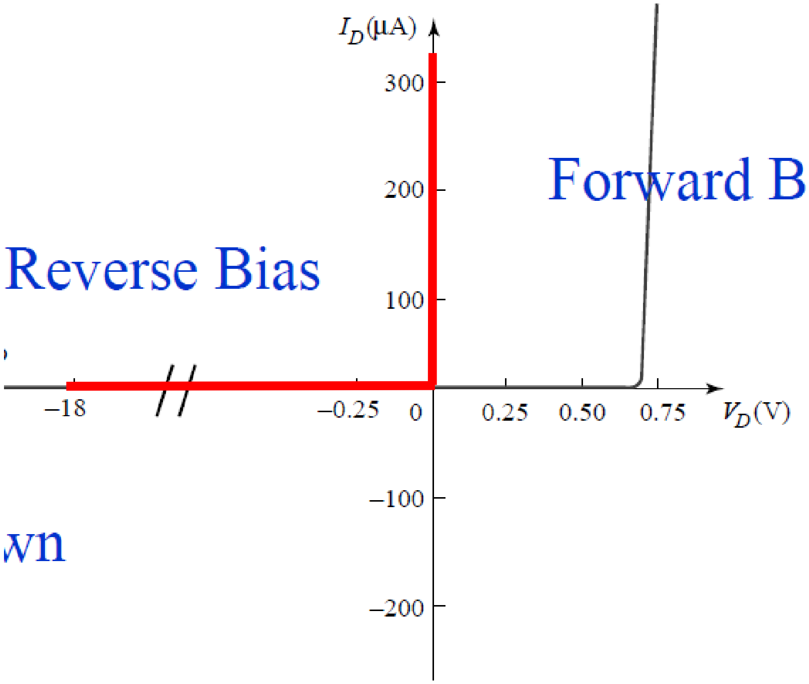
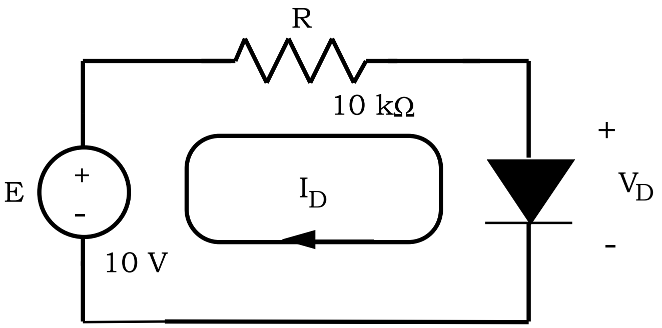
DIODE CIRCUITS

1 DC and low-frequency diode models
2 The diode-resistance circuit
3 Peak and power detectors
4 Rectifiers
5 Thermal sensor

