Introduction to Principles of Circuits

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Introduction

- The course focuses on the analog and digital components of electronic circuits which can be used in control systems area.



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Analog electronic circuits Lections 1-7; Practice 1-4; Labs 1-3		Digital electronic circuits Lections 8; Practice 5; Labs 4	

Course structure

Main course topics:

- Semiconductor materials;
- Components of analog electronics (diode, transistors (BJT and FET));
- Components of digital electronics (logic elements, flip-flops, encoders, decoders multiplexers, registers, counters);
- Operational amplifiers;
- Active filter;
- Simple analog and digital circuits design.

Course structure

- In our course you will have:

- Lecture part – 9(10);
- Practice part – 5;
- Laboratory part – 4;
- Control tests – 4;
- Final written test.

Course content (Week 1)

№	Class Type	Topic	Date		Score: +-min/+max
			AT	CS	
1	**Lecture 1**	Introduction in Principles of Circuits. Semiconductor materials and devices	**21.10.2024**	**21.10.2024**	Attendance: Min:+1/ Max:+2;
2	**Lecture 2**	Transistor circuits basics (BJT transistors, FET transistors, MOSFET transistors)	**21.10.2024**	**21.10.2024**	Attendance: Min:+1/ Max:+2;
3	**Lab 1**	Simple semiconductor device circuits design and simulation	**22.10.2024**	**22.10.2024**	Min:+1/ Max:+2;
4	**Practice 1 (task)**	Simple semiconductor device circuits design			Min:+1/ Max:+2;
5	**Lecture 3.1**	BJT, JFETs, MOSFET amplifier configurations	**25.10.2024**	**25.10.2024**	Attendance: Min:+1/ Max:+2;
6	**Lecture 3.2**		**25.10.2024**	**25.10.2024**	Attendance: Min:+1/ Max:+2;

Week 2

№	Class Type	Topic	Date AT	Date CS	Score: +-min/+max
7	Practice 2 (task)	BJT, JFETs, MOSFET amplifier configuration	28.10.2024	28.10.2024	Min:+1/ Max:+2
8	Control test 1	Semiconductor materials and devices. BJT, JFETs, MOSFET amplifier configuration (Comprehension check/theory control test)			Min:+6/ Max:+10;
9	Lecture 4	Operational amplifiers: ideal operational amplifier and its characteristics	29.10.2024	29.10.2024	Attendance: Min:+1/ Max:+2;
9	Lecture 5	Operational amplifiers circuits design basics	29.10.2024	29.10.2024	Attendance: Min:+1/ Max:+2;
11	Lab 2	Operational amplifiers circuits design and simulation	30.10.2024	29.10.2024	Min:+1/ Max:+2;
12	Practice 3 (task)	Operational amplifiers circuits design	31.10.2024	30.10.2024	Min:+1/ Max:+2;
13	Control test 2	Operational amplifiers: ideal operational amplifier and its characteristics. Operational amplifiers circuits design basics (Comprehension check/theory control test)			Min:+6/ Max:+10;
14	Lecture 6	Filter theory introduction	01.11.2024	01.11.2024	Attendance: Min:+1/ Max:+2;
15	Lecture 7	Active filter circuits design	01.11.2024	01.11.2024	Attendance: Min:+1/ Max:+2;

Week 3

№	Class Type	Topic	Date		Score: +-min/+max
			AT	CS	
16	Lab 3	Active filter circuits design and simulation	04.11.2024	04.11.2024	Min:+1/ Max:+3;
17	Practice 4 (task)	Active filter circuits design	06.11.2024	06.11.2024	Min:+1/ Max:+2;
18	Control test 3	Filter theory introduction. Active filter circuits design. (Comprehension check)			Min:+6/ Max:+10;

Week 4-6

Week	№	Class Type	Topic	Date AT	Date CS	Score: +-min/+max
4	19	Lecture 8	Digital circuits design basics. Transistor switch logic families (DTL, TTL, ESL, MOSFET)	15.11.2024	15.11.2024	Attendance: Min:+1/ Max:+2;
5	20	Lecture 9	Digital circuits design basics. Flip-flops (SR, D, JK), Decoders, Decoders Multiplexers, Registers, Counters	19.11.2024	19.11.2024	Attendance: Min:+1/ Max:+2;
	21	Lab 4	Simple digital circuits design and simulation	18.11.2024	21.11.2024	Min:+1/ Max:+3;
	22	Practice 5 (task)	Simple digital circuits design	20.11.2024	22.11.2024	Min:+1/ Max:+2
	23	Control test 4	Digital circuits design basics. Transistor switch logic families (DTL, TTL, ESL, MOSFET). Flip-flops (SR, D, JK), Decoders, Decoders Multiplexers, Registers, Counters (Comprehension check)			Min:+6/ Max:+10;
6	24	Final test	Consultation Final written test	25.11.2024	26.11.2024	Min:+12/ Max:+20;

Semiconductor materials and devices

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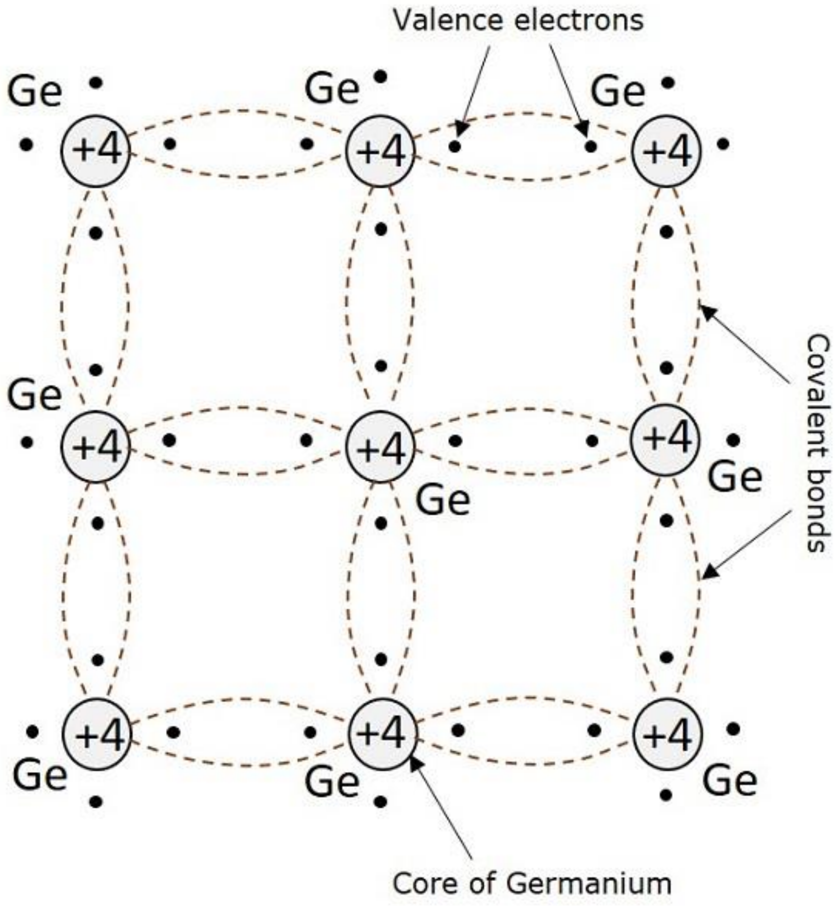
Semiconductor materials

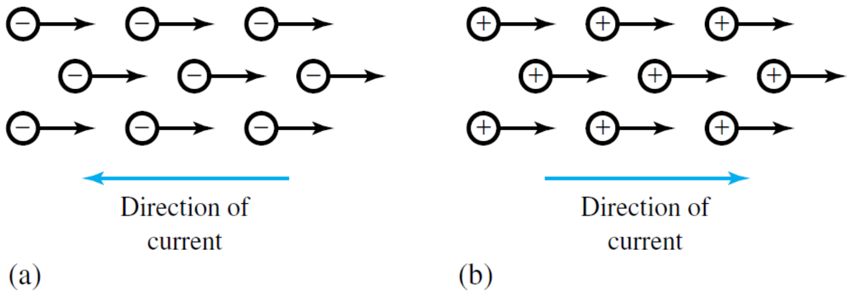
- resistivity
  - insulators
  - Semiconductor
  - conductors

- Semiconductor
  - Intrinsic
    Or
    Pure Semiconductor
  - Extrinsic
    Or
    unpure Semiconductor
    - p-type
    - n-type

IV grope: Si, Ge, C, SiGe
III-V grope: GaAs, InP, GaN
etc

Doping by elements
>V group <III group



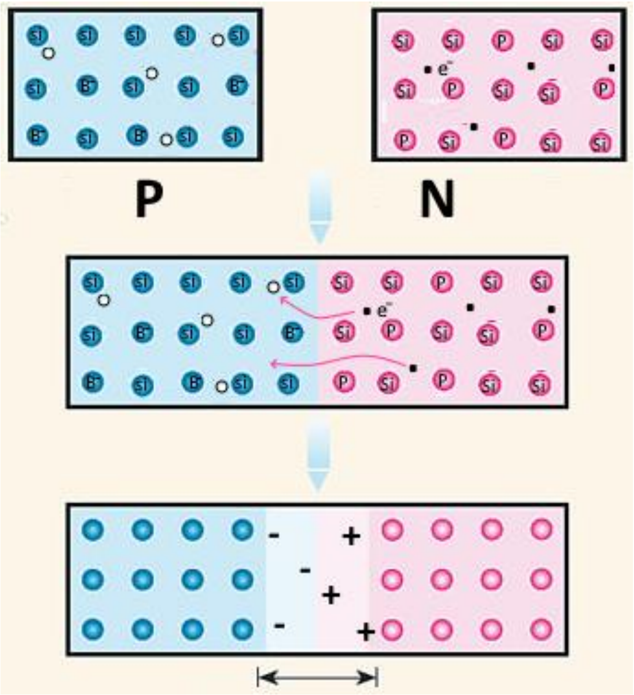


- Electrical conduction.
- **(a)** Electrons moving from left to right give rise to a current directed from right to left.
- **(b)** Holes moving from left to right give rise
- to a current directed from left to right.

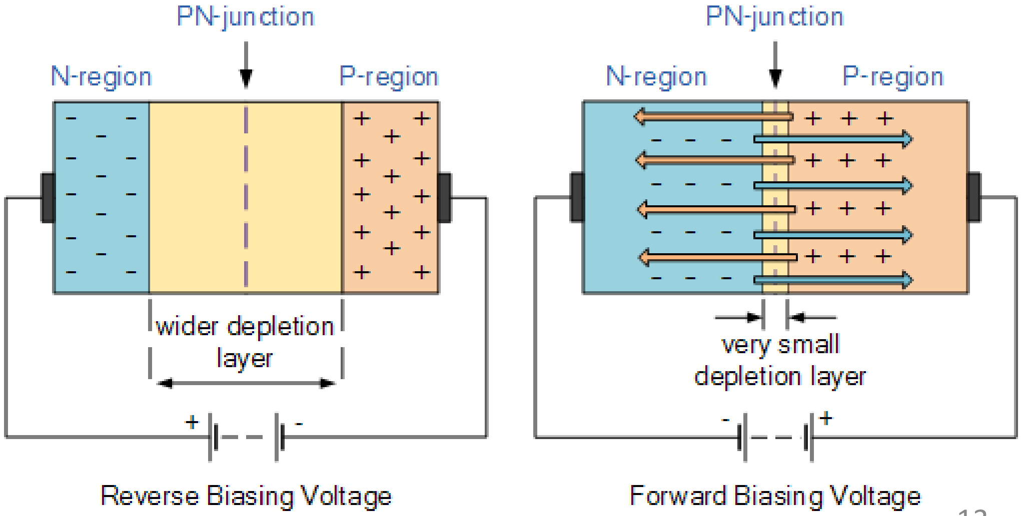
Why Silicon is Preferred in Semiconductors?

- The energy band gap is 0.7eV, whereas it is 0.2eV for germanium.
- The thermal pair generation is smaller.
- The formation of SiO_2 layer is easy for silicon, which helps in the manufacture of many components along with integration technology.
- Si is easily found in nature than Ge.
- Noise is less in components made up of Si than in Ge.

