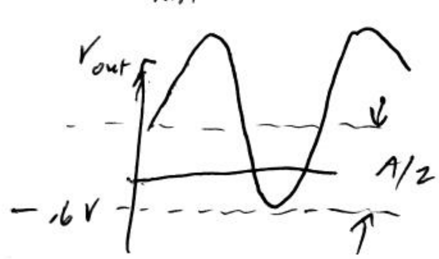
Variation -- dc restoration/shifting



no

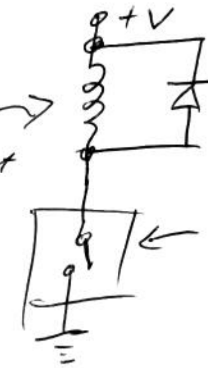
(chosen so $Z_C(\omega) << Z_{load}$)

When diode conducts, C charges. So its voltage builds up until conduction stops:



Zero is shifted by $\frac{A}{2}$ $(-.6V)$

Protection from back-emf:

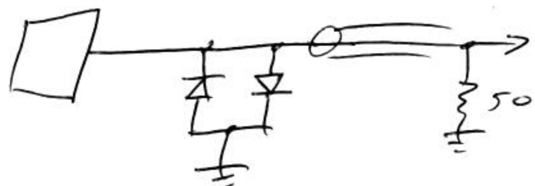


solenoid or
no relay coil →
or electromagnet

← protection diode

← transistor switching circuit,
such as emitter follower (next)

For detectors with small signals, can even use

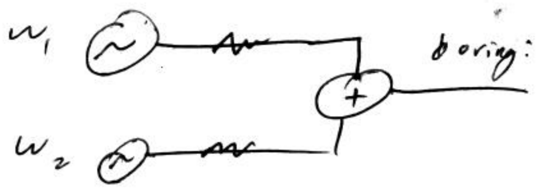


→ to scope, $-0.6 < V < +0.6$

Diode Mixers & such:

Can explicitly exploit nonlinearity as a log converter.

Or can exploit it to generate new freq's -- see lab!



boring: just $\cos(\omega_1 t) + \cos(\omega_2 t)$

Has beat note --

yes

But replace ⊕ with

$\rightarrow V_{out} = IR = I_0\left(e^{V/A_{diode}} - 1\right)R$,

where $V = V_1 \cos \omega_1 t + V_2 \cos \omega_2 t$

To get

Has new freq's ---

$e^{V/A} \sim \frac{V}{A} + \frac{1}{2}\left(\frac{V}{A}\right)^2 + \cdots$

gives $\omega_1 + \omega_2$, $2\omega_1$, ...

Can see $\omega_1 - \omega_2$ here in avg.

To reduce distortion, bias diode into conduction.

If $\omega_1 \ll \omega_2$, this is an amplitude modulator; if comparable, it's a mixer.