Ideal diode model

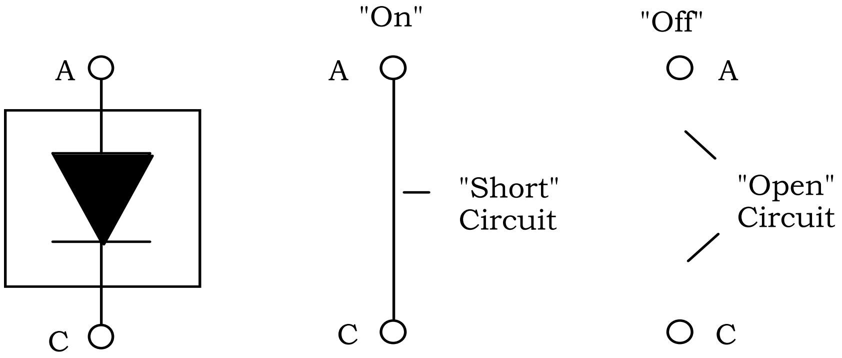




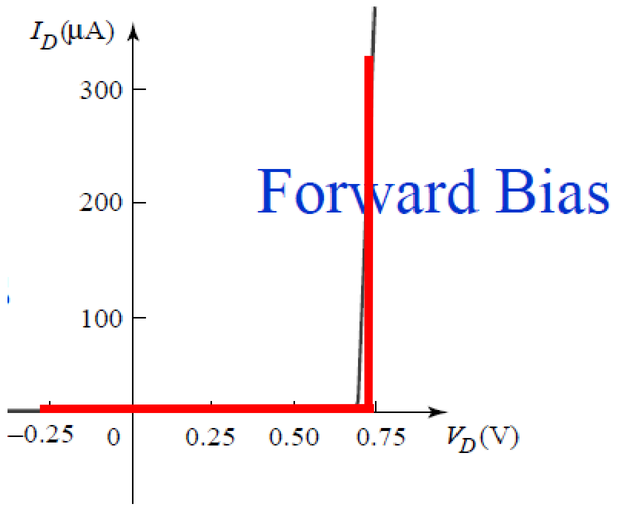
$$I_D = \frac{E - V_D}{R}$$

$$I_D = \frac{10V}{10k\ \Omega}$$

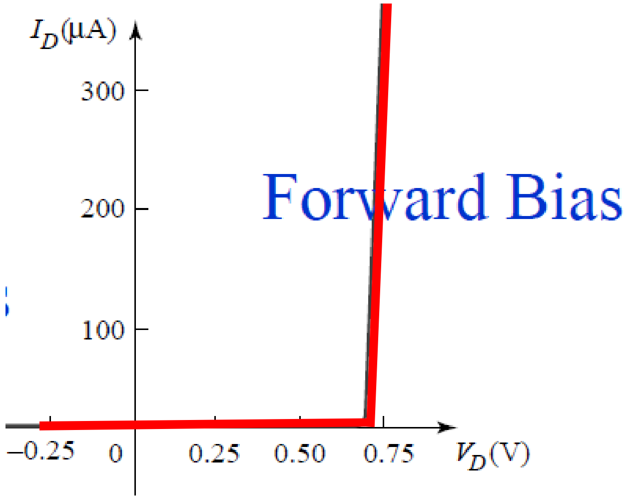
$$I_D = 1mA$$

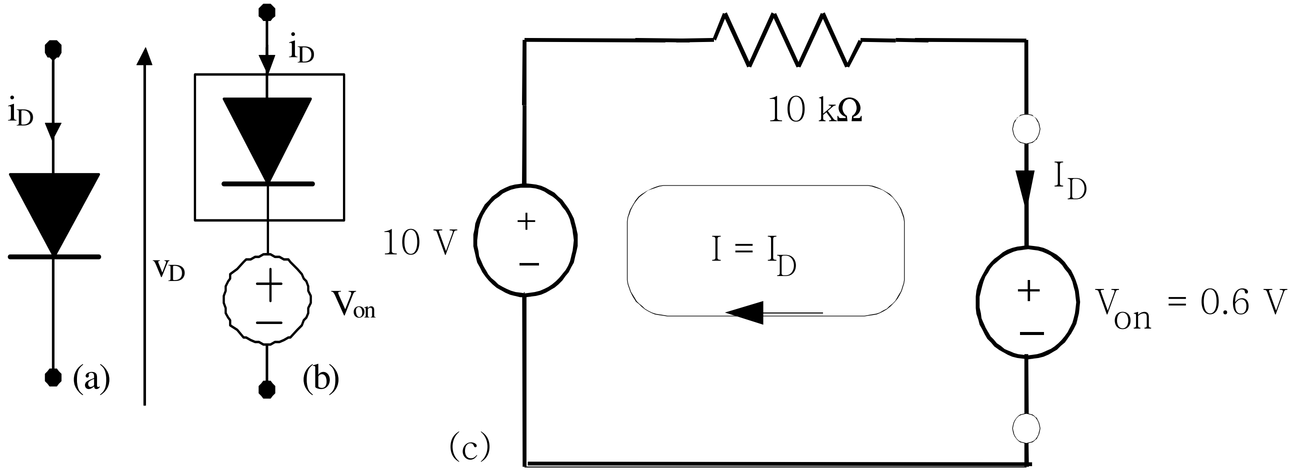


- **Constant-voltage-drop model**



Constant-voltage-drop + resistance model



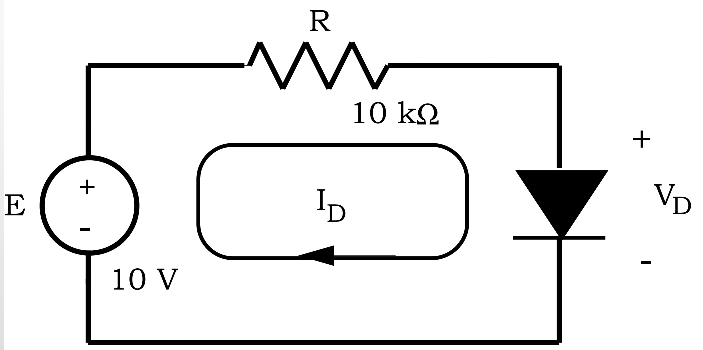


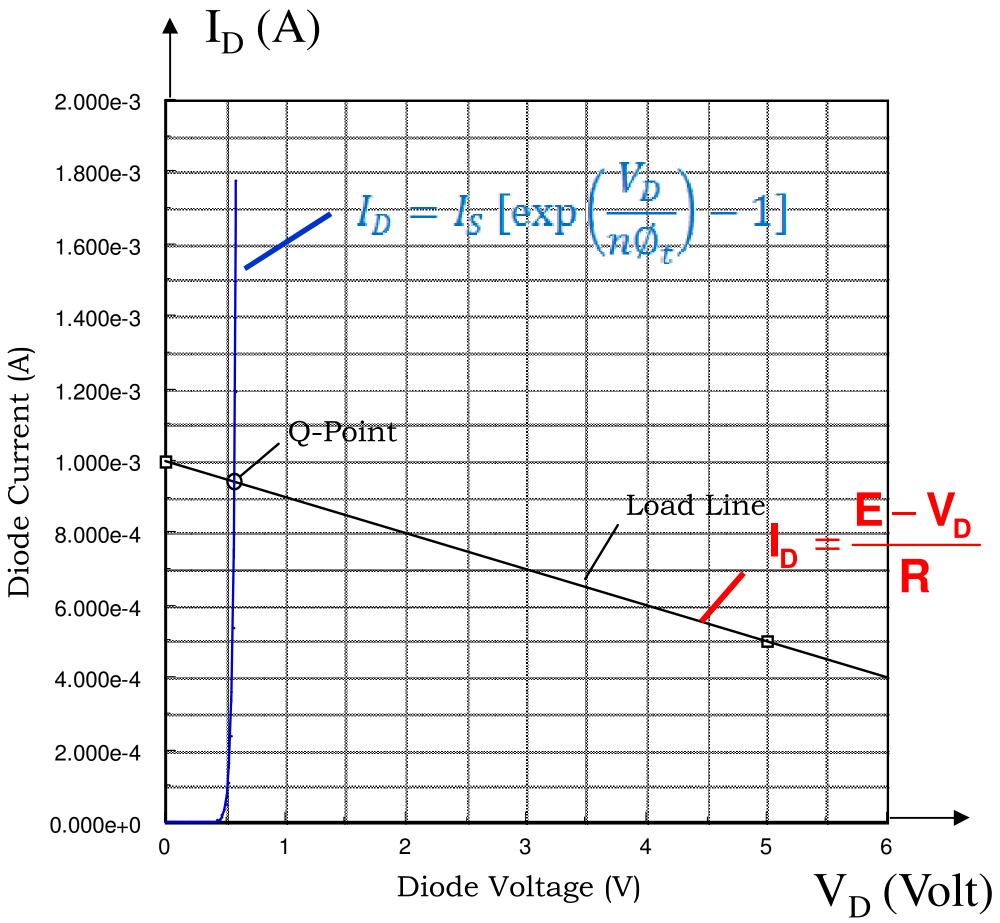
$$I = \frac{10 - 0.6}{10\text{ k}\Omega}$$

$$I = 0.94\text{ mA}$$

What if the input voltage is 1 V? 0.1V?

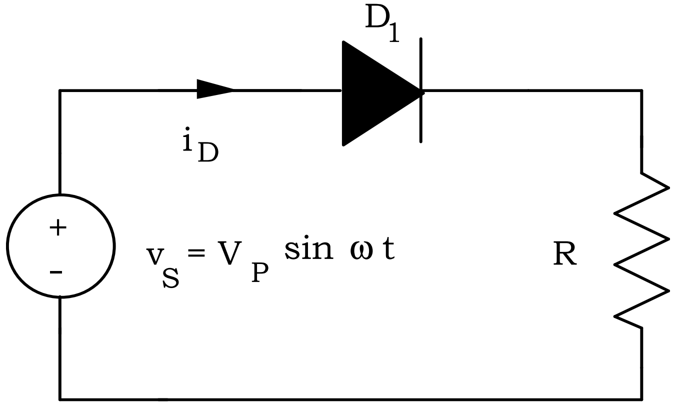
Graphical analysis





Diode i-v characteristic and load line

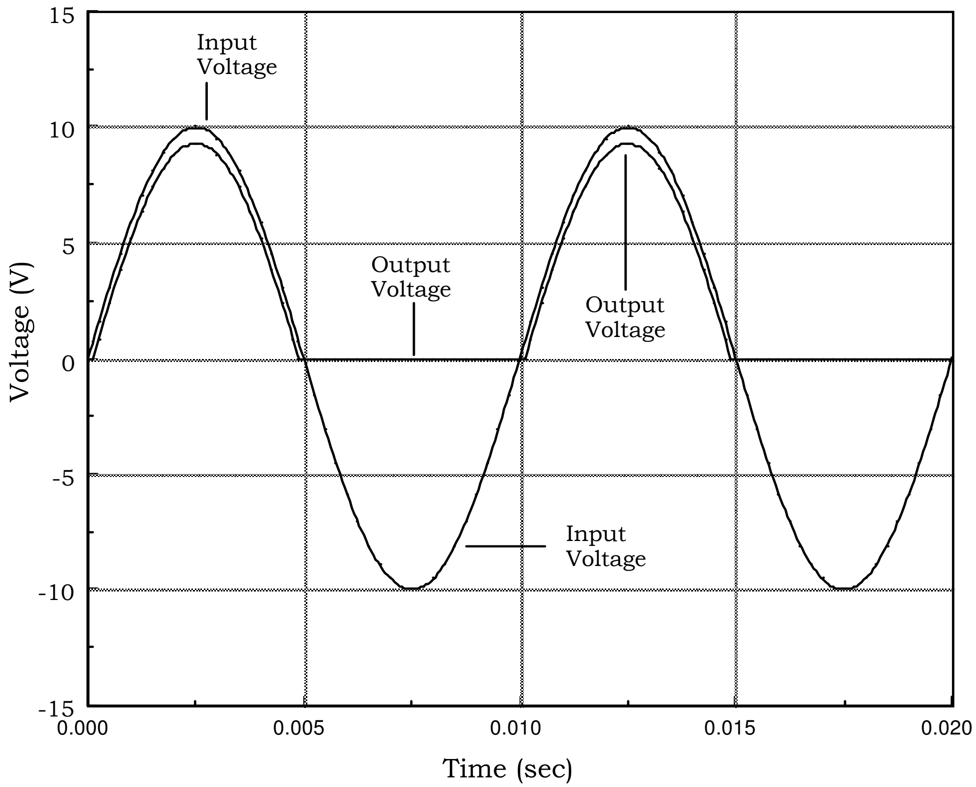
Half-wave rectifier circuit: resistive load