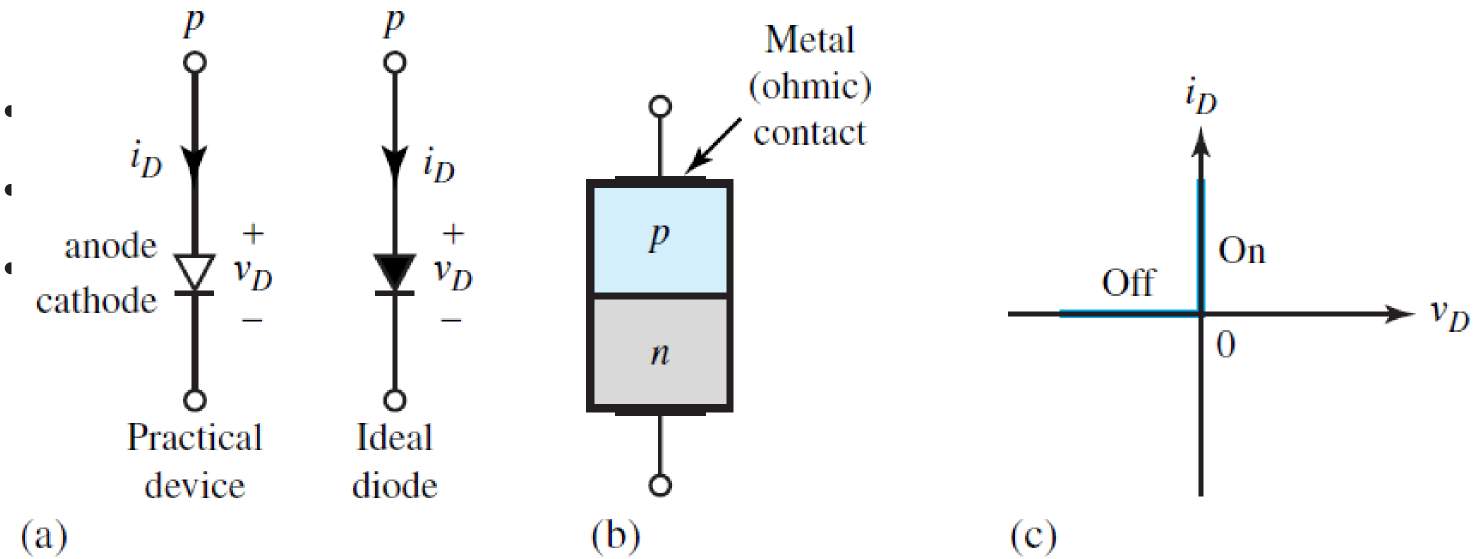
pn-junction



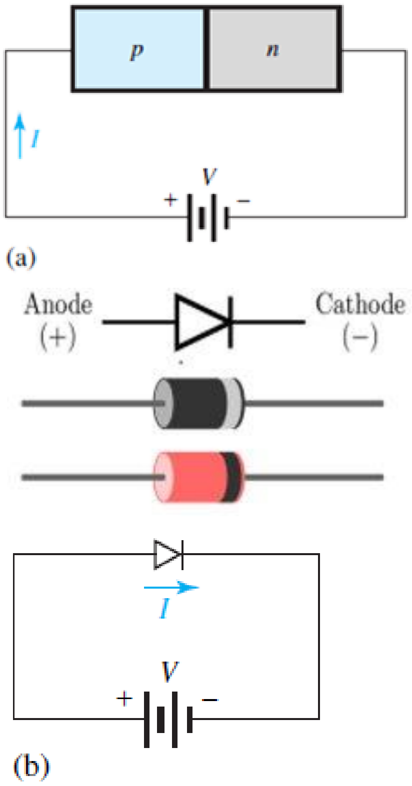
- N-type material has electrons as majority carriers and few holes as minority carriers.
- P-type material has holes as majority carriers and few electrons as minority carriers.

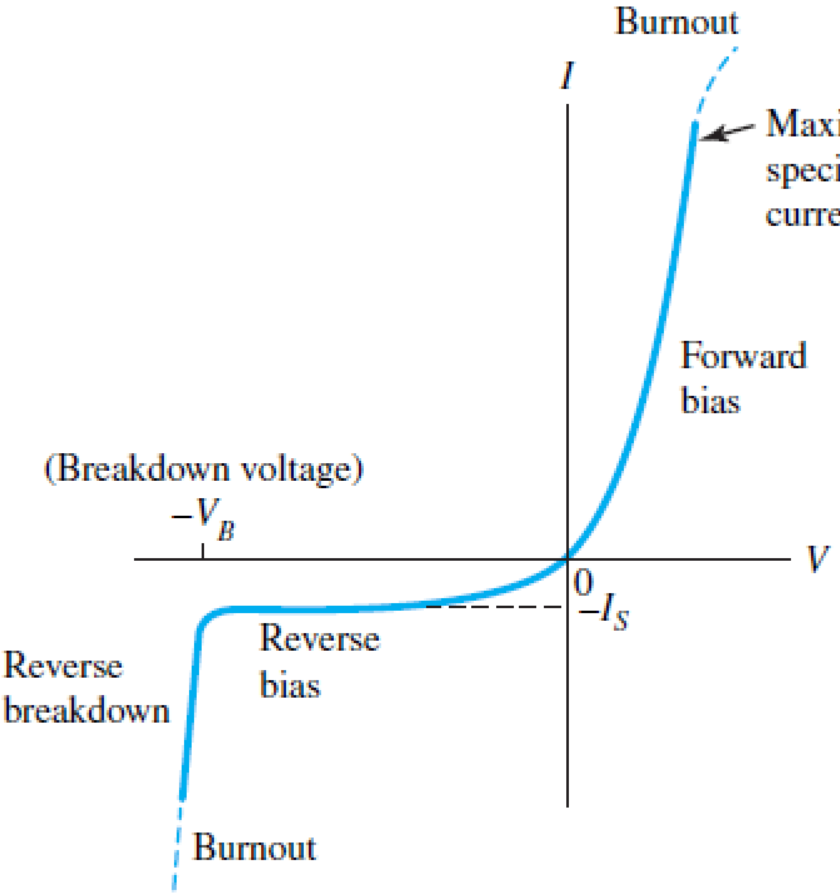


pn-junction



p
i_D
anode
cathode
+
v_D
−
Practical device
p
i_D
+
v_D
−
Ideal diode
(a)
Metal (ohmic) contact
p
n
(b)
i_D
On
Off
v_D
0
(c)





the *Boltzmann diode equation*

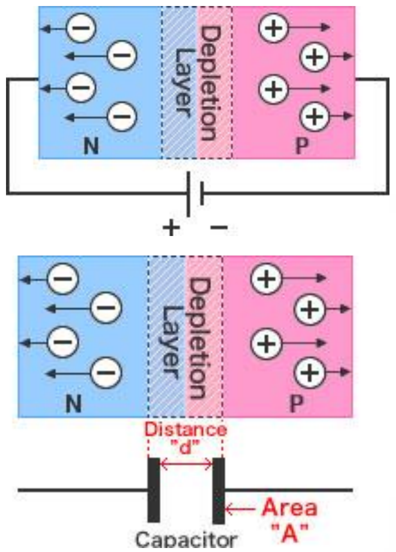
$$I = I_S(e^{V/\eta V_T} - 1)$$

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

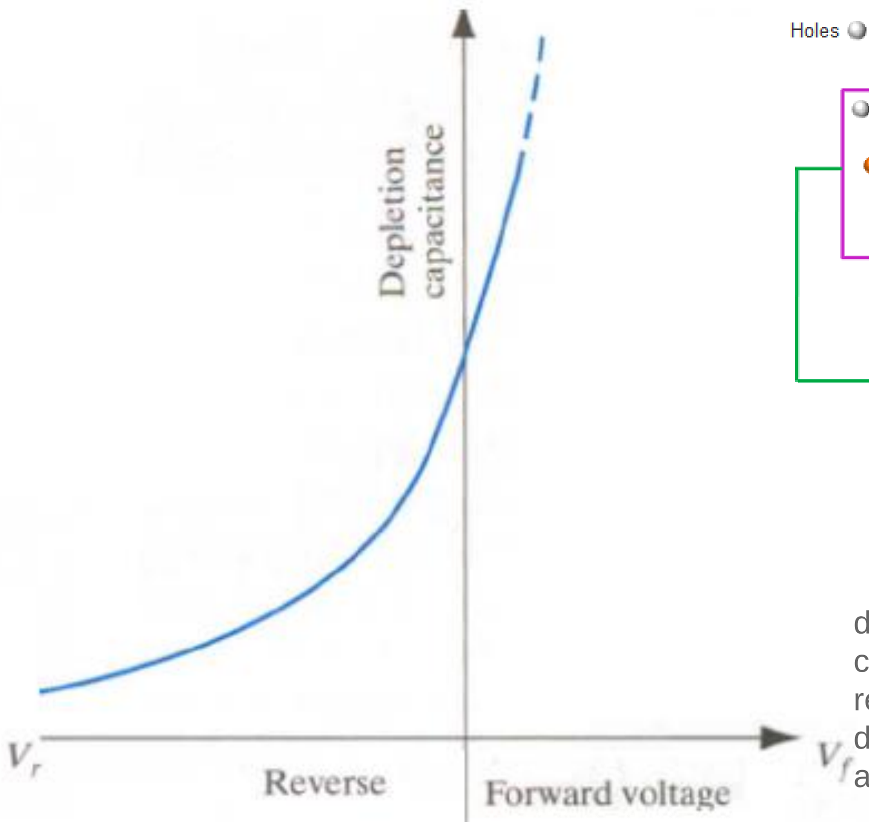
$$\eta = \begin{cases} 1, \text{for Si} \\ 2, \text{for Ge} \end{cases}$$

Diode capacitance

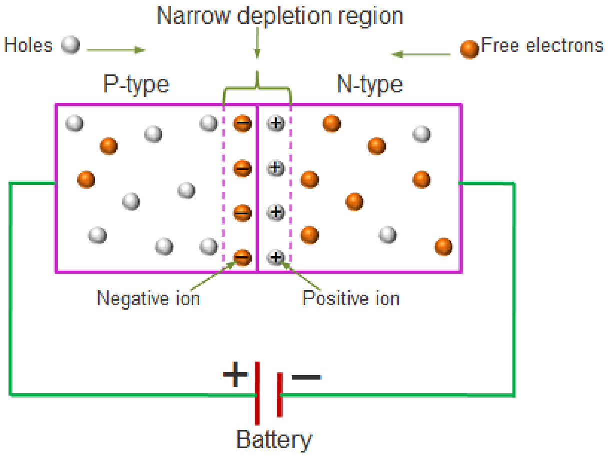
Transition Capacitance



$$\text{Capacitance}(C_t) = \varepsilon \frac{\text{Area "A"}}{\text{Distance "d"}}$$



Diffusion Capacitance



Forward bias

$$C_D = dQ / dV$$

dQ = Change in number of minority carriers stored outside the depletion region

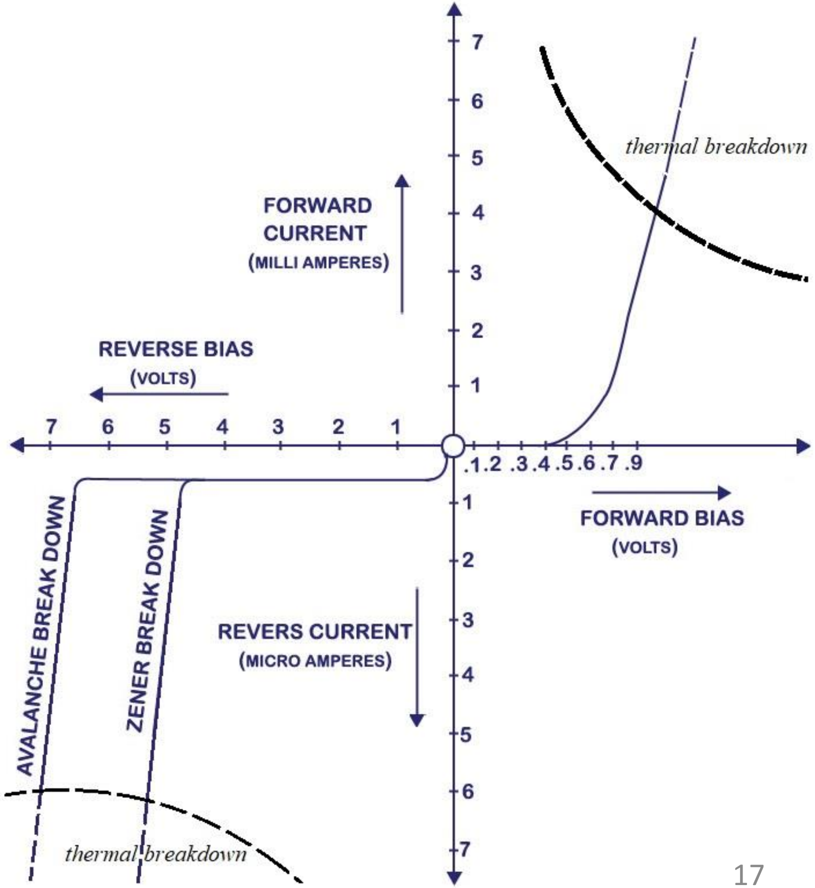
dV = Change in voltage applied across diode

Diode breakdown

Diode breakdown

Reversible:
Zener breakdown
(at low voltages)
Avalanche breakdown
(at higher voltages)

Irreversible:
thermal
breakdown



Zener and Avalanche breakdown find application in stabilitrons.

