Lecture11:
Diode models and circuits (3)

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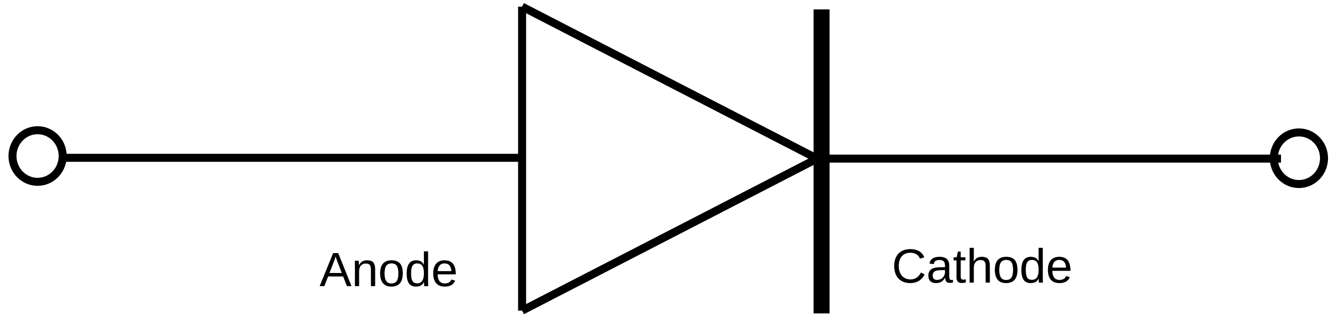
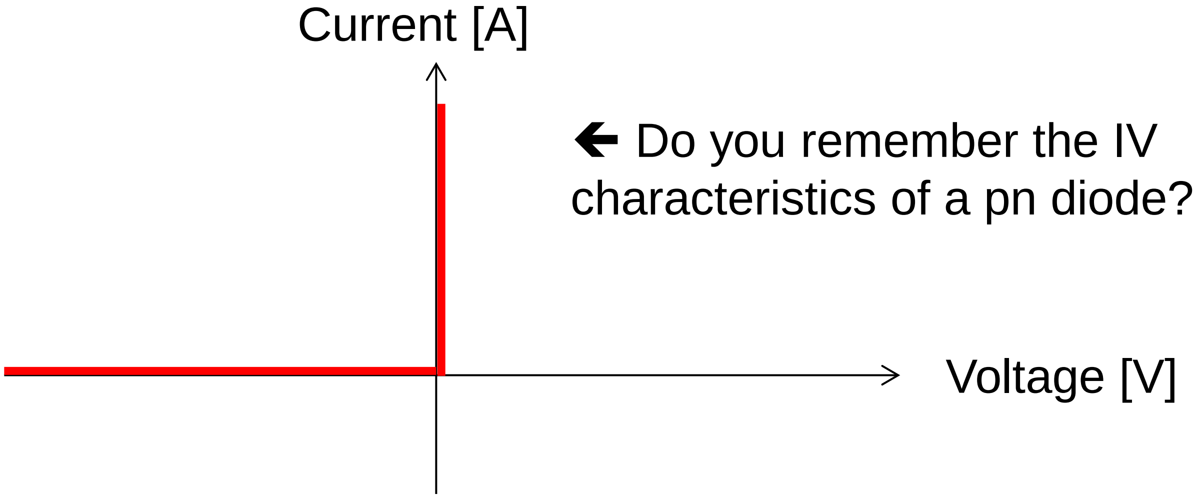
Diode

- Its symbol



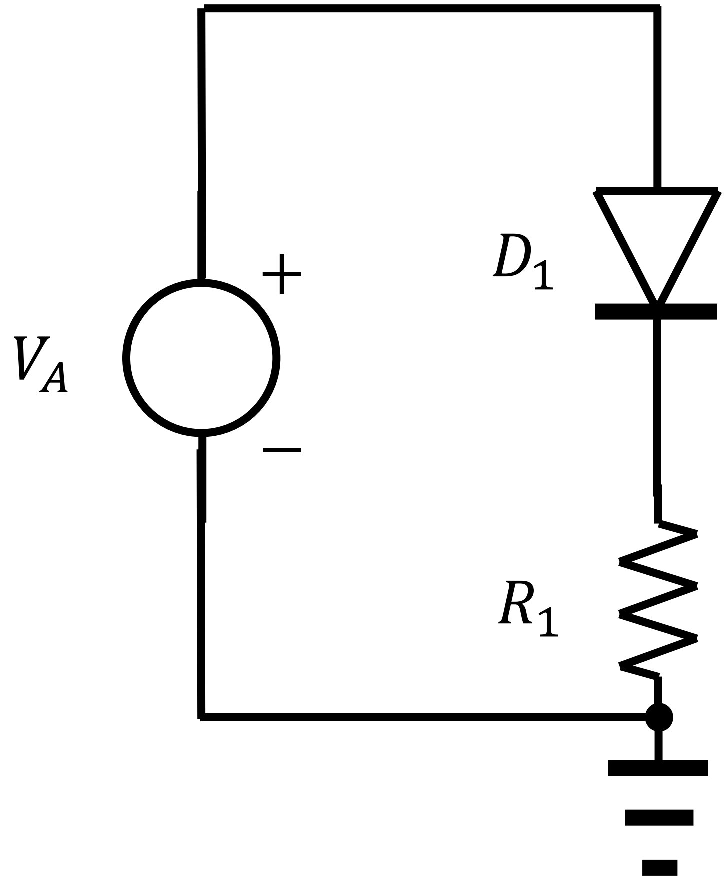
- Ideally, a perfect rectifier



← Do you remember the IV characteristics of a pn diode?

Example 3.4

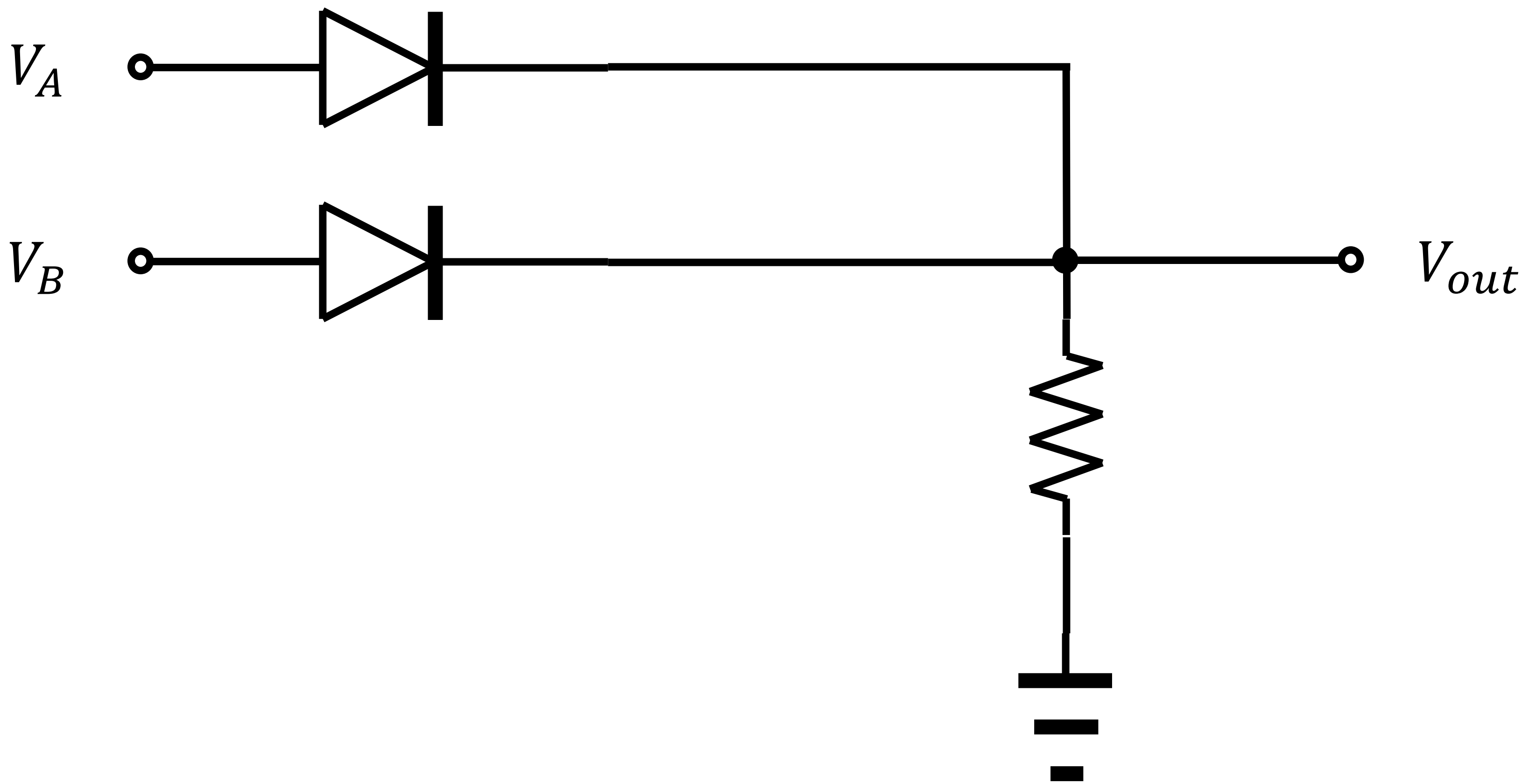
- A diode-resistor combination



← Consider two cases, $V_A > 0$ and $V_A < 0$.
← Draw the IV curve.