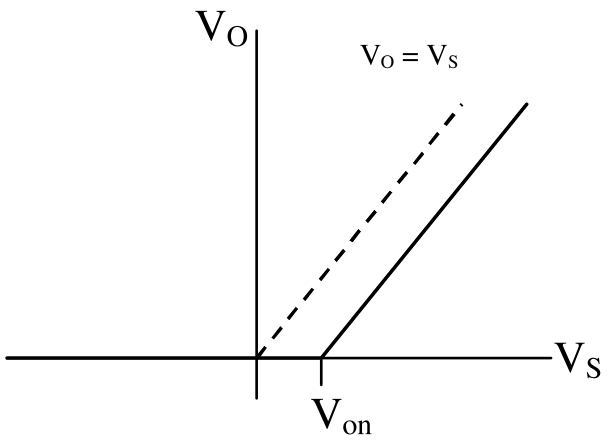
Simplified analysis

$V_S \leq V_{on} \rightarrow$ Diode is ON

$V_S > V_{on} \rightarrow$ Diode is OFF



V_P = 10 V and V_{on} = 0.7 V



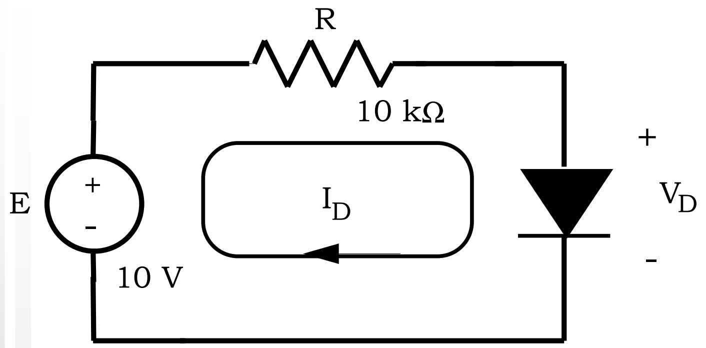
If $V_p >> V_{on}$

$$\bar{i}_D = \frac{1}{\pi}\frac{V_p}{R}$$

(average value)

$$i_{Dmax} = \frac{V_p}{R}$$

$$PIV = V_p$$



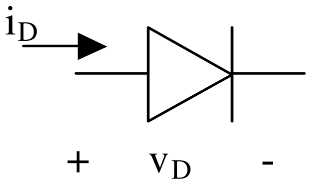
If you know I, it is simple to calculate E

$$E = RI + n\phi_t \ln\left(\frac{I}{I_S} + 1\right)$$

Example:
R= 10 kΩ,
I_S=1 nA, $n\phi_t$ = 50 mV

I/I_S	E (mV)
0	0
1	50 ln2
9	50 ln10
10^3	$10+50 \ln 10^3$
10^6	$10^4 + 50 \ln 10^6$
-0.5	-50 ln2
-0.9	-50 ln10
-1	-∞
-9	???????

As you can see, for this specific example the resistor does not play an important role for current less than 1 µA whereas the diode voltage drop is small for currents greater than, say, 1 mA.

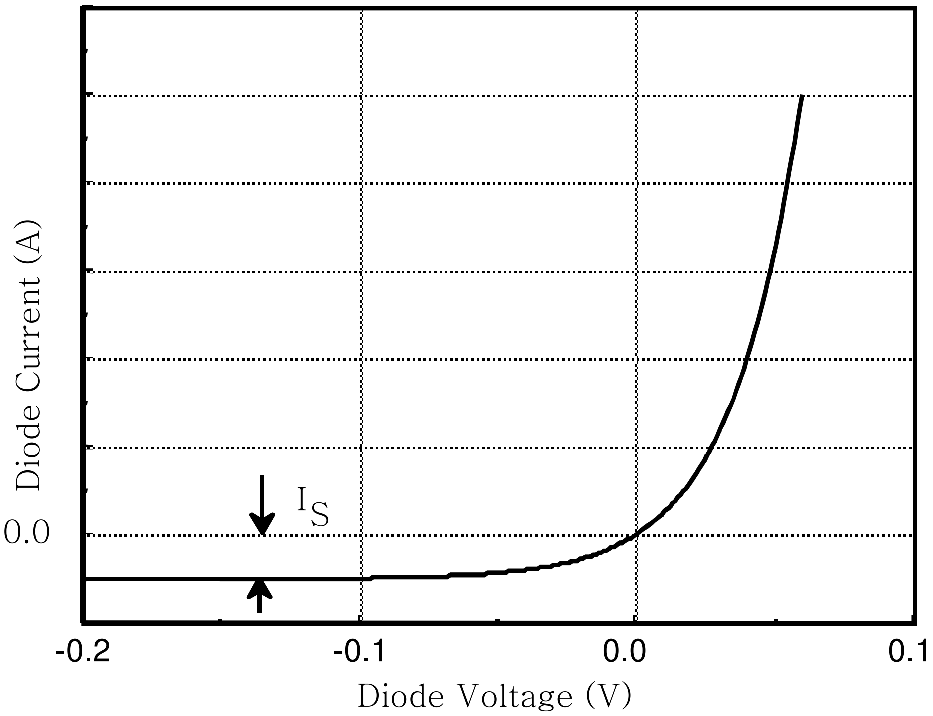


$$\phi_t = kT/q$$

$$i_D = I_S\left[\exp\left(\frac{v_D}{n\varphi_t}\right) - 1\right]$$

$\varphi_t \cong 25$ mV @ 290 K

$n \sim 1$ to 1.5



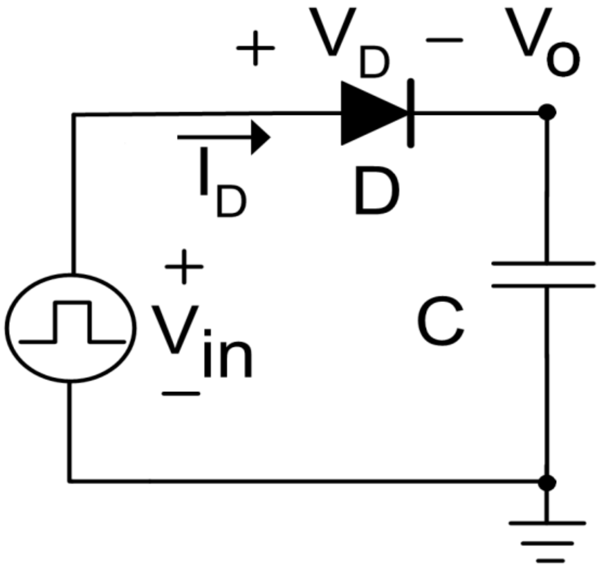
In an IC implementation, most diodes (or diode-connected MOSFETs) can be represented by Shockley equation.