Type diode

By used material

- Si
- Ge
- GaAs
- etc

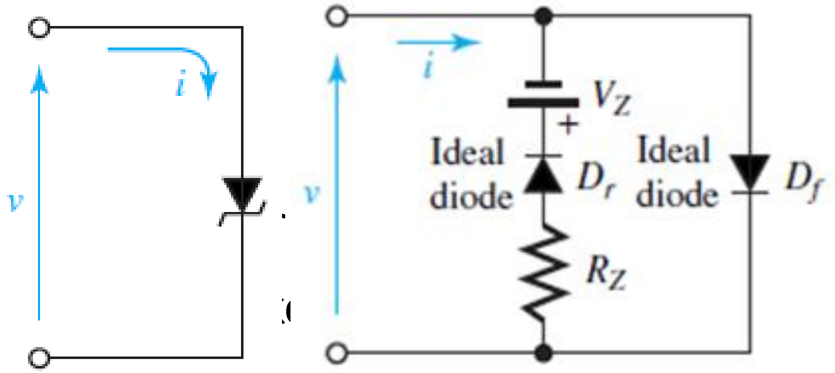
By type of p-n junction

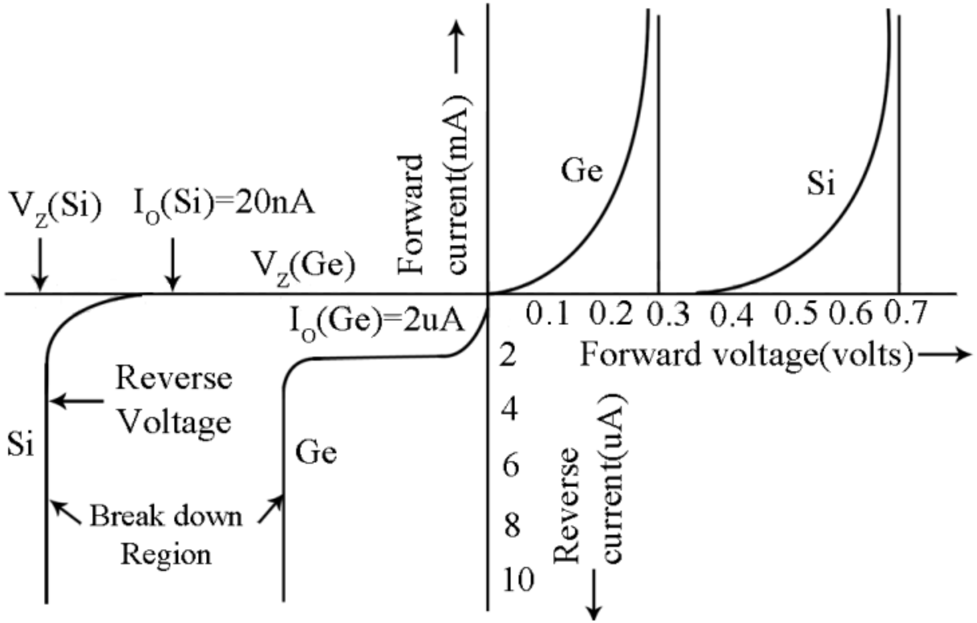
- p-n junction
- pin junction
- metal-semiconductor junctions

By purpose

- Rectifying diodes
- Zener Diode
- Schottky Diode
- Tunnel Diode
- Light Emitting Diode (LED)
- Laser Diode (LD)
- Transient Voltage Suppression Diode
- Peltier Diode
- Avalanche Diode
- etc

Zener diode





Main parameters:

Zener Voltage V_Z

Breakover Current I_{ZK}

Power Dissipation

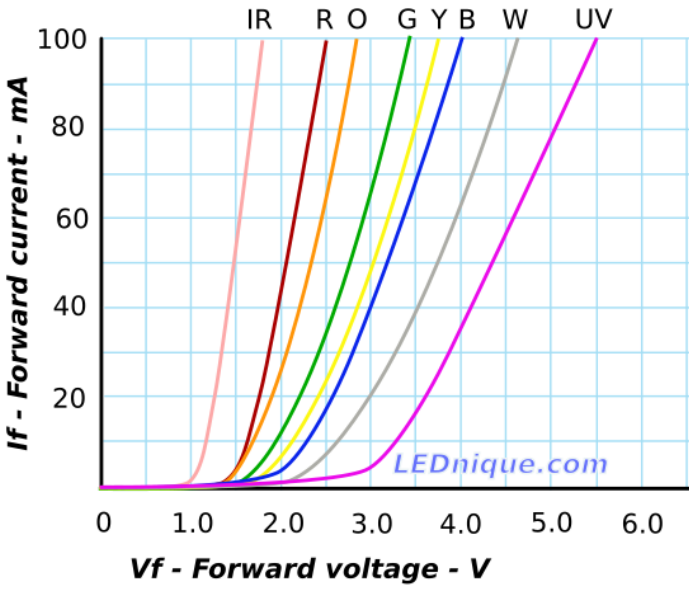
Dynamic Impedance

Effect of Temperature on V_Z Voltage

Light-emitting diode

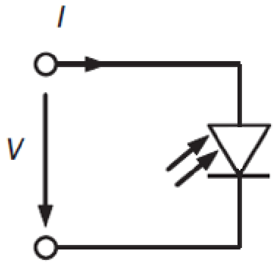
Light-emitting diode

Light-emitting diode (LED) | Laser diode (LD) | Superluminescent diodes (SLDs)



Typical LED Characteristics			
Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8.v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaLnN	450nm	White	4.0v

Photodiode



Load reference-arrow system

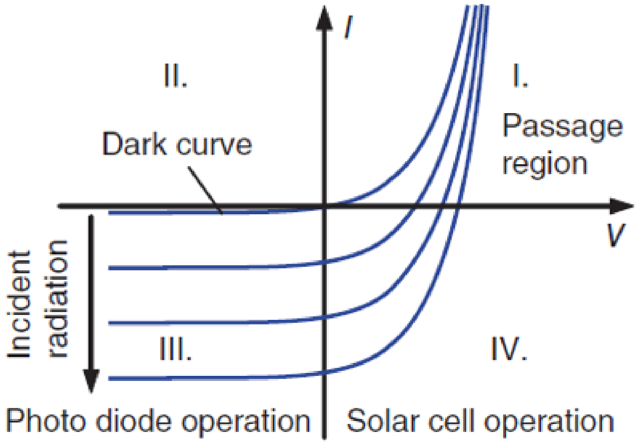
Photodiode (PD)

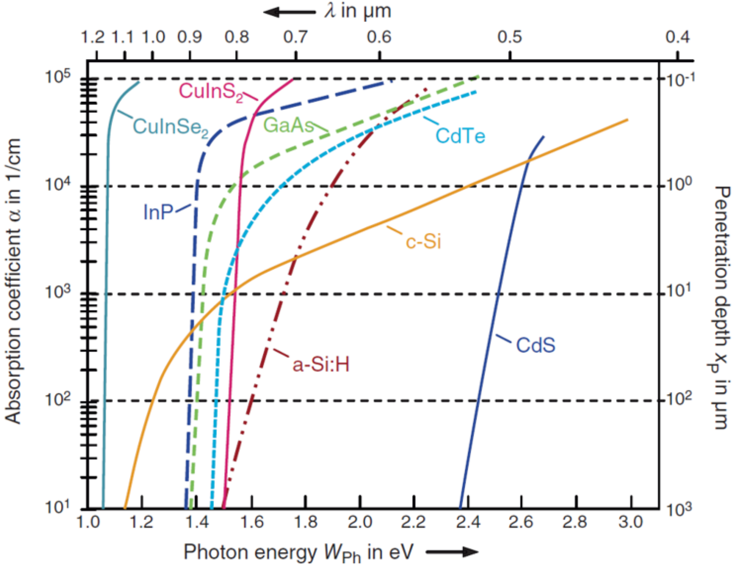
pn-PD

pin-PD

APD (Avalanche-PD)

This is the most basic photodiode. The physics of how the P-N junction photodiode operates was reviewed earlier. The PIN and APD photodiode are variations from the P-N junction.



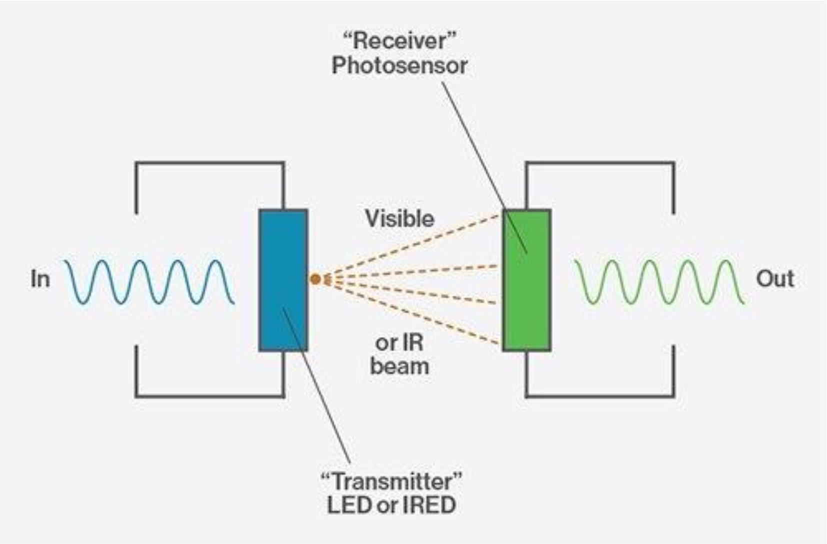


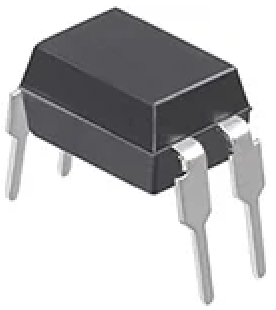
Source: K. Mertens: textbook-pv.or

Comparison of different type PD

	P-N	PIN	APD
PHOTOVOLTAIC	Best	Good	Poor
REVERSE BIASED	Good	Best	Good
LOW LIGHT	Poor	Good	Best
COST	Best	Good	Poor
LOW NOISE	Good	Best	Poor

Optocoupler





The Current – Transfer – Ratio (CTR)

$$CTF = \frac{I_C}{I_F} * 100\%$$

were:
$I_F -$ current flowing through the LED,
$I_C -$ current flowing through the photosensor

An Optocoupler Can Effectively:

- Remove electrical noise from signals
- Isolate low-voltage devices from high-voltage circuits. The device is able to avoid disruptions from voltage surges (ex: from radio frequency transmissions, lightning strikes, and spikes in a power supply)
- Allow the usage of small digital signals to control larger AC voltages

Areas of diode operation

	Rectifier diode	Zener diode	LED	PD
Forward bias	√	X	√	X
Reverse bias	√	√	X	√
Reverse breakdown	X	√	X	X

Elementary Diode Circuits

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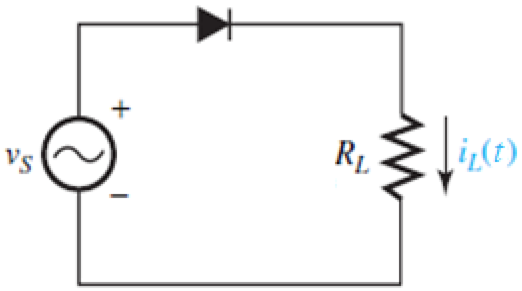
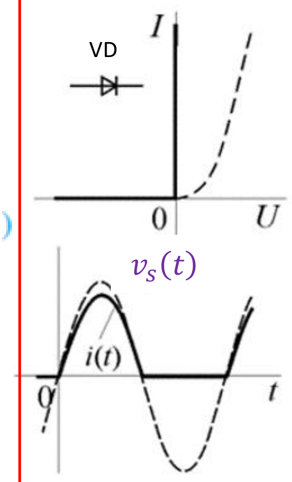
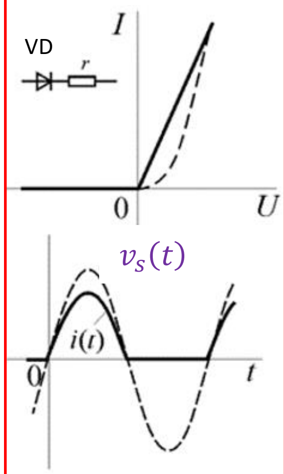
Real half-wave rectifier