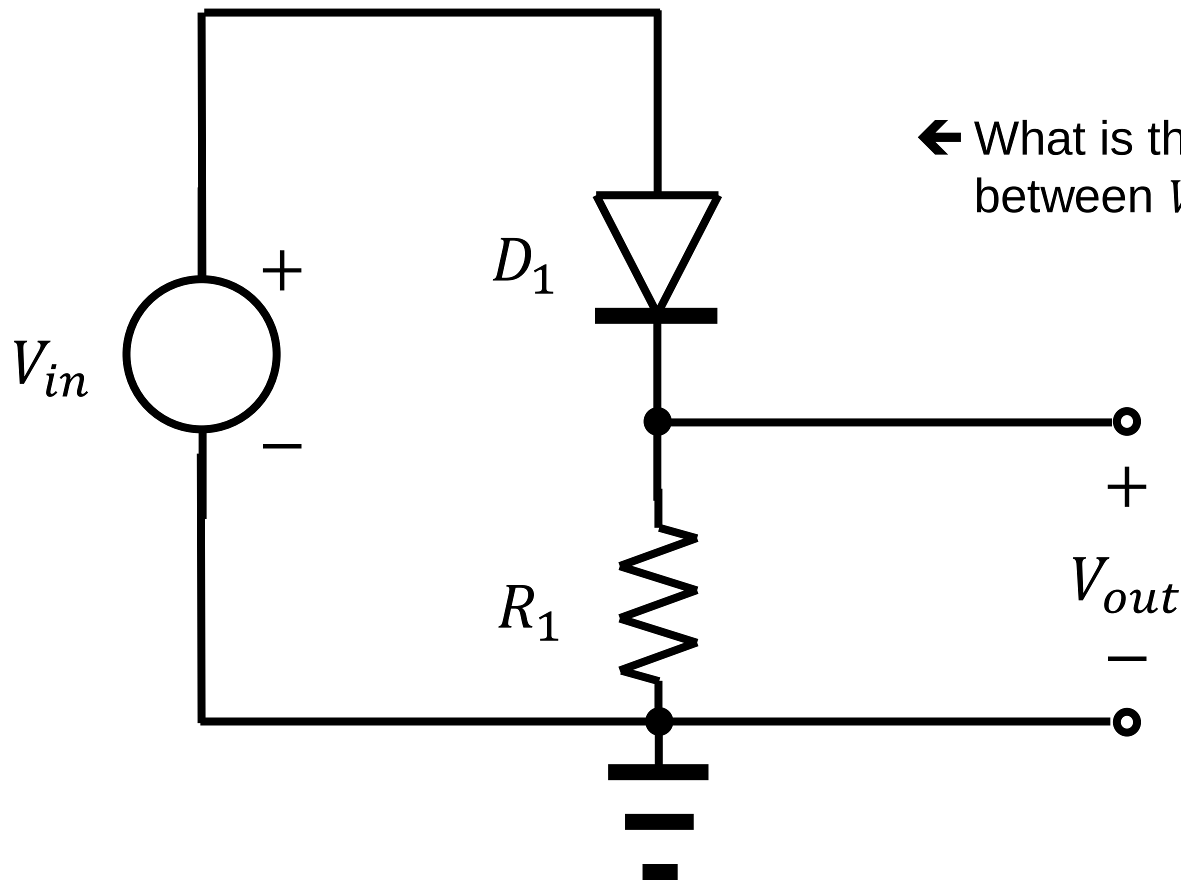
Example 3.6

- An OR gate



Rectifier

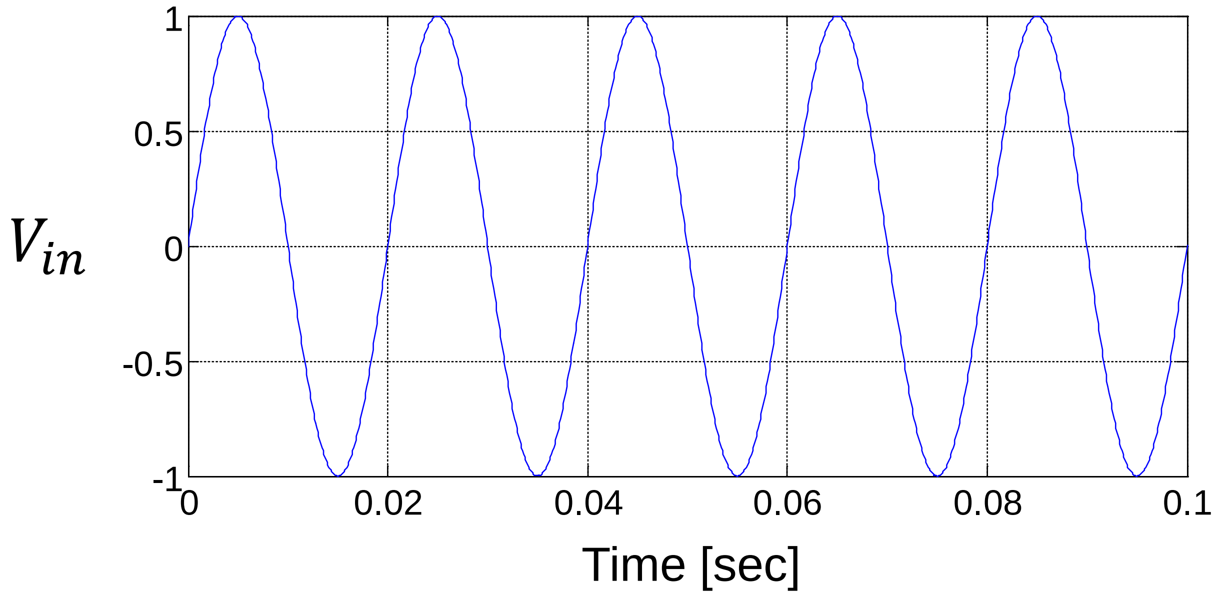
- Same circuit shown in Example 3.4.



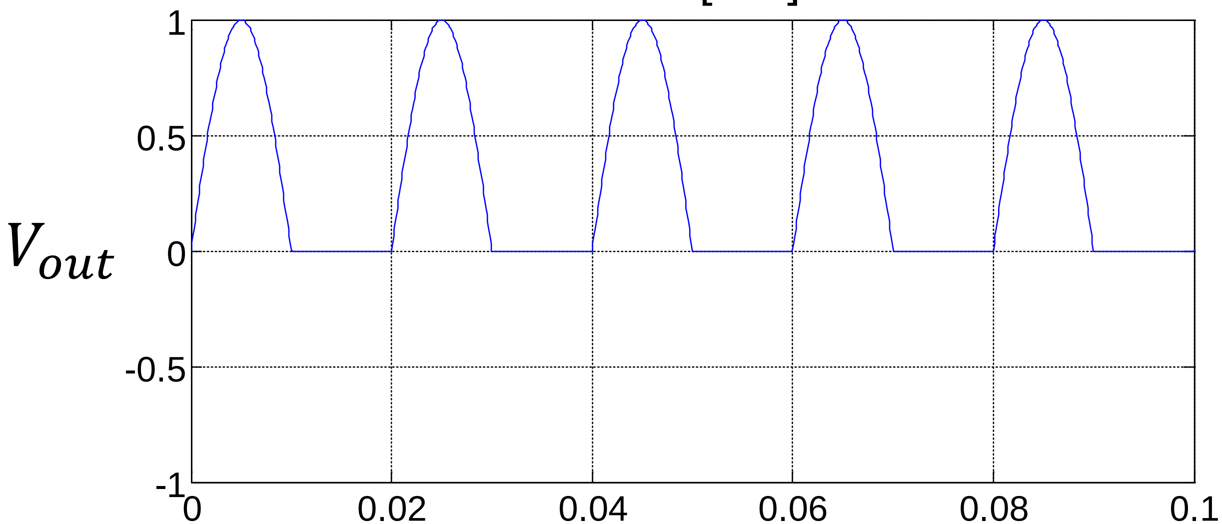
← What is the relation between V_{in} and V_{out}?