I_S (saturation current)- design parameter.

Voltage rectifier: fundamentals

A simple case: square-wave input

Steady-state analysis



Basic principle: charge conservation/ average current through diode = 0

$$\frac{1}{T}\int_{-T/2}^{T/2} I_D dt = 0 \qquad I_D = I_S[e^{\frac{V_D}{n\phi_t}} - 1]$$

$$\frac{I_S}{T}\left[\int_{-T/2}^{0}\left(e^{\left(\frac{-V_P - V_o}{n\phi_t}\right)} - 1\right)dt + \int_{0}^{T/2}\left(e^{\left(\frac{V_P - V_o}{n\phi_t}\right)} - 1\right)dt\right] = 0$$

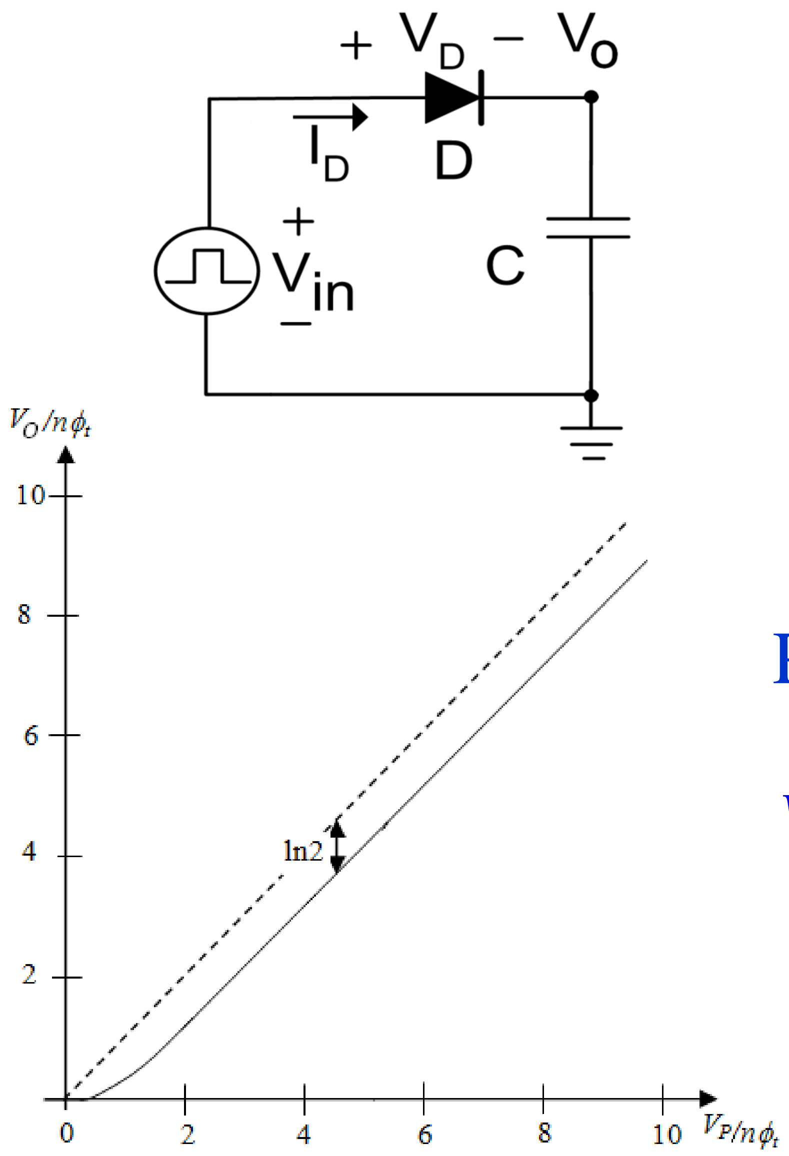
Assumption: very low ripple (high C)

→ $V_o \cong$ constant

$$\frac{V_o}{n\phi_t} = \ln\left[\frac{e^{V_P/n\phi_t} + e^{-V_P/n\phi_t}}{2}\right] = \ln\left[\cosh\left(V_P/n\phi_t\right)\right]$$

Power/Peak Detector

A simple case: square-wave input



$$\frac{V_o}{n\phi_t} = \ln\left[\cosh\left(V_P/n\phi_t\right)\right]$$

Power Detector

$$V_P \ll n\phi_t \quad \rightarrow \quad \frac{V_o}{n\phi_t} \cong \frac{1}{2}\left(\frac{V_P}{n\phi_t}\right)^2$$

Peak Detector

$$V_P \gg n\phi_t \quad \rightarrow \quad V_L \cong V_P - \overbrace{n\phi_t \ln 2}^{\text{Diode “ON” voltage drop}}$$

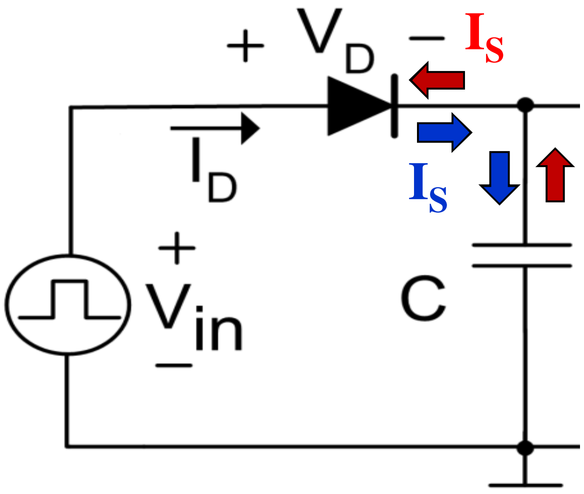
Input

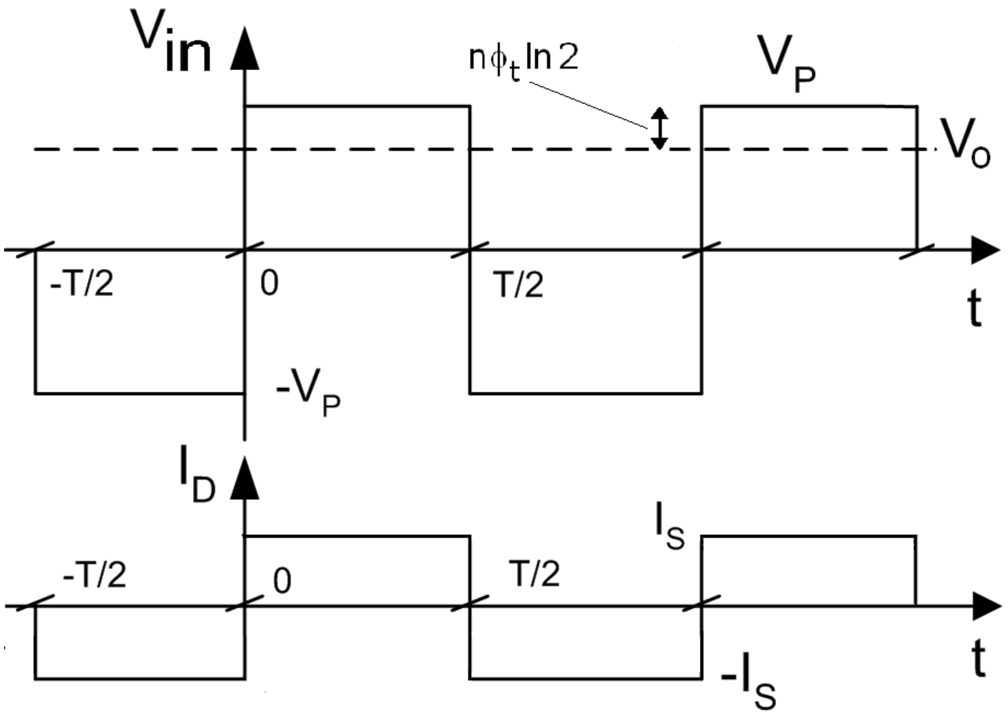
Why?