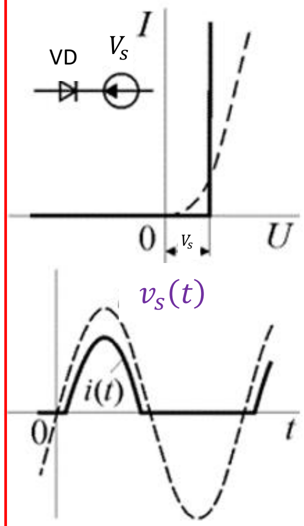
Ideal

- no offset voltage
- no internal resistance
- lossless



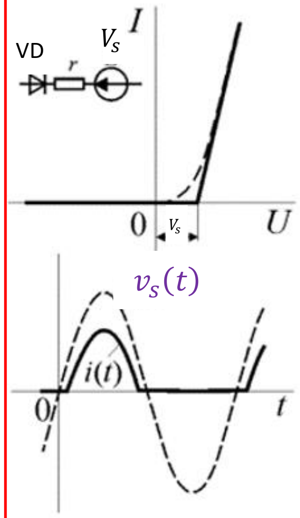
Linear

- no offset voltage



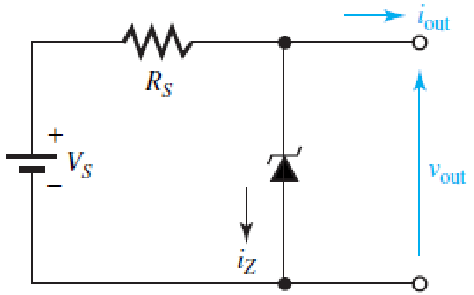
Offset

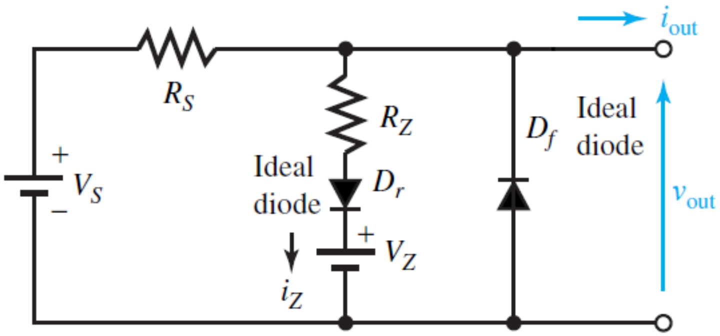
- no internal resistance

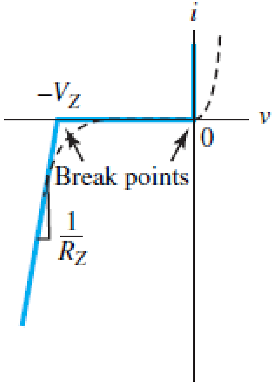


Linear with offset

- offset voltage
- internal resistance
- losses







The forward diode D_f and reverse diode D_r will be off

$$V_S - R_S i_{out} < V_Z$$

$$v_{out} \cong V_S$$

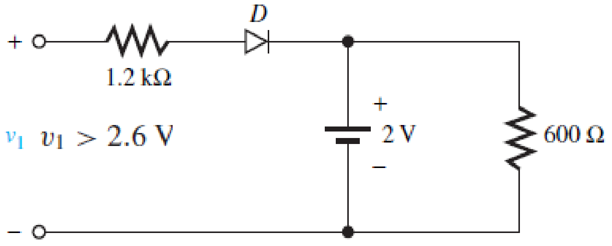
$V_s > V_Z$

The forward diode D_f will be off while the reverse diode D_r is on

$$V_S - R_S i_{out} > V_Z$$

$$v_{out} \cong V_Z$$

- Use the offset diode model with a threshold voltage of 0.6 V to determine the value of v1 for which the diode D will first conduct

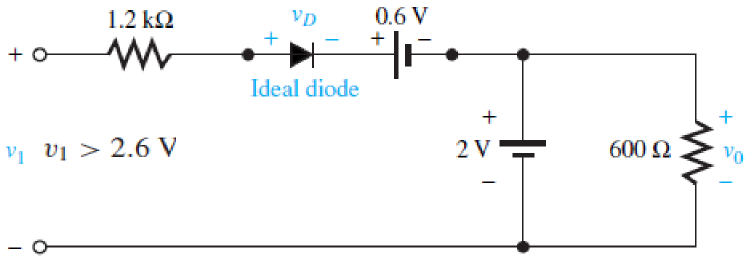


(a)

$$v_1 = v_D + 0.6 + 2$$

$$v_0 = 2$$

$$v_D = v_1 - 2.6$$

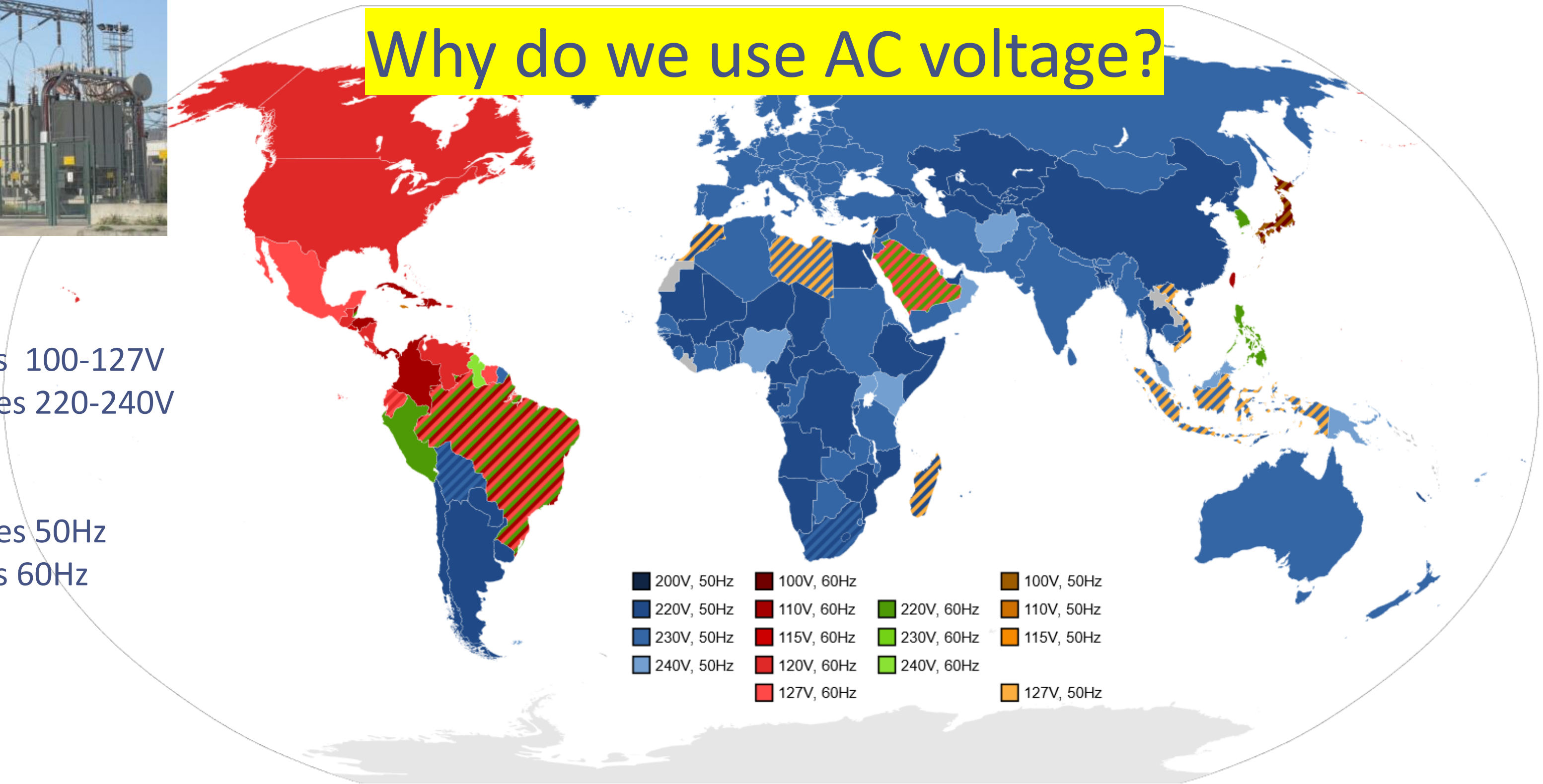


(b)

Elementary rectifiers circuits

Energy consumers

AC GRID



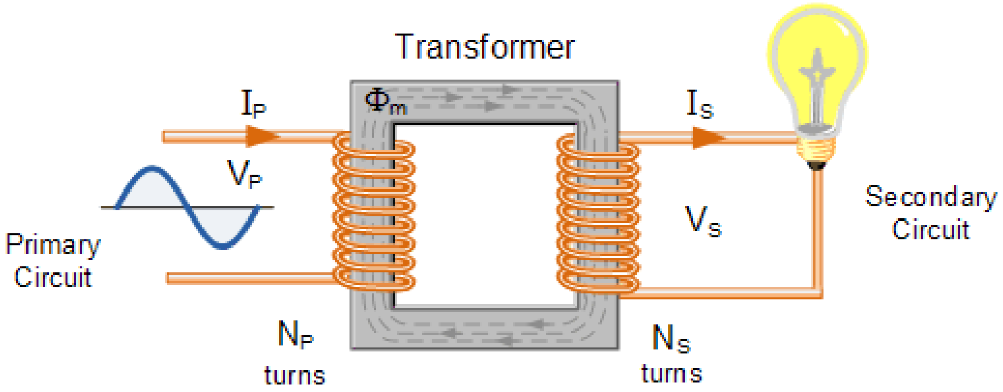
Why do we use AC voltage?

AC Voltage:

- ~50 countries 100-127V
- ~200 countries 220-240V

- ~180 countries 50Hz
- ~50 countries 60Hz

AC GRID



Transformers!

√ Only AC amplitude changes

√ Very efficient!

Power losses reduces with voltage increase

$$P_{losses} = I^2 * R$$

If

$P_{total} = UI = P_{load} + P_{losses}$ = CONST

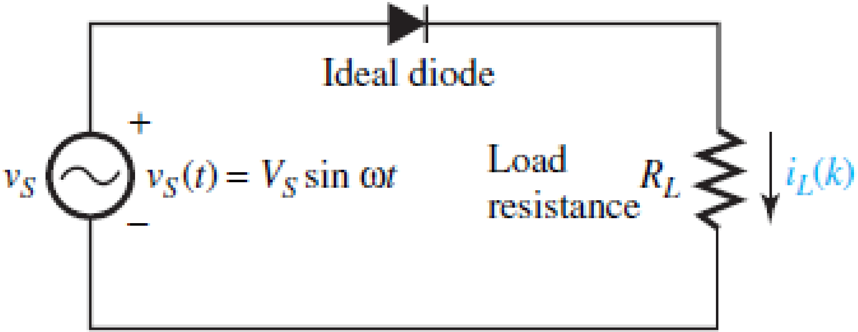
and if U↑

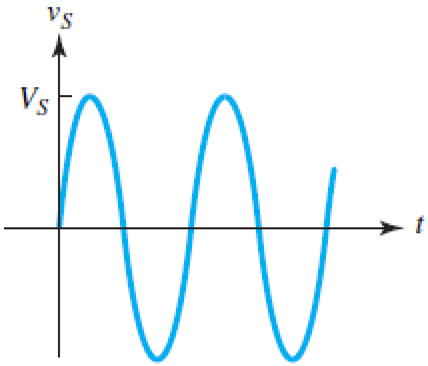
then I↓

and consequently,

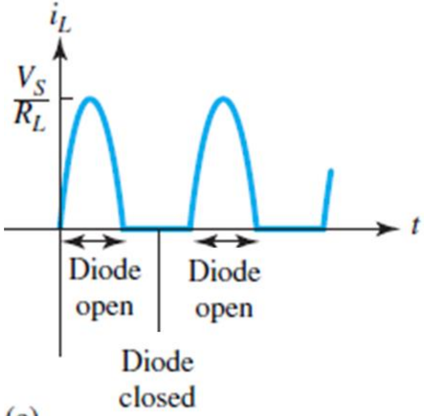
√ P_{losses} ↓

Half-Wave Rectifier (HWR)





(b)



(c)

Source voltage $v_s(t)$

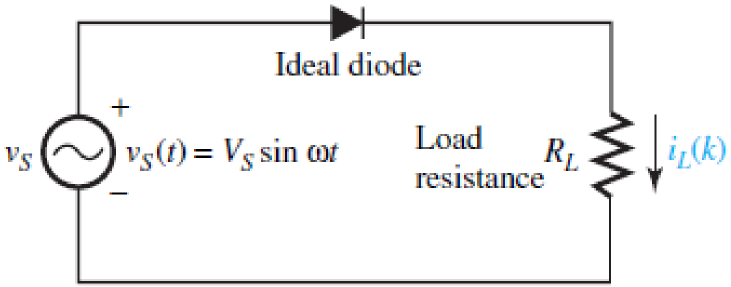
$$v_s(t) = V_s \cdot \sin(\mathrm{f} \cdot 2\pi \cdot t) = V_s \cdot \sin(\omega \cdot t)$$

$$V_{S_{RMS}} = \frac{V_S}{\sqrt{2}}$$

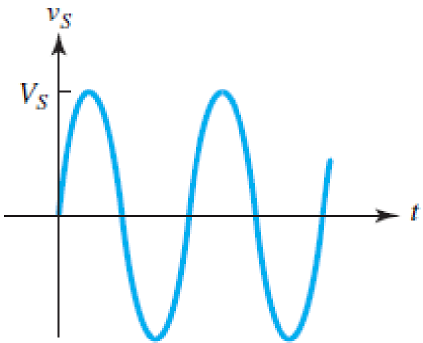
Voltage on the load resistance $\mathrm{R_L}$

$$v_{R_L}(t) = \begin{cases} 0, & if \quad v_s(t) \leq 0 \\ v_s(t), & if \quad v_s(t) > 0 \end{cases}$$