Input vs. output

- Input
  - 50 Hz
  - Pure sine
  - No dc

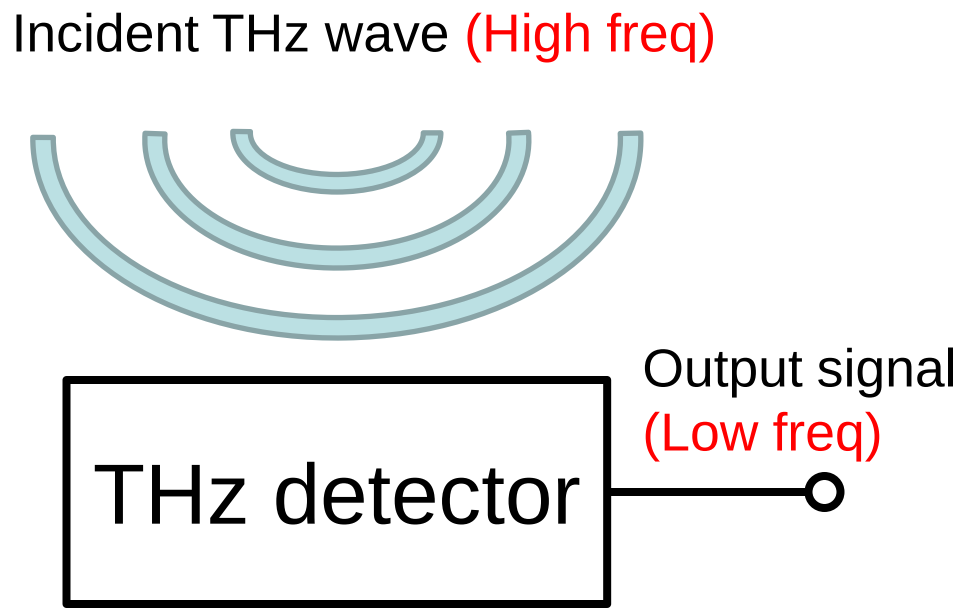


- Output
  - 0, 50, 100, … Hz
  - dc voltage: $\frac{1}{\pi}$ V



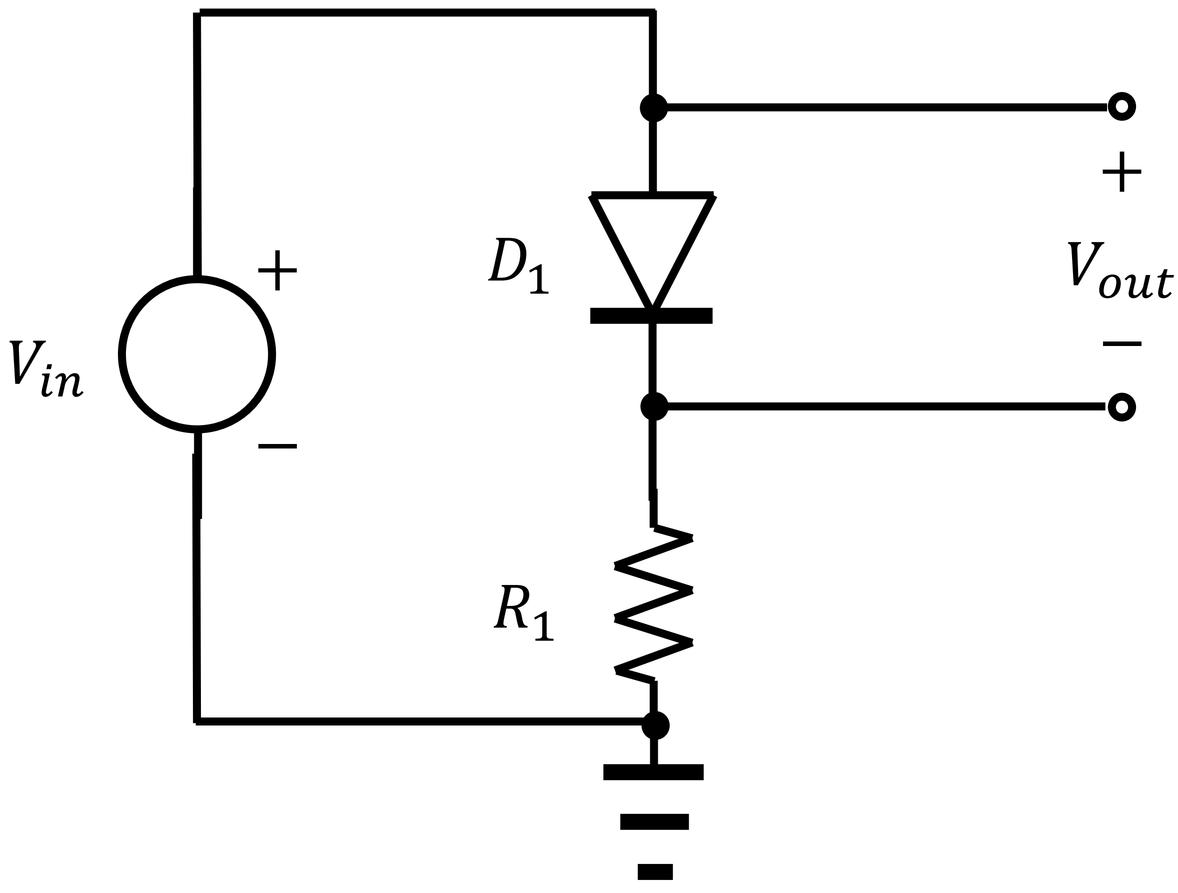
Concept!

- How to detect the electromagnetic radiation
  - Nonlinearity is required.



Rectifier, revisited

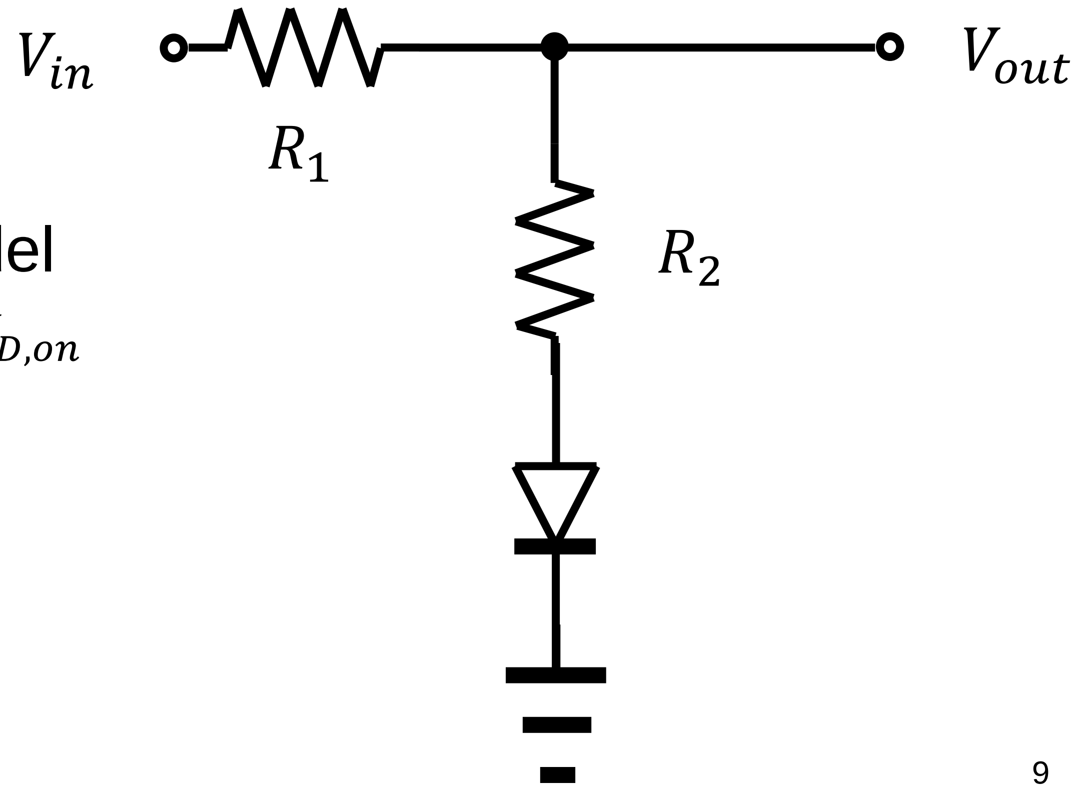
- Same circuit shown in Example 3.4.



pn junction as a diode

- Exponential model

$$I_D = I_s\left(\exp\frac{V_D}{V_T} - 1\right)$$



- Constant-voltage model
  - An "offset" voltage of $V_{D,on}$

A simple math, again

- Taylor series expansion
  - Consider a function, $f(x)$.
  - Then, at $x_0 + \Delta x$ (Δx is small.), the function value would be similar to that at x_0:

$$f(x_0 + \Delta x) \approx f(x_0)$$

  - A better approximation?

$$f(x_0 + \Delta x) \approx f(x_0) + \left.\frac{df(x)}{dx}\right|_{x=x_0} \Delta x$$

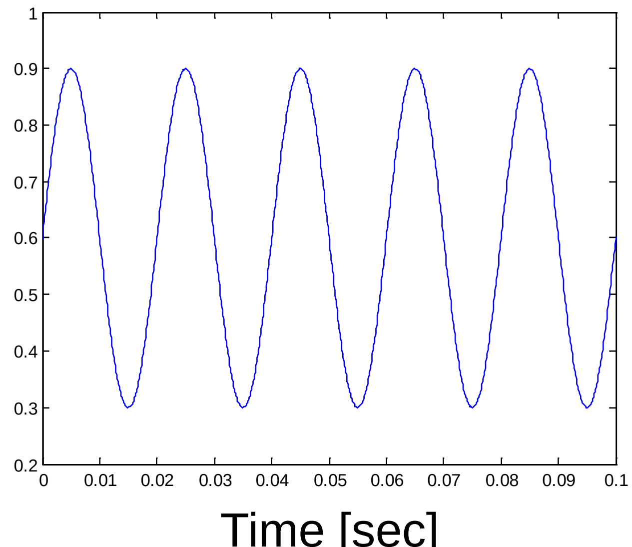
  - Nonlinear function ➔ linearly approximated!

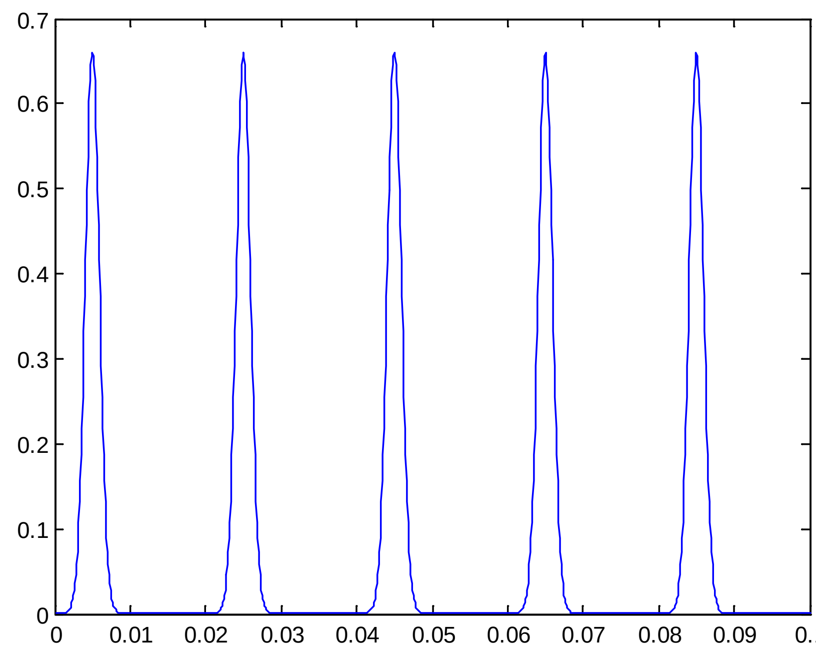
A system

- A system (You know what it actually represents.)

$$V_{in} \longrightarrow \boxed{I_{out} = I_s \exp\frac{V_{in}}{V_T}} \longrightarrow I_{out}$$

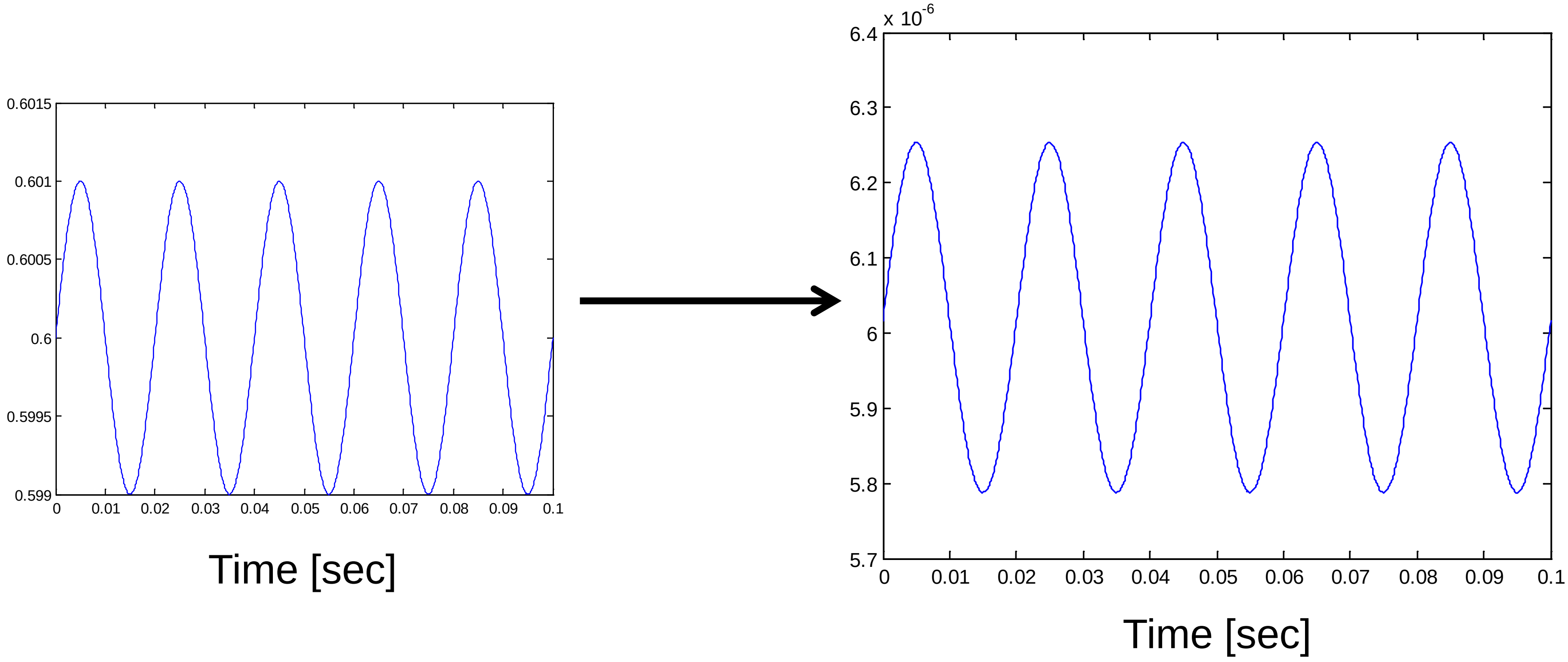
- When $V_{in} = 0.6 + 0.3\sin 2\pi f t$,
  - Certainly, nonlinear!





Smaller amplitude?

- When $V_{in} = 0.6 + 0.001 \sin 2\pi f t$,
  - Nonlinear?



Verbatim (p. 66)

- These thought lead us to the extremely important concept of "*small-signal operation*," whereby the circuit experiences only small changes in voltages and currents.

- Therefore it can be simplified through the use of "*small-signal models*" for nonlinear devices.

- The simplicity arises because such models are linear, allowing standard circuit analysis and obviating the need for iteration.

Exponential

- Simple, but important example
  - A diode is biased to a voltage V_{D1}.
  - The current is given by I_{D1}.

$$I_{D2} = I_s \exp \frac{V_{D1} + \Delta V}{V_T} = I_s \exp \frac{V_{D1}}{V_T} \exp \frac{\Delta V}{V_T}$$

$$I_{D2} \approx I_{D1} \left(1 + \frac{\Delta V}{V_T} \right)$$

Example3.18

- A diode is biased at a current of 1 mA.
  - Determine the current change if V_D changes by 1 mV.

$$\Delta I_D = \frac{I_D}{V_T}\Delta V_D \approx 40\mu\mathrm{A}$$

- Small-signal resistance
  - As far as small changes in the diode current and voltage are concerned, the device behaves as a linear resistor.

$$r_d = \frac{V_T}{I_D}$$

Example3.19

- When the small change in the diode voltage is time-varying,
  - What happens?

$$I_{D2} = I_s \exp\frac{V_{D1} + \Delta V}{V_T} = I_s \exp\frac{V_{D1}}{V_T} \exp\frac{\Delta V}{V_T}$$

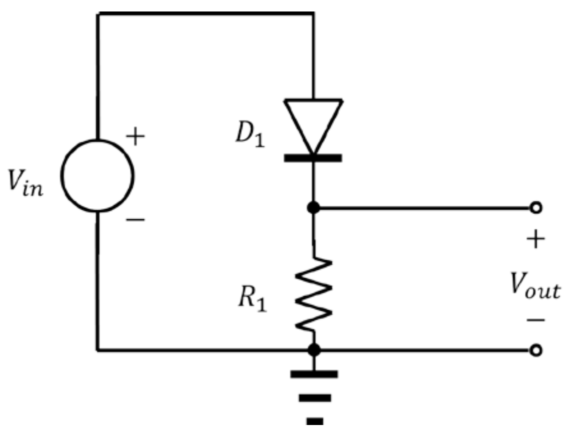
$$I_{D2} \approx I_{D1}\left(1 + \frac{\Delta V}{V_T}\right)$$

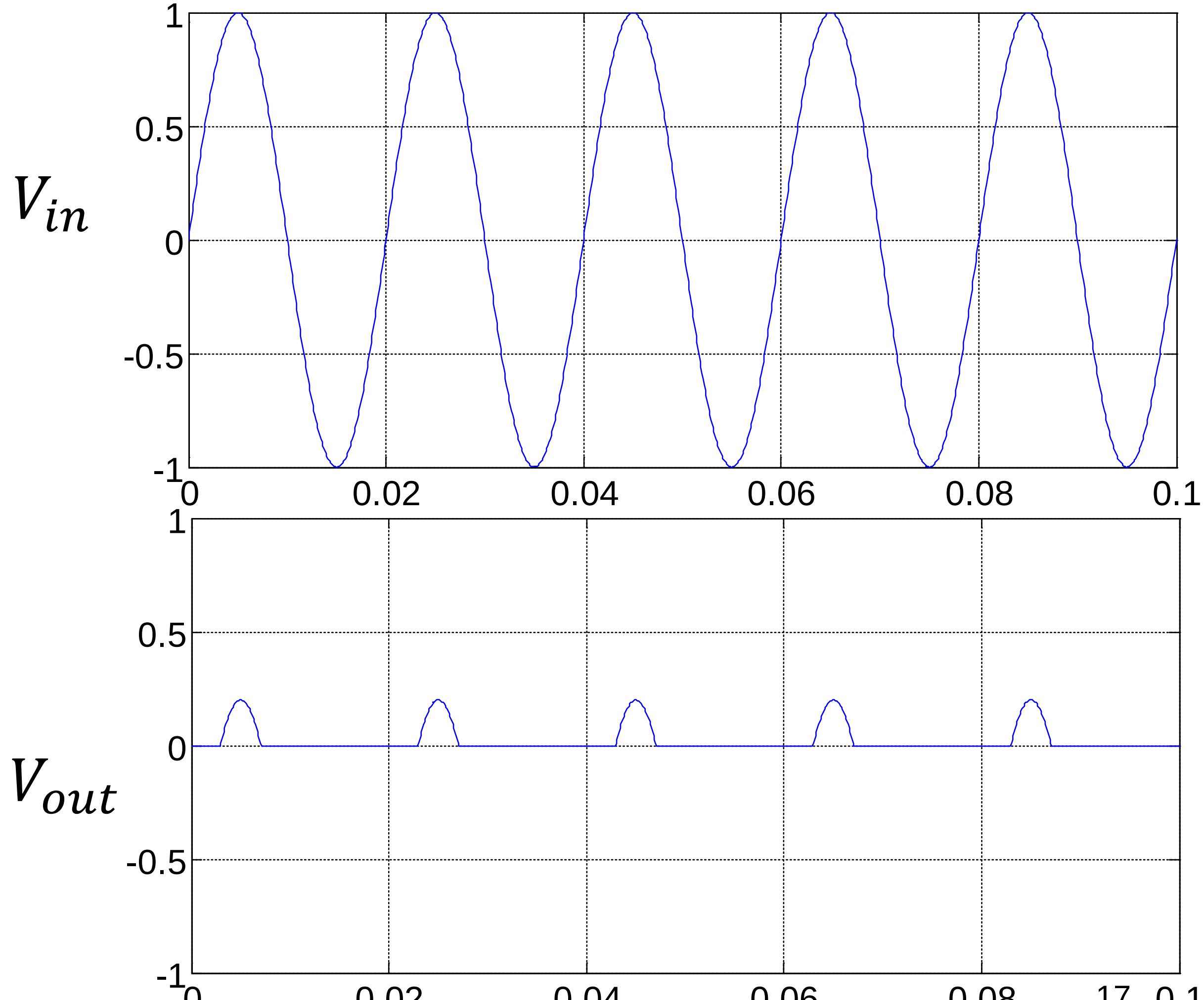
$$I_{D2} = I_s \exp\frac{V_{D1} + \Delta V \cos\omega t}{V_T} = I_s \exp\frac{V_{D1}}{V_T} \exp\frac{\Delta V \cos\omega t}{V_T}$$

$$I_{D2} \approx I_{D1}\left(1 + \frac{\Delta V \cos\omega t}{V_T}\right)$$

Rectifier, revisited

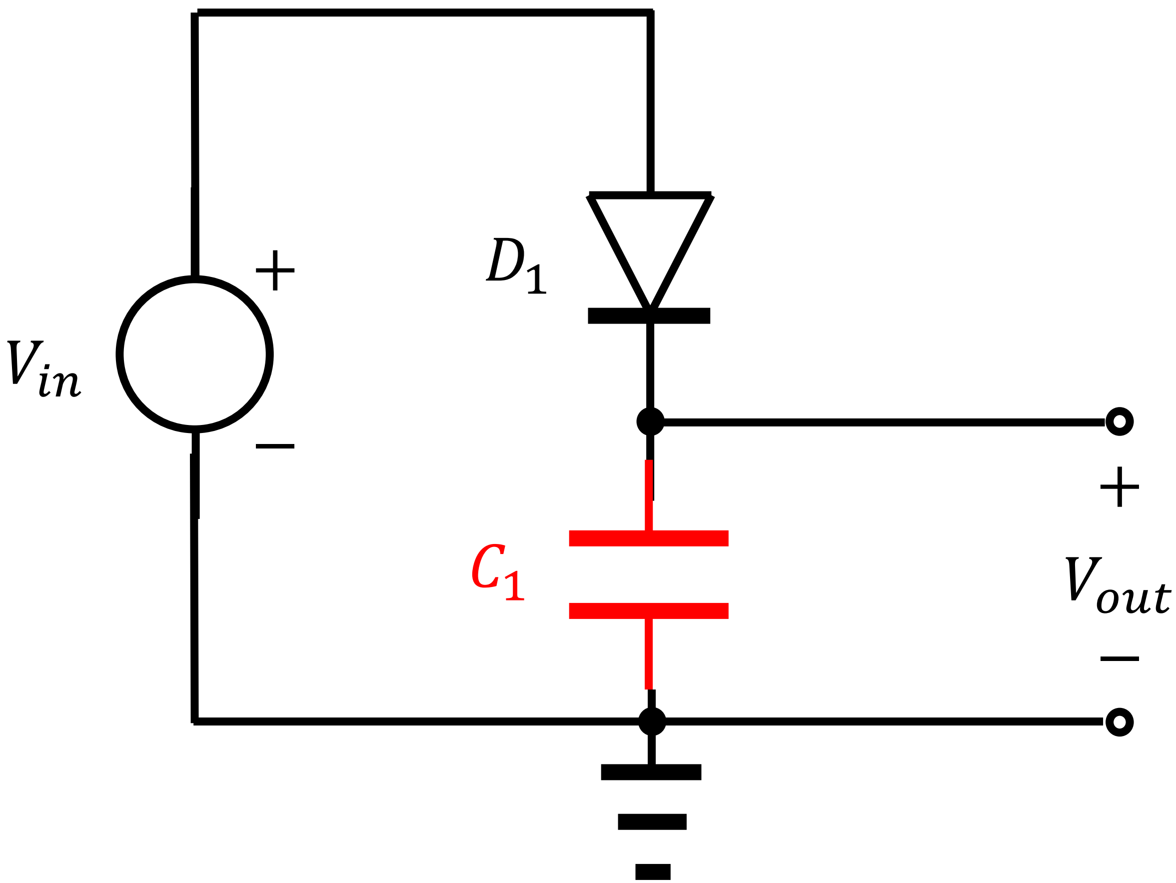
- Constant-voltage model?





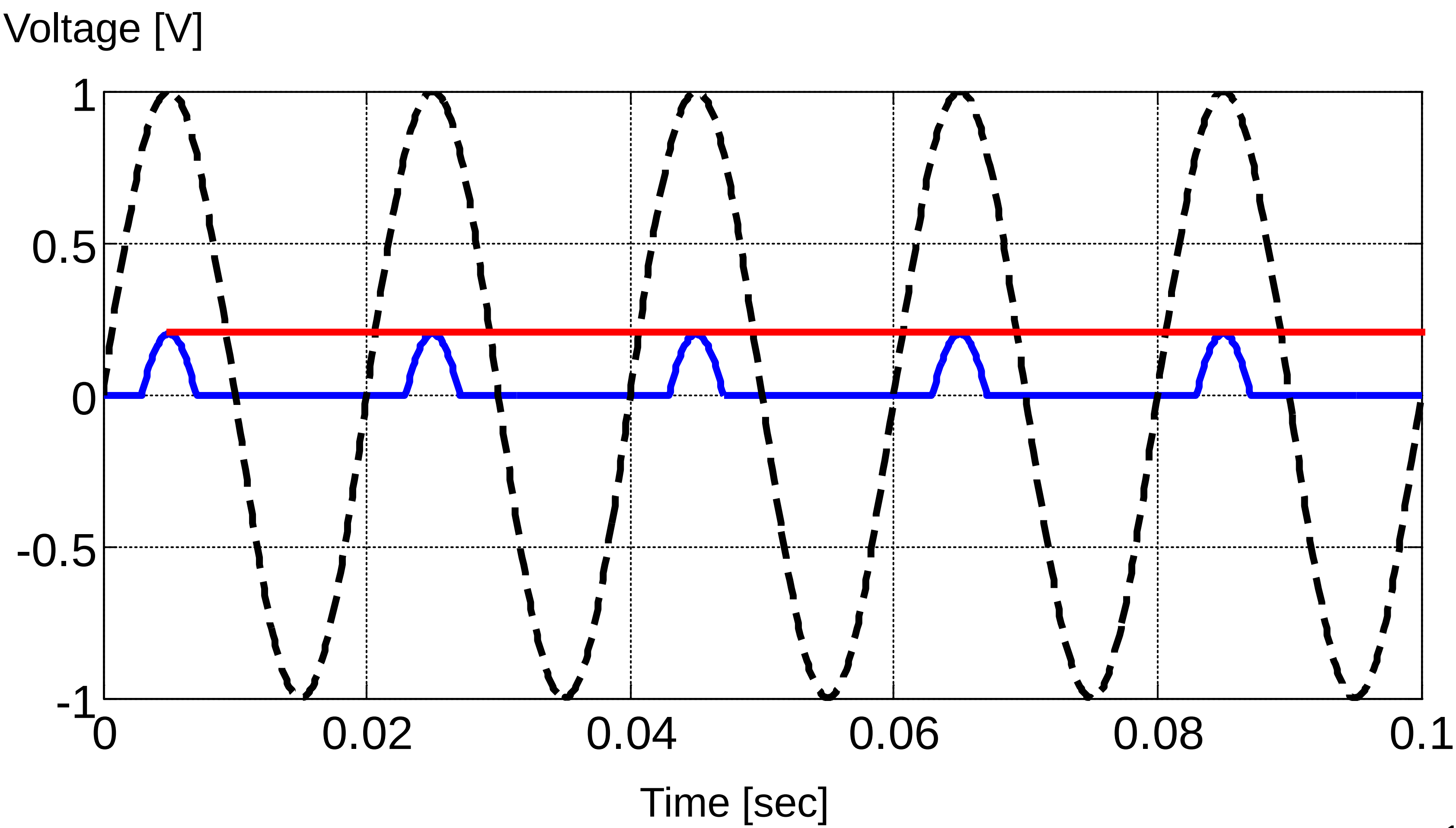
Introducing a capacitor

- Difference from the previous one?



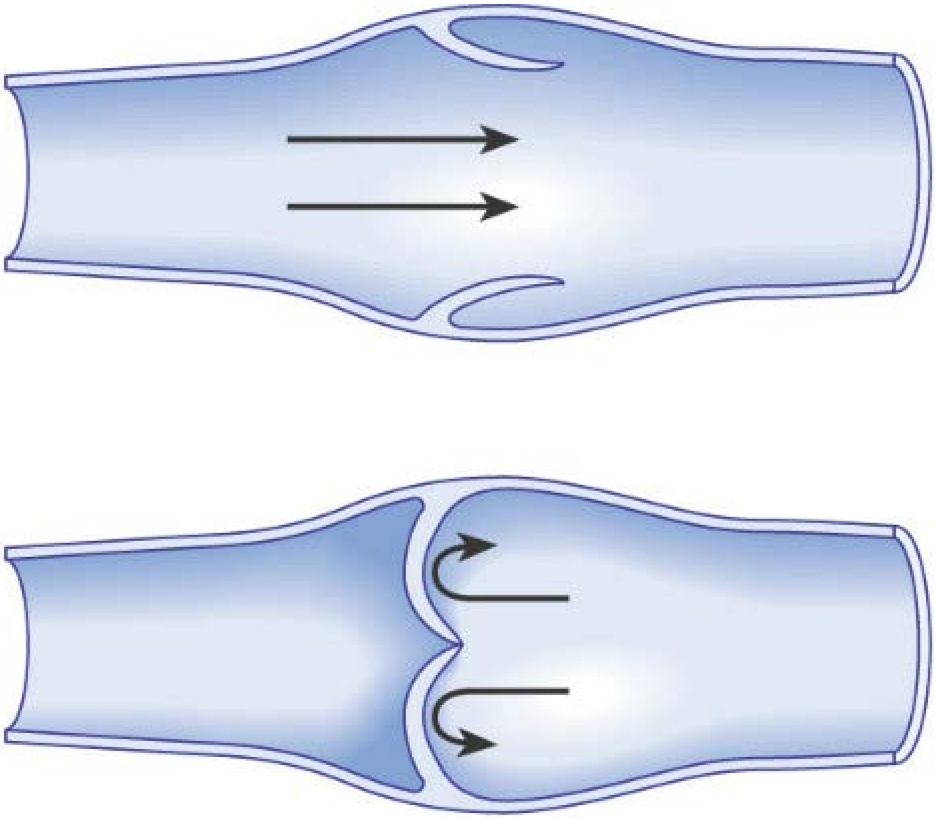
Introducing a capacitor

- Difference from the previous one?



Analogy

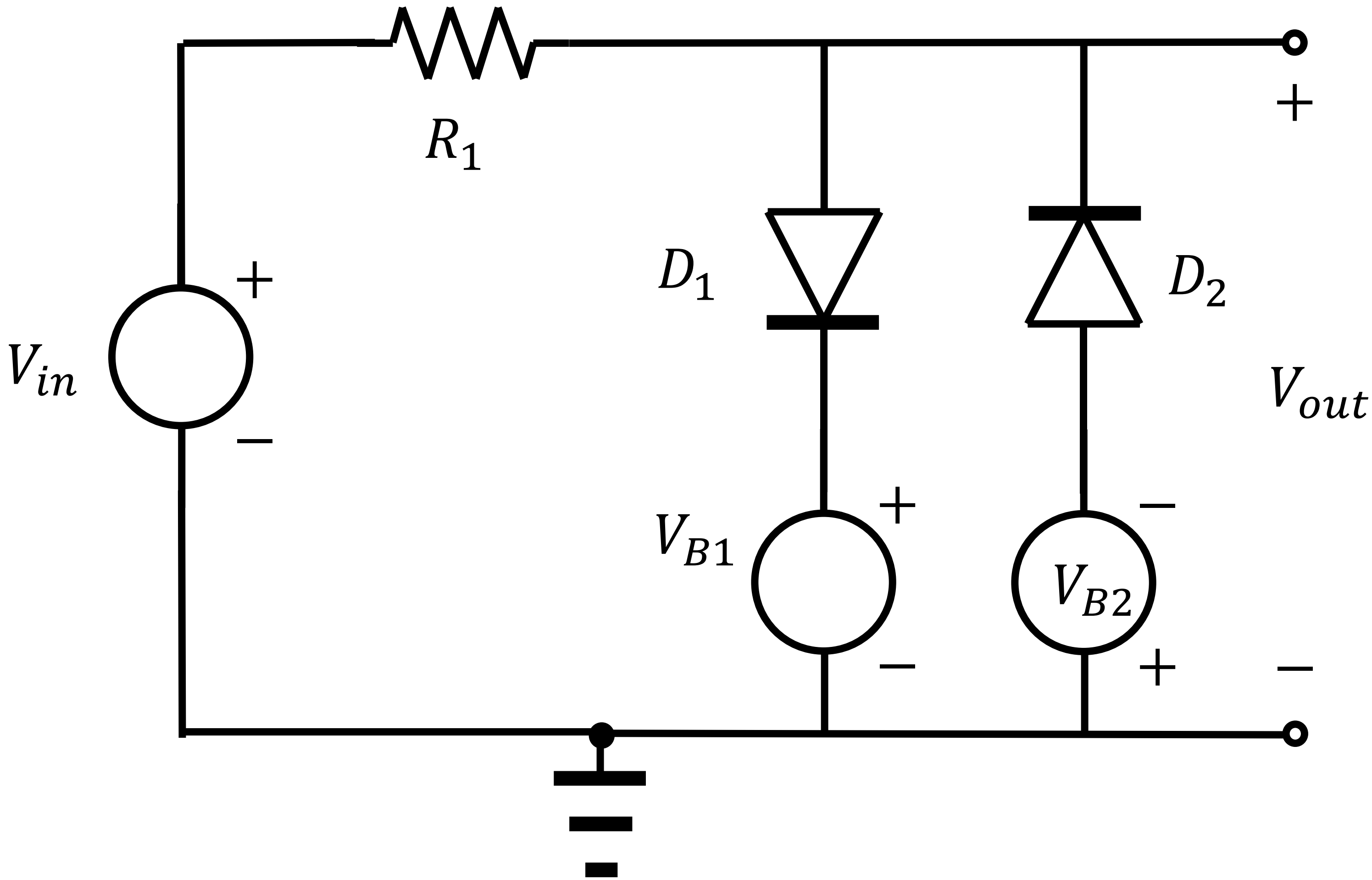
- A blood vessel



(Google image)

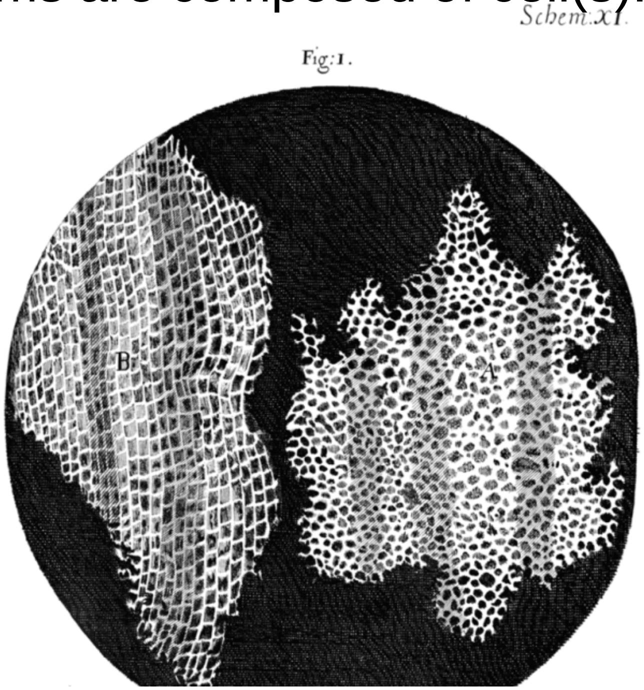
Limiter

- Level-shift for both half cycles



MOSFET

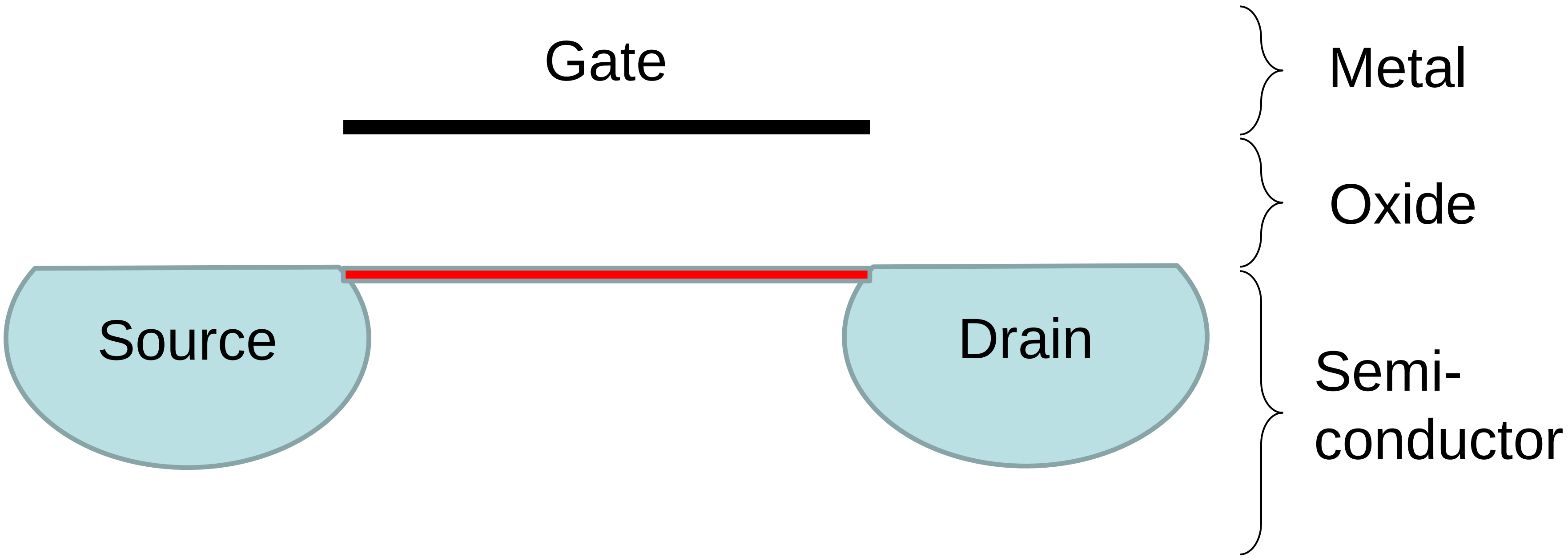
- Metal-Oxide-Semiconductor Field-Effect Transistor
  - *How can I explain its importance properly?*
- In the biology,
  - All living organisms are composed of cell(s).



Structure of cork (Wikipedia)

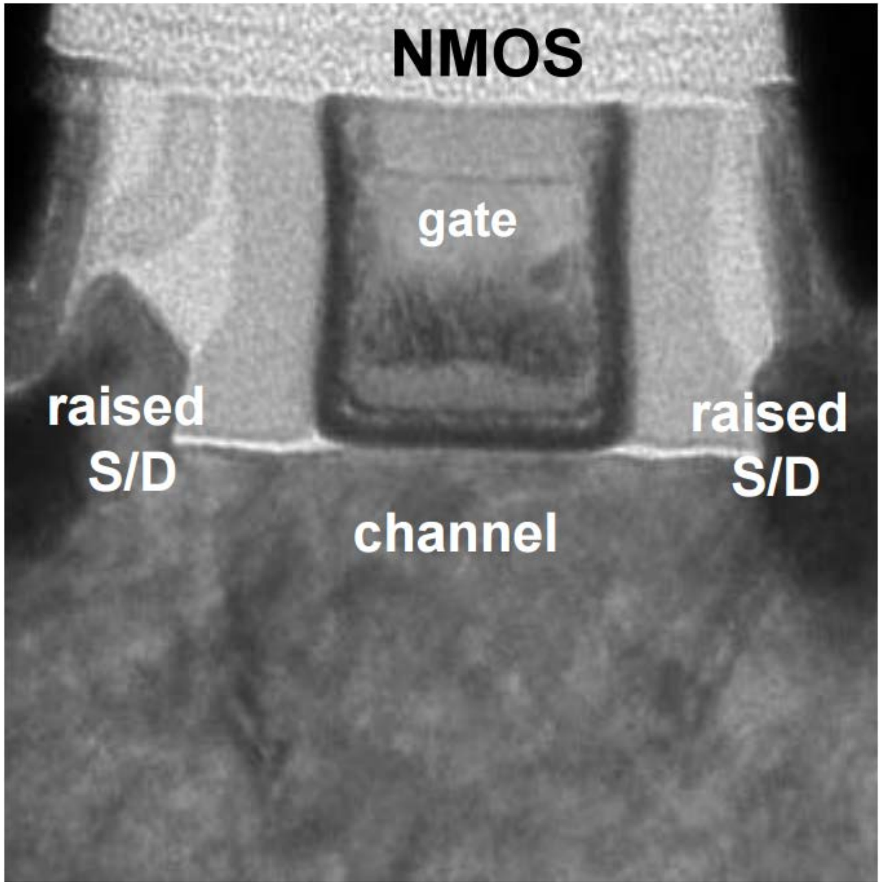
Its generic structure

- Vertical structure
  - Metal-Oxide-Semiconductor
- Terminals
  - Gate, Source, Drain, (and substrate)



Actual device

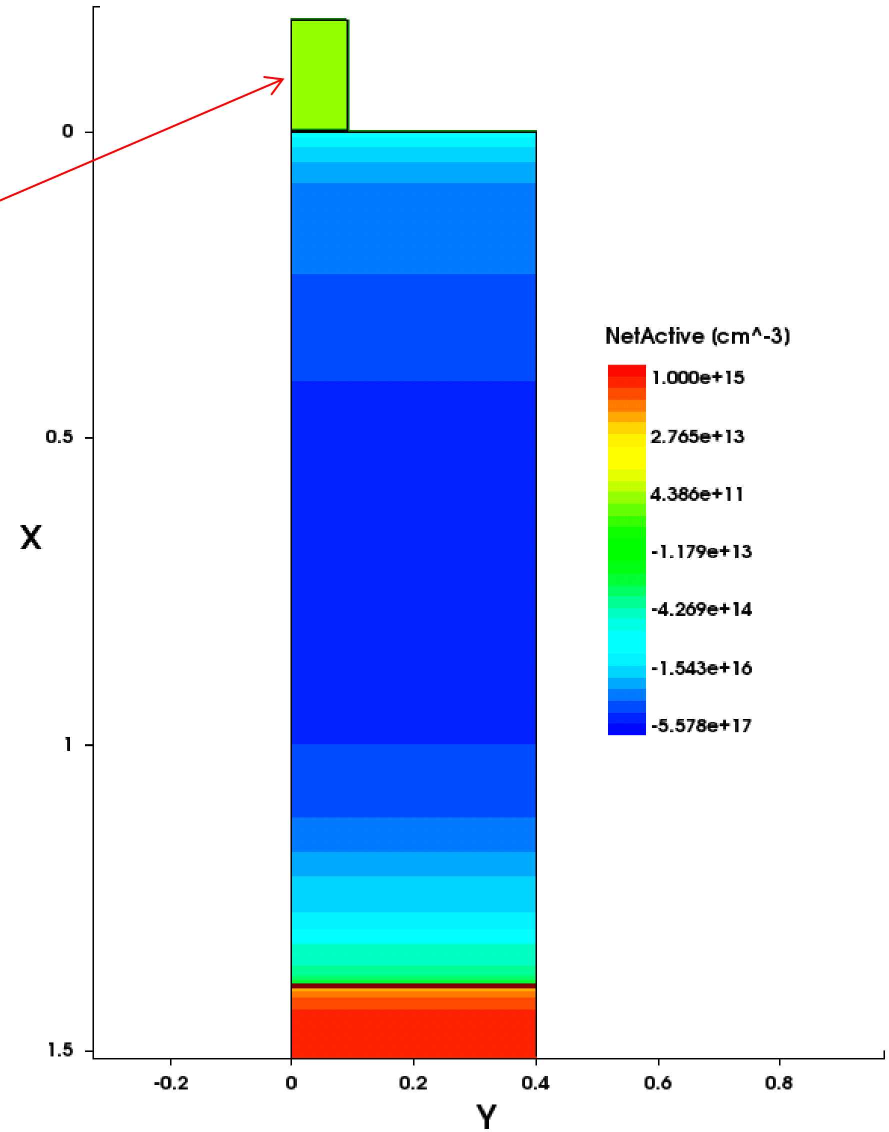
- TEM image of a MOSFET
  - 32nm node
  - (somewhat old…)



(Packan et al., IEDM 2009)

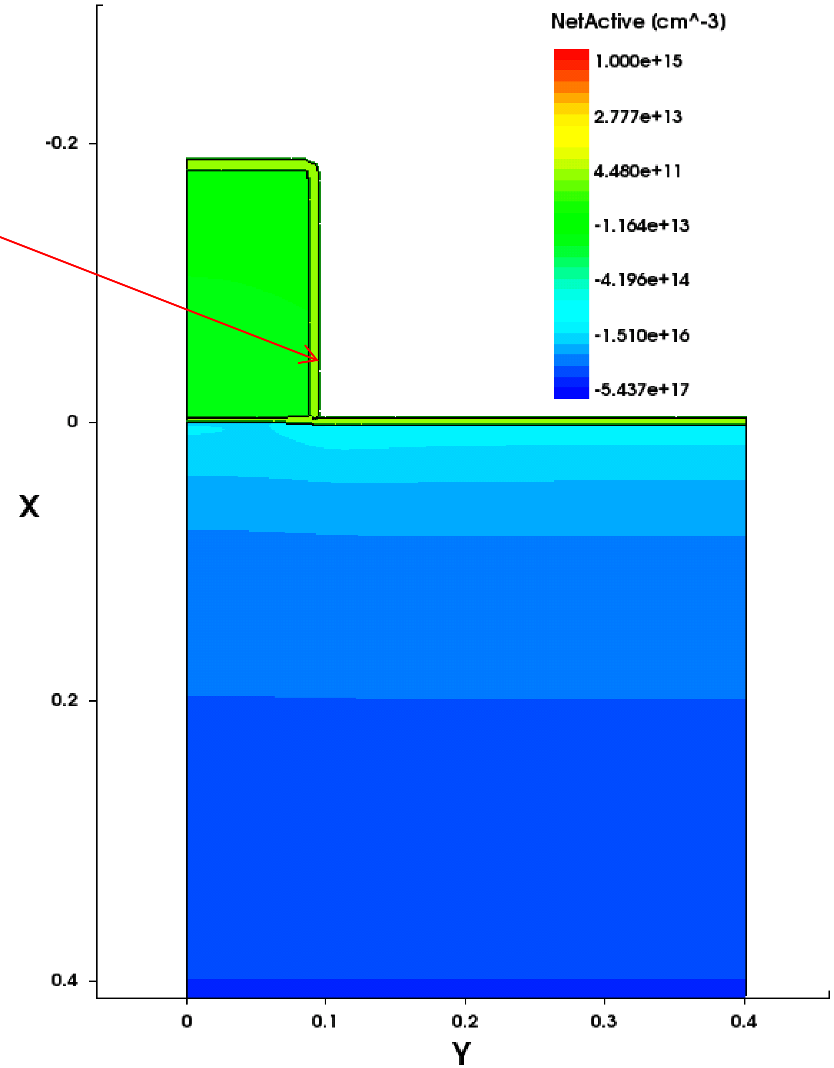
How to fabricate it (1/6)

- 0.18 μm NMOSFET
  - P-well formation
  - Gate oxidation
  - Gate definition
  - (Half structure is shown.)



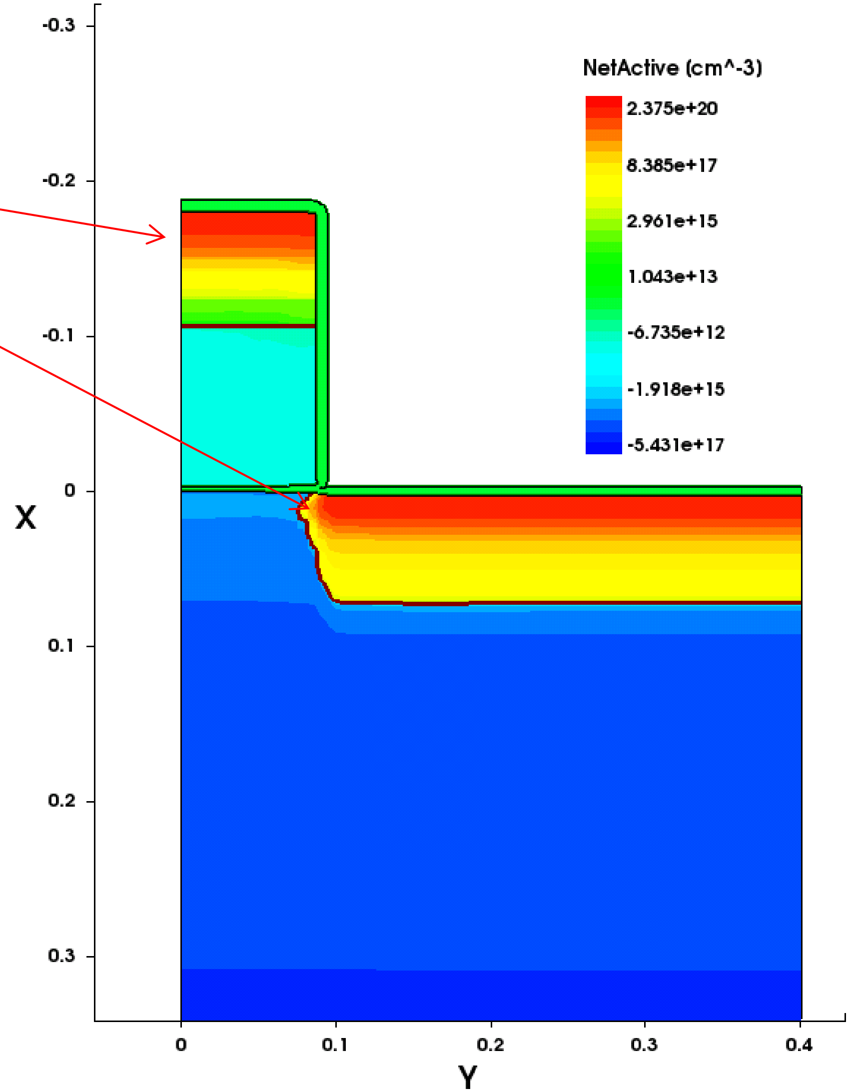
How to fabricate it (2/6)

- 0.18 µm NMOSFET
  - Gate re-oxidation



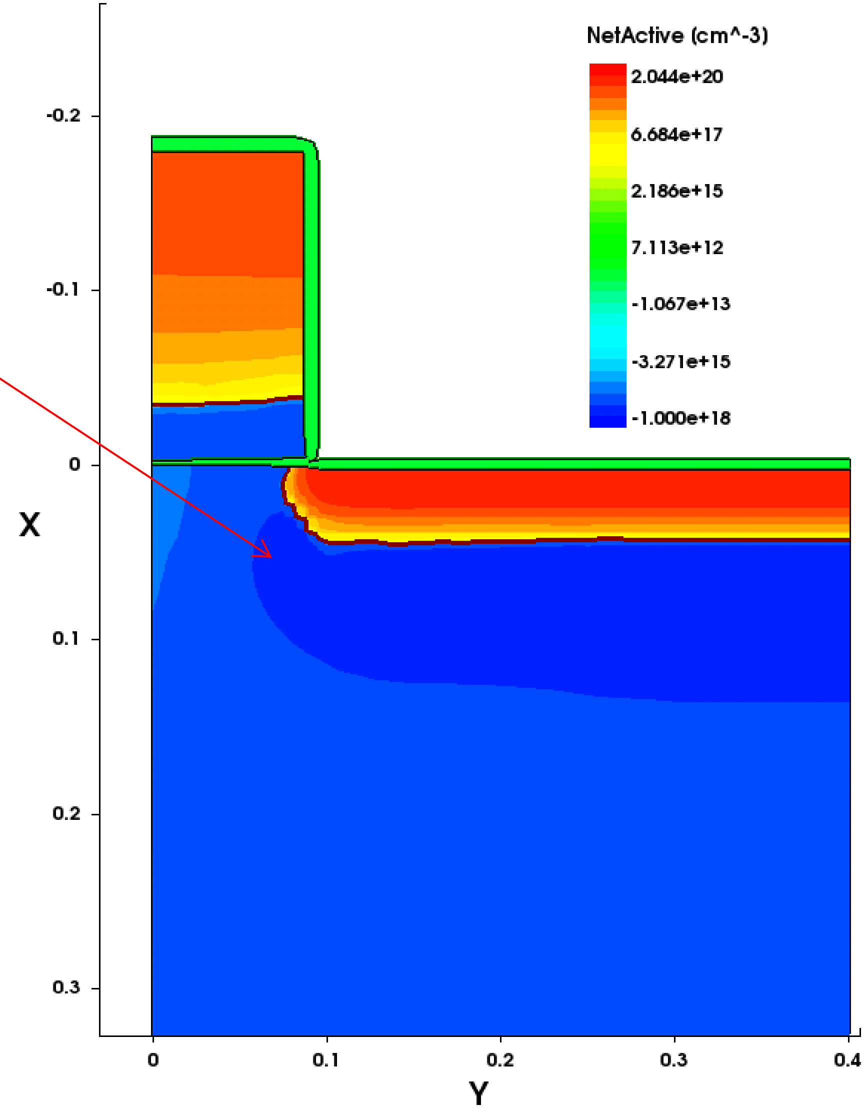
How to fabricate it (3/6)

- 0.18 μm NMOSFET
  - LDD implant



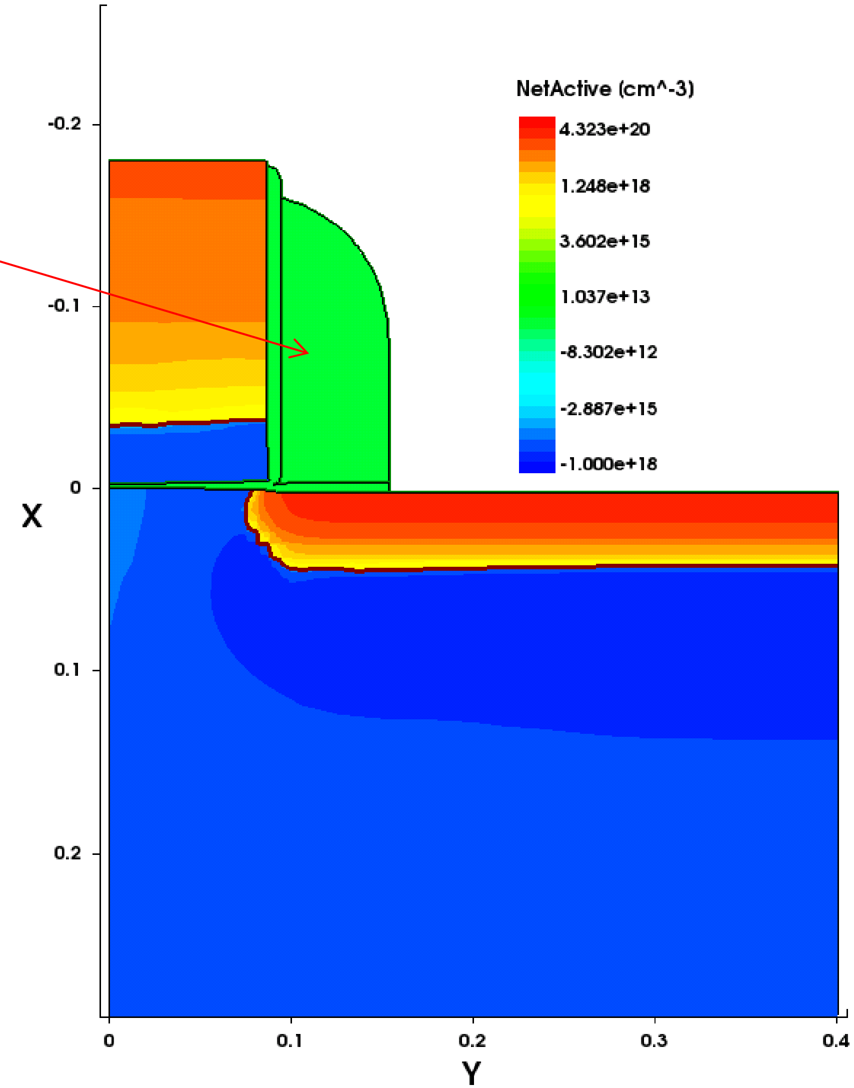
How to fabricate it (4/6)

- 0.18 µm NMOSFET
  - Halo implant