Results for sine input are similar.
Difference is a “form factor”

Voltage rectifier: fundamentals

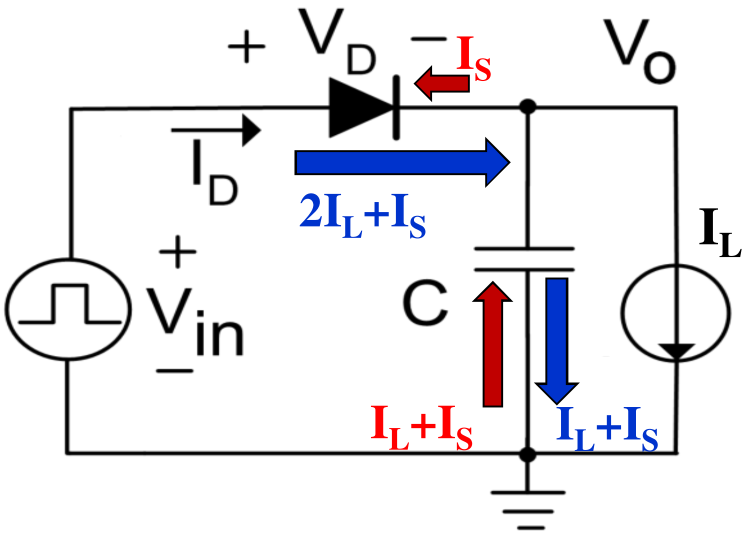
A simple case: square-wave input





Waveforms for $V_P >> n\phi_t$

Voltage rectifier: fundamentals

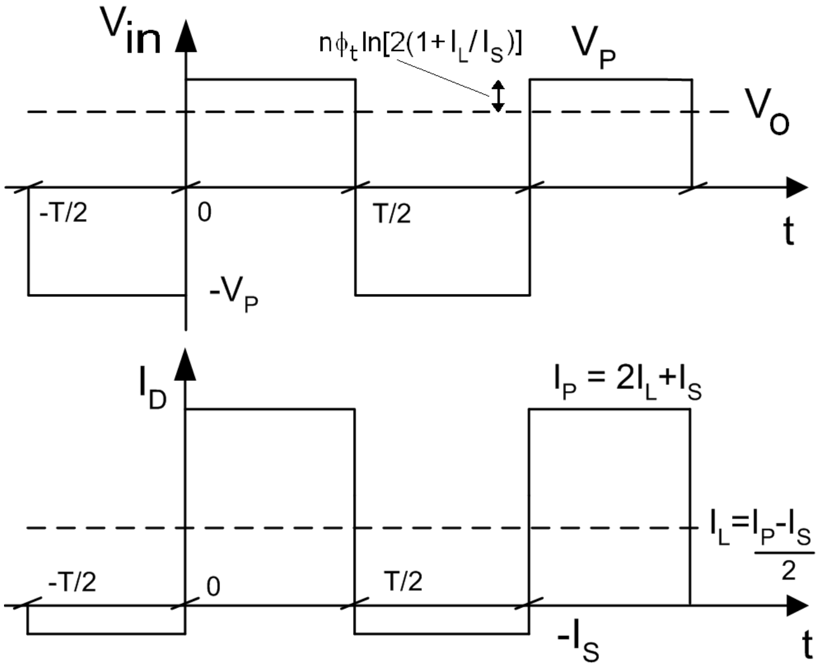


Steady-state analysis

$$\frac{I_S}{T}\left[\int_{-T/2}^{0}\left(e^{\left(\frac{-V_P-V_o}{n\phi_t}\right)}-1\right)dt+\int_{0}^{T/2}\left(e^{\left(\frac{V_P-V_o}{n\phi_t}\right)}-1\right)dt\right]=I_L$$

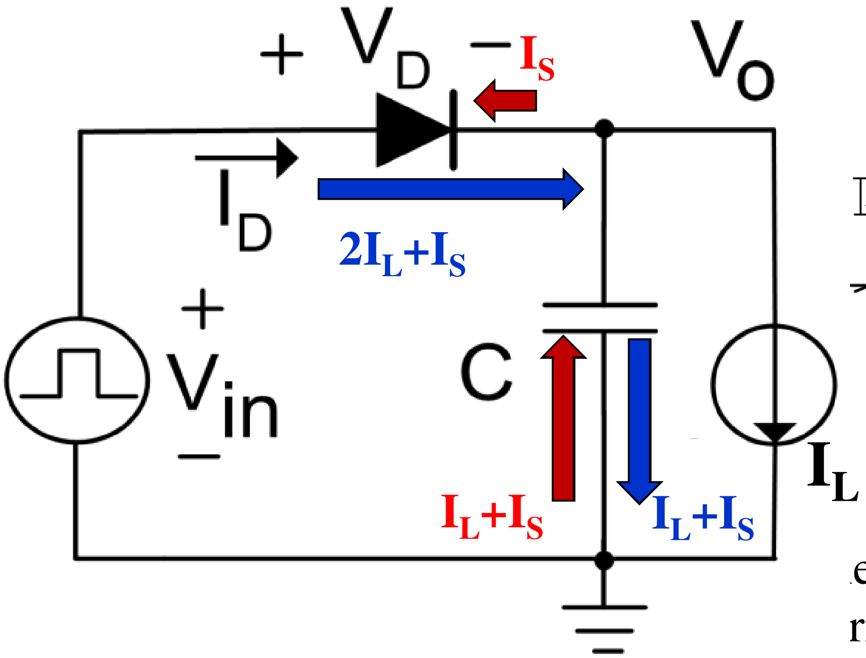
Assumption: very low ripple → $V_o \cong$ constant

$$\frac{V_o}{n\phi_t}=\ln\left[\frac{\cosh\left(V_P/n\phi_t\right)}{1+I_L/I_S}\right]$$