Half-wave rectifier



(a)

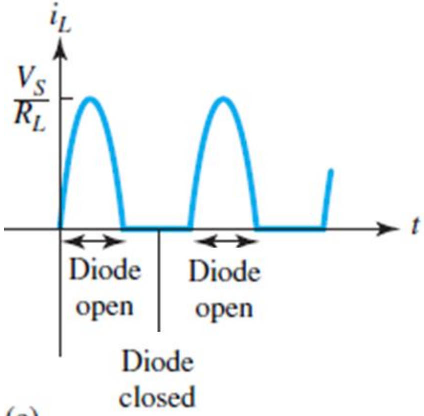


(b)

$$v_{R_L}(t) = \begin{cases} 0, & if \quad v_s(t) \le 0 \\ v_s(t), & if \quad v_s(t) > 0 \end{cases}$$

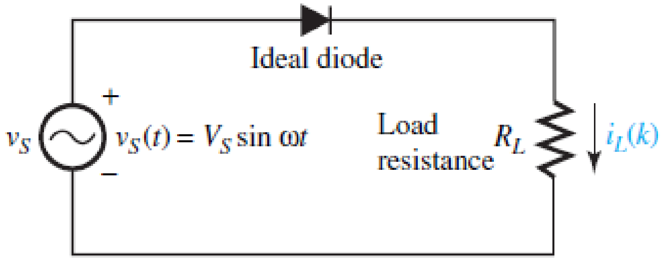
Load voltage is the sum of the DC ($V_{R_{L_{AVG}}}$) and AC ($v_{R_{L_\sim}}(t)$) components

$$v_{R_L}(t) = V_{R_{L_{AVG}}} + v_{R_{L_\sim}}(t)$$



(c)

Half-Wave Rectifier (HWR)



Source voltage $v_s(t)$

$$v_s(t) = V_s \cdot \sin(\mathrm{f} \cdot 2\pi \cdot t) = V_s \cdot \sin(\omega \cdot t)$$

Voltage on the load resistance $\mathrm{R_L}$

$$v_{R_L}(t) = \begin{cases} 0, & if \quad v_s(t) \leq 0 \\ v_s(t), & if \quad v_s(t) > 0 \end{cases}$$

Voltage on the load resistance is $\mathrm{R_L}$ a sum of DC voltage $V_{R_{L\,AVG}}$ and voltage ripple $v_{R_{L\sim}}(t)$

$$v_{R_L}(t) = V_{R_{L\,AVG}} + v_{R_{L\sim}}(t)$$

Average voltage on the load resistance $\mathrm{R_L}$:

$$V_{R_{L\,AVG}} = \int_0^{2\pi/\omega} V_s \cdot \sin(\omega \cdot t)dt = \int_0^{T} V_s \cdot \sin(\omega \cdot t)dt = \frac{V_s}{T \cdot \omega}\cos(\omega \cdot t)\,\Big|_0^{T/2} = \frac{V_s}{\pi} = \frac{\sqrt{2} \cdot V_{S_{RMS}}}{\pi} \approx 0.45 \cdot V_{S_{RMS}}$$

RMS value of the voltage on the load resistance $\mathrm{R_L}$:

$$V_{R_{L\sim\,RMS}} = \sqrt{V^2_{R_{L_{1\sim RMS}}} + V^2_{R_{L_{2\sim RMS}}} + V^2_{R_{L_{3\sim RMS}}} + \cdots + V^2_{R_{L_{n\sim RMS}}}} = \sqrt{V^2_{R_{L\,RMS}} - V^2_{R_{L\,AVG}}}$$

$$\text{Ripple factor } K_P = \frac{V_{R_{L\sim\,RMS}}}{V_{R_{L\,AVG}}} = \sqrt{\frac{(V^2_{R_{L\,RMS}} - V^2_{R_{L\,AVG}})}{V^2_{R_{L\,AVG}}}} = \sqrt{\frac{V^2_{R_{L\,RMS}}}{V^2_{R_{L\,AVG}}} - 1} = \sqrt{(\frac{\pi}{2})^2 - 1} = 1.21$$

Half-wave rectifier main parameters

Rectifier Main parameters

Average load voltage:

$$V_{R_{L_{AVG}}} = V_{S_{RMS}}$$

RMS value of the variable voltage component

$$V_{R_{L\sim RMS}} = \sqrt{V_{R_{L_{RMS}}}^2 - V_{R_{L_{AVG}}}^2}$$

RMS value of load current

$$I_L = \frac{V_s}{2\,R_L} = 0.707\frac{V_{S_{RMS}}}{R_L}$$

RMS voltage on the load

$$V_{R_{L_{RMS}}}^2 \approx 0.707 V_{S_{RMS}}$$

Average load current

$$I_{L_{AVG}} \approx 0.45\frac{V_{S_{RMS}}}{\mathrm{R_L}}$$

Ripple factor

$$K_p = \gamma = \sqrt[2]{\left(\frac{V_{S_{RMS}}}{V_{R_{L_{AVG}}}}\right)^2 - 1} = 1.21$$

Diode Main parameters

Average current flowing through the diode

$$I_{VD_{AVG}} = I_{L_{AVG}} = 0.45\,\frac{V_{S_{RMS}}}{R_L}$$

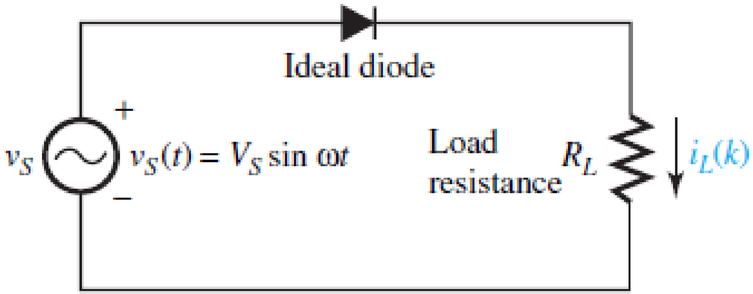
Maximum reverse voltage across the diode

$$V_{VD_{max}} = V_s$$

Maximum diode current

$$I_{VD_{max}} = \frac{V_s}{R_L}$$

Half-Wave Rectifier (HWR)



Source voltage $v_s(t)$

$$v_s(t) = V_s \cdot \sin(f \cdot 2\pi \cdot t) = V_s \cdot \sin(\omega \cdot t)$$

Voltage on the load resistance R_L

$$v_{R_L}(t) = \begin{cases} 0, & if \quad v_s(t) \le 0 \\ v_s(t), & if \quad v_s(t) > 0 \end{cases}$$

Load parameters:

Average load voltage

$$V_{R_{L\,AVG}} = \frac{V_S}{\pi} = \frac{\sqrt{2}V_{S_{RMS}}}{\pi} \approx 0.45 V_{S_{RMS}}$$

RMS load voltage

$$V_{R_{L\,RMS}} = \frac{V_S}{2} = \frac{V_{S_{RMS}}}{\sqrt{2}} \approx 0.707 V_{S_{RMS}}$$

Average load current

$$I_{L_{AVG}} = \frac{V_{R_{L\,AVG}}}{\mathrm{R_L}} = \frac{\sqrt{2}V_{S_{RMS}}}{\pi \mathrm{R_L}} \approx 0.45 \frac{V_{S_{RMS}}}{\mathrm{R_L}}$$

RMS load current through diode

$$I_{L_{RMS}} = \frac{V_S}{2\mathrm{R_L}} = \frac{V_{S_{RMS}}}{\sqrt{2}\mathrm{R_L}} \approx 0.707 \frac{V_{R_{L\,RMS}}}{\mathrm{R_L}}$$

Diode parameters:

Average diode current

$$I_{VD_{AVG}} = I_{L_{AVG}} = \frac{\sqrt{2}V_{S_{RMS}}}{\pi \mathrm{R_L}} \approx 0.45 \frac{V_{S_{RMS}}}{\mathrm{R_L}}$$

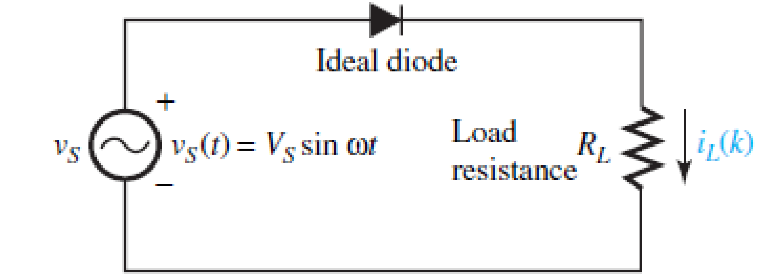
MAX diode current

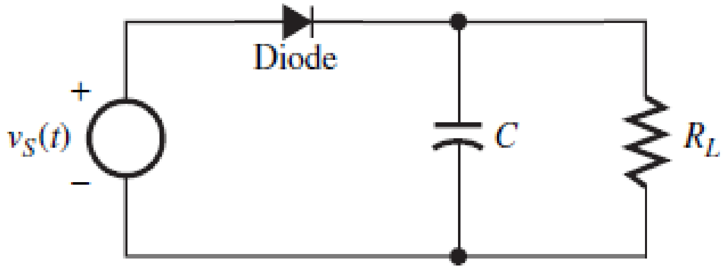
$$I_{VD_{max}} = \frac{V_S}{\mathrm{R_L}}$$

MAX diode reverse voltage

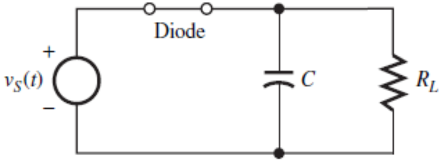
$$V_{VD_{max}} = V_S$$

Half-Wave Rectifier with DC filter capacitor

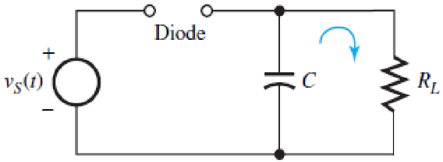




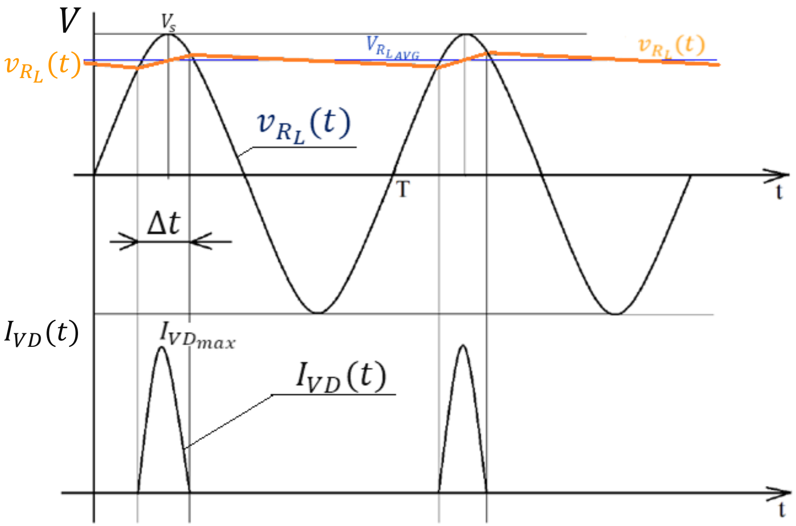
$0 \leq t \leq t_1$

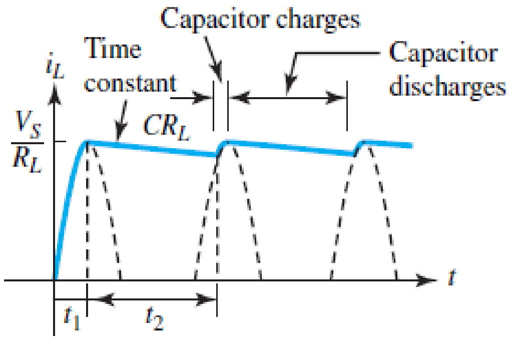


$0 \leq t \leq t_1$



$t_1 \leq t \leq t_2 + t_1$





Half-Wave Rectifier with DC filter capacitor

$$v_{R_L}(t) = V_{R_{L_{AVG}}} + v_{R_{L\sim}}(t) \approx V_{R_L} \quad \text{=const}$$

