Chapter 3

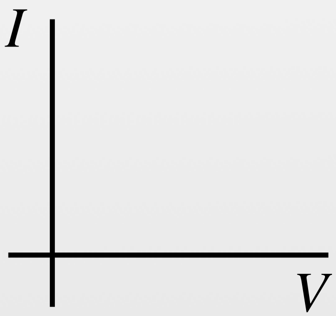
Band Theory and Diode Circuits

1) Non-linear components

R, L, C are “linear” because v is prop to i

That is, $v = iz$

(a) Current-voltage characteristics

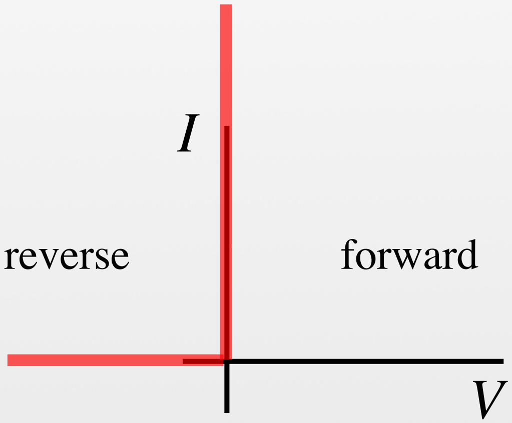


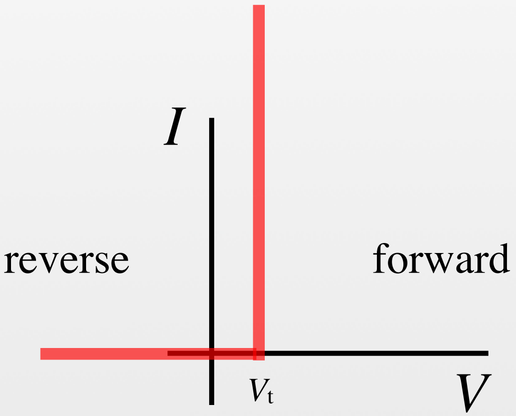
IV dependence determines properties

usually measured and analyzed graphically

- ideally, components considered here do not have frequency dependence
- real components have stray capacitance and inductance

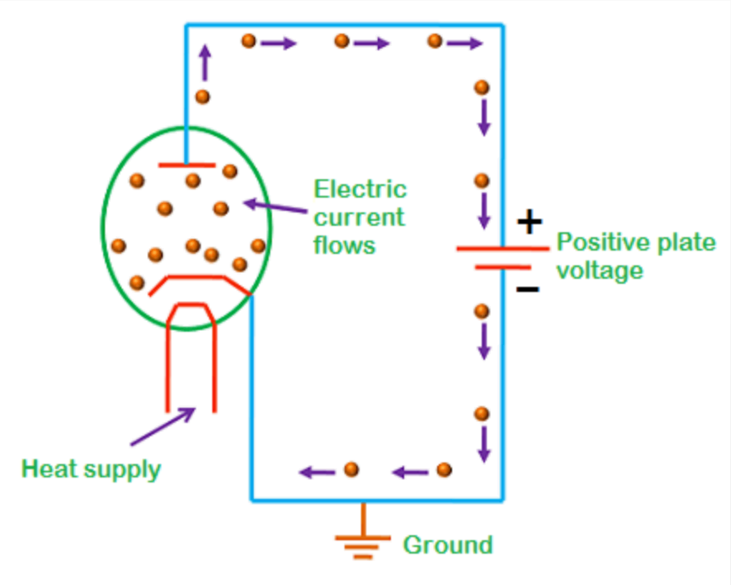
(b) The ideal rectifier (conducts in one direction only)

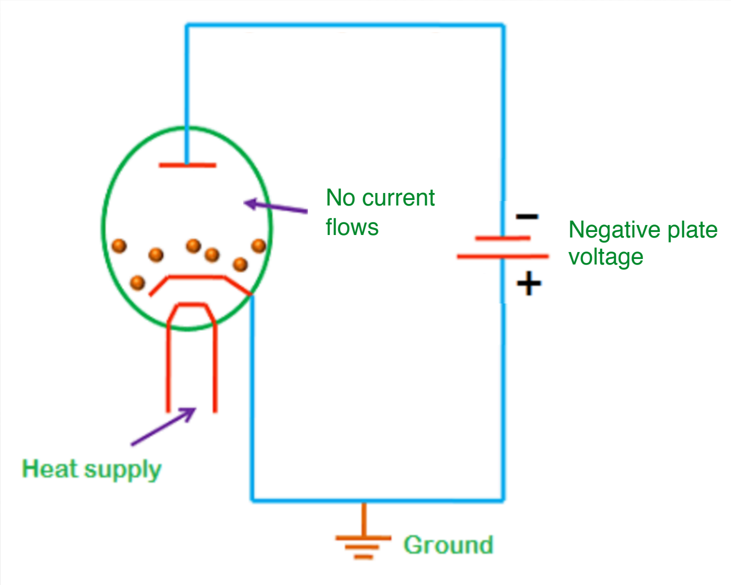




non-zero turn-on voltage

Rectifier example; vacuum tube diode

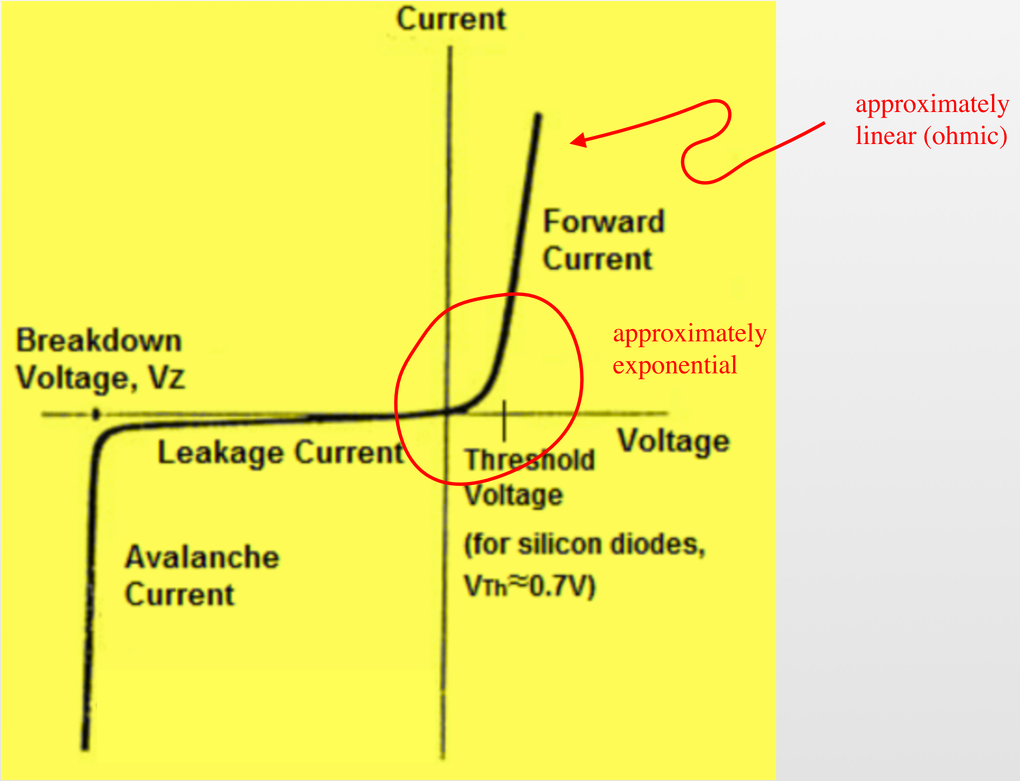


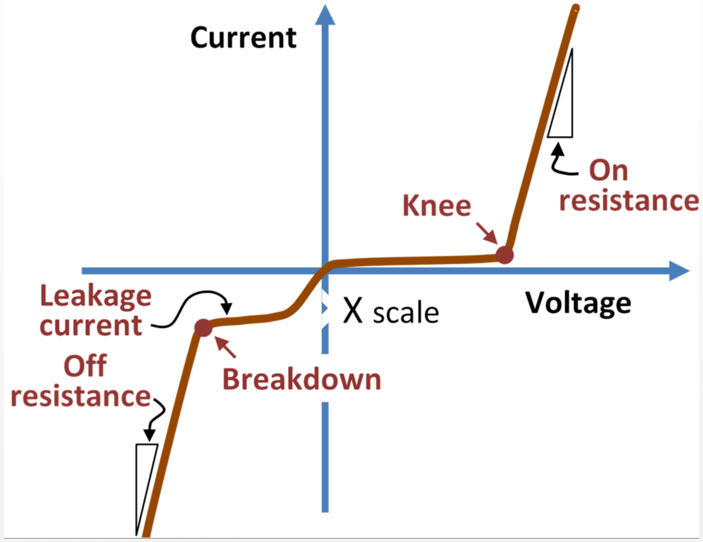


2) The junction diode (pn)

p - means positive charge carriers
n - means negative charge carriers

(a) IV characteristics





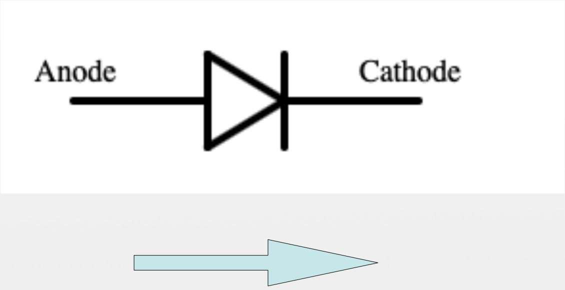
- Turn-on (or threshold) voltage: $V_t \sim$ 0.7 V (Si); 0.2 V (Ge)
- Leakage (or reverse) current: $I_0 \sim$ pA (Si); μA (Ge)

(depends exponentially on temperature; unusable @ > ~ 200 ºC)

- Forward resistance: $r_D = \frac{dV}{dI} = \frac{1}{dI/dV} \rightarrow 0$ (~ Ω)

  - ignore in nearly all circuits
  - needs series resistor for protection

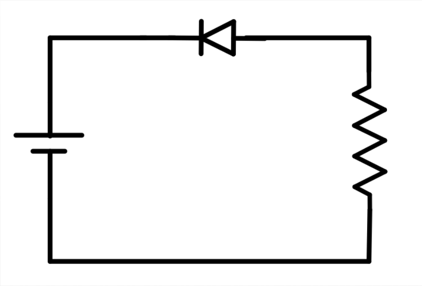
(b) Symbol for solid state diode



direction of positive current flow

(c) Equivalent circuits

Reverse
biased



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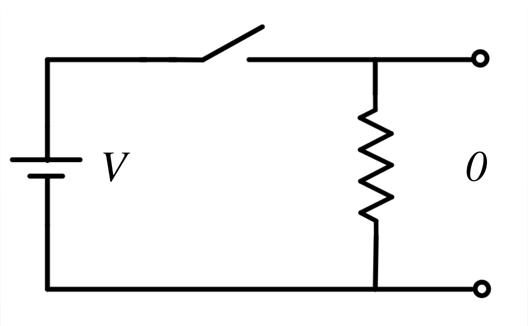
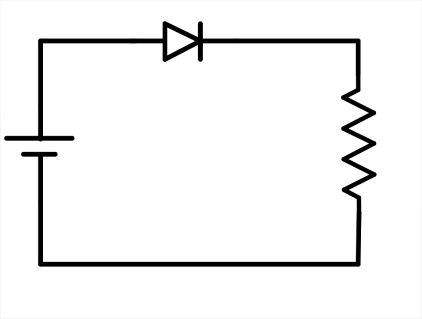


Forward
biased



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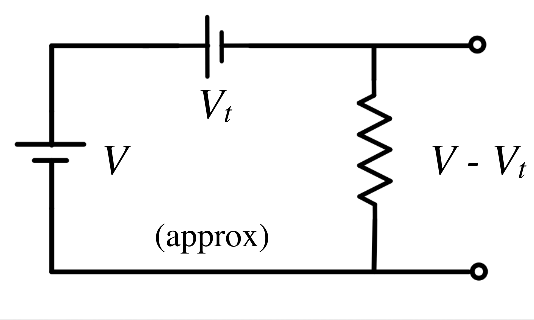
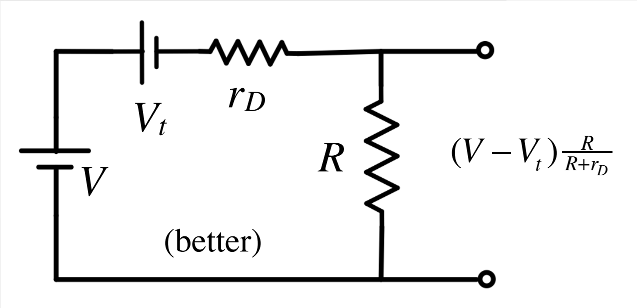




(d) Schockley diode equation (justified later)

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

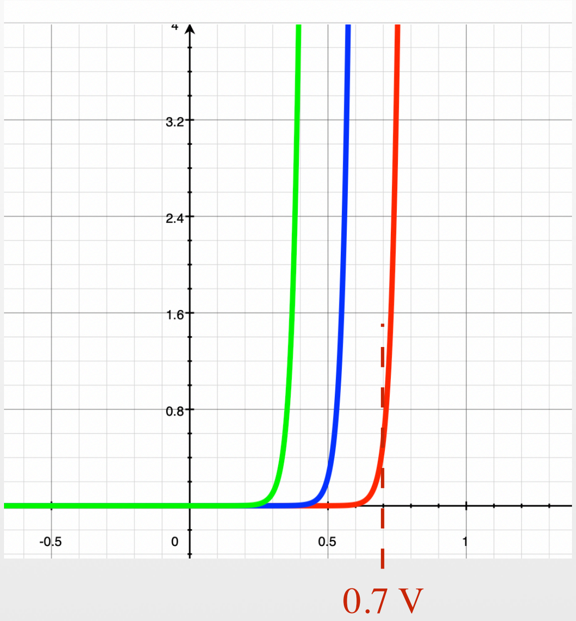
$$\boxed{I = I_0\left(e^{V_d/\eta V_{th}} - 1\right)}$$

q - elementary charge
k - Boltzmann constant
T - thermodynamic temperature
V_d - diode voltage
η - ideality factor
(1 for ideal diode; > 1 for Si)
I_0 - reverse saturation current

$$V_{th} = \frac{kT}{q} = 25.85\ \mathrm{mV}\ \text{at}\ T = 300\ \mathrm{K}$$

is the thermal voltage

$$I = I_0\left(e^{V_d/\eta V_{th}} - 1\right)$$



$\eta = 1$

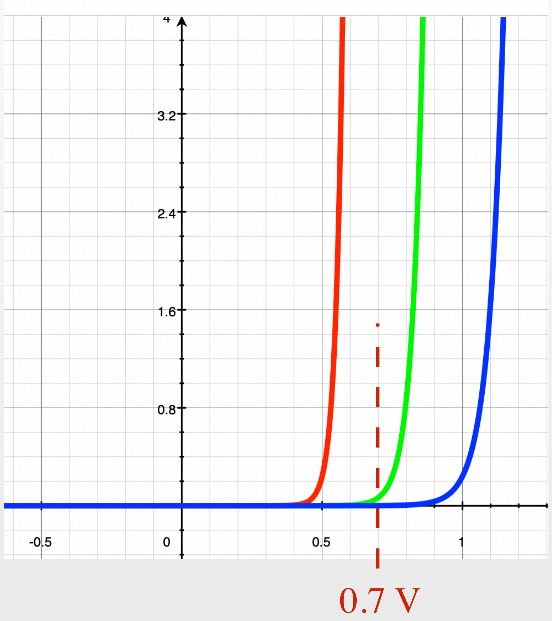
$I_0 = \mathrm{pA}$

$I_0 = \mathrm{nA}$

$I_0 = \mu\mathrm{A}$

For positive bias,

$$I \cong I_0 e^{V_d/\eta V_{th}}$$



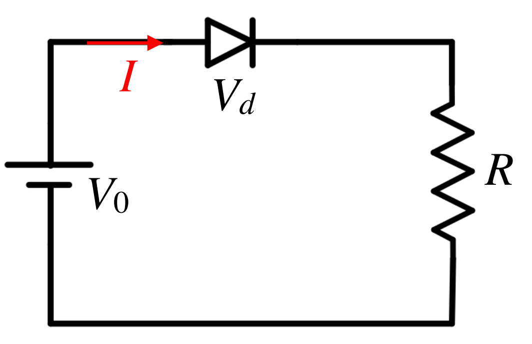
$I_0 = \mathrm{pA}$

$\eta = 1$

$\eta = 1.5$

$\eta = 2$

(e) Load line analysis

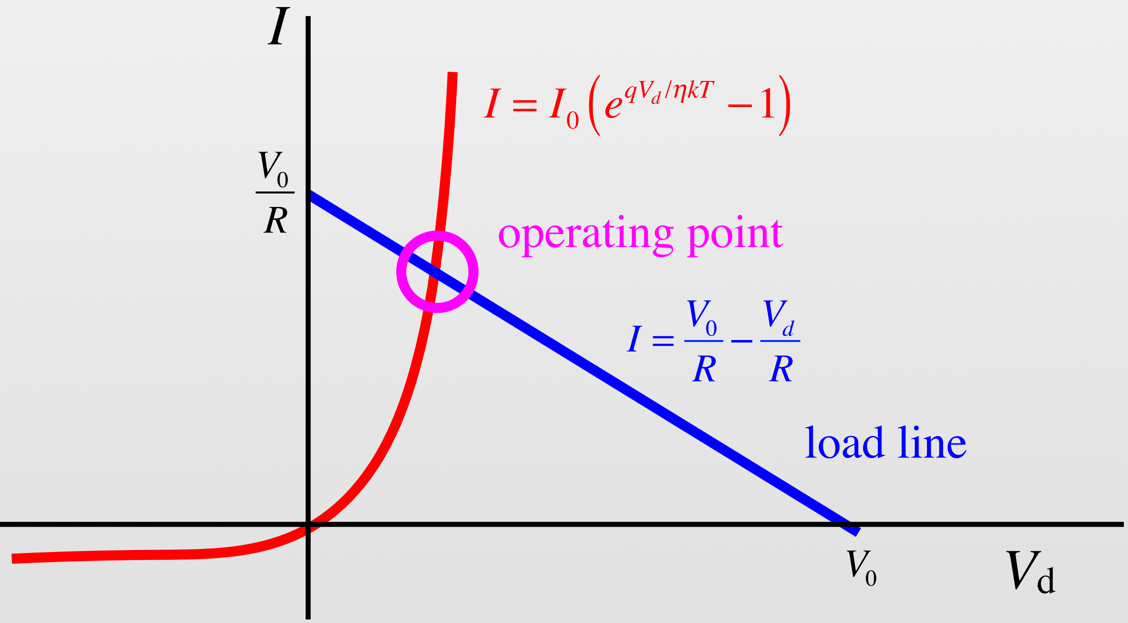


$$V_0 - V_d - IR = 0$$

$$I = \frac{V_0}{R} - \frac{V_d}{R} \qquad \text{but} \qquad I = I_0\left(e^{qV_d/\eta kT} - 1\right)$$