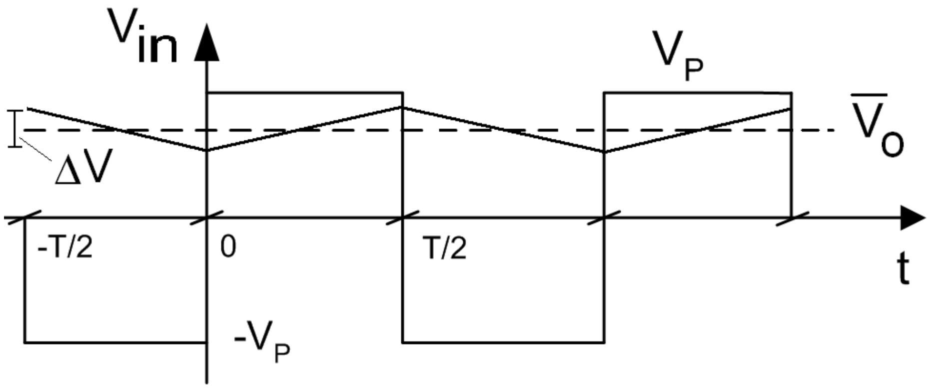


Waveforms for $V_P >> n\phi_t$

Voltage rectifier: fundamentals



Output voltage ripple



e discharge rate of the capacitor diode ring the negative half-cycle of the input is

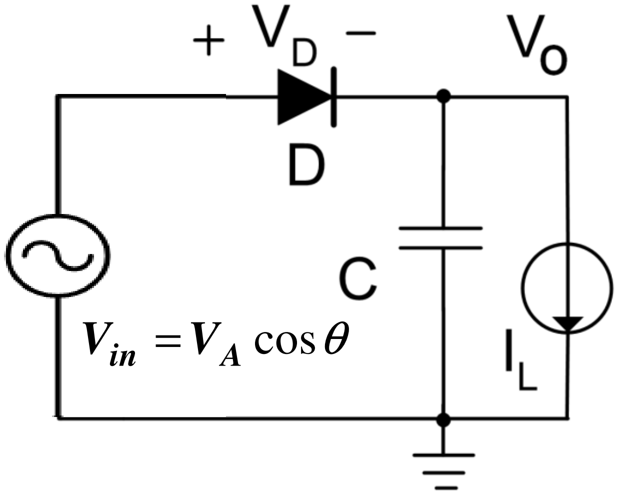
$$I_C = \frac{dQ_C}{dt} = C\frac{dV_C}{dt} \cong I_L + I_S$$

$$\int_{-T/2}^{0} dV_C = \Delta V \cong \frac{I_L + I_S}{C}\frac{T}{2} = \frac{I_L + I_S}{2fC}$$

Voltage rectifier: fundamentals

Sine-wave input

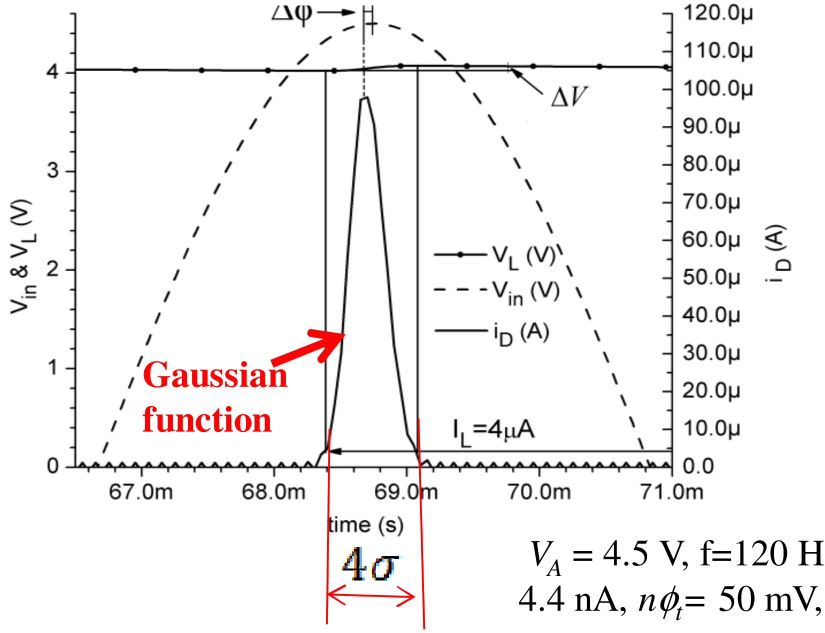
Steady-state analysis



Basic principle: charge conservation

$$\frac{1}{T}\int_{-T/2}^{T/2} I_D\,dt = I_L \qquad I_D = I_S[e^{\frac{V_D}{n\phi_t}} - 1]$$

$$\frac{I_S}{2\pi}\left[\int_{-\pi}^{0}\left(e^{\left(\frac{-V_A\cos\theta - V_o}{n\phi_t}\right)} - 1\right)d\theta + \int_{0}^{\pi}\left(e^{\left(\frac{V_A\cos\theta - V_o}{n\phi_t}\right)} - 1\right)d\theta\right] = I_L$$



Assumption: very low ripple (high C)
→ $V_o \cong$ constant

$$\frac{V_o}{n\phi_t} = \ln\left[\frac{I_0(V_A/n\phi_t)}{1 + I_L/I_S}\right]$$

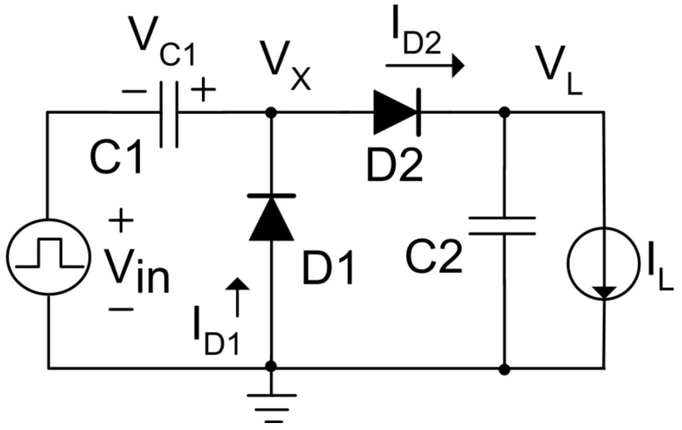
$$I_0(z) = \frac{1}{\pi}\int_0^{\pi} e^{z\cos\theta}\,d\theta$$

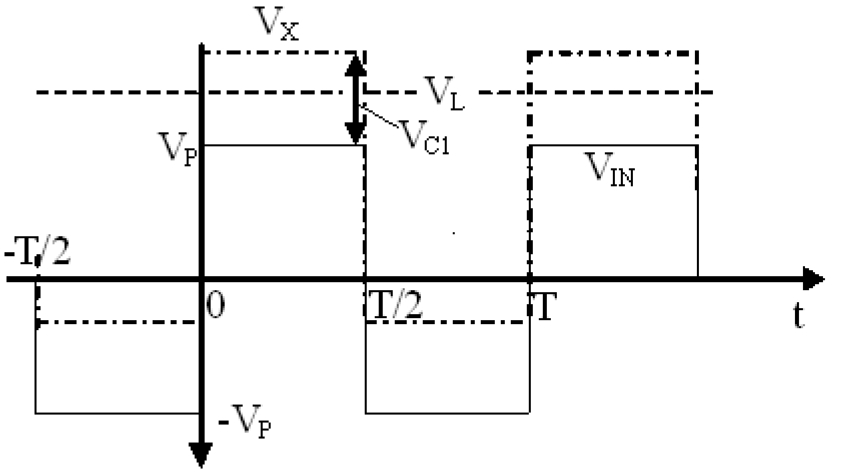
modified Bessel function of the first kind of zero order

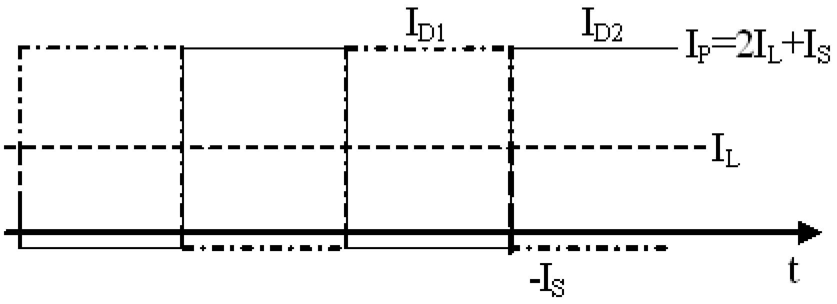
V_A = 4.5 V, f=120 Hz, I_L=4μA. I_S = 4.4 nA, $n\phi_t$= 50 mV, C=150 nF.