Diode Voltage

$$v_{VD}(t) = v_s(t) - V_{R_{L_{AVG}}}$$

Average diode current

$$I_{L_{AVG}} = I_{VD_{AVG}} = \frac{1}{T}\sqrt{\int_0^T I_{VD}(t)dt}$$

$$I_{L_{AVG}} = \frac{1}{T}\sqrt{\int_{\frac{T}{4}-\theta/(2\cdot\omega)}^{\frac{T}{4}+\theta/(2\cdot\omega)} \frac{1}{r_{IN}}(V_s \cdot \sin(\omega \cdot t) - V_{R_{L_{AVG}}}))dt} = \frac{V_{R_{L_{AVG}}}}{R_L}$$

where

$r_{IN} = r_{VD} + r_{V_S}$ – input resistance of the rectifier

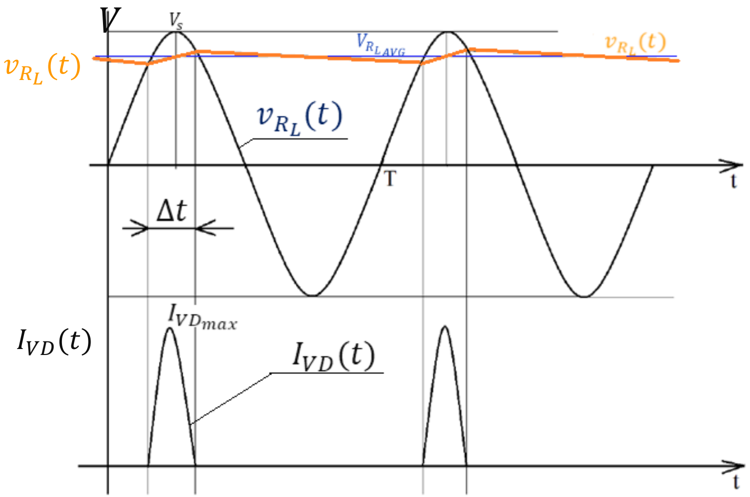
r_{VD} – diode resistance

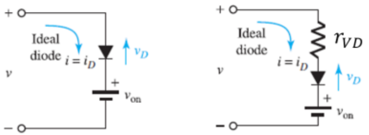
r_{V_S} – voltage source resistance

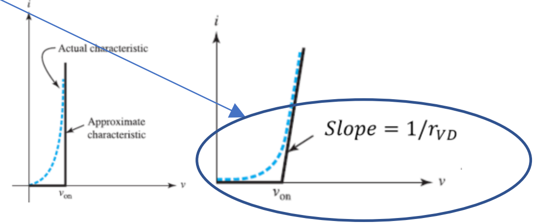
$\theta = \omega \cdot \Delta t = \frac{2\pi}{T} \cdot \Delta t$ – angle of diode open state

Δt – diode open state time interval

$$\frac{V_{R_{L_{AVG}}}}{V_S} = \frac{R_L}{\pi r_{IN}}\left(\sin\left(\frac{\theta}{2}\right) - \frac{V_{R_{L_{AVG}}}}{V_S}\frac{\theta}{2}\right)$$

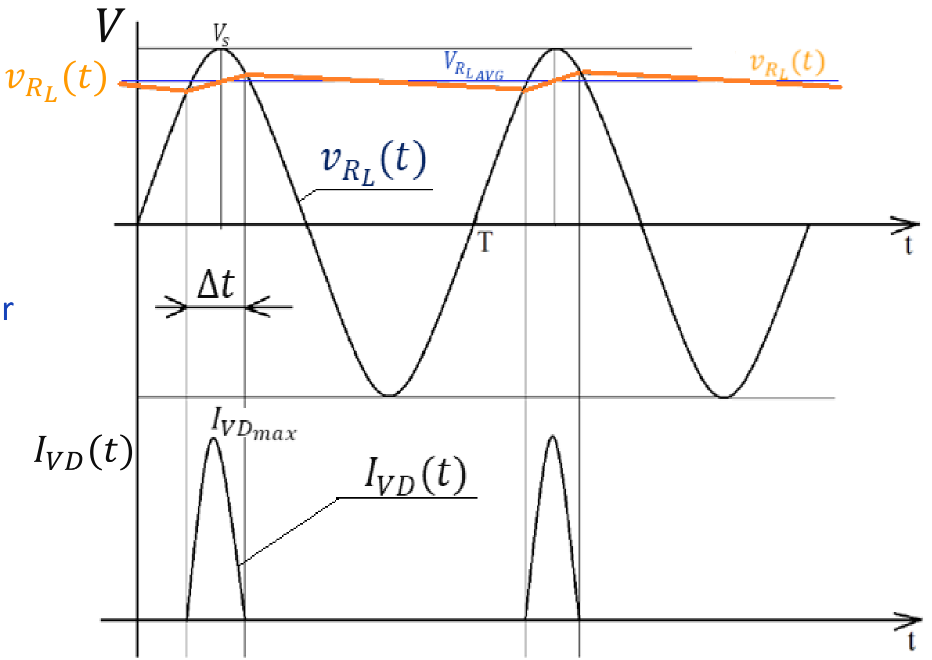






Average diode current

$$I_{L_{AVG}} = \frac{1}{T}\sqrt{\int_{\frac{T}{4}-\theta/(2\cdot\omega)}^{\frac{T}{4}+\theta/(2\cdot\omega)} \frac{1}{r_{IN}}(V_s\cdot\sin(\omega\cdot t) - V_{R_{L_{AVG}}}))dt} = \frac{V_{R_{L_{AVG}}}}{\mathrm{R_L}}$$



where

$r_{IN} = r_{VD} + r_{V_S}$ — input resistance of the rectifier

r_{VD} — diode resistance

r_{V_S} — voltage source resistance

$\theta = \omega \cdot \Delta t = \frac{2\pi}{T}\cdot\Delta t$ — angle of diode open state

Δt — diode open state time interval

$$\frac{V_{R_{L_{AVG}}}}{V_S} = \frac{\mathrm{R_L}}{\pi r_{IN}}\left(\sin\left(\frac{\theta}{2}\right) - \frac{V_{R_{L_{AVG}}}}{V_S}\frac{\theta}{2}\right)$$

$$V_{VD}\left(\frac{T}{4}\pm\frac{\theta}{2\cdot\omega}\right) = V_S\sin\left(\omega\left(\frac{T}{4}\pm\frac{\theta}{2\cdot\omega}\right)\right) - V_{R_{L_{AVG}}} = 0 \Rightarrow V_{R_{L_{AVG}}} = V_S\left(\omega\left(\frac{T}{4}\pm\frac{\theta}{2\cdot\omega}\right)\right) = V_S\sin\left(\frac{\pi}{2}\pm\frac{\theta}{2}\right)$$

$$\frac{V_{R_{L_{AVG}}}}{V_S} = \cos\left(\frac{\theta}{2}\right) \Rightarrow \cos\left(\frac{\theta}{2}\right) = \frac{\mathrm{R_L}}{\pi r_{IN}}\left(\sin\left(\frac{\theta}{2}\right) - \cos\left(\frac{\theta}{2}\right)\cdot\frac{\theta}{2}\right) \Rightarrow \frac{r_{IN}}{\mathrm{R_L}} = \frac{1}{\pi}\left(\tan\left(\frac{\theta}{2}\right) - \frac{\theta}{2}\right)$$

From $\frac{r_{IN}}{\mathrm{R_L}} = \frac{1}{\pi}\left(\tan\left(\frac{\theta}{2}\right) - \frac{\theta}{2}\right)$
angle of diode open state θ can be evaluated:

$$\tan\left(\frac{\theta}{2}\right) \approx \frac{\theta}{2} + \frac{1}{3}\left(\frac{\theta}{2}\right)^3 \Rightarrow \theta = 2 \cdot \sqrt[3]{3\pi \frac{r_{IN}}{\mathrm{R_L}}}$$

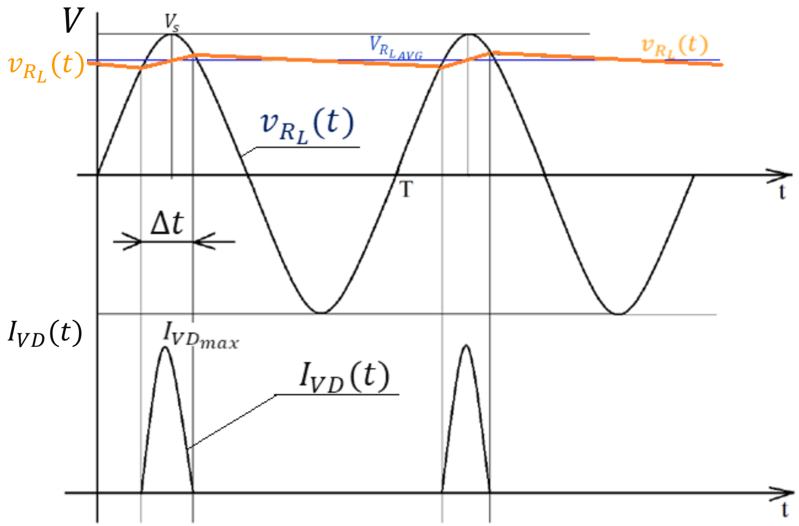
Average load voltage: $V_{R_{L\,AVG}} = V_S \cos\left(\frac{\theta}{2}\right)$

Average diode current: $I_{VD} = \frac{V_S}{\mathrm{R_L}} \cos\left(\frac{\theta}{2}\right)$

Peak (repetitive) diode current: $I_{VD_{max}} = \frac{V_S - V_{R_{L\,AVG}}}{r_{IN}}$

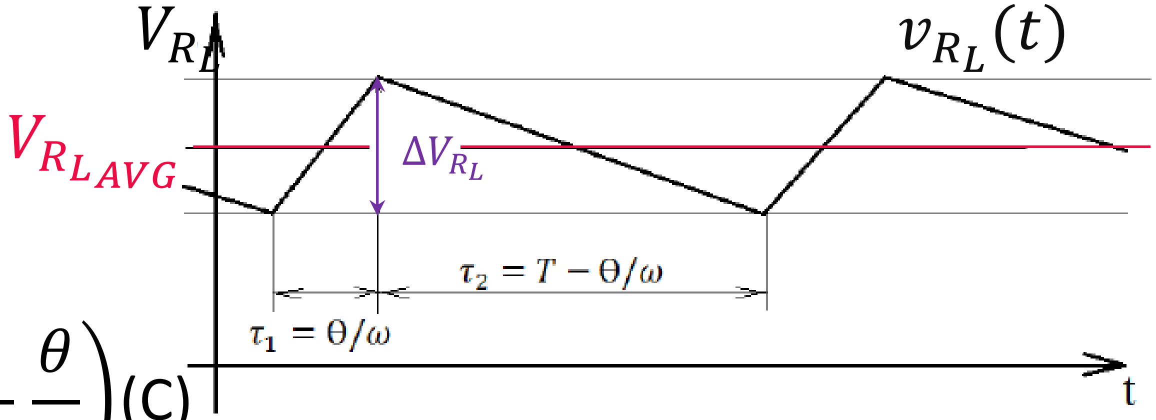
Peak (turn on) diode current: $I_{VD_{ON}} = \frac{V_S}{r_{IN}}$

Diode reverse voltage: $V_{VD_{max}} = V_S + V_{R_{L\,AVG}} \approx 2 \cdot V_S$



From the charge balance condition at

$$\tau_1 < t < \tau_2 = T - \frac{\theta}{\omega}$$

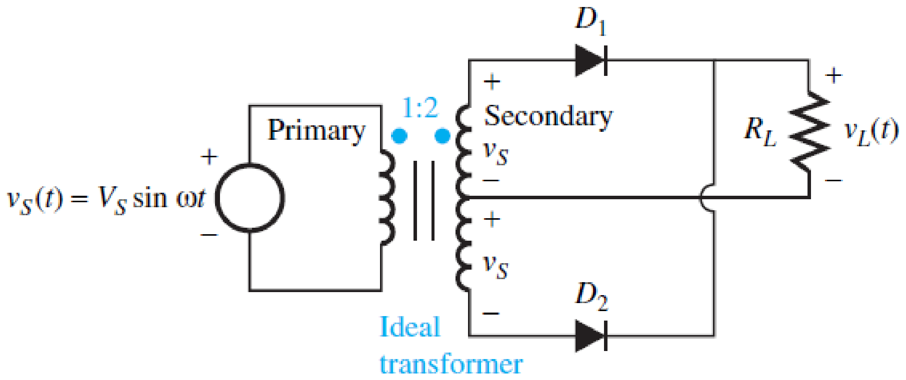


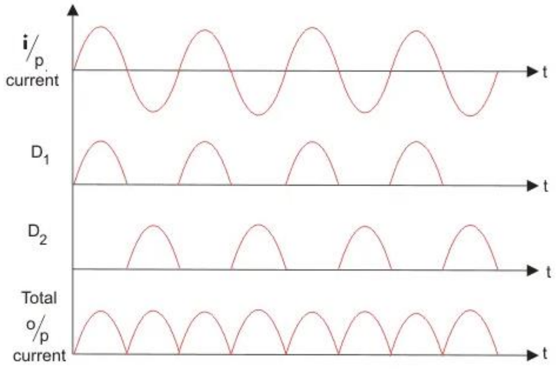
$$\Delta Q = C \cdot \Delta V_{R_L} = I_C \left(T - \frac{\theta}{\omega}\right) \quad \text{(C)}$$

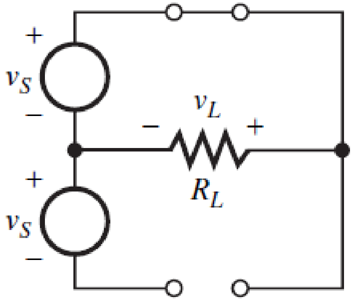
capacitance value depending on the value of the permissible voltage ripple on the load

$$C = \frac{I_C}{2\pi f \cdot \Delta V_{R_L}}(2\pi - \theta) = \frac{I_C}{\omega \cdot \Delta V_{R_L}}(2\pi - \theta) \quad \text{(F)}$$