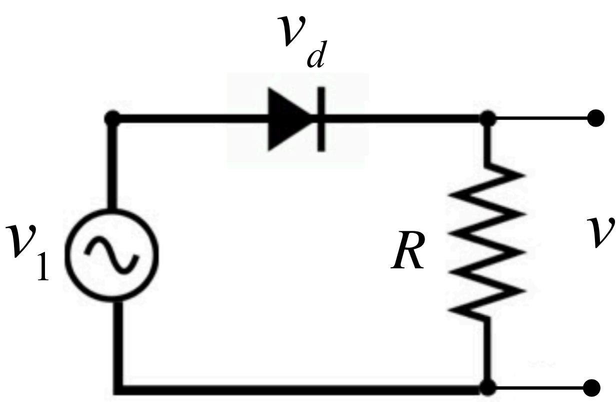
so $$\frac{V_0 - V_d}{R} = I_0\left(e^{qV_d/\eta kT} - 1\right)$$ no simple analytical solution

graphical analysis

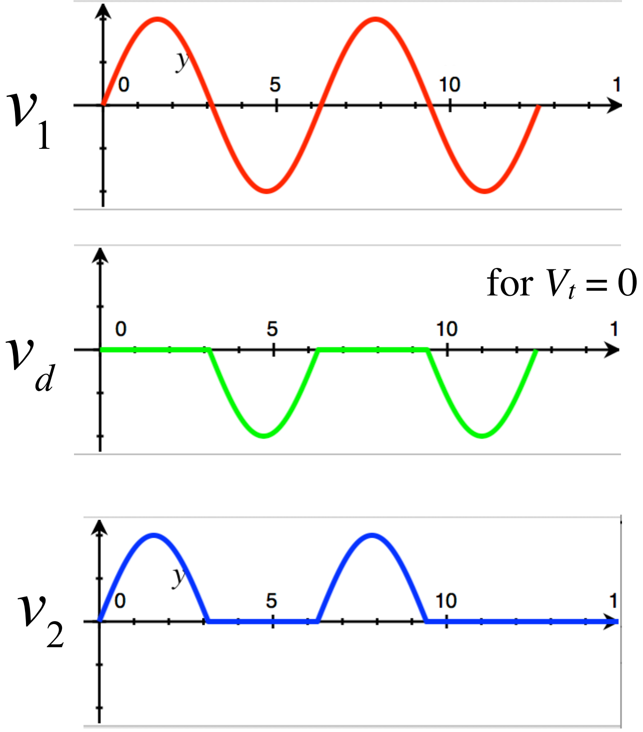


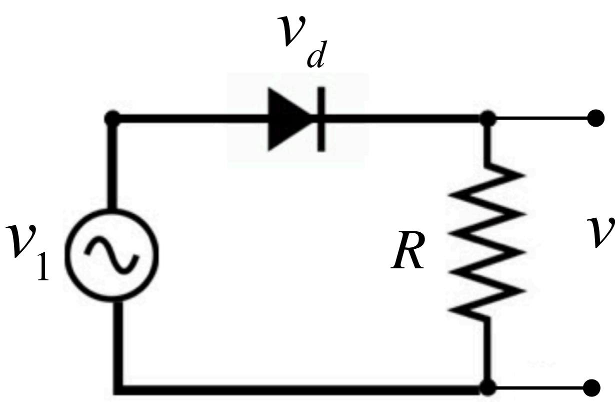
3) Rectifier circuits

(a) Half-wave rectifier

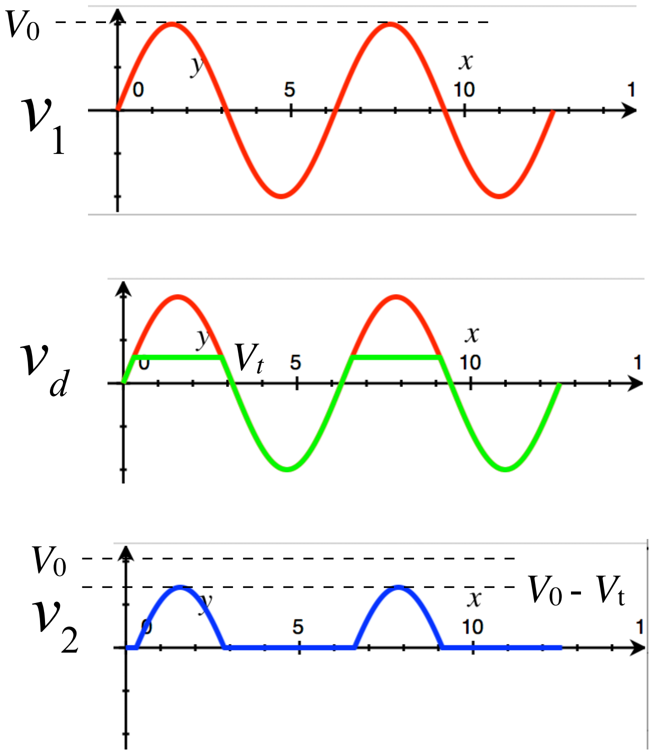


$$v_2 = v_1 - v_d$$

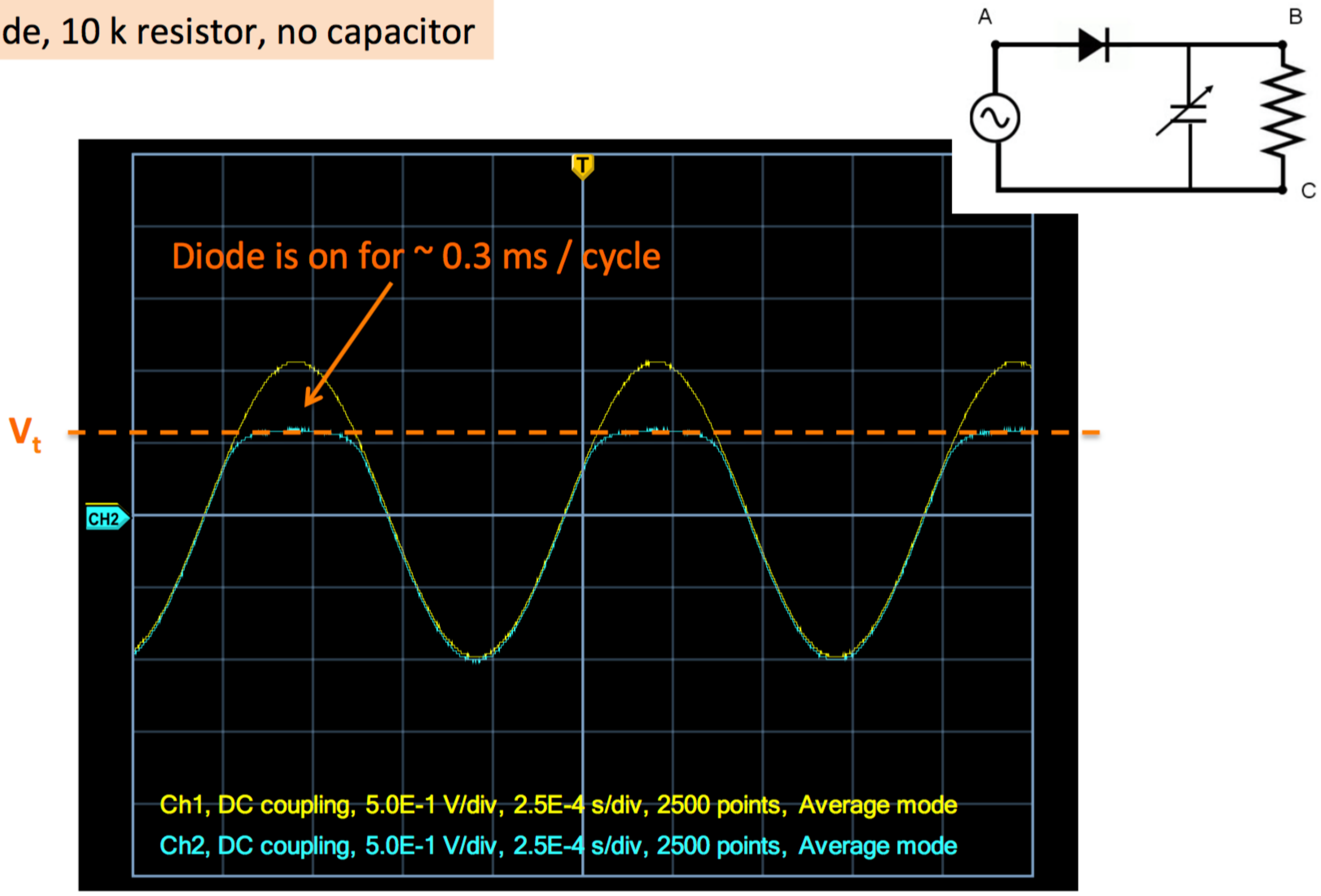




$$v_2 = v_1 - v_d$$



Signal diode, 10 k resistor, no capacitor



Diode is on for ~ 0.3 ms / cycle

Ch1, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

Ch2, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

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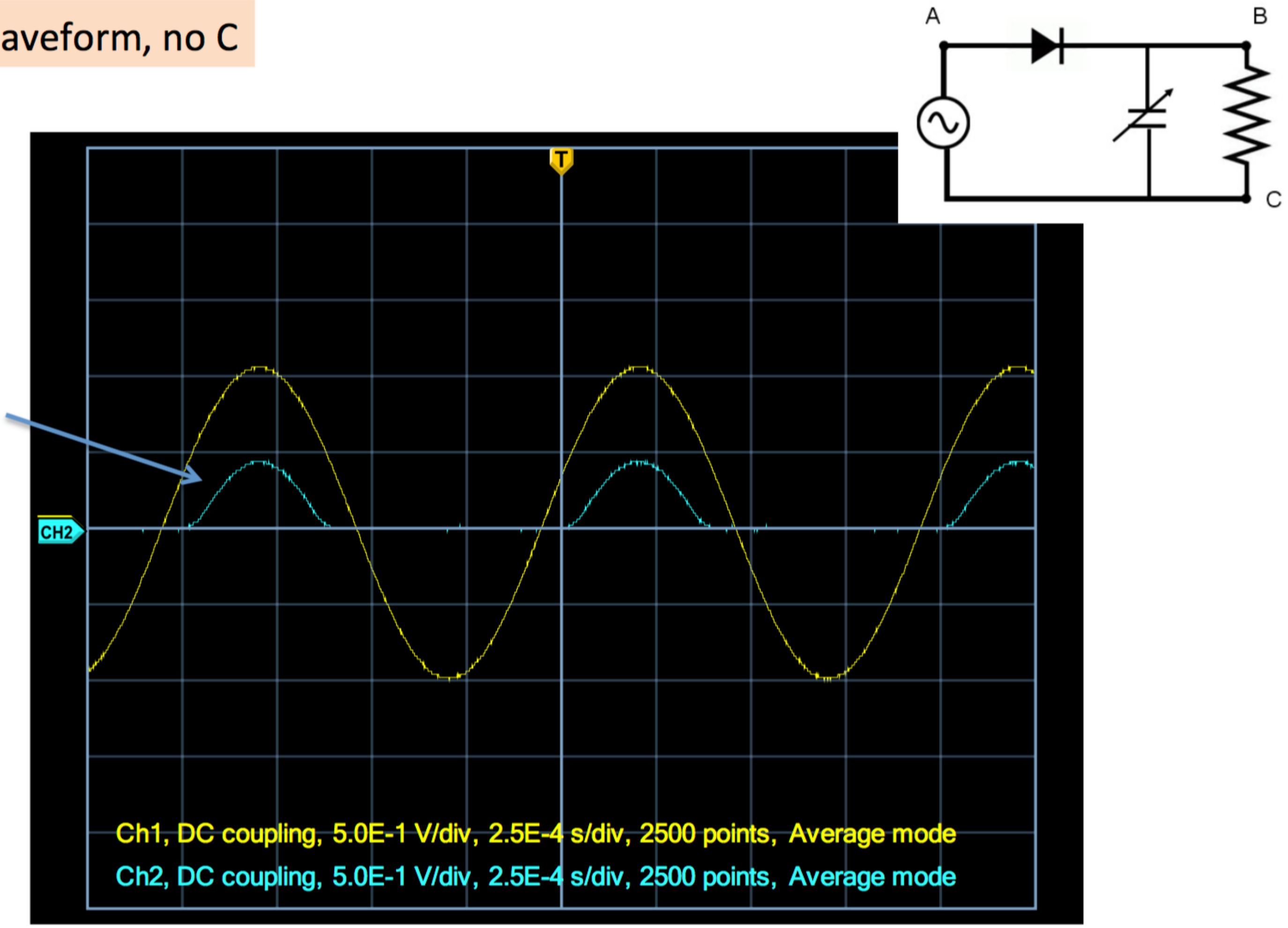
Resistor waveform, no C

Diode on



Ch1, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode
Ch2, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

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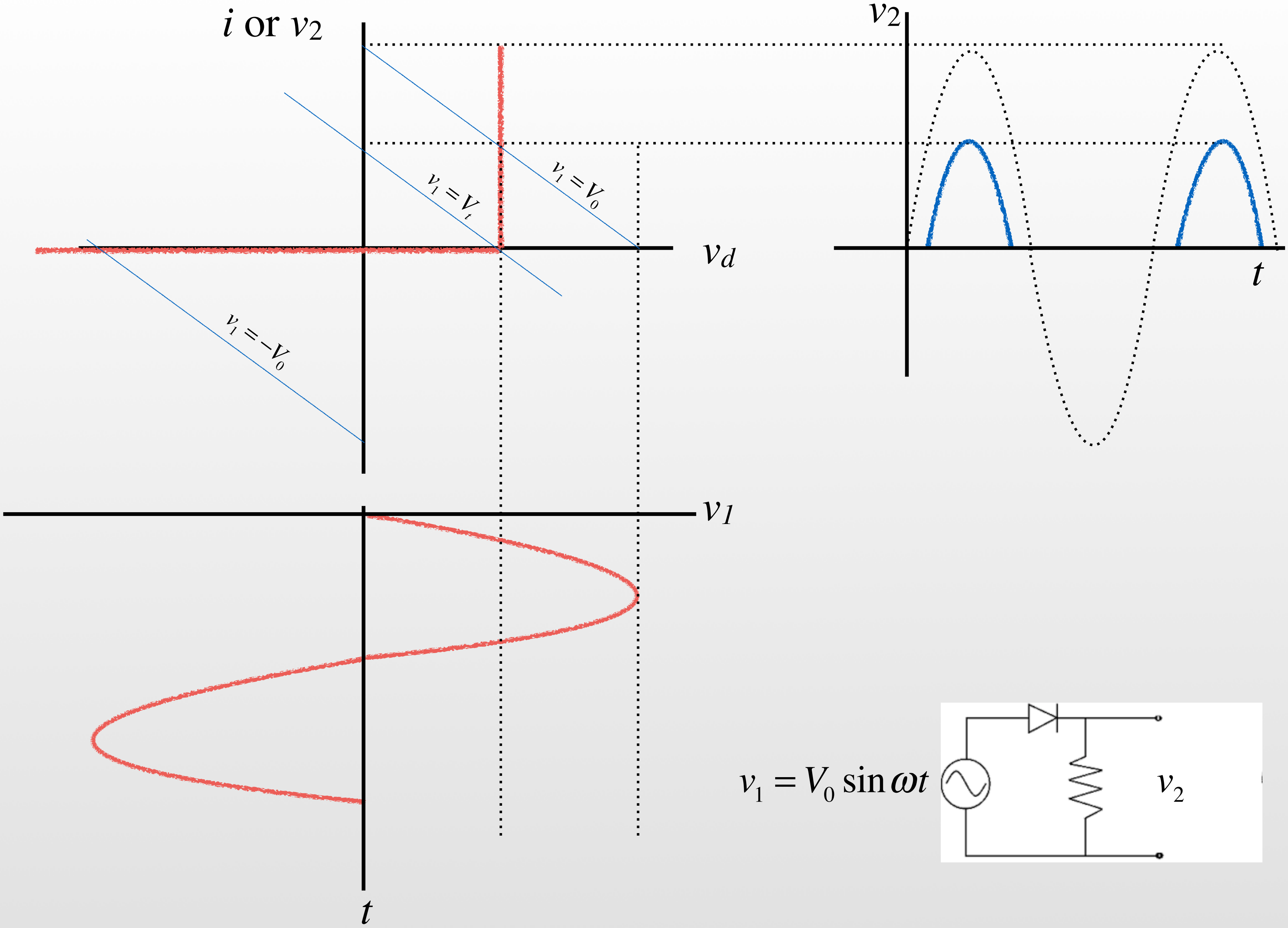
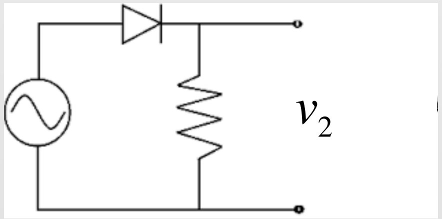
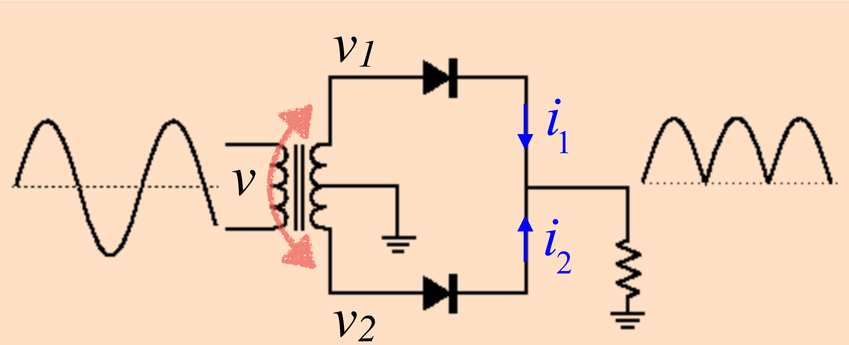