The voltage multiplier

Voltage doubler → Clamping circuit & peak detector





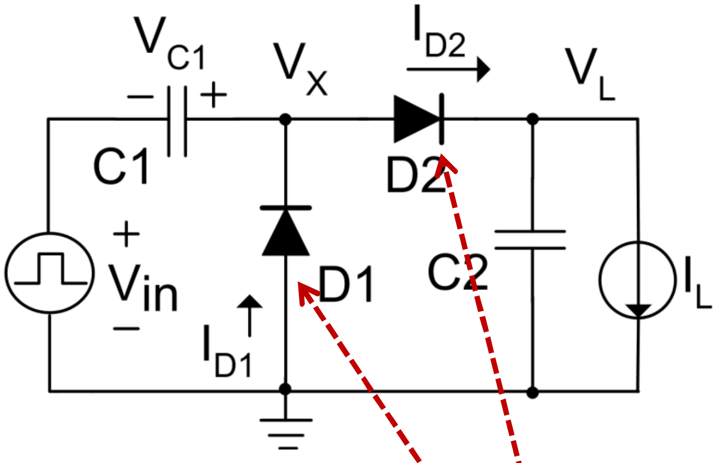


D_1, C_1, and V_{in} →half-wave rectifier. V_{C1} stored in C1 is a dc voltage equal to that of a half-wave rectifier. $V_X = V_{in}+V_{C1}$. The dc output voltage of the doubler is equal to the value calculated for the half-wave rectifier plus V_{C1}.

$$V_L = 2V_{C1}$$

The voltage multiplier

Voltage doubler



$$PCE = \frac{P_{load}}{P_{in}} = \frac{V_L I_L}{P_{load} + P_{loss}}$$

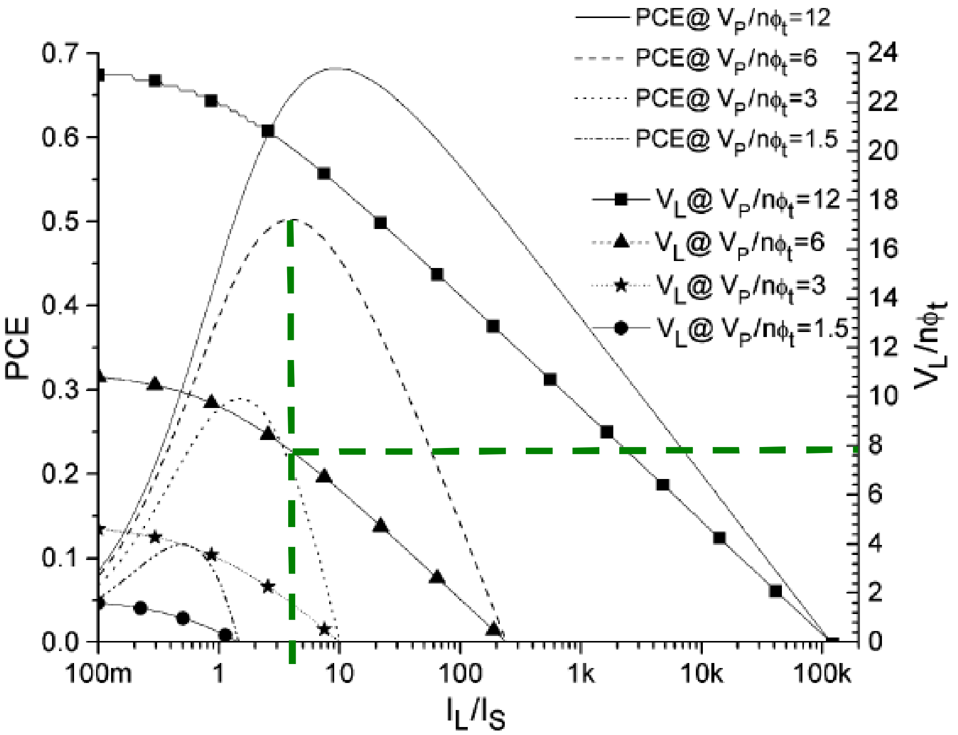


Fig. 3. Power conversion efficiency and load voltage of the voltage doubler versus normalized load current for values of $V_P/n\phi_t$ equal to 1.5, 3, 6, and 12.

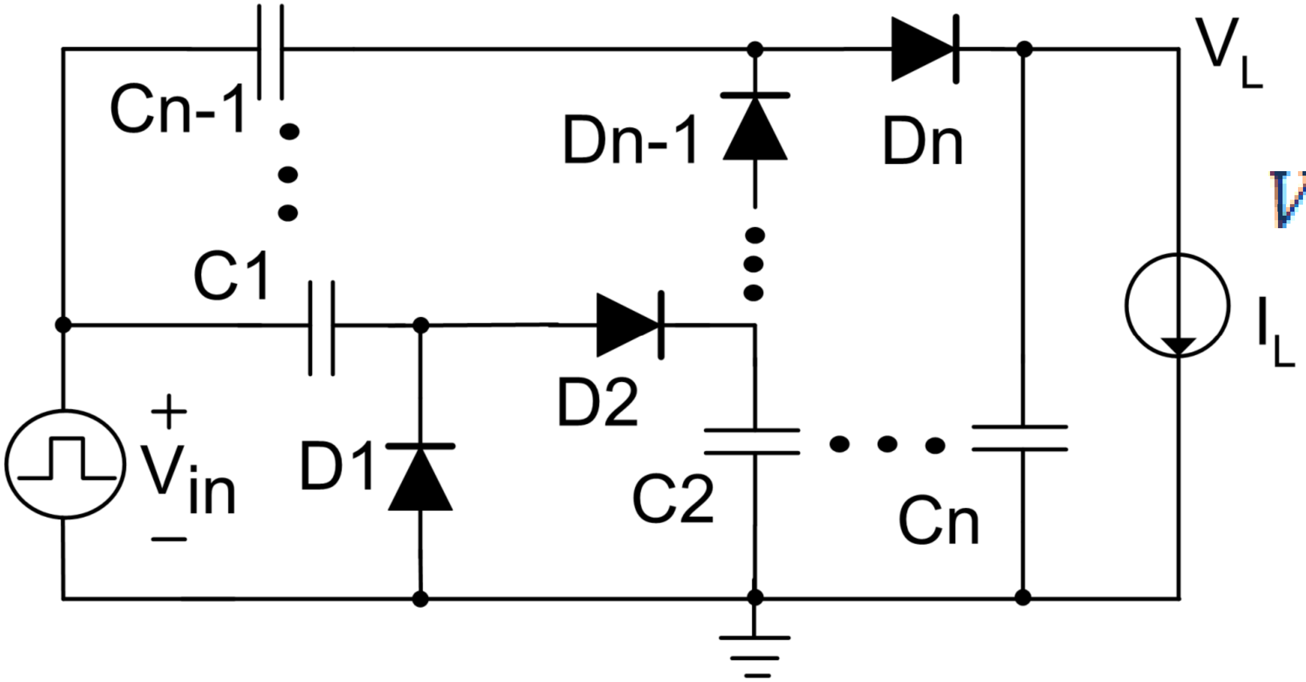
$$PCE_{\max} = PCE \ @ \ \frac{V_L}{2(N)n\Phi_t} = \frac{I_L}{I_S}$$