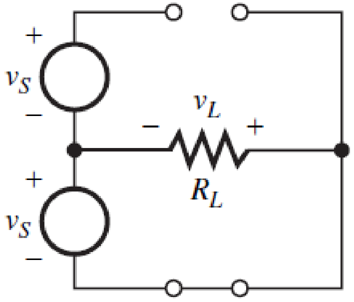
Center-tapped Full Wave Rectifier



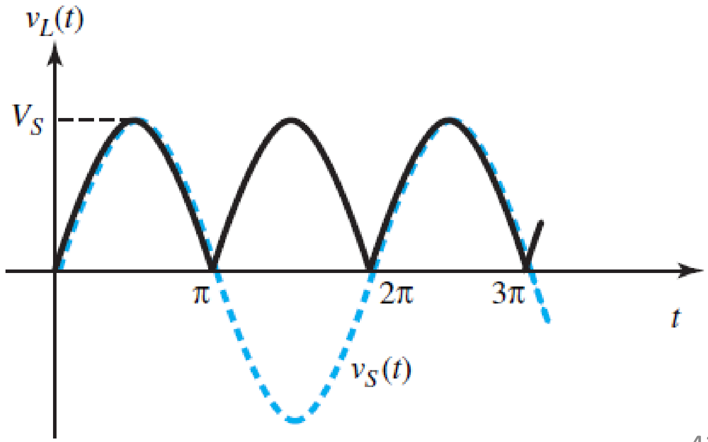




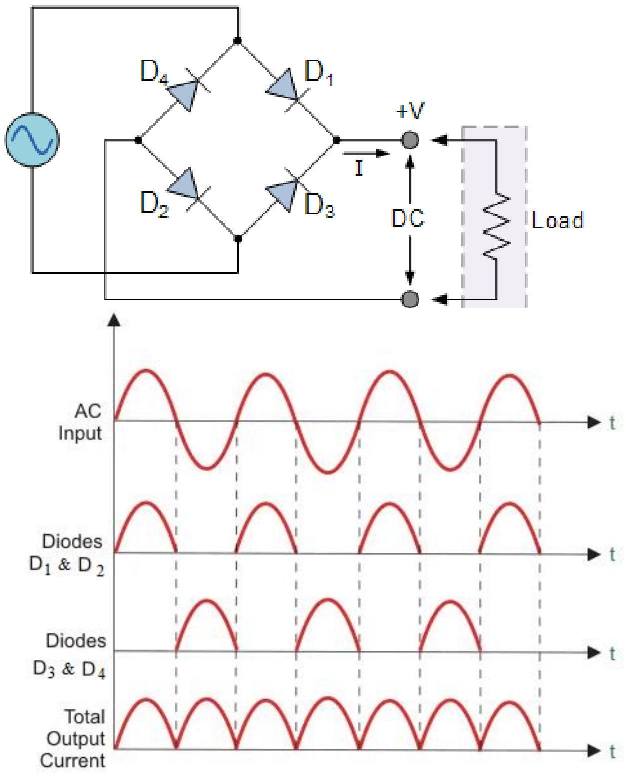
$v_S > 0$ (positive half-cycle)



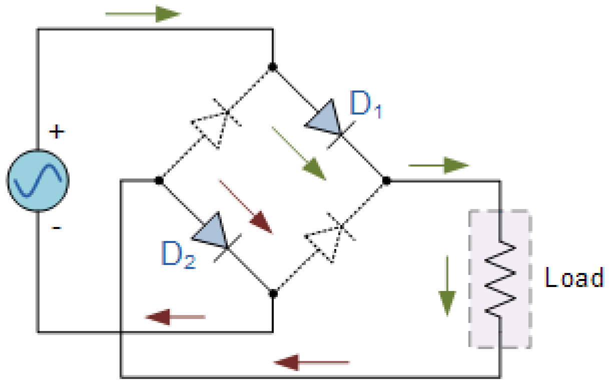
$v_S < 0$ (negative half-cycle)



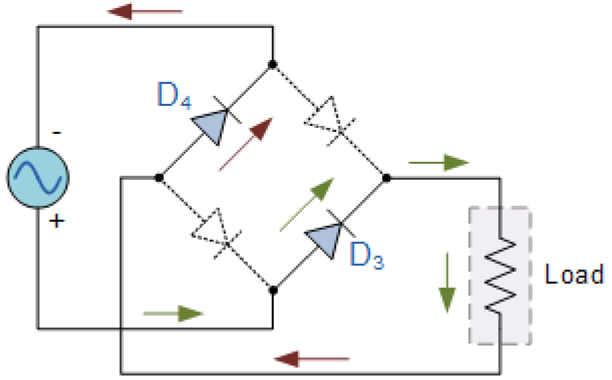
Full Wave Bridge Rectifier



The Positive Half-cycle



The Negative Half-cycle



Full-Wave rectifiers

- **Average load voltage:** $$V_{R_{L_{AVG}}} = \begin{cases} \frac{V_S}{\pi}, & for \text{ HWR } schemes \\ \frac{2 \cdot V_S}{\pi}, & for \text{ FBR or CTR } schemes \end{cases} \quad \text{(V)}$$

- **RMS load voltage:** $$V_{R_{L_{RMS}}} = \begin{cases} \frac{V_S}{2}, & for \text{ HWR } schemes \\ \frac{V_S}{\sqrt{2}}, & for \text{ FBR or CTR } schemes \end{cases} \quad \text{(V)}$$

- **Max peak diode reverse voltage:** $$V_{VD_{max}} = V_{VD_{max}} = \begin{cases} 2V_S, & for \text{ CTR } schemes \\ V_S, & for \text{ HWR and FBR } scheme \end{cases} \quad \text{(V)}$$

- **Average load current:** $$I_{L_{AVG}} = \frac{V_{R_{L_{AVG}}}}{R_L} = \begin{cases} \frac{V_S}{\pi R_L}, & for \text{ HWR } schemes \\ \frac{2 \cdot V_S}{\pi R_L}, & for \text{ FBR or CTR } schemes \end{cases} \quad \text{(A)}$$

- **RMS load current:** $$I_{L_{RMS}} = \frac{V_{R_{L_{RMS}}}}{R_L} = \begin{cases} \frac{V_S}{2R_L}, & for \text{ HWR } schemes \\ \frac{V_S}{\sqrt{2}R_L}, & for \text{ FBR or CTR } schemes \end{cases} \quad \text{(A)}$$

Full-Wave rectifiers

- **Average diode rectified output current:** $I_{VD} = \begin{cases} I_{L_{AVG}}, & for\ \mathrm{HWR}\ schemes \\ \frac{I_{L_{AVG}}}{2}, & for\ \mathrm{FBR\ or\ CTR}\ schemes \end{cases}$ (A)
- **Peak repetitive forward output current:**
- $I_{VD_{max}} = \begin{cases} \frac{V_S}{R_L}, & for\ \mathrm{HWR}\ schemes \\ \frac{V_S}{2R_L}, & for\ \mathrm{FBR\ or\ CTR}\ schemes \end{cases}$ (A)
- **Voltage ripple factor:** $K_p = \sqrt{\left(\frac{V_{R_{L_{RMS}}}}{V_{R_{L_{AVG}}}}\right)^2 - 1}$
- **Voltage ripple evaluated for the rectifier scheme:** $\Delta V_{R_L} = 2 \cdot K_p \cdot V_{R_{L_{AVG}}}$ (V)

Full-Wave rectifiers

- **Source output resistance (overcurrent protection):** $r_{on} = \frac{V_S}{I_{FSM}}$ (Ω)
- **Input rectifier resistance:** $r_{IN} = \begin{cases} r_{vd} + r_{V_S}, & for\ \text{HWR or CTR}\ schemes \\ 2 \cdot r_{vd} + r_{V_S}, & for\ \text{FBR}\ schemes \end{cases}$ (Ω)
- **Diode opening state angle:** $\theta = \begin{cases} 2 \cdot \sqrt[3]{3 \cdot \pi \cdot \frac{r_{IN}}{R_L}}, & for\ \text{HWR}\ schemes \\ 2 \cdot \sqrt[3]{\frac{3}{2} \cdot \pi \cdot \frac{r_{IN}}{R_L}}, & for\ \text{FBR or CTR}\ schemes \end{cases}$ (rad)
- **Average load voltage** $V_{R_{L\,AVG}} = V_S \cdot \cos(\frac{\theta}{2})$ (V)
- **Average load current:** $I_{L_{AVG}} = \begin{cases} \frac{1}{\pi \cdot r_{IN}} (V_S \cdot \sin\left(\frac{\theta}{2}\right) - V_{R_{L\,AVG}} \cdot \frac{\theta}{2}), & \text{for } \textbf{HWR} \text{ schemes} \\ \frac{2}{\pi \cdot r_{IN}} (V_S \cdot \sin\left(\frac{\theta}{2}\right) - V_{R_{L\,AVG}} \cdot \frac{\theta}{2}), & \text{for } \textbf{FBR} \text{ or } \textbf{CTR} \text{ schemes} \end{cases}$ (A)
- **Average diode current:** $I_{VD} = \begin{cases} \frac{V_S}{R_L} \cdot \cos\left(\frac{\theta}{2}\right), & for\ \text{HWR}\ schemes \\ \frac{V_S}{2 \cdot R_L} \cdot \cos(\frac{\theta}{2}), & for\ \text{FBR or CTR}\ schemes \end{cases}$ (A)

Full-Wave rectifiers

1.Maximum repetitive rectifier scheme diode current: $I_{VD_{max}} = \frac{V_S - V_{R_{L\,AVG}}}{r_{IN}}$ (A)

2.Starting (Non-repetitive) maximum peak surge diode current in rectifier scheme: $I_{VD_{ON}} = \frac{V_S}{r_{IN}}$ (A)

3.Peak repetitive reverse voltage: $V_{VD_{max}} = \begin{cases} V_S + V_{R_{L\,AVG}}, & for \text{ HWR or CTR } schemes \\ \frac{V_S + V_{R_{L\,AVG}}}{2}, & for \text{ FBR } schemes \end{cases}$ (V)

4.Voltage ripple evaluated for the rectifier scheme with C-filter: $\Delta V_{R_L} = 2 \cdot K_p \cdot V_{R_{L\,AVG}}$ (V)

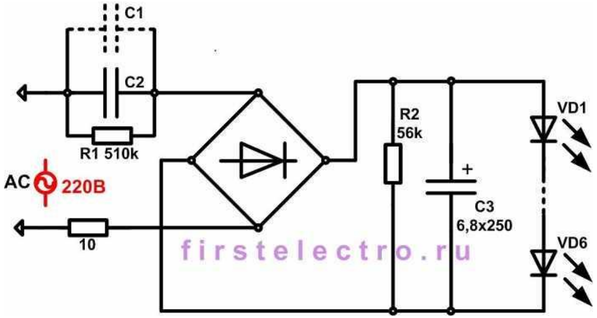
5.Capacitance evaluation: $C = \begin{cases} \frac{I_{L\,AVG}}{2\pi f \cdot \Delta V_{R_L}}(2\pi - \theta), & for \text{ HWR } schemes \\ \frac{I_{L\,AVG}}{2\pi f \cdot \Delta V_{R_L}}(\pi - \theta), & for \text{ FBR or CTR } schemes \end{cases}$ (F)

6.Voltage ripple: $\Delta V_{R_L} = \begin{cases} \frac{I_{L\,AVG}}{2\pi f \cdot C}(2\pi - \theta), & for \text{ HWR } schemes \\ \frac{I_{L\,AVG}}{2\pi f \cdot C}(\pi - \theta), & for \text{ FBR or CTR } schemes \end{cases}$ (V)

Evaluations

	$I_{VD_{AVG}}$	$I_{VD_{max}}$	$V_{VD_{max}}$	r_{IN}
Half – wave rectifier	$= I_{L_{AVG}}$	$\approx 7I_{L_{AVG}}$	$= V_S \cdot 2 \approx 3V_{R_{L_{AVG}}}$	$= r_{vd} + r_{V_S}$
Central tap rectifier	$= \frac{I_{L_{AVG}}}{2}$	$\approx 3.5I_{L_{AVG}}$	$= V_S \cdot 2 \approx 3V_{R_{L_{AVG}}}$	$= r_{vd} + r_{V_S}$
Full bridge (Graetz) rectifier	$= \frac{I_{L_{AVG}}}{2}$	$\approx 3.5I_{L_{AVG}}$	$= V_S \approx 1.5V_{R_{L_{AVG}}}$	$= 2r_{vd} + r_{V_S}$