$$v_1 = V_0 \sin \omega t$$

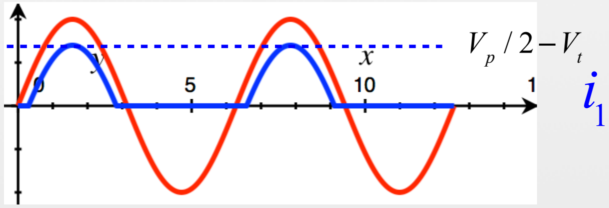


(b) centre-tapped full wave rectifier

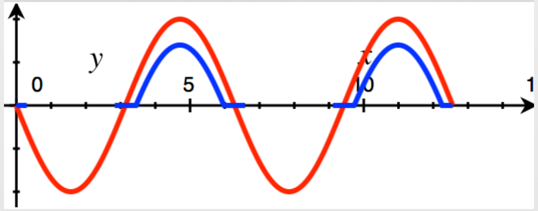


Secondary: $v = V_p \sin \omega t$

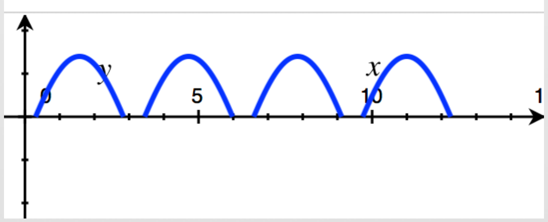
$$v_1 = \frac{V_p}{2} \sin \omega t$$



$$v_2 = -\frac{V_p}{2} \sin \omega t$$

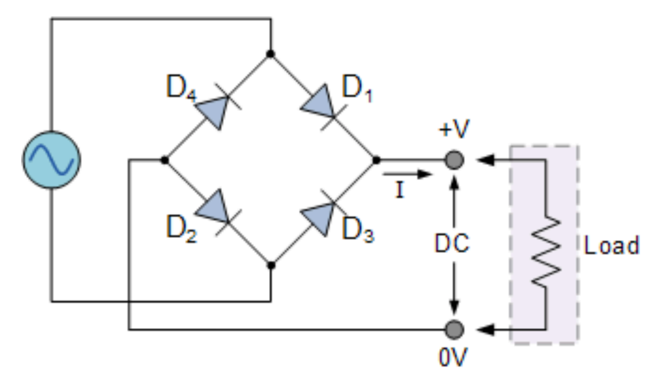


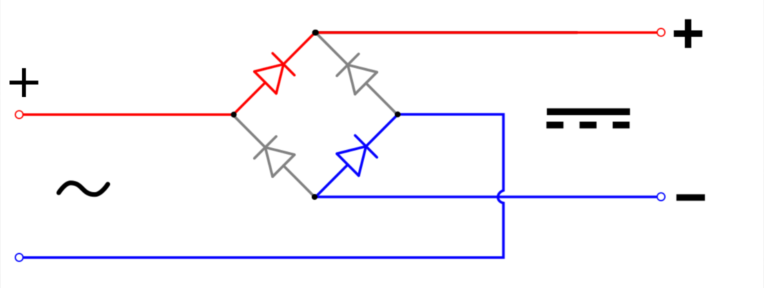
$$v_o = (i_1 + i_2) R$$

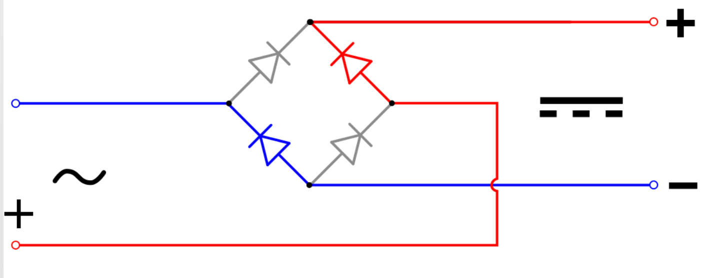


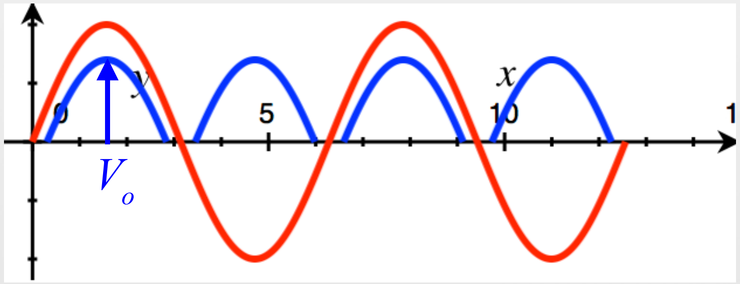
(c)Bridge rectifier

Input: $v = V_p \sin \omega t$



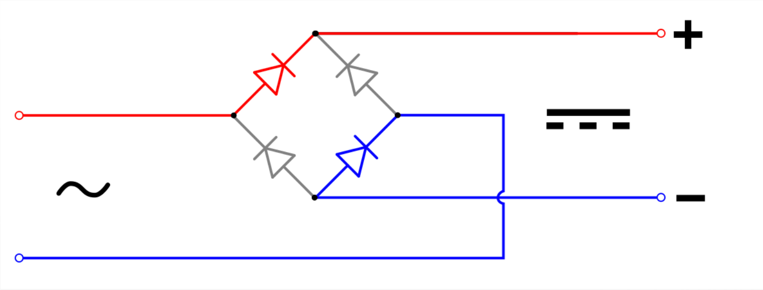




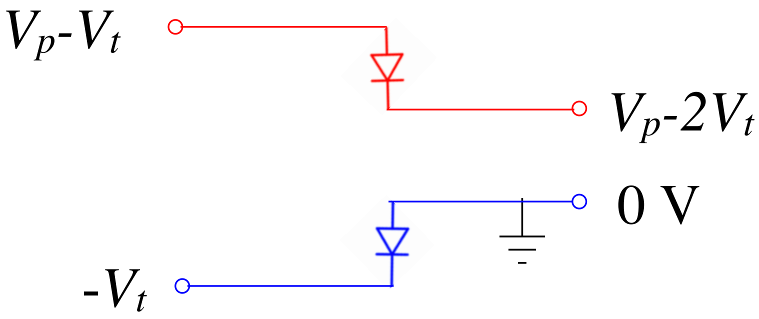


Peak output: $V_o = V_p - 2V_t$

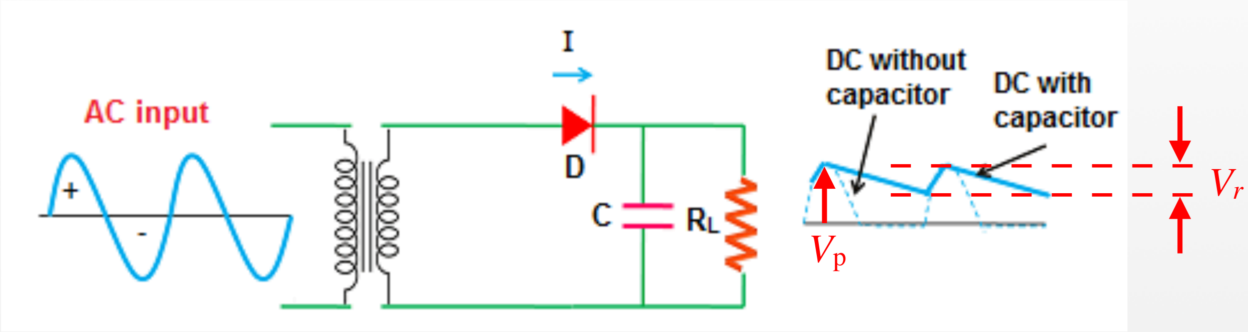
$$v = V_p \sin \omega t$$



For $v = V_p$



4) Capacitor filters

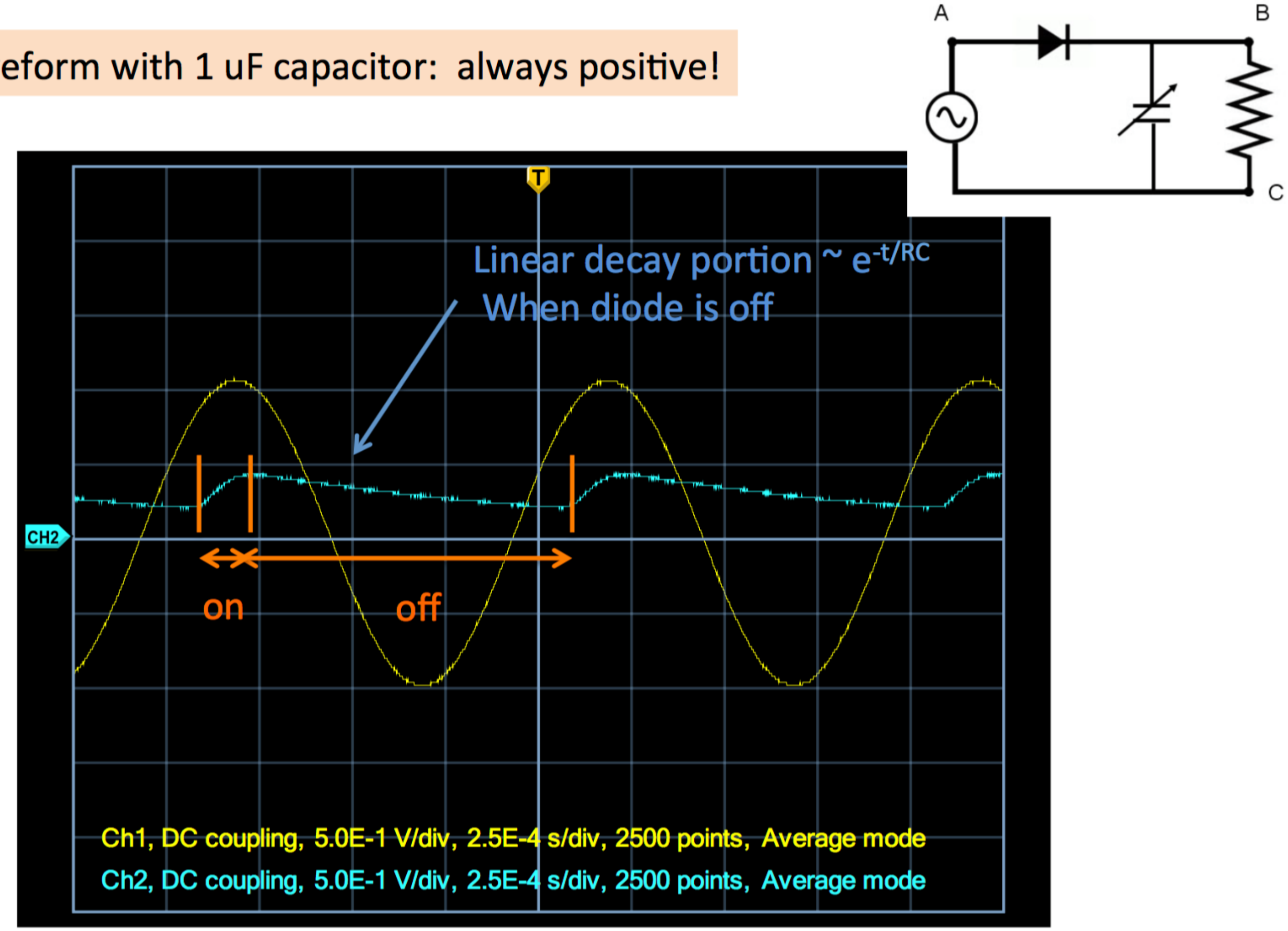


$$\boxed{\frac{V_r}{V_p} = \frac{1}{fR_LC}}$$

If f represents output frequency, same equation applies for full-wave rectifier

$$r = \frac{V_{rms}(ac)}{V_{dc}} \cong \frac{1}{2\sqrt{3}fR_LC}$$

Resistor waveform with 1 uF capacitor: always positive!



Ch1, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

Ch2, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

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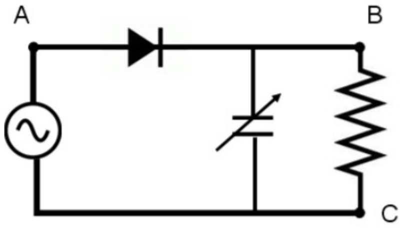
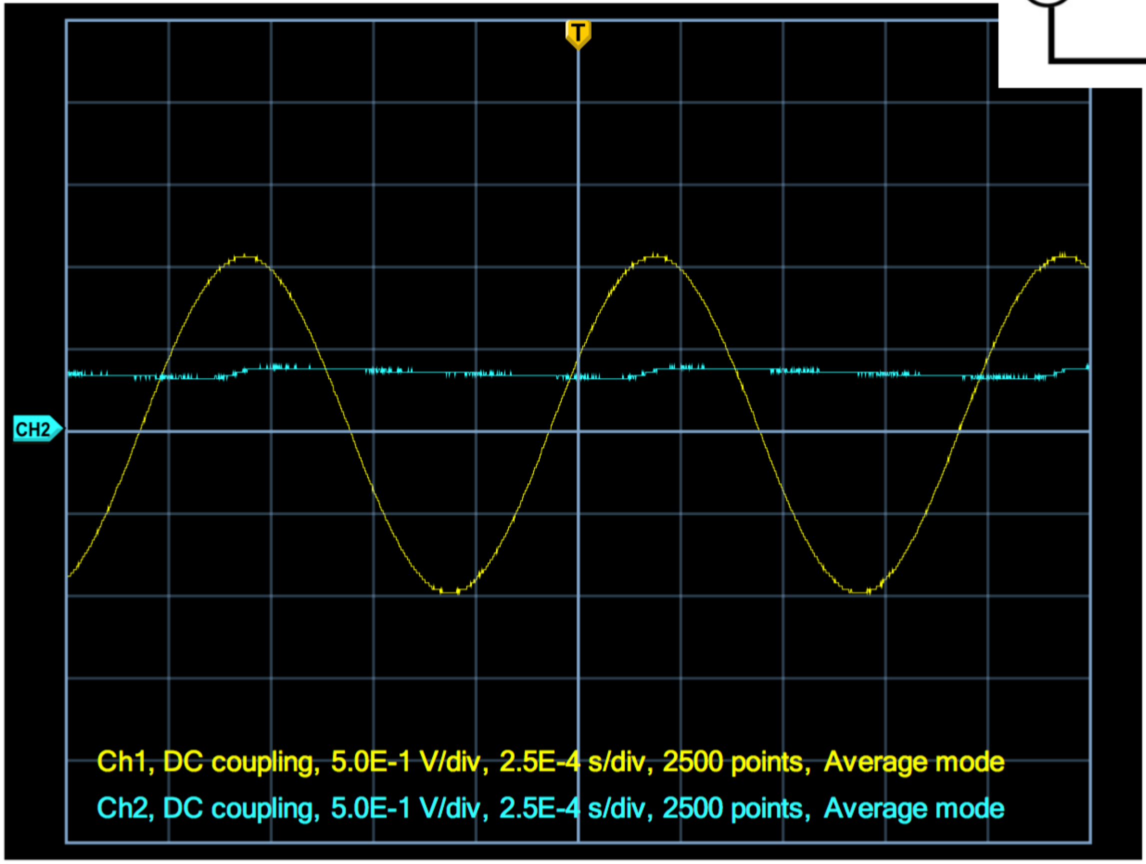
Resistor waveform, 4 uF capacitor





Ch1, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

Ch2, DC coupling, 5.0E-1 V/div, 2.5E-4 s/div, 2500 points, Average mode

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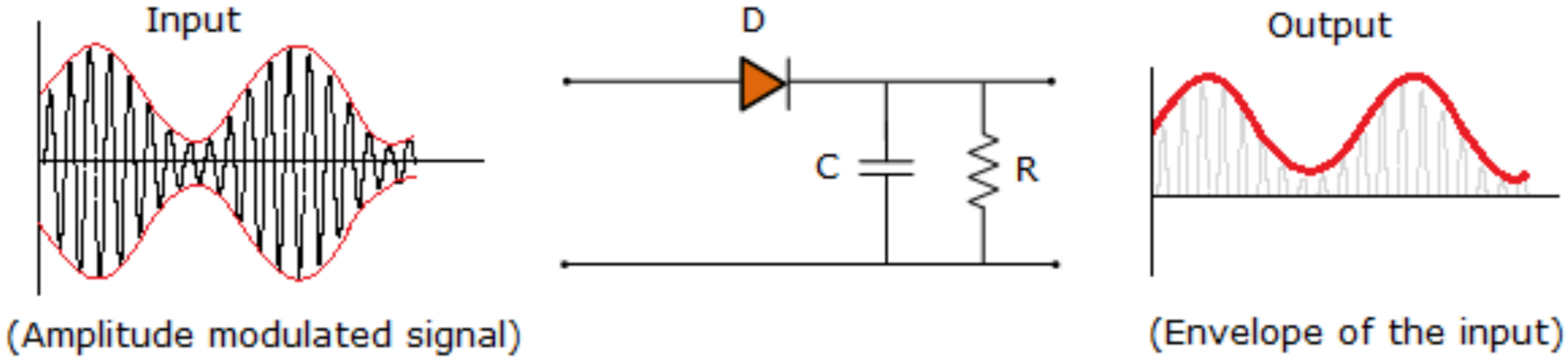
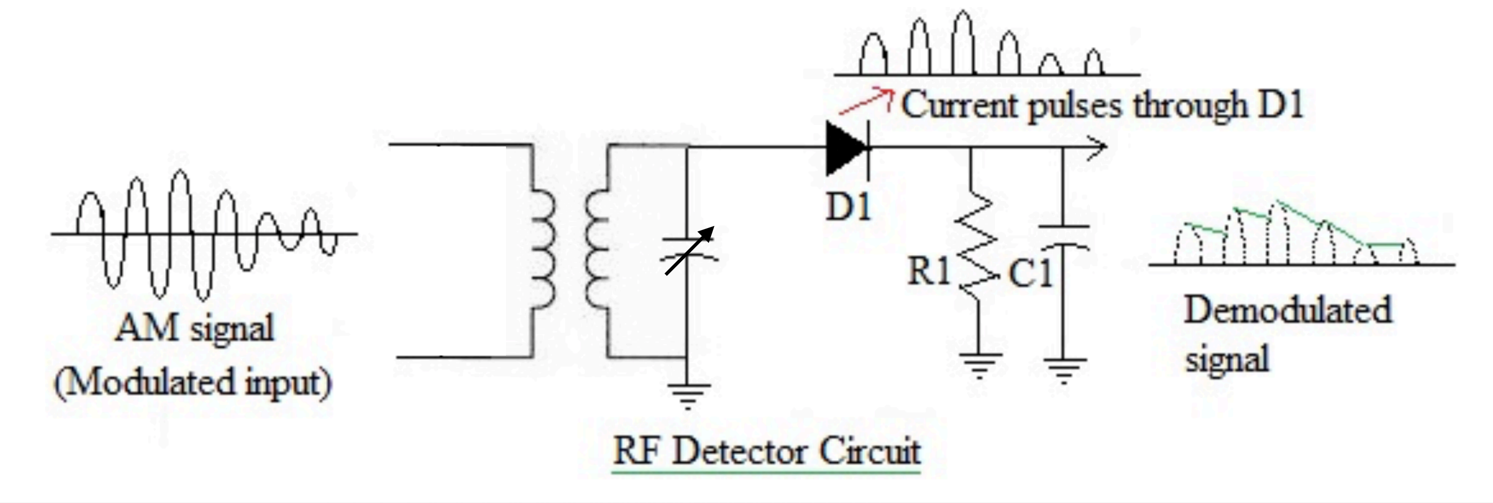
5) AM diode detector

Demodulation by a diode envelope detector: -



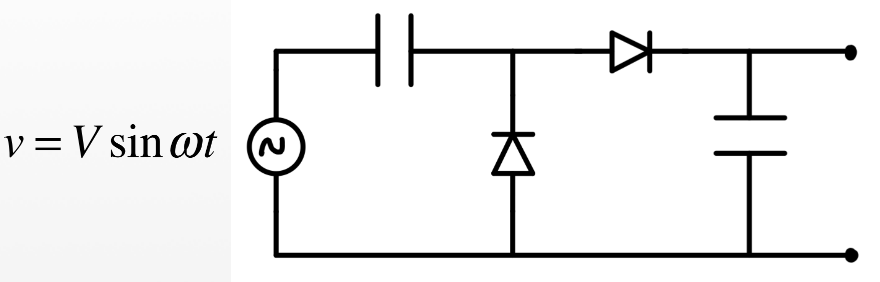
- carrier signal $f \sim 1$ MHz
- modulating audio signal $f \sim$ 10 kHz

- to smooth carrier frequency, $RC \gg T_c = 1/f_c = \sim 1\ \mu s$
- to preserve audio signal, $RC \ll T_m = 1/f_m = \sim 1$ ms
- Choose $RC = \sim 10\ \mu s$

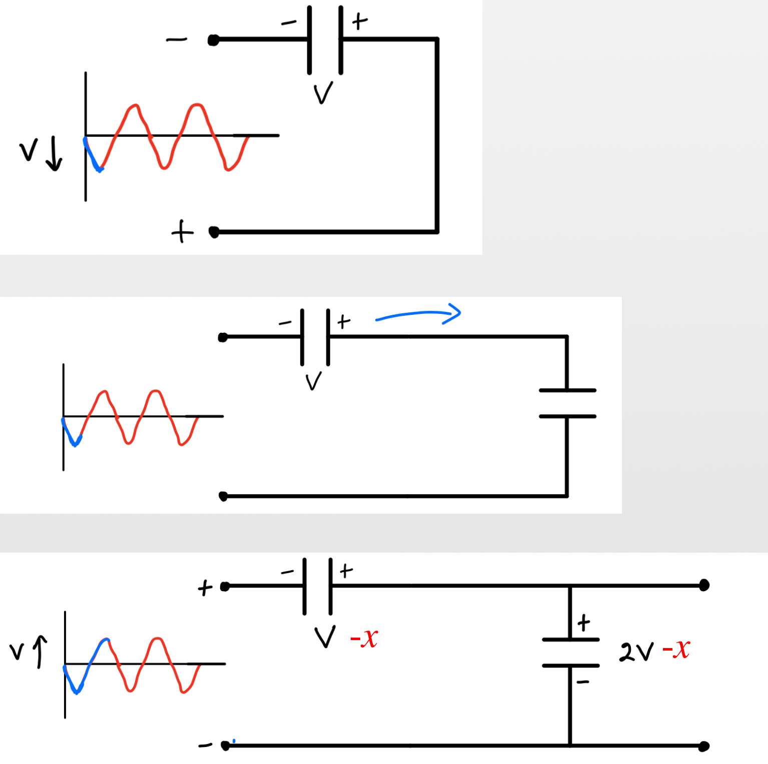

Current pulses through D1
D1
R1
C1
AM signal
(Modulated input)
Demodulated
signal
RF Detector Circuit

6) Voltage doubler / multiplier

(a) Doubler

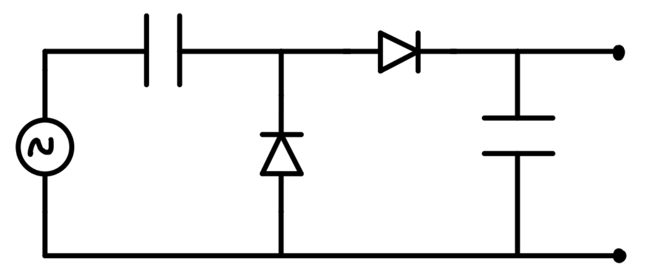


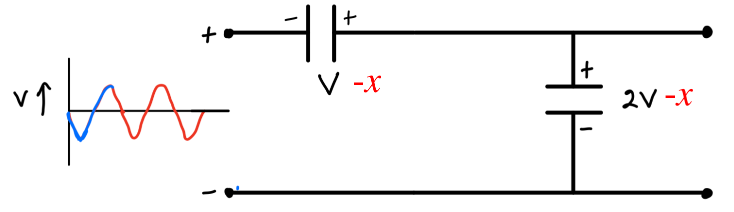
$v = V \sin \omega t$

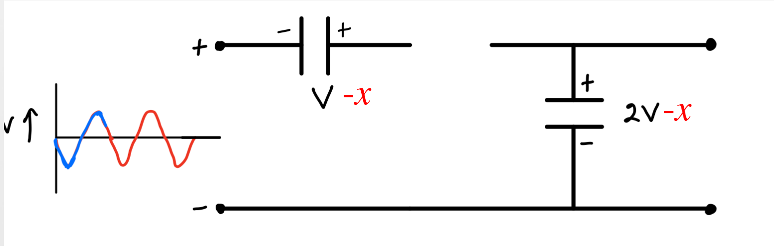


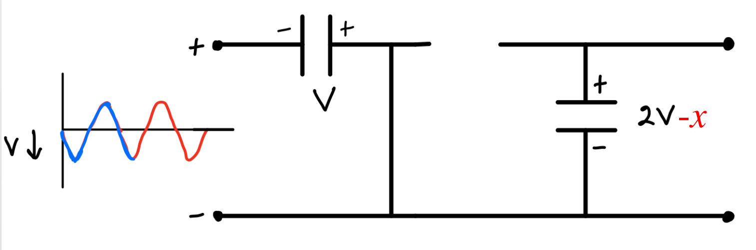
Full voltage is not reached in the first cycle, but rapidly converges to these values.

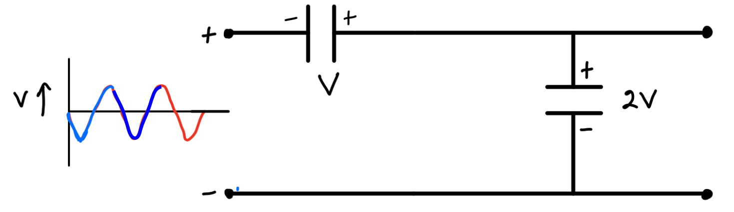
$v = V \sin \omega t$



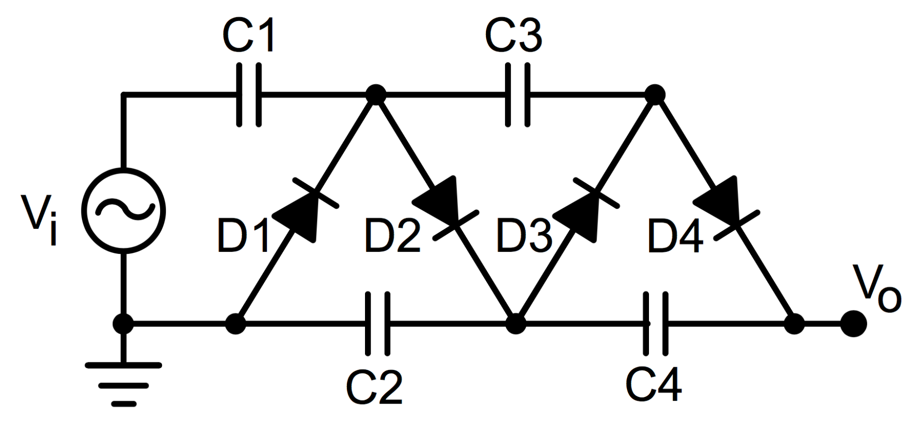




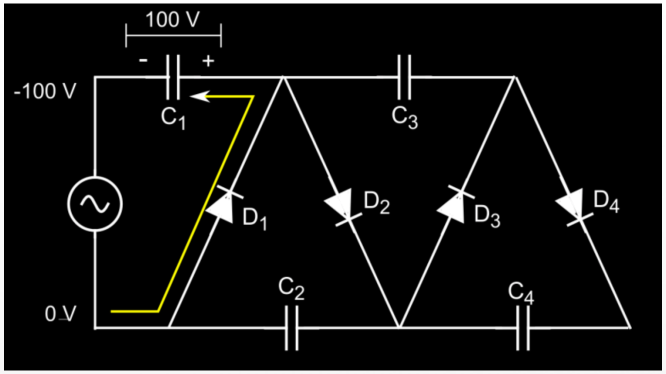




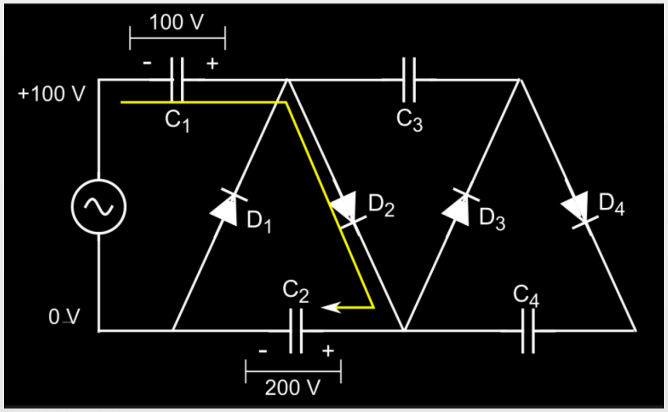
b) Cockroft-Walton generator



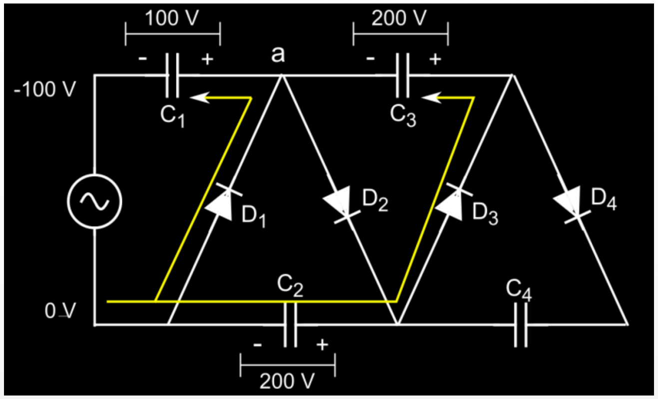
- When the input voltage Vi reaches its negative peak –Vp, current flows through diode D1 to charge capacitor C1 to a voltage of Vp.
- When Vi reverses polarity and reaches its positive peak +Vp, it adds to the capacitor's voltage to produce a voltage of 2Vp on C1s righthand plate. Since D1 is reverse-biased, current flows from C1 through diode D2, charging capacitor C2 to a voltage of 2Vp.
- When Vi reverses polarity again, current from C2 flows through diode D3, charging capacitor C3 also to a voltage of 2Vp.
- When Vi reverses polarity again, current from C3 flows through diode D4, charging capacitor C4 also to a voltage of 2Vp.



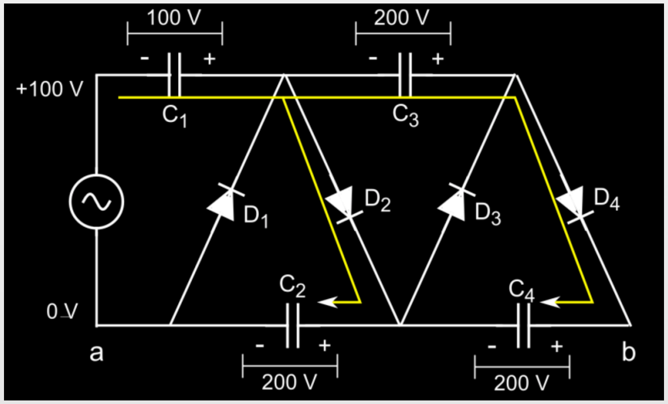
1. Capacitor C_1 charges through diode D_1 at the voltage U (100 V) of the power supply, which is at its negative peak. Note that this leads the capacitor to be positive at its right side and negative at its left. The yellow line indicates the direction of current flow



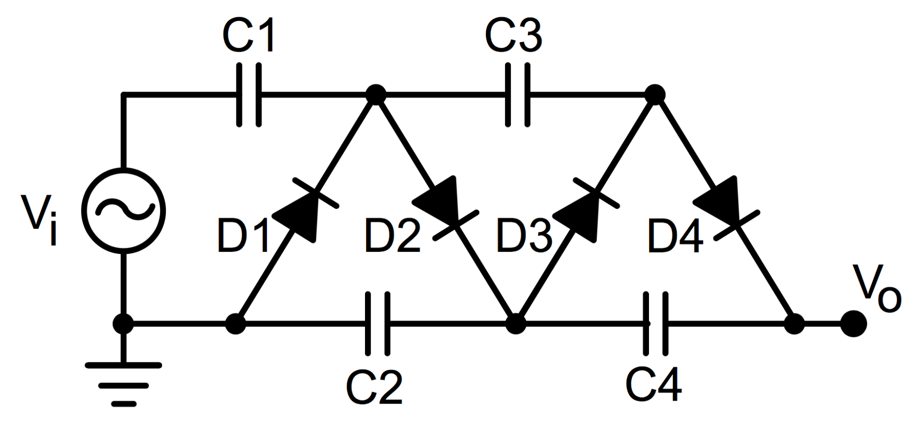
2. We now have +100 V at the upper side of the power supply, and this voltage adds to that of C_1 that was charged in the previous step. Therefore capacitor C2 charges through D_2 to 200 V, or 2U (100 V from the power supply plus 100 V from C2).



3. The charge stored in C_1 was used in the previous cycle to charge C_2, so C_1 is now charging through D_1 as in step 1. Also, capacitor C_3 is charged through D_3 to 2U. Why 2U? Because since C_1 is discharged, point "a" in the schematic is at zero potential and C_3 sees the 200 V of C2.

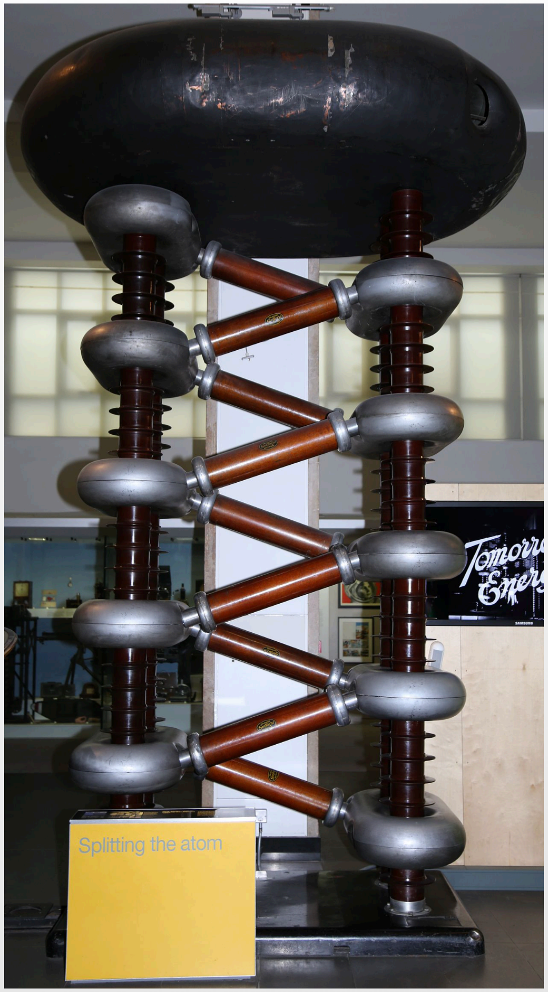


4. The power supply is again at its positive peak, and C2 is now being recharged as in step 2. At the same time, capacitor C_4 charges to 200 V, because it is the potential difference that it sees: 400 V at its positive side (100 V of the supply plus 100 V of C_1 plus 200 V of C_3), and 200 V at its negative side, which is the potential of C_2.



- All the capacitors are charged to a voltage of $2V_p$, except for $C1$, which is charged to V_p.

- The key to the voltage multiplication is that while the capacitors are charged in parallel, they are connected to the load in series.



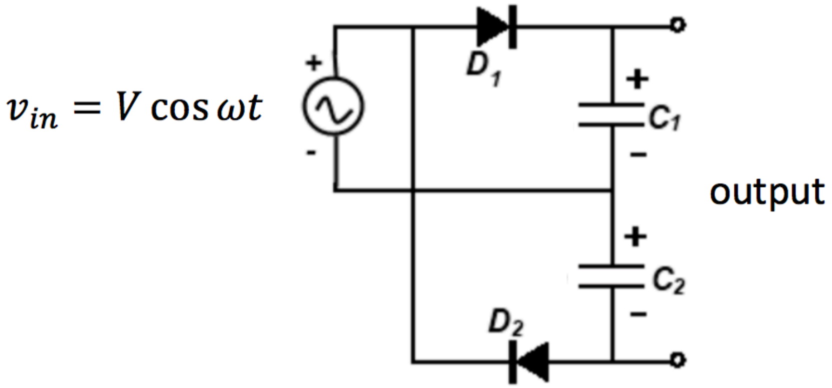
This Cockcroft–Walton voltage multiplier was part of one of the early particle accelerators responsible for development of the atomic bomb. Built in 1937 by Philips of Eindhoven it is now in the National Science Museum in London, England.

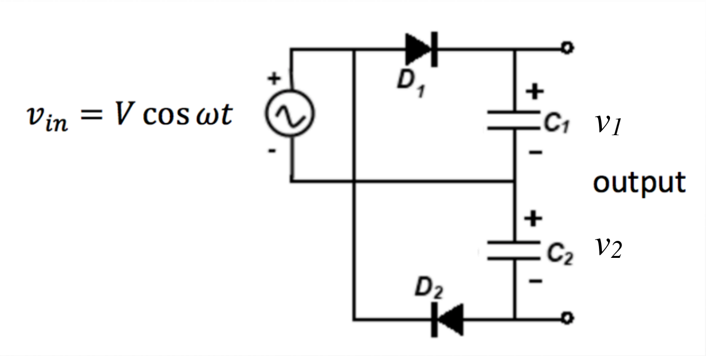
Cockroft and Walton used this voltage multiplier cascade to generate potentials up to 1 MV, used to accelerate particles. In 1932 they split lithium nuclei by bombarding them with 700 keV protons.

In 1951 won they were awarded the Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles”.

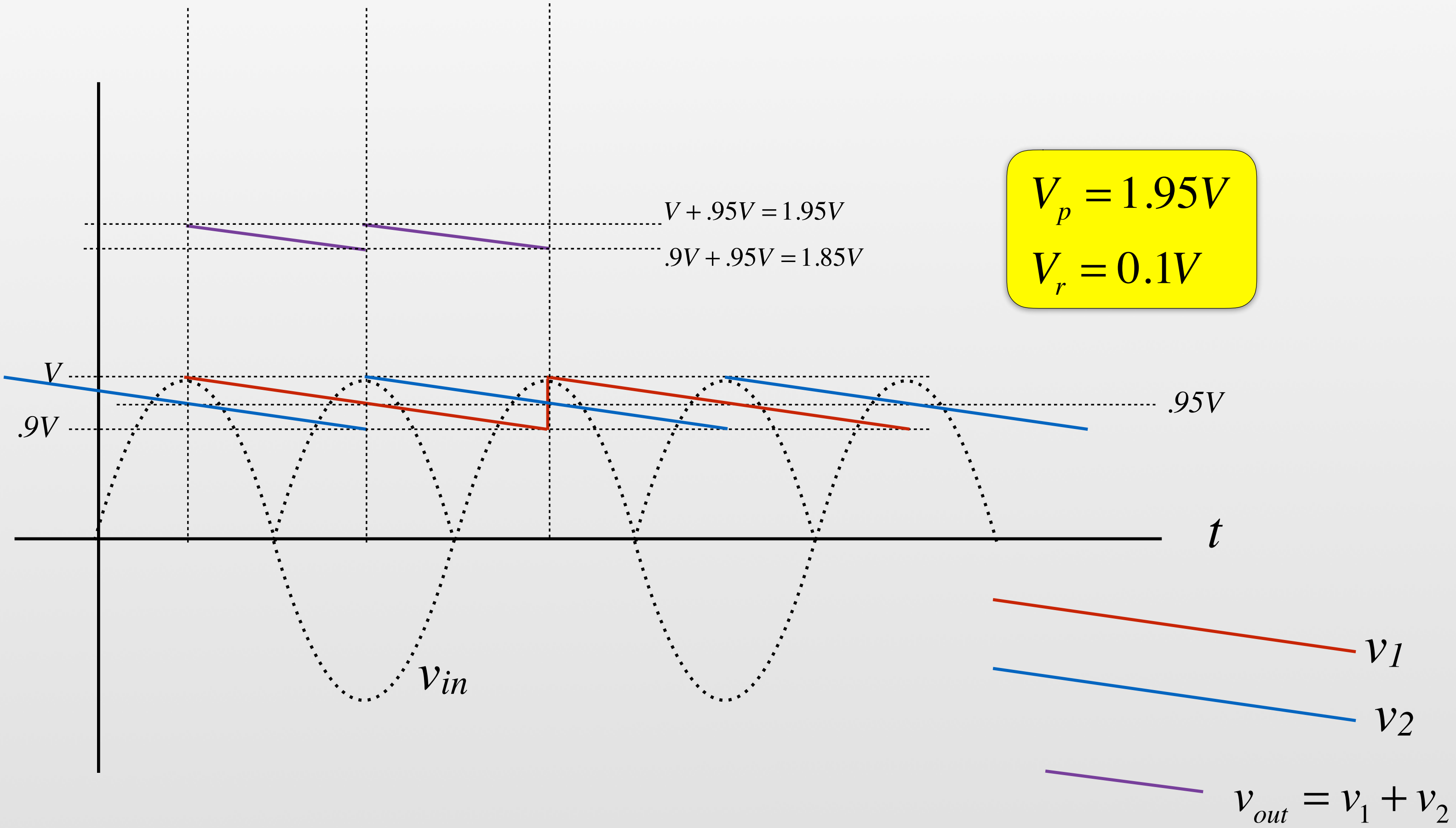
Example:

3. (a) For zero load current, the output of the voltage doubler is pure dc. What happens to the output when the load becomes appreciable? Sketch the input and output waveforms for a load resistance R_L connected across the output so that the decay time constant is about 10 times the input period. Give approximate expressions for the peak output voltage and the peak-to-peak ripple in this case. Ignore the voltage drop across the diodes.





$$V_{r2} = V_{r1} = \frac{VT}{\tau} = 0.1V$$

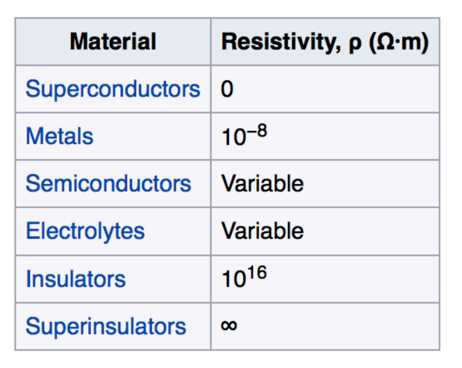


$$V_p = 1.95V$$

$$V_r = 0.1V$$

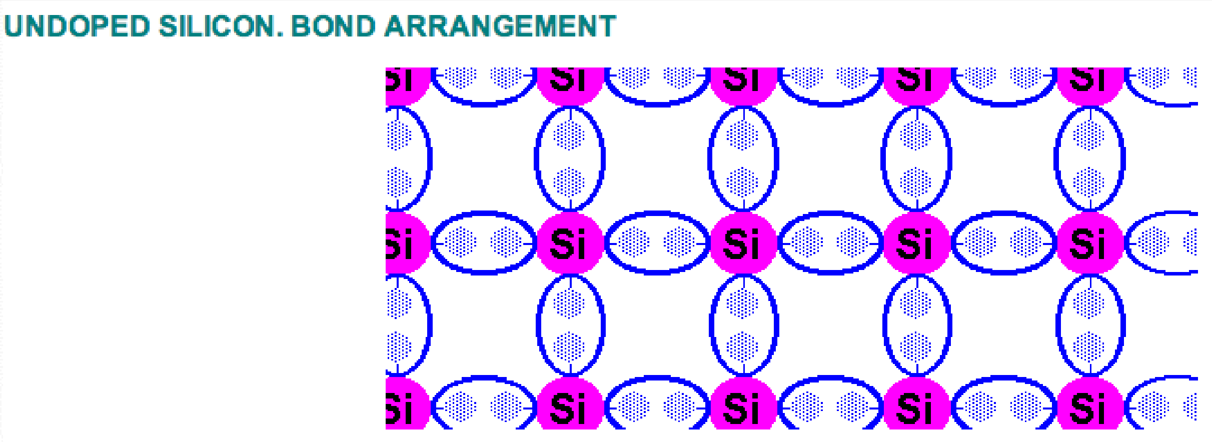
Part 2 - band theory

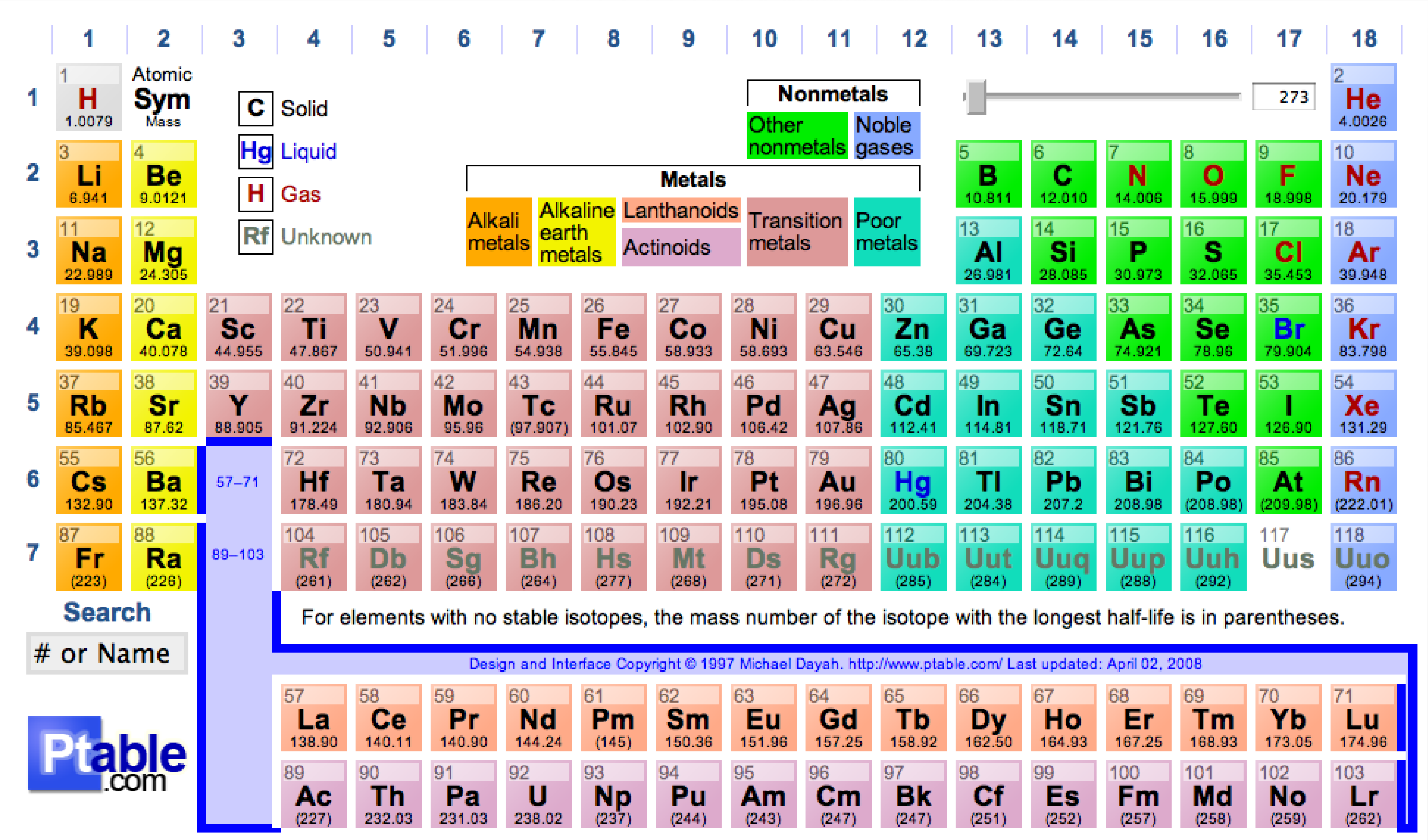
7) Semiconductors



Material	Resistivity, ρ (Ω·m)
Superconductors	0
Metals	10^{-8}
Semiconductors	Variable
Electrolytes	Variable
Insulators	10^{16}
Superinsulators	∞

- resistivity ~ 1 Ωm, decreases with temperature
- pure Si (or Ge, or GaAs): 4 valence electrons
- in crystal, all participate in covalent bond: no free charge carriers





	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.0079	Atomic Sym Mass																2 He 4.0026
2	3 Li 6.941	4 Be 9.0121											5 B 10.811	6 C 12.010	7 N 14.006	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.989	12 Mg 24.305											13 Al 26.981	14 Si 28.085	15 P 30.973	16 S 32.065	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.955	22 Ti 47.867	23 V 50.941	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.921	34 Se 78.96	35 Br 79.904	36 Kr 83.798
5	37 Rb 85.467	38 Sr 87.62	39 Y 88.905	40 Zr 91.224	41 Nb 92.906	42 Mo 95.96	43 Tc (97.907)	44 Ru 101.07	45 Rh 102.90	46 Pd 106.42	47 Ag 107.86	48 Cd 112.41	49 In 114.81	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.90	56 Ba 137.32	57–71	72 Hf 178.49	73 Ta 180.94	74 W 183.84	75 Re 186.20	76 Os 190.23	77 Ir 192.21	78 Pt 195.08	79 Au 196.96	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (208.98)	85 At (209.98)	86 Rn (222.01)
7	87 Fr (223)	88 Ra (226)	89–103	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Uub (285)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (292)	117 Uus	118 Uuo (294)
				57 La 138.90	58 Ce 140.11	59 Pr 140.90	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.25	69 Tm 168.93	70 Yb 173.05	71 Lu 174.96
				89 Ac (227)	90 Th 232.03	91 Pa 231.03	92 U 238.02	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)

C Solid
Hg Liquid
H Gas
Rf Unknown

Nonmetals
Other nonmetals
Noble gases

Metals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Poor metals

273

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Search
or Name

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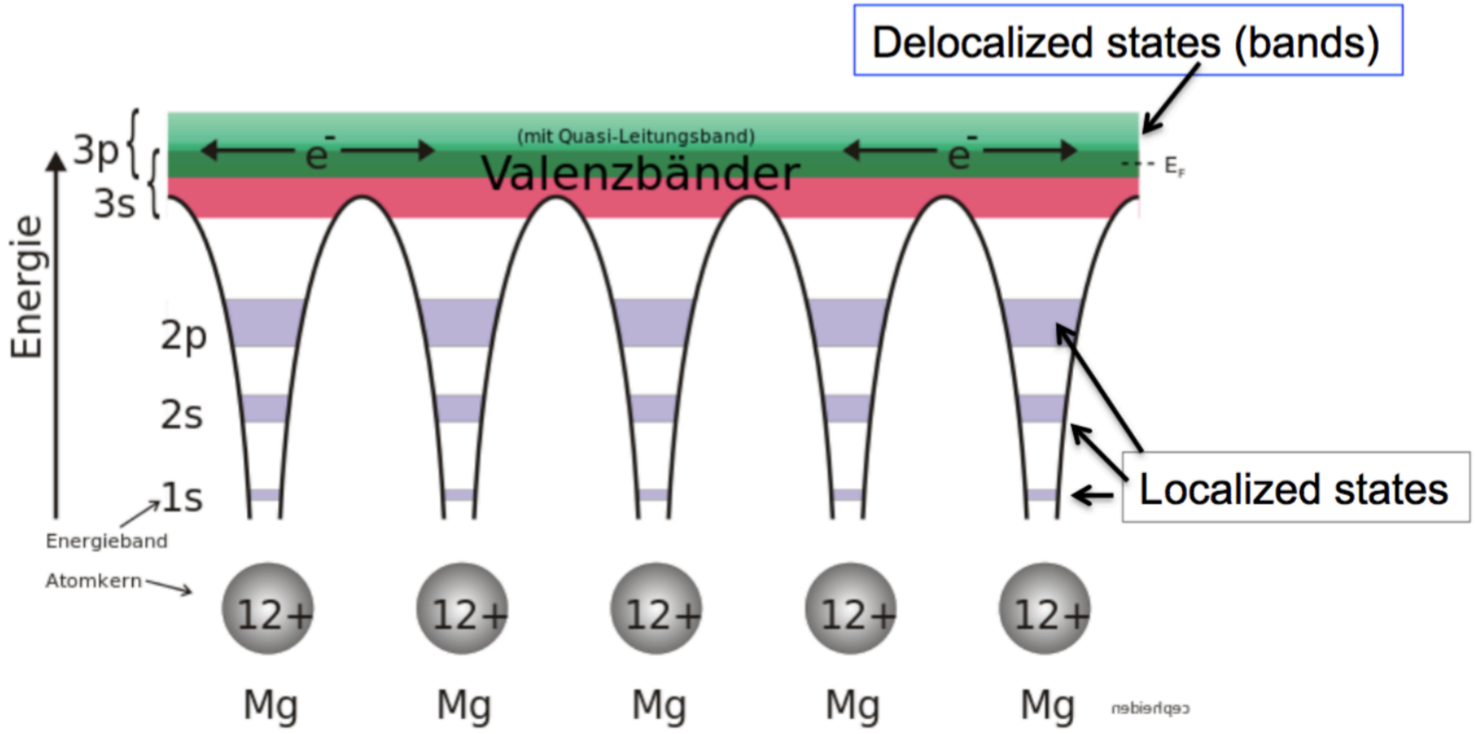
8) Energy bands

Key to understanding semiconductor devices: electron energy levels in a solid!

These are different from the discrete energy levels in an atom, because in a solid, the outermost electron wave functions overlap → formation of energy bands !



Delocalized states (bands)

Localized states

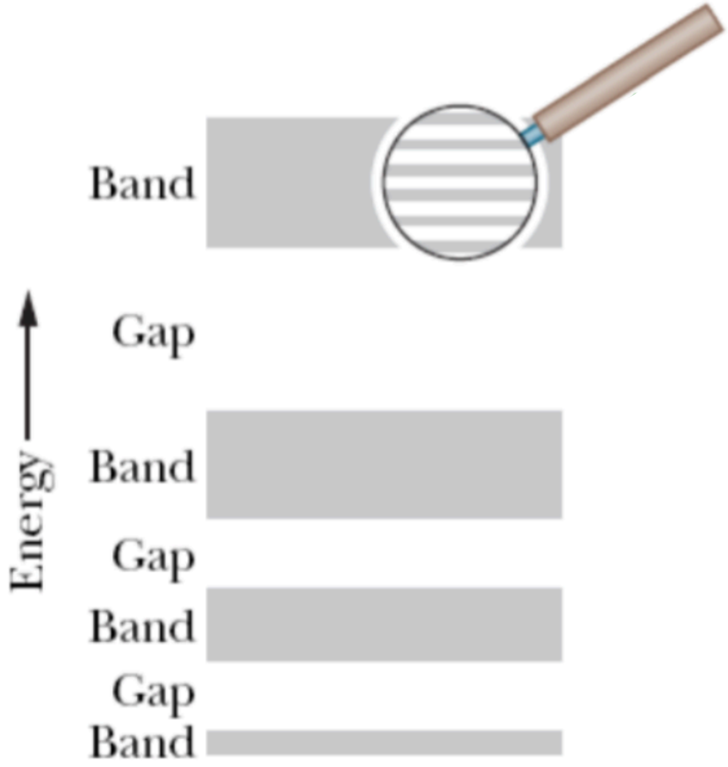
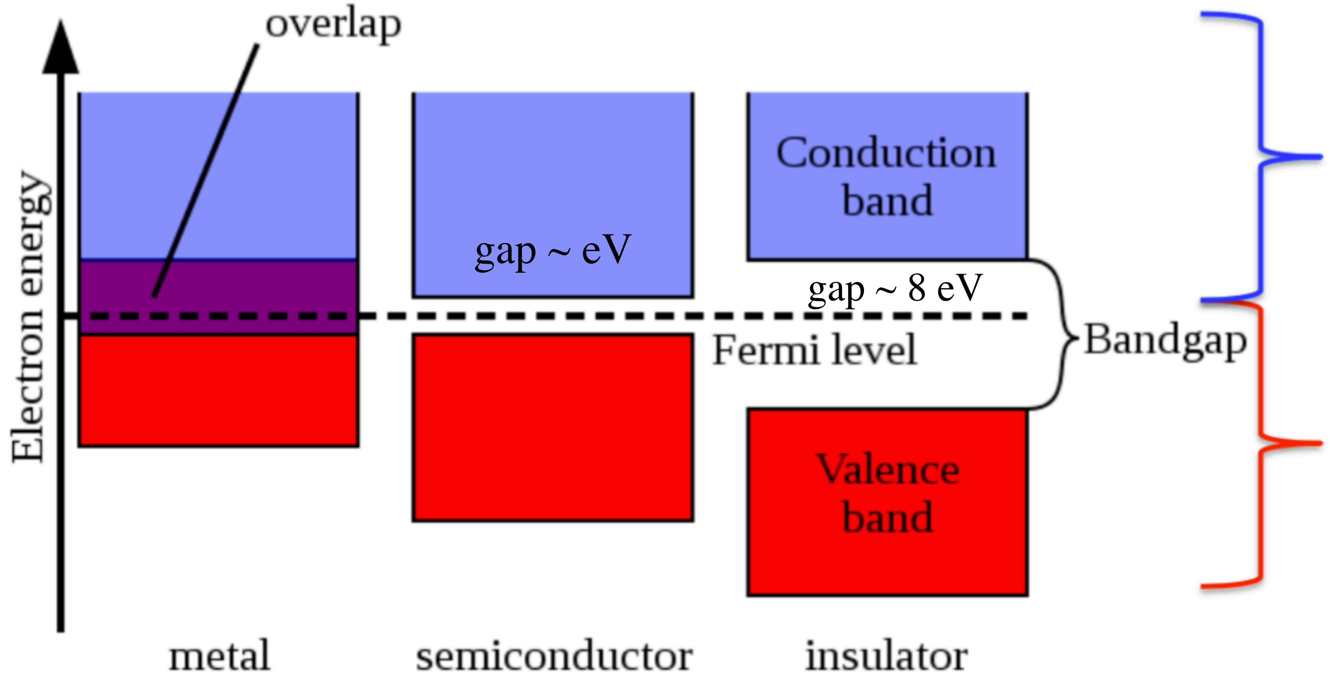


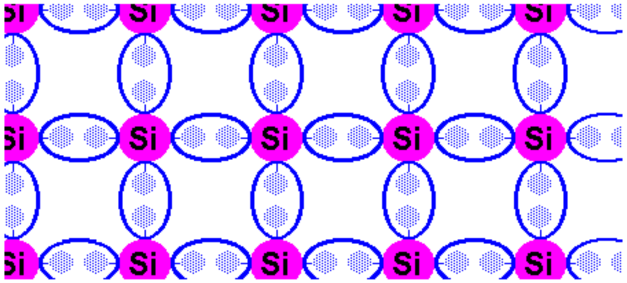
Fig. 41-3 The band–gap pattern of energy levels for an idealized crystalline solid. As the magnified view suggests, each band consists of a very large number of very closely spaced energy levels. (In many solids, adjacent bands may overlap; for clarity, we have not shown this condition.)



States available (higher energy)

States full, e- can't move

UNDOPED SILICON. BOND ARRANGEMENT



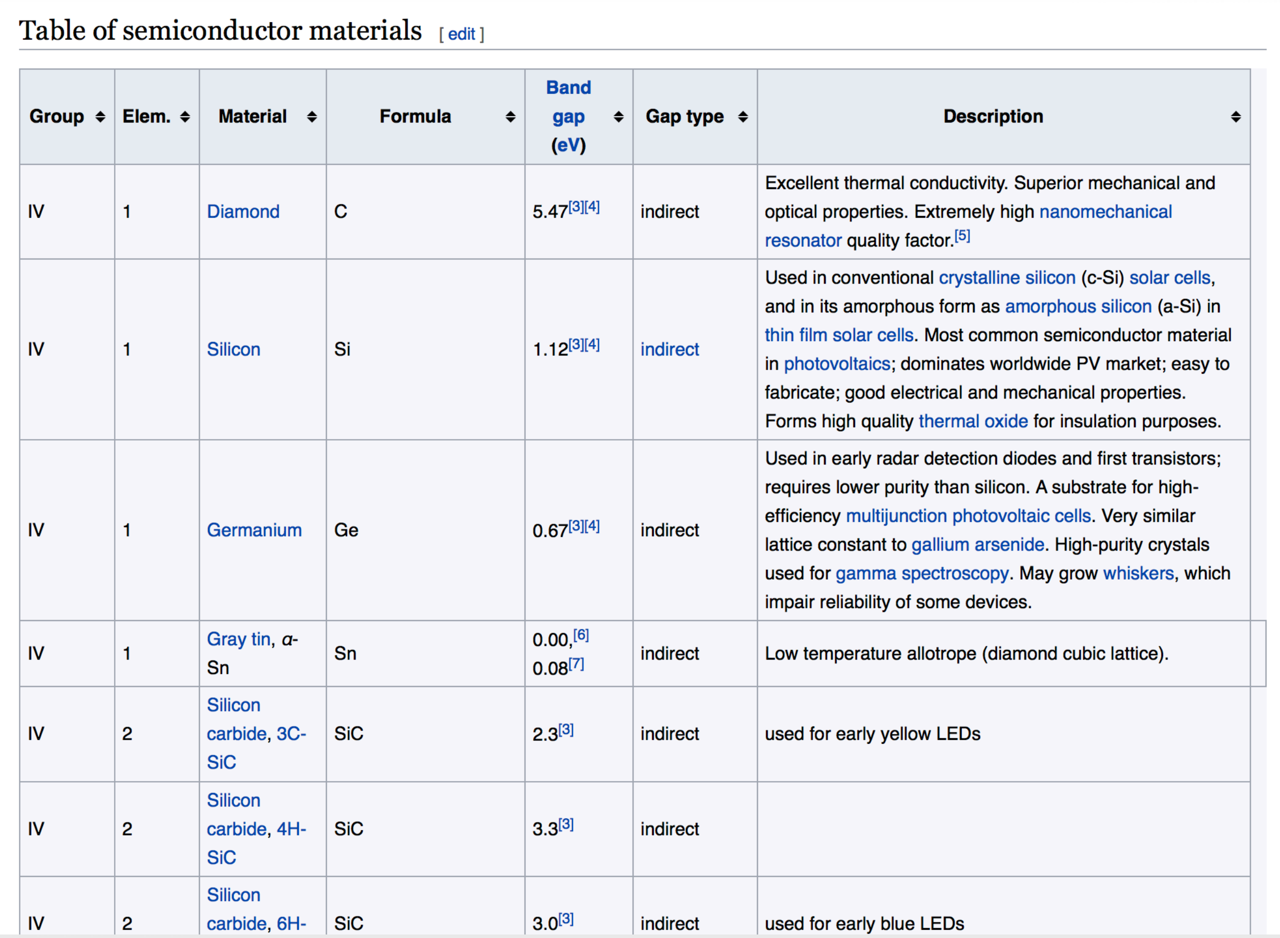
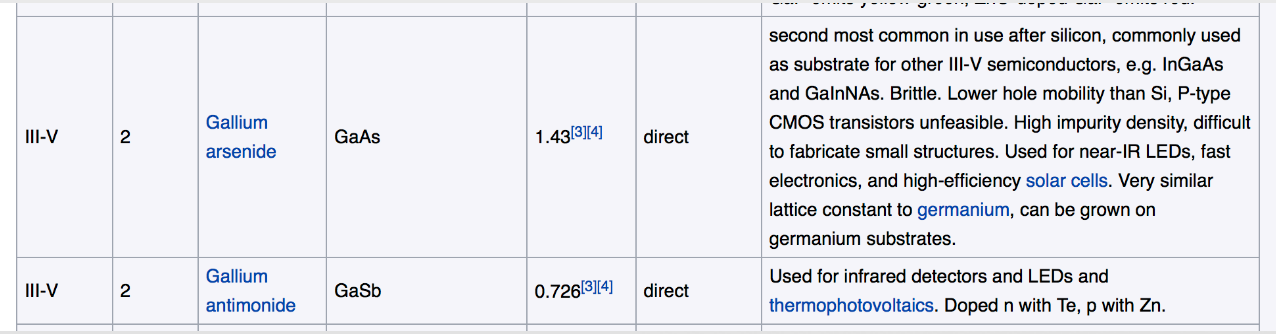


Table of semiconductor materials [edit]

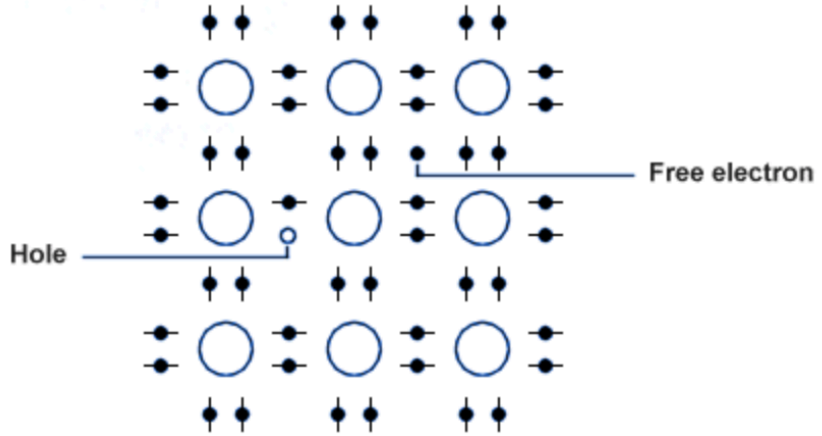
Group	Elem.	Material	Formula	Band gap (eV)	Gap type	Description
IV	1	Diamond	C	5.47[3][4]	indirect	Excellent thermal conductivity. Superior mechanical and optical properties. Extremely high nanomechanical resonator quality factor.[5]
IV	1	Silicon	Si	1.12[3][4]	indirect	Used in conventional crystalline silicon (c-Si) solar cells, and in its amorphous form as amorphous silicon (a-Si) in thin film solar cells. Most common semiconductor material in photovoltaics; dominates worldwide PV market; easy to fabricate; good electrical and mechanical properties. Forms high quality thermal oxide for insulation purposes.
IV	1	Germanium	Ge	0.67[3][4]	indirect	Used in early radar detection diodes and first transistors; requires lower purity than silicon. A substrate for high-efficiency multijunction photovoltaic cells. Very similar lattice constant to gallium arsenide. High-purity crystals used for gamma spectroscopy. May grow whiskers, which impair reliability of some devices.
IV	1	Gray tin, α-Sn	Sn	0.00,[6] 0.08[7]	indirect	Low temperature allotrope (diamond cubic lattice).
IV	2	Silicon carbide, 3C-SiC	SiC	2.3[3]	indirect	used for early yellow LEDs
IV	2	Silicon carbide, 4H-SiC	SiC	3.3[3]	indirect	
IV	2	Silicon carbide, 6H-	SiC	3.0[3]	indirect	used for early blue LEDs



Group	Elem.	Material	Formula	Band gap (eV)	Gap type	Description
III-V	2	Gallium arsenide	GaAs	1.43[3][4]	direct	second most common in use after silicon, commonly used as substrate for other III-V semiconductors, e.g. InGaAs and GaInNAs. Brittle. Lower hole mobility than Si, P-type CMOS transistors unfeasible. High impurity density, difficult to fabricate small structures. Used for near-IR LEDs, fast electronics, and high-efficiency solar cells. Very similar lattice constant to germanium, can be grown on germanium substrates.
III-V	2	Gallium antimonide	GaSb	0.726[3][4]	direct	Used for infrared detectors and LEDs and thermophotovoltaics. Doped n with Te, p with Zn.

9) Electrons and holes

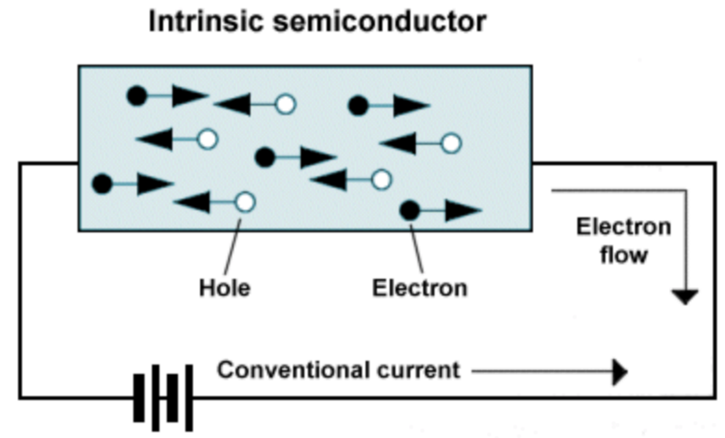
- At room temperature, a small number of electrons are promoted to the conduction band by thermal energy.



Silicon crystal lattice with free electron and hole

- This leaves a vacancy, called a hole; which can migrate.

- Both holes and electrons carry current; holes are less mobile.



Current flow in an intrinsic semiconductor

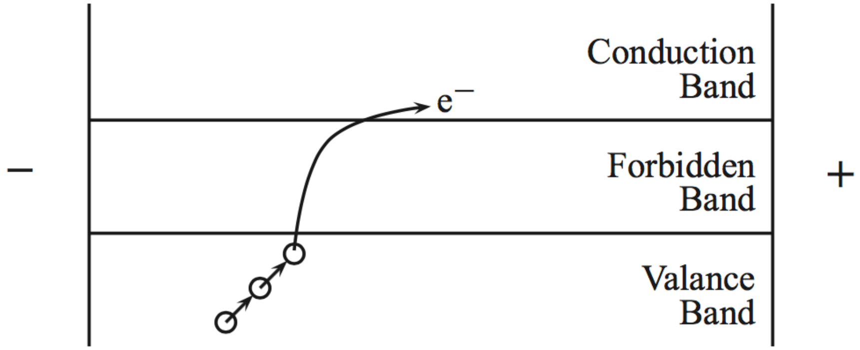
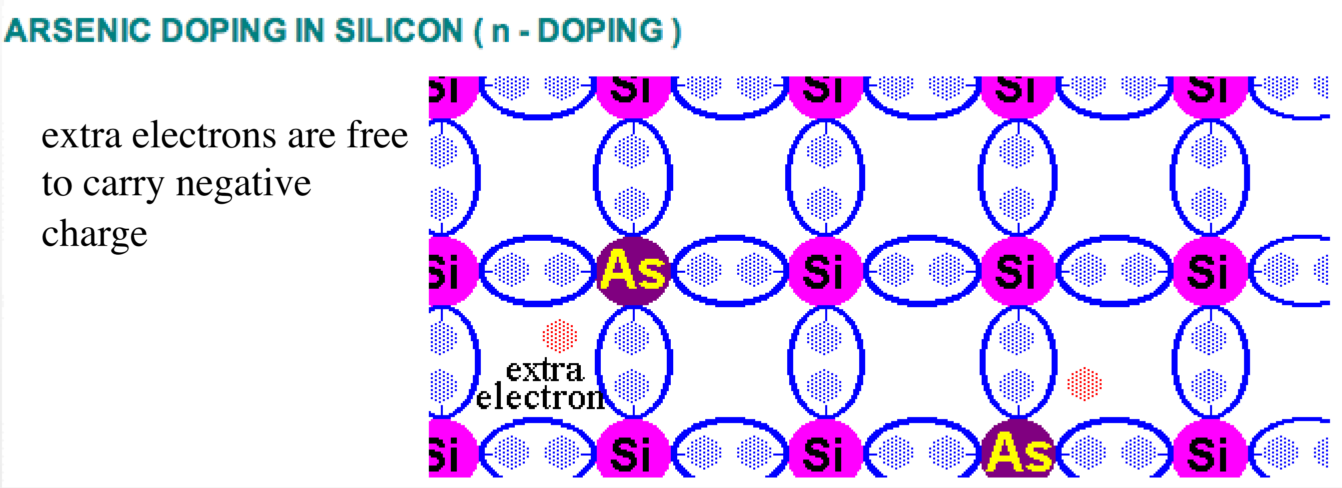


Figure 3.5 Schematic depiction of hole formation and transport when an electron is promoted.

10) Doping; extrinsic semi-conductors

- **n-type**: doped at ppb level with 5 valence-electron element (e.g. As)



ARSENIC DOPING IN SILICON (n - DOPING)

extra electrons are free to carry negative charge

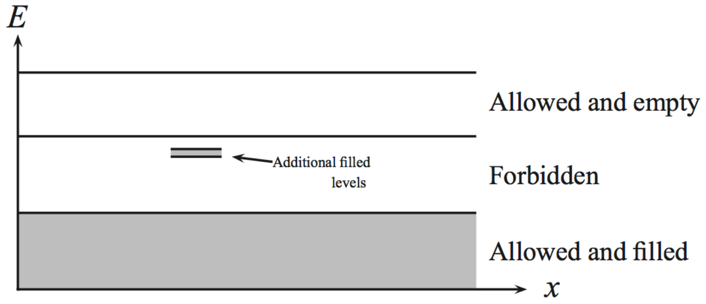


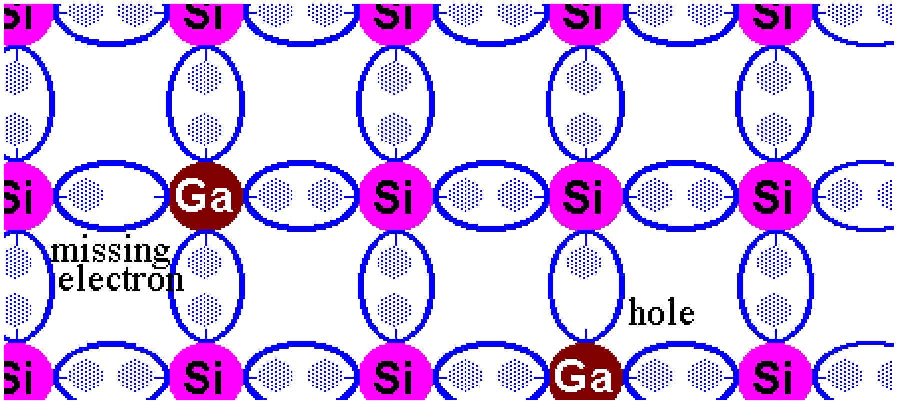
Figure 3.6 Schematic representation of an n-type semiconductor.

- negative electrons are majority charge carriers

- **p-type**: doped at ppb level with 3 valence-electron element (e.g. Ga)

GALLIUM DOPING IN SILICON (p - DOPING)

“holes” act as positive charge carriers



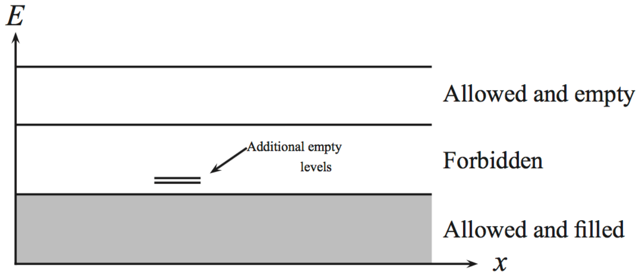


Figure 3.7 Schematic representation of a p-type semiconductor.

- positive holes are majority carriers

p and n type semiconductors are on average neutral, and conduct electricity

11) pn junction (2)

- electrons from n-type diffuse across to fill vacancies in the p-type
- forms a depletion region with E field; at eq’m diffusion stops

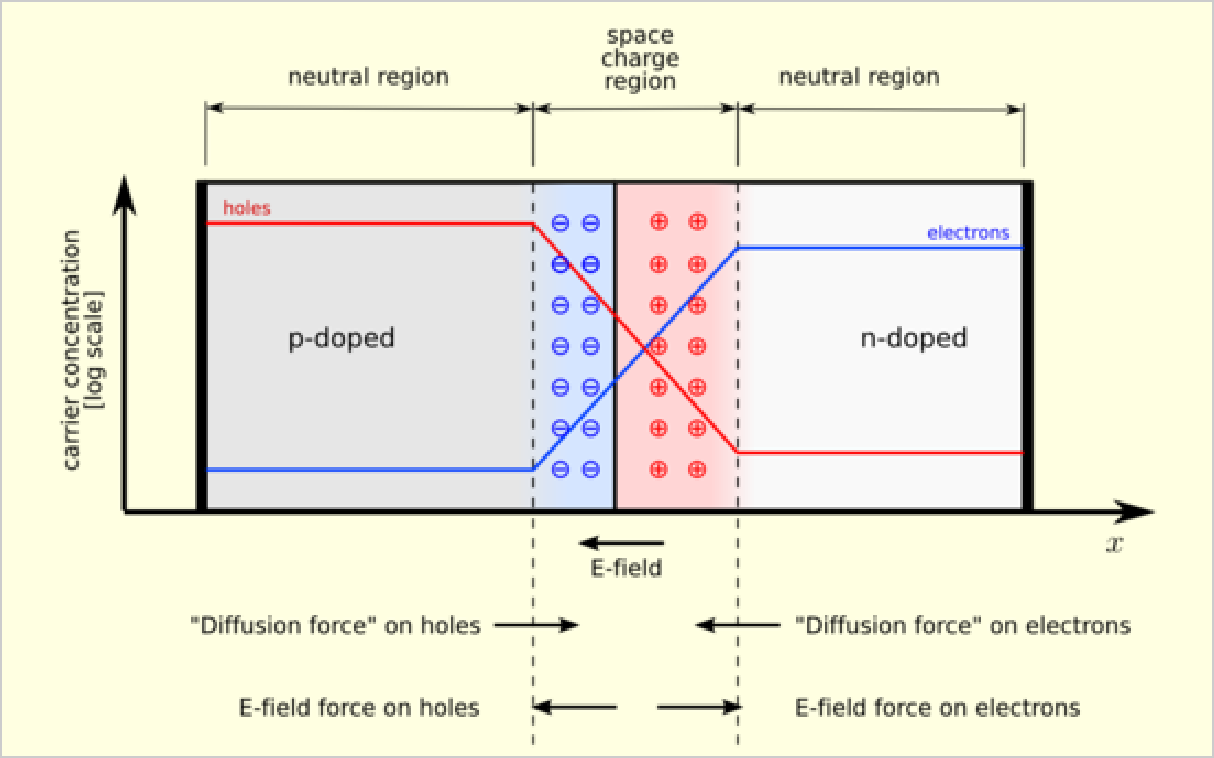
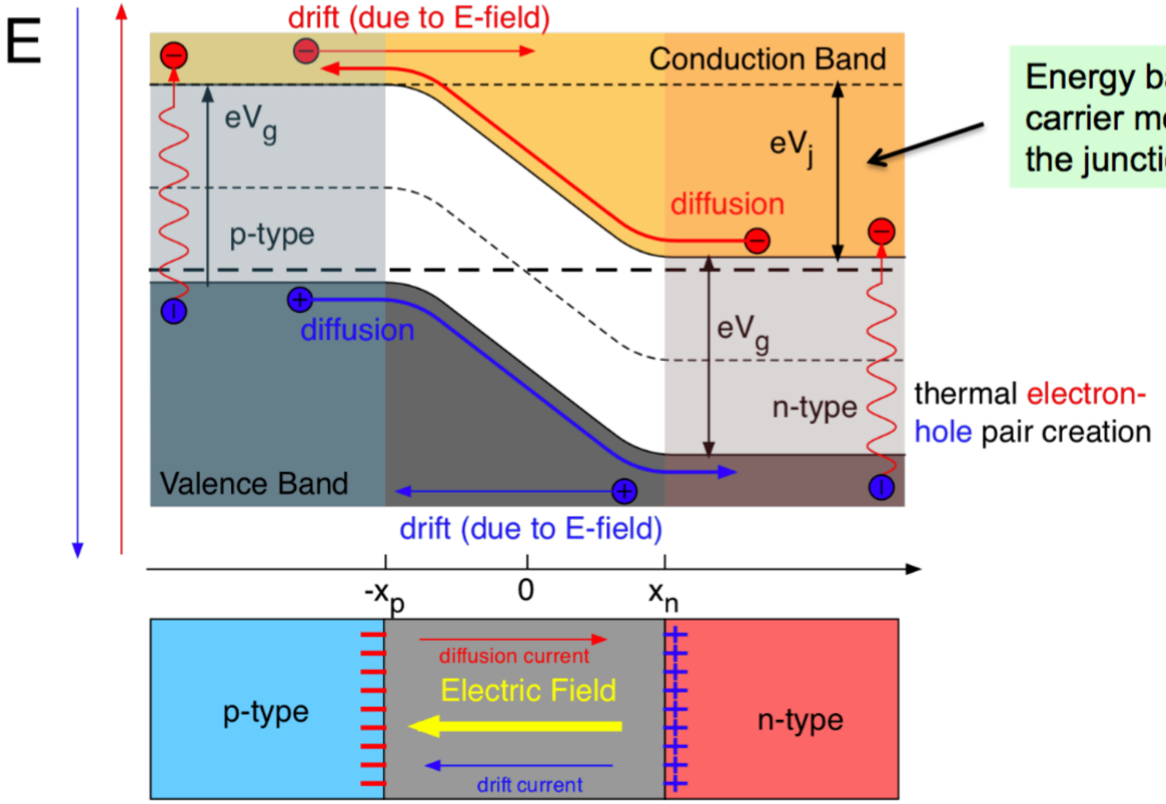


Figure A. A p-n junction in thermal equilibrium with zero bias voltage applied. Electrons and holes concentration are reported respectively with blue and red lines. Gray regions are charge neutral. Light red zone is positively charged. Light blue zone is negatively charged. The electric field is shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes.

Band diagram of pn junction



Energy barrier prevents carrier motion across the junction at zero bias

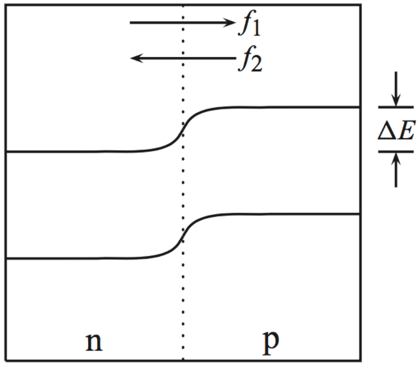


Figure 3.9 An unbiased p-n junction.

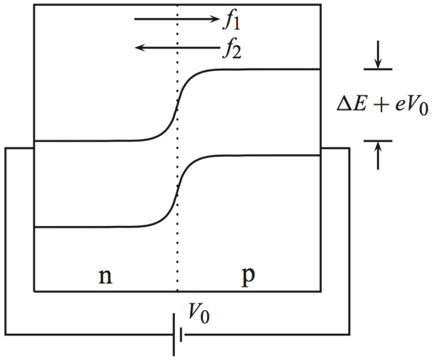


Figure 3.10 Reverse bias of the p-n junction.

small current due
to minority carriers

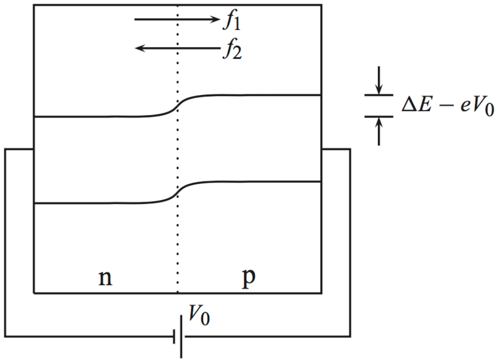


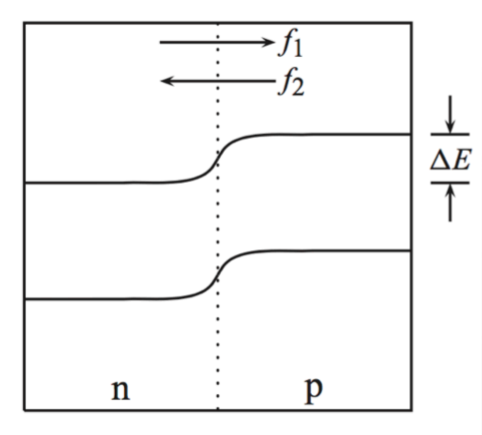
Figure 3.11 Forward bias of the p-n junction.

conducts when thermal
energy of electrons (holes)
exceeds barrier

Unbiased diode

Density of particles at energy *E*, at temp *T*:

$$F = Ae^{-E/kT}$$



Number of particles with energy > $E + \Delta E$

$$N = A\int_{E_0+\Delta E}^{\infty} \mathrm{e}^{-E/kT}\,\mathrm{d}E = -AkT\left(\mathrm{e}^{-\infty} - \mathrm{e}^{-(E_0+\Delta E)/kT}\right) = AkT\mathrm{e}^{-E_0}\mathrm{e}^{-\Delta E/kT}$$

Electron flow is proportional to N (and are equal with no bias):

$$f_1 = C\mathrm{e}^{-\Delta E/kT}$$

$$f_2 = C\mathrm{e}^{-\Delta E/kT}$$

Biased diode

Applying a bias only affects f_1.

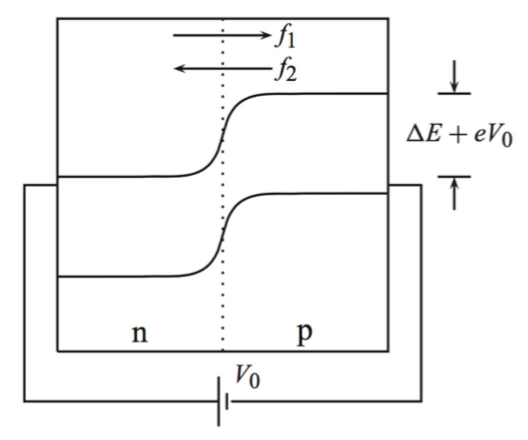
Taking $V_d > 0$ for forward bias:

$$f_1 = Ce^{-(\Delta E - eV_d)/kT}$$

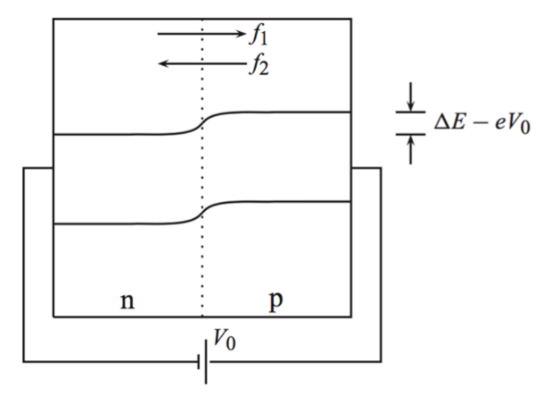
so,

$$f_{net} = f_1 - f_2 = Ce^{-\Delta E/kT}\left(e^{eV_d/kT} - 1\right)$$

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

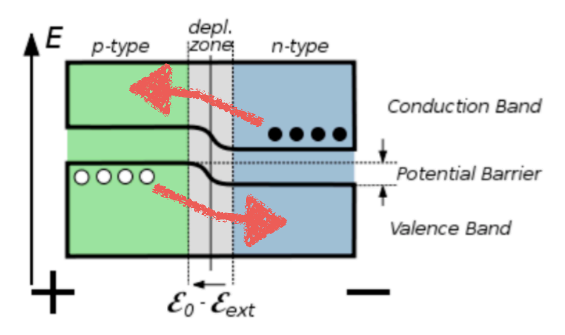


$V_d = -V_0$



$V_d = V_0$

Minority carrier injection:



A fwd biased diode, injects electrons into p-type, and holes into n-type.

12) Breakdown, Zener diodes

For high doping, depletion region is small and electric field is large.

High reverse bias can cause two breakdown phenomena:

1. **Avalanche breakdown.** Electrons from the p-side gain high energy and ionize other atoms in the depletion layer, producing a new electron-hole pair. The new electron produces more pairs and so on.
2. **Zener breakdown.** The electric field in the depletion layer directly produces ionization.

When breakdown occurs, current increase is nearly vertical.

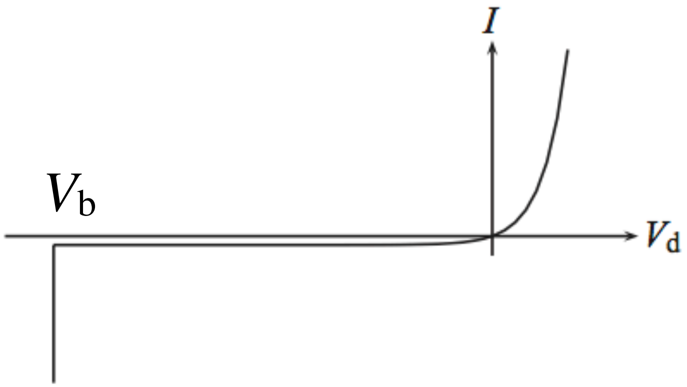


Figure 3.14 Diode *I*–*V* characteristic showing breakdown at large reverse bias.

Zener diode symbol

13) Zener diode regulator

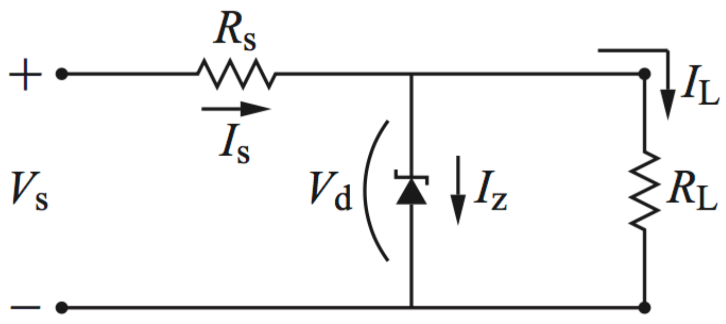
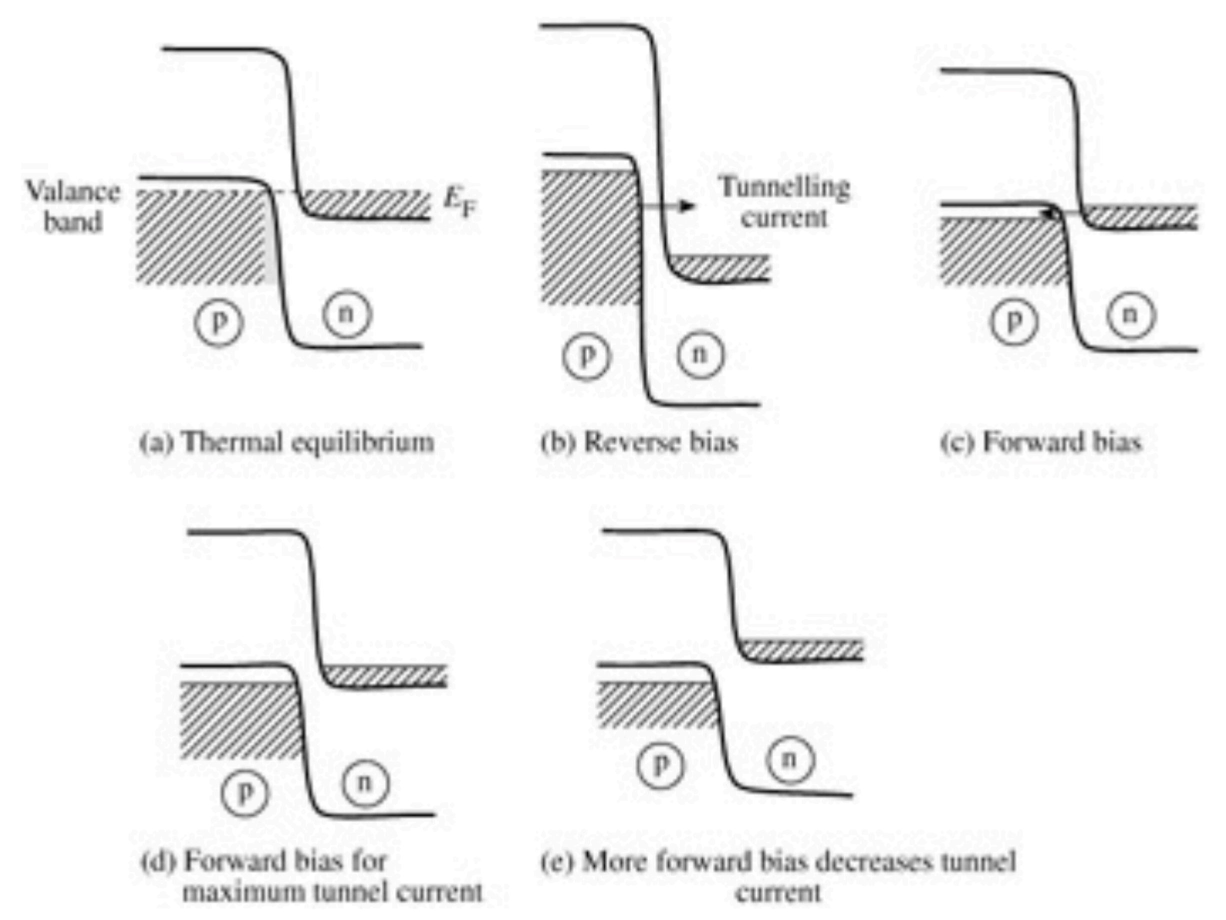


Figure 3.38 Zener diode circuit.

- If $\left(\frac{R_L}{R_s + R_L}\right) V_s > V_b$ output voltage is V_b
- The zener must be able to handle $(V_s - V_b)/R_s$
- dynamic resistance about 1 Ω if breakdown is exceeded.

14) Tunnel diode

Highly doped pn junction ==> narrow depletion region
(10 - 100 atomic dimensions)



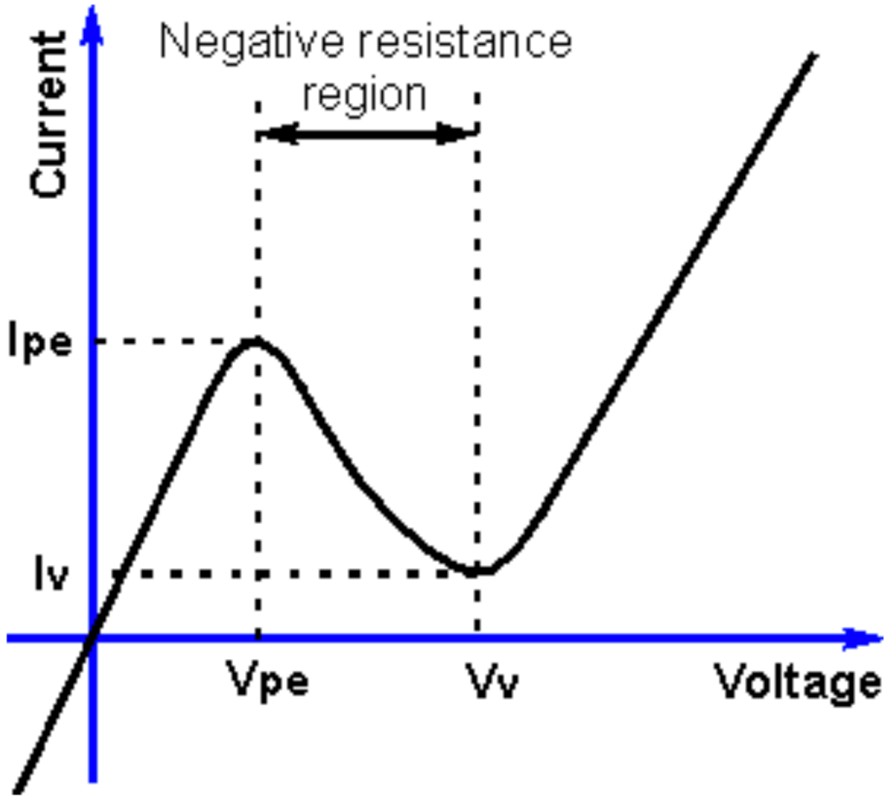
(a) Thermal equilibrium

(b) Reverse bias

(c) Forward bias

(d) Forward bias for maximum tunnel current

(e) More forward bias decreases tunnel current



Tunnel diode IV characteristic

- *narrow depletion region —>fast response*
- *negative differential resistance*
  - high frequency oscillator (microwave range)
  - amplifier

15) Silicone controlled rectifier (SCR)

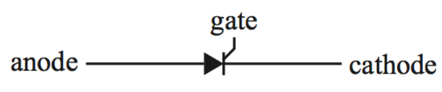


Figure 3.44 Electronic symbol for an SCR.

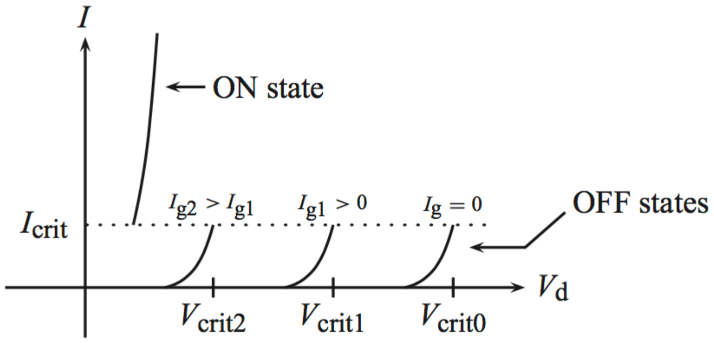


Figure 3.45 *I–V* characteristics for the SCR.

Light dimmer, etc

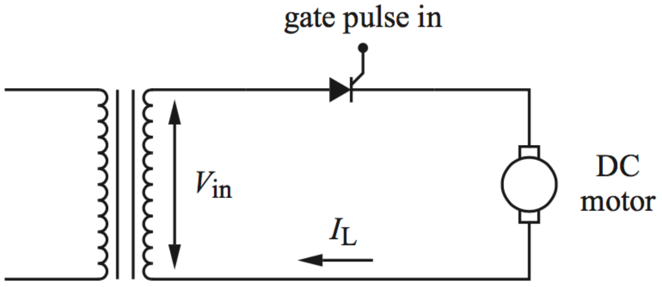


Figure 3.47 DC motor speed control.

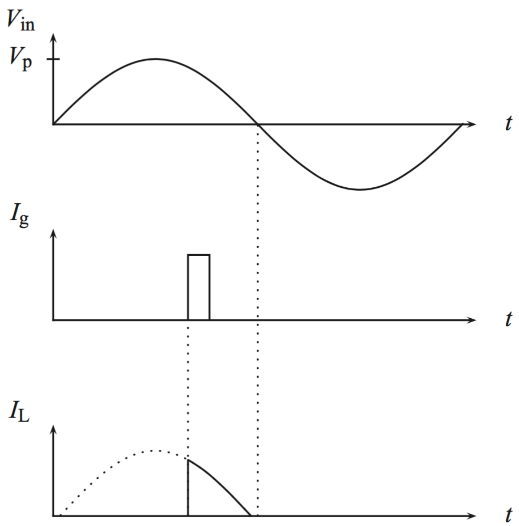
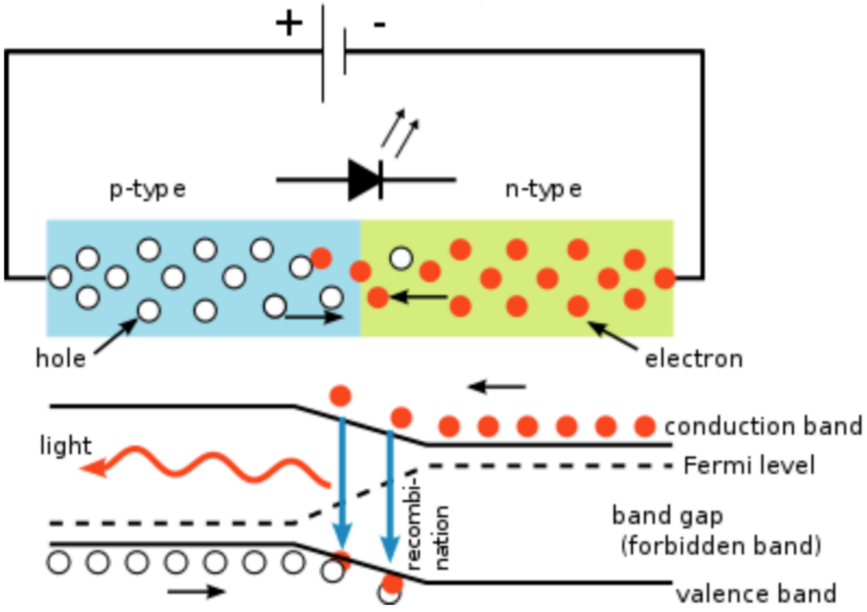


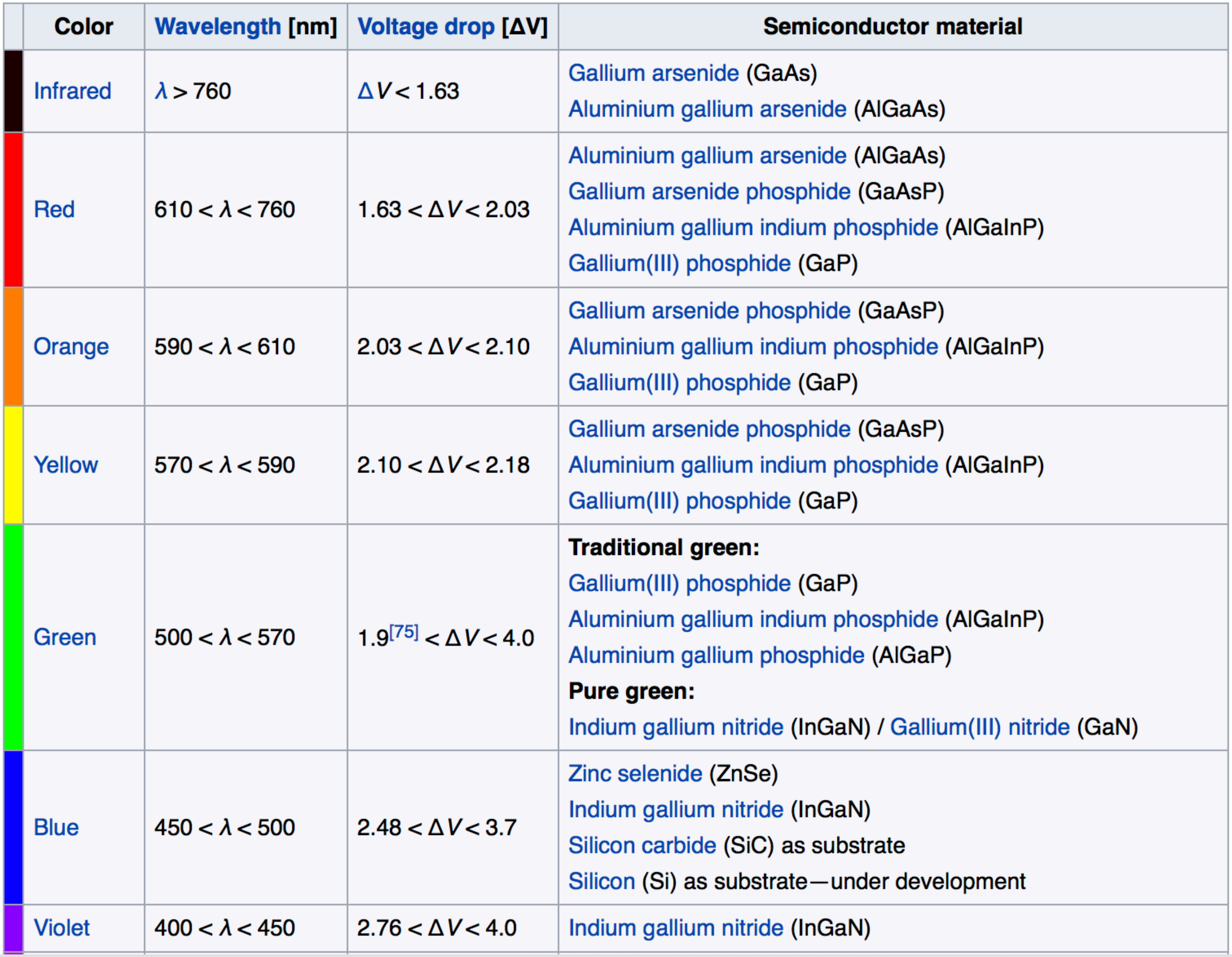
Figure 3.48 DC motor speed control waveforms. For comparison, the dotted line for I_L shows the waveform for an ordinary diode.

16) Photon emission and absorption

Light Emitting Diode

- Under forward bias, diode “on”, energy levels line up
- Assume the band gap is equal to eV_t → color of light indicates this!





	Color	Wavelength [nm]	Voltage drop [ΔV]	Semiconductor material
⬛	Infrared	$\lambda > 760$	$\Delta V < 1.63$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
🟥	Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟧	Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟨	Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟩	Green	$500 < \lambda < 570$	1.9[75] $< \Delta V < 4.0$	**Traditional green:** Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP) **Pure green:** Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)
🟦	Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate—under development
🟪	Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)

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Swedish (pdf)

Press Release

7 October 2014

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2014 to

Isamu Akasaki
Meijo University, Nagoya, Japan and Nagoya University, Japan

Hiroshi Amano
Nagoya University, Japan

and

Shuji Nakamura
University of California, Santa Barbara, CA, USA

"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

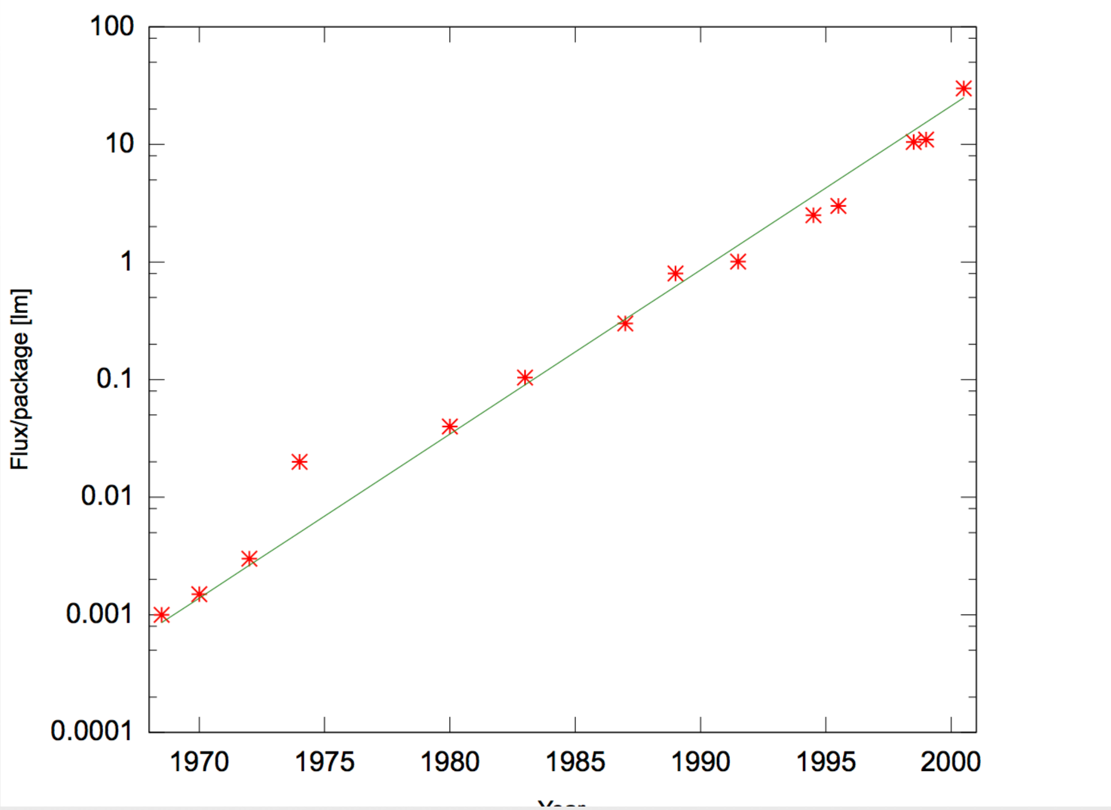
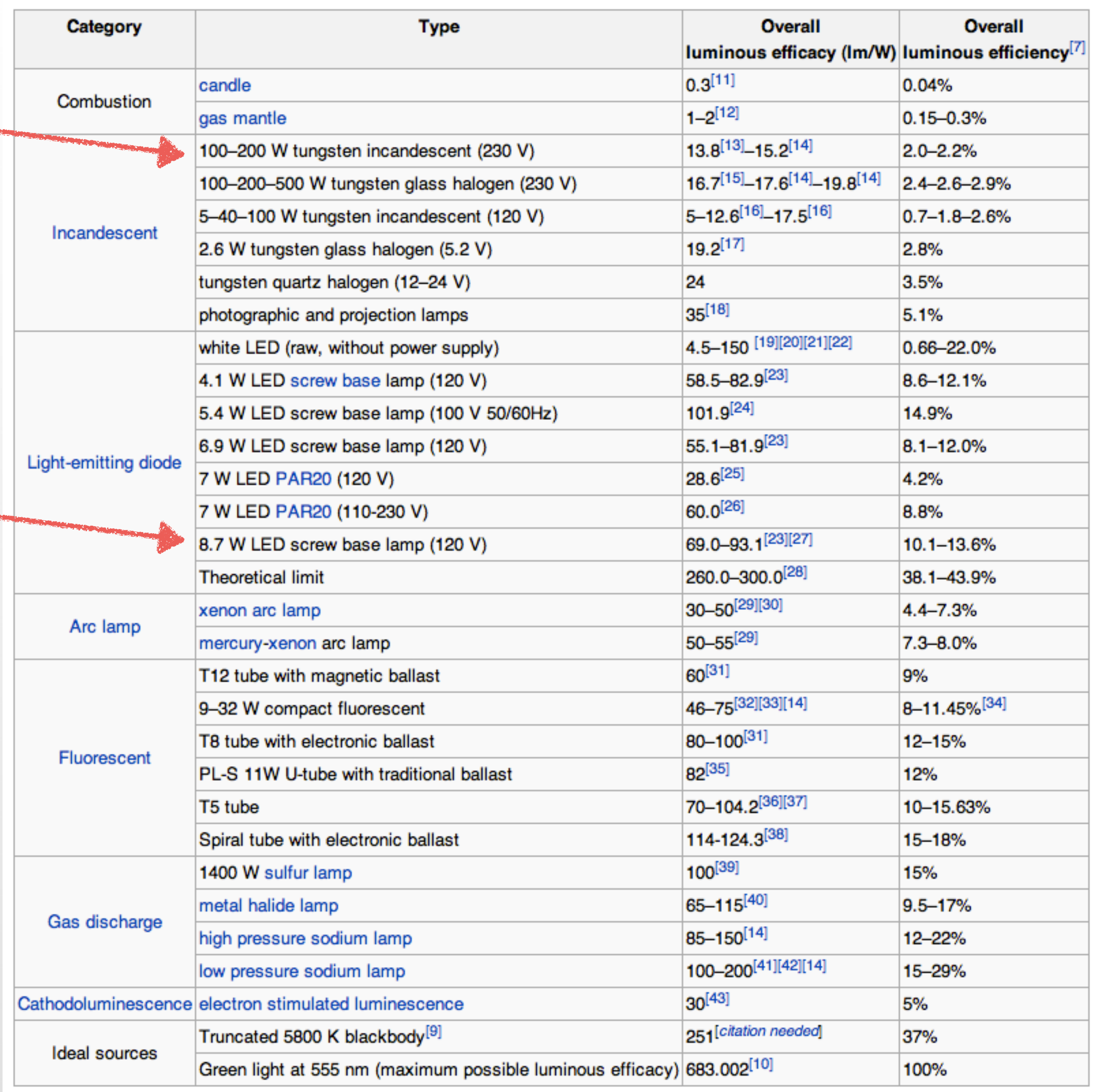


Illustration of Haitz's law, showing improvement in light output per LED over time, with a logarithmic scale on the vertical axis

1500 lm

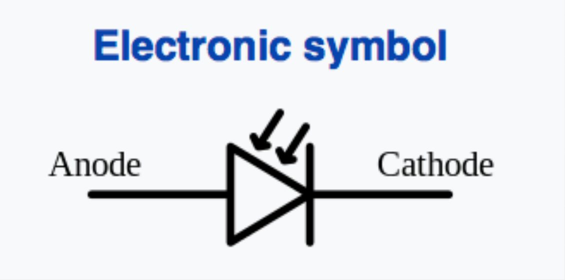
800 lm



Category	Type	Overall luminous efficacy (lm/W)	Overall luminous efficiency[7]
Combustion	candle	0.3[11]	0.04%
	gas mantle	1–2[12]	0.15–0.3%
Incandescent	100–200 W tungsten incandescent (230 V)	13.8[13]–15.2[14]	2.0–2.2%
	100–200–500 W tungsten glass halogen (230 V)	16.7[15]–17.6[14]–19.8[14]	2.4–2.6–2.9%
	5–40–100 W tungsten incandescent (120 V)	5–12.6[16]–17.5[16]	0.7–1.8–2.6%
	2.6 W tungsten glass halogen (5.2 V)	19.2[17]	2.8%
	tungsten quartz halogen (12–24 V)	24	3.5%
	photographic and projection lamps	35[18]	5.1%
Light-emitting diode	white LED (raw, without power supply)	4.5–150 [19][20][21][22]	0.66–22.0%
	4.1 W LED screw base lamp (120 V)	58.5–82.9[23]	8.6–12.1%
	5.4 W LED screw base lamp (100 V 50/60Hz)	101.9[24]	14.9%
	6.9 W LED screw base lamp (120 V)	55.1–81.9[23]	8.1–12.0%
	7 W LED PAR20 (120 V)	28.6[25]	4.2%
	7 W LED PAR20 (110-230 V)	60.0[26]	8.8%
	8.7 W LED screw base lamp (120 V)	69.0–93.1[23][27]	10.1–13.6%
	Theoretical limit	260.0–300.0[28]	38.1–43.9%
Arc lamp	xenon arc lamp	30–50[29][30]	4.4–7.3%
	mercury-xenon arc lamp	50–55[29]	7.3–8.0%
Fluorescent	T12 tube with magnetic ballast	60[31]	9%
	9–32 W compact fluorescent	46–75[32][33][14]	8–11.45%[34]
	T8 tube with electronic ballast	80–100[31]	12–15%
	PL-S 11W U-tube with traditional ballast	82[35]	12%
	T5 tube	70–104.2[36][37]	10–15.63%
	Spiral tube with electronic ballast	114-124.3[38]	15–18%
Gas discharge	1400 W sulfur lamp	100[39]	15%
	metal halide lamp	65–115[40]	9.5–17%
	high pressure sodium lamp	85–150[14]	12–22%
	low pressure sodium lamp	100–200[41][42][14]	15–29%
Cathodoluminescence	electron stimulated luminescence	30[43]	5%
Ideal sources	Truncated 5800 K blackbody[9]	251[*citation needed*]	37%
	Green light at 555 nm (maximum possible luminous efficacy)	683.002[10]	100%

Photodiode

Light produces electron-hole pair, which produces current if near enough to the depletion region



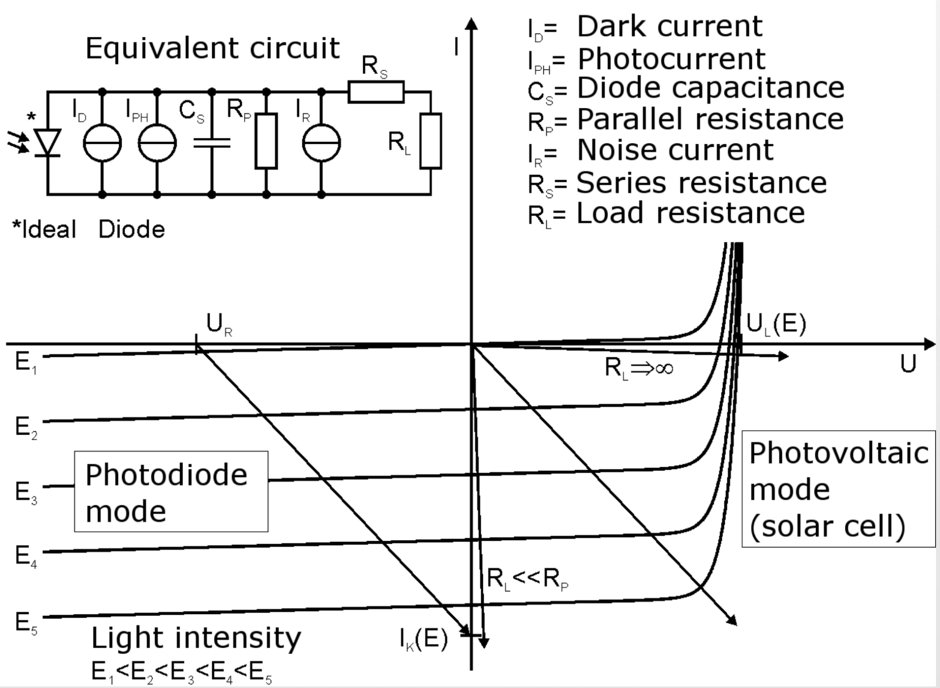
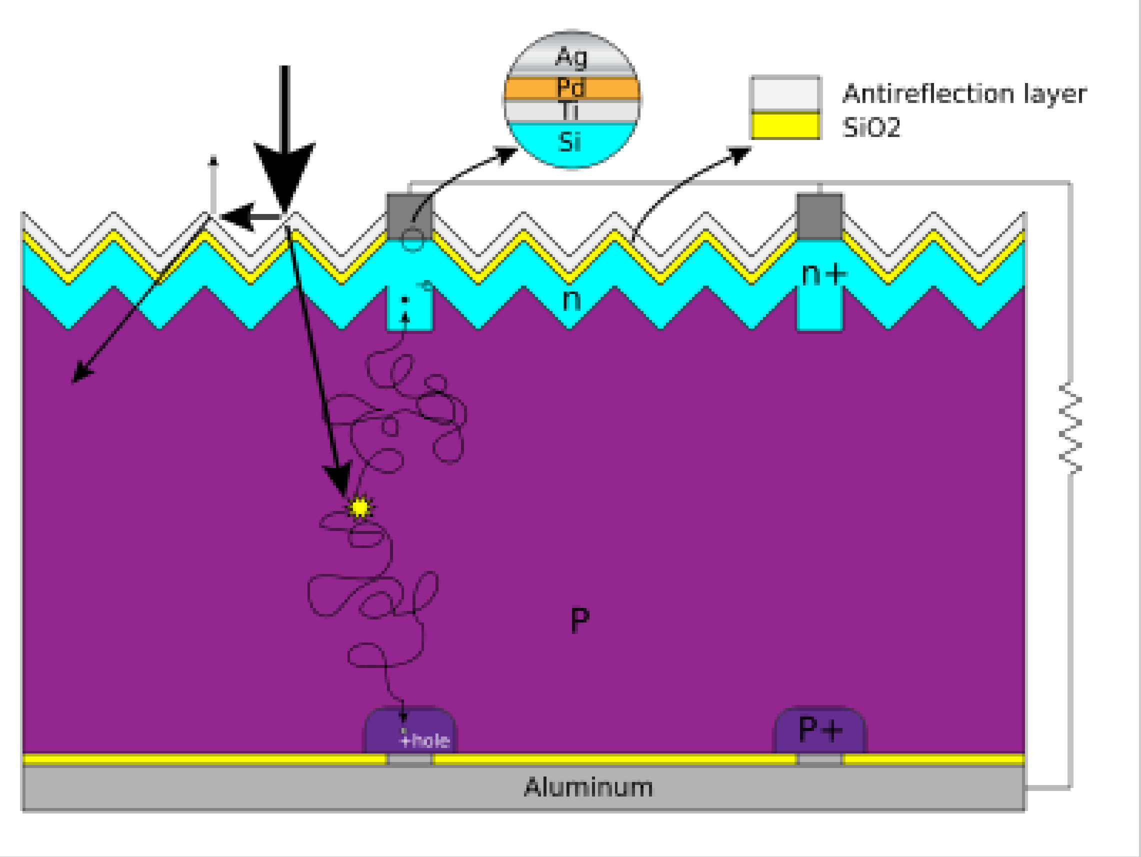


photo-voltaics

- photon excites electron to conduction band (photoelectric effect)
- E-field in depletion region separates charge, produces electricity



Basic structure of a silicon based solar cell and its working mechanism.