PCE: Power Conversion Efficiency

Voltage doubler

N-stage voltage multiplier

The voltage multiplier



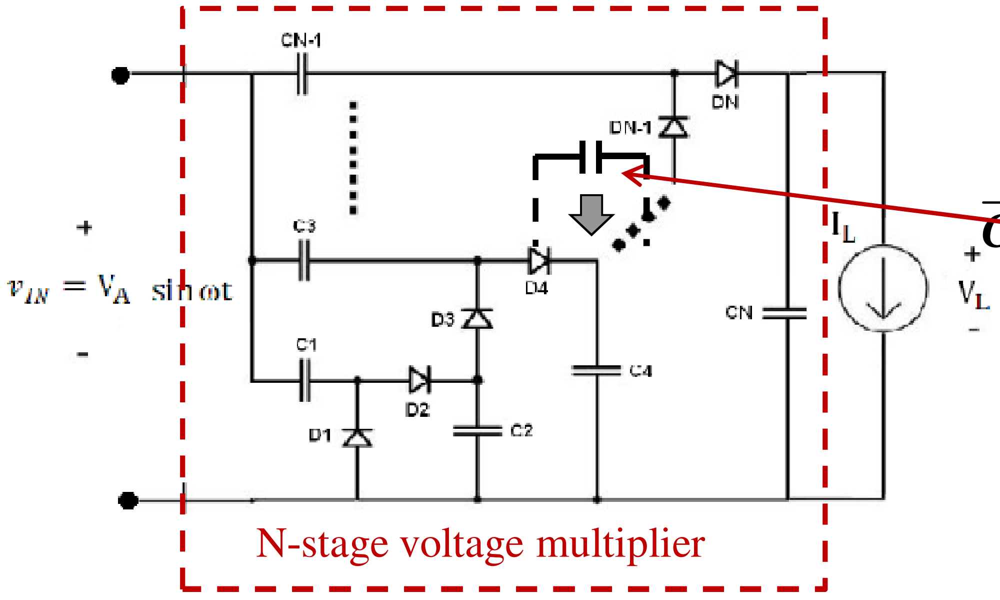
$$V_L = nV_{CI}$$

N-stage voltage multiplier

Applications:

- Generation of voltages higher than the supply voltage, for EEPROMs, flash memories
- Energy harvesting for RFID tag chips, for example

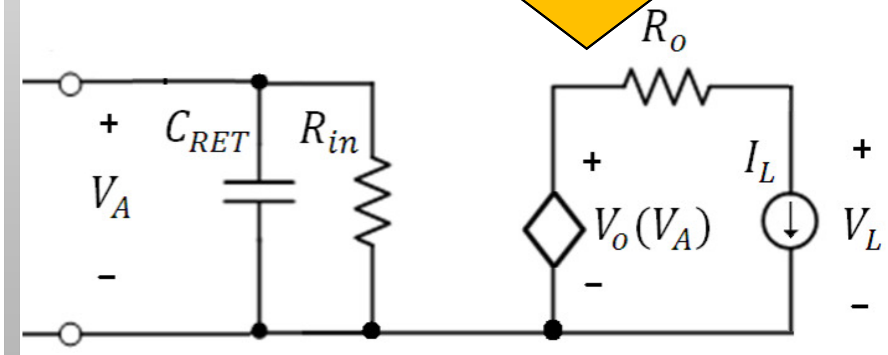
The voltage multiplier model



$\overline{C_D}$ → Average diode capacitance

$$\frac{V_L}{Nn\phi_t} = \ln\left[\frac{I_0(v_{AP})}{1+\frac{I_L}{I_S}}\right] \qquad v_{AP} = \frac{V_A}{n\phi_t}$$

$$R_O = \frac{V_O - V_L}{I_L} = \frac{Nn\phi_t}{I_S}\,\frac{\ln\left[1+\frac{I_L}{I_S}\right]}{\frac{I_L}{I_S}}$$

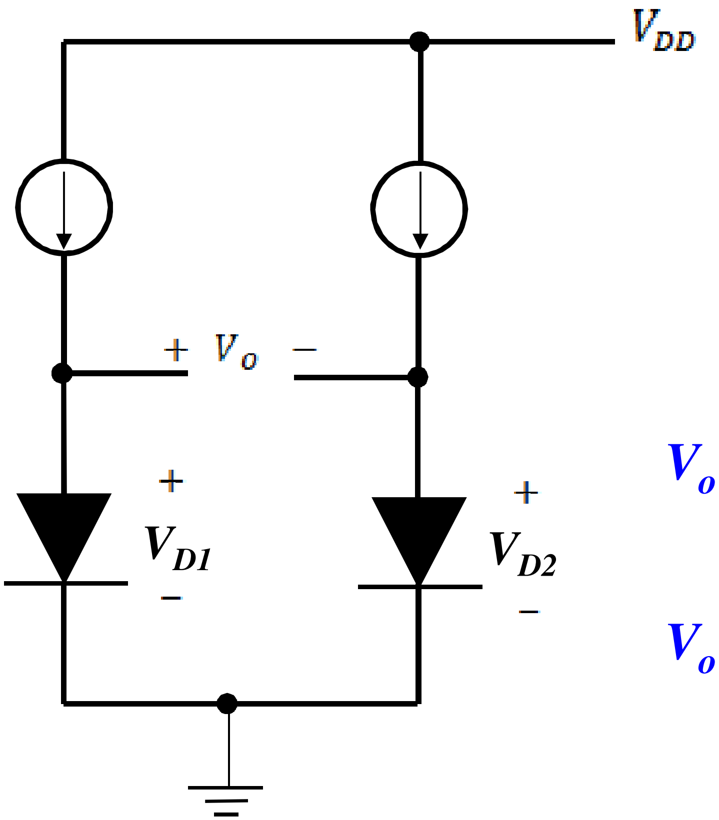


$$R_{in} = \frac{V_A^2}{2P_{in}} \qquad R_{in} = \frac{V_A}{2\alpha_P N(I_L + I_S)}\,\frac{I_0(v_{AP})}{I_1(v_{AP})}$$

$$I_1(v_{ap}) = I_0'(v_{ap})$$

$$C_{RET} \simeq N\overline{C_D}$$

Temperature sensor



$$V_o = V_{D1} - V_{D2} = n\phi_t \left[\ln\left(1 + \frac{I_1}{I_S}\right) - \ln\left(1 + \frac{I_2}{I_S}\right) \right]$$

$$V_o \cong n\phi_t \left[\ln\frac{I_1}{I_S} - \ln\frac{I_2}{I_S} \right] = n\phi_t \ln\frac{I_1}{I_2}$$

References

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