Examples


C1
C2
R1 510k
AC
220B
10
R2
56k
+
C3
6,8x250
VD1
VD6
firstelectro.ru

LED –lamp parameters

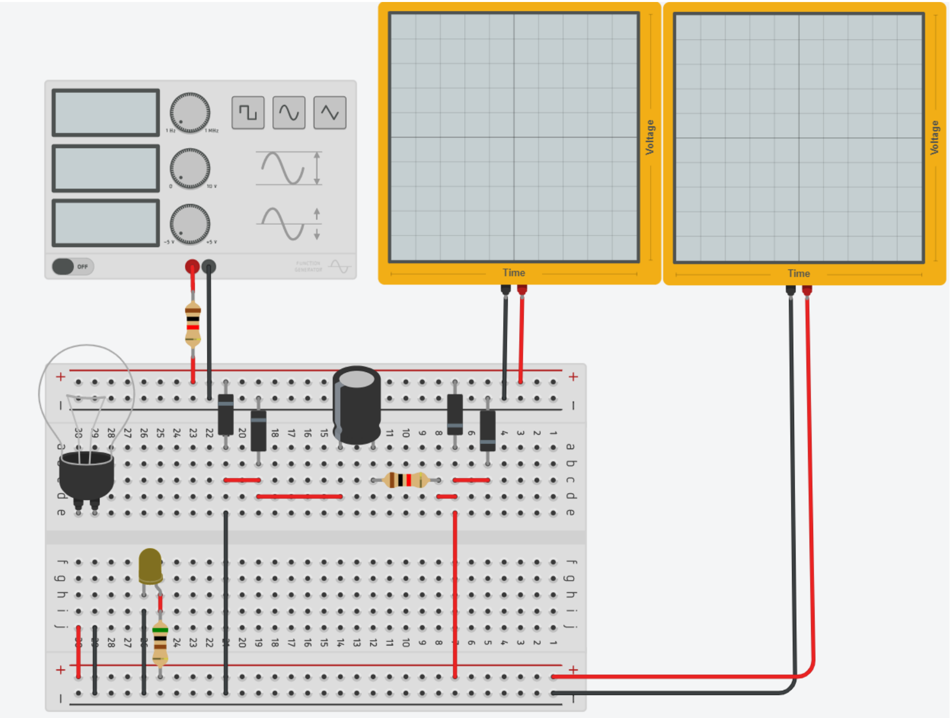
$$K_p = \sqrt{\left(\frac{V_{R_{L_{RMS}}}}{V_{R_{L_{AVG}}}}\right)^2 - 1}$$

$$K_p \cong \frac{V_{R_{L_{max}}} - V_{R_{L_{min}}}}{V_{R_{L_{max}}} + V_{R_{L_{min}}}} = \frac{V_{R_{L_{max}}} - V_{R_{L_{min}}}}{2V_{R_{L_{AVG}}}}$$

		бренд	модель	описание	цена	Вт	Лм	эфф	экв	К	CRI	угол	пул	ВИ	итог	гар	акт
		Smartbuy	SBL-P45-05-30K-E14	G45 350Lm 5W 3000K M E14		4.8	471	98.1	50	3054	73.5	126	1		3.5		+
		Smartbuy	SBL-P45-07-30K-E14	G45 530Lm 7W 3000K M E14		5.8	451	77.8	50	2798	72.6	176	1	-	3.1	24	+
		Smartbuy	SBL-P45-07-30K-E14 2	G45 530Lm 7W 3000K M E14		5.7	480	84.2	55	2786	73.7	132	2	-	3.2	24	+
		Smartbuy	SBL-P45DF-5-40K-E14	G45 370Lm 5W 4000K F E14	221	3.6	267	75.2	30	3755	85.5	294	100	+	0.2	24	+

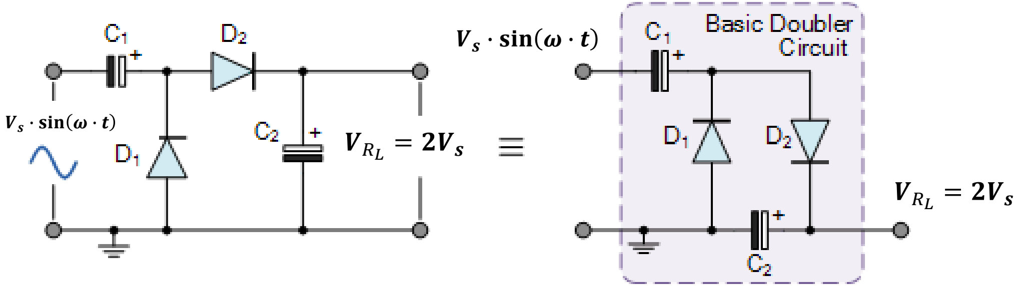
Rectifier example

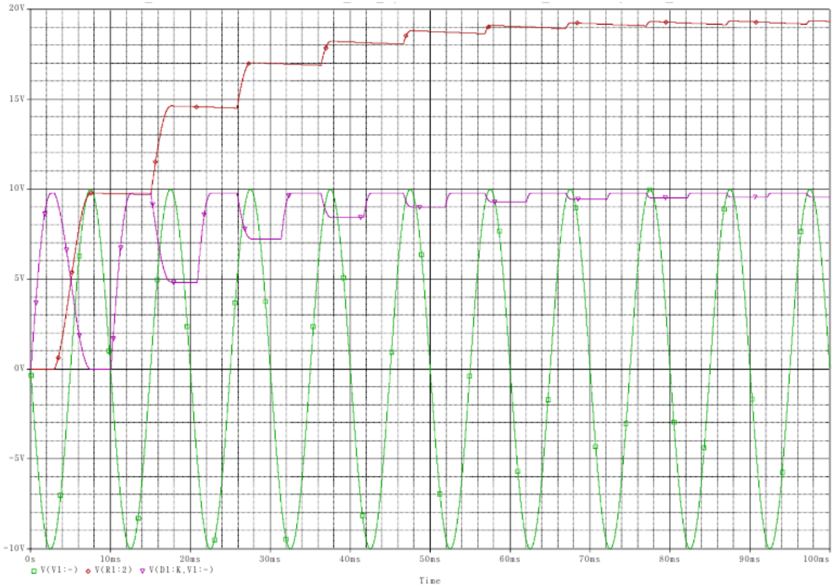
https://www.tinkercad.com



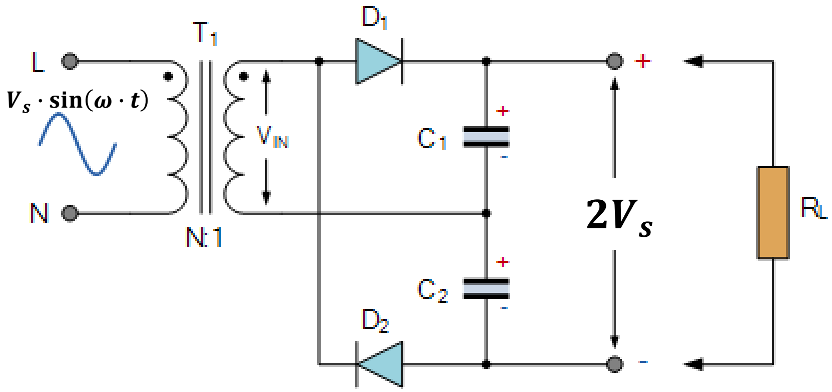
Voltage doubler (Greinacher multiplier)

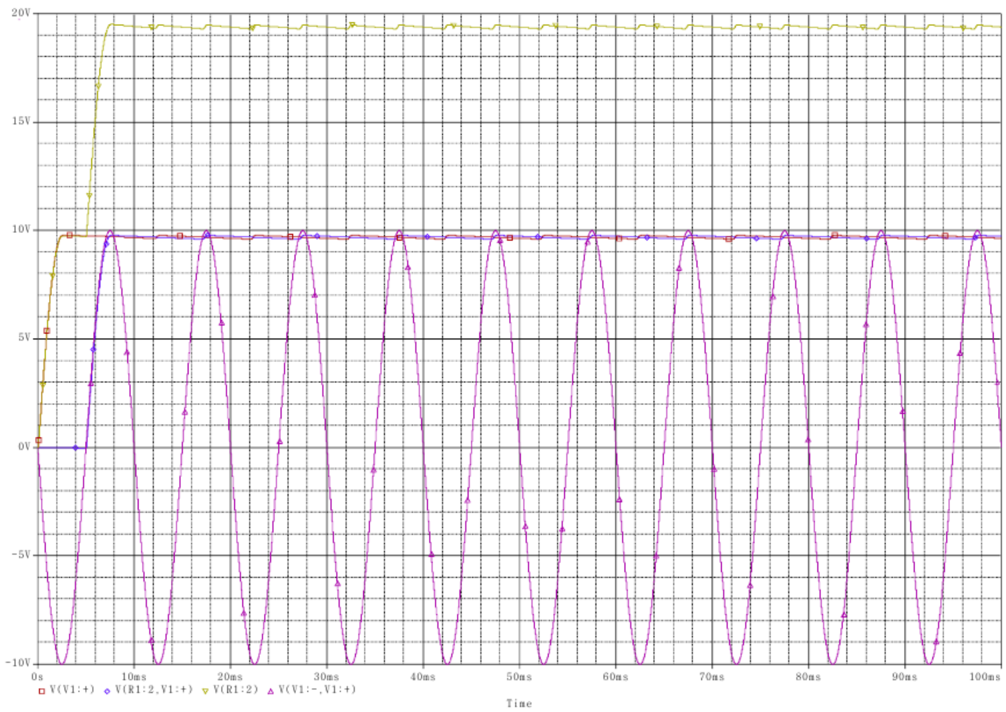
Heinrich Greinacher, 1914



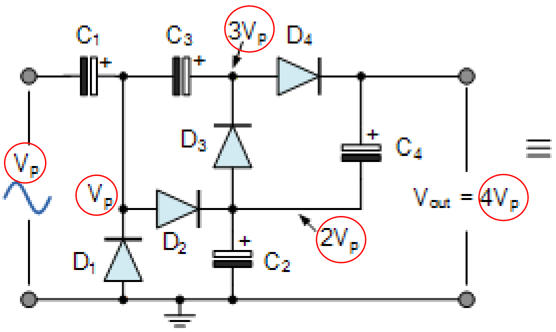


Full-wave voltage doubler





Voltage multiplier



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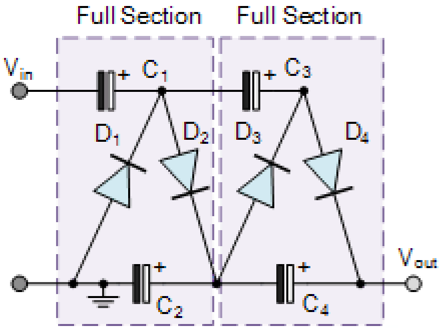

$$C = \frac{N^2+N}{2}\frac{I_L}{f\Delta U_L}$$

$$U_L = NU_{IN_{MAX}} - \frac{I_L(N^3+\frac{9}{4}N^2+\frac{1}{2}N)}{12fC}$$

This Cockcroft–Walton particle accelerator was used during the development of the atomic bomb. Built in 1937 by Philips of Eindhoven it is now in the National Science Museum in London, England.

750 kV Cockcroft-Walton accelerator used as the initial particle injector of the Japanese KEK accelerator, Tsukuba, Japan. The CW generator is on the right, the particle source is on the left.

Ernest Walton

Ernest Walton

Born	6 October 1903 Abbeyside, Dungarvan, Co. Waterford, Ireland
Died	25 June 1995 (aged 91) Belfast, Northern Ireland
Nationality	Irish
Alma mater	Trinity College Dublin Trinity College, Cambridge
Known for	The first disintegration of an atomic nucleus by artificially accelerated protons ("splitting th atom")
Awards	Hughes Medal (1938) Nobel Prize in Physics (1951)
Scientific career	
Fields	Physics
Institutions	Trinity College Dublin University of Cambridge Methodist College Belfast Dublin Institute for Advanced Studies
Doctoral advisor	Ernest Rutherford

Sir John Cockcroft

Born	27 May 1897 Todmorden, West Riding of Yorkshire, England
Died	18 September 1967 (aged 70) Cambridge, Cambridgeshire, England
Nationality	British
Alma mater	Victoria University of Manchester Manchester Municipal College of Technology St. John's College, Cambridge
Known for	Splitting the atom
Awards	Hughes Medal (1938) Commander of the Order of the British Empire (1944) Knight Bachelor (1948) Nobel Prize in Physics (1951) Royal Medal (1954) Faraday Medal (1955) Order of Merit (1957) Atoms for Peace Award (1961) Wilhelm Exner Medal (1961) Knight Commander of the Order of the Bath (1963) Medal of Freedom with golden palms (United States, 1947) Chevalier de la Legion d'Honneur (France, 1950) Knight Commander of the Military Order of Christ (Portugal, 1955) Grand Cross of the Order of Alfonso X (Spain, 1958)
Scientific career	
Fields	Physics
Institutions	Atomic Energy Research Establishment
Thesis	*On phenomena occurring in the condensation of molecular streams on surfaces* (1928)
Academic advisors	Ernest Rutherford
1st Master of Churchill College, Cambridge	
In office	1959–1967
Succeeded by	Sir William Hawthorne

Thank you for your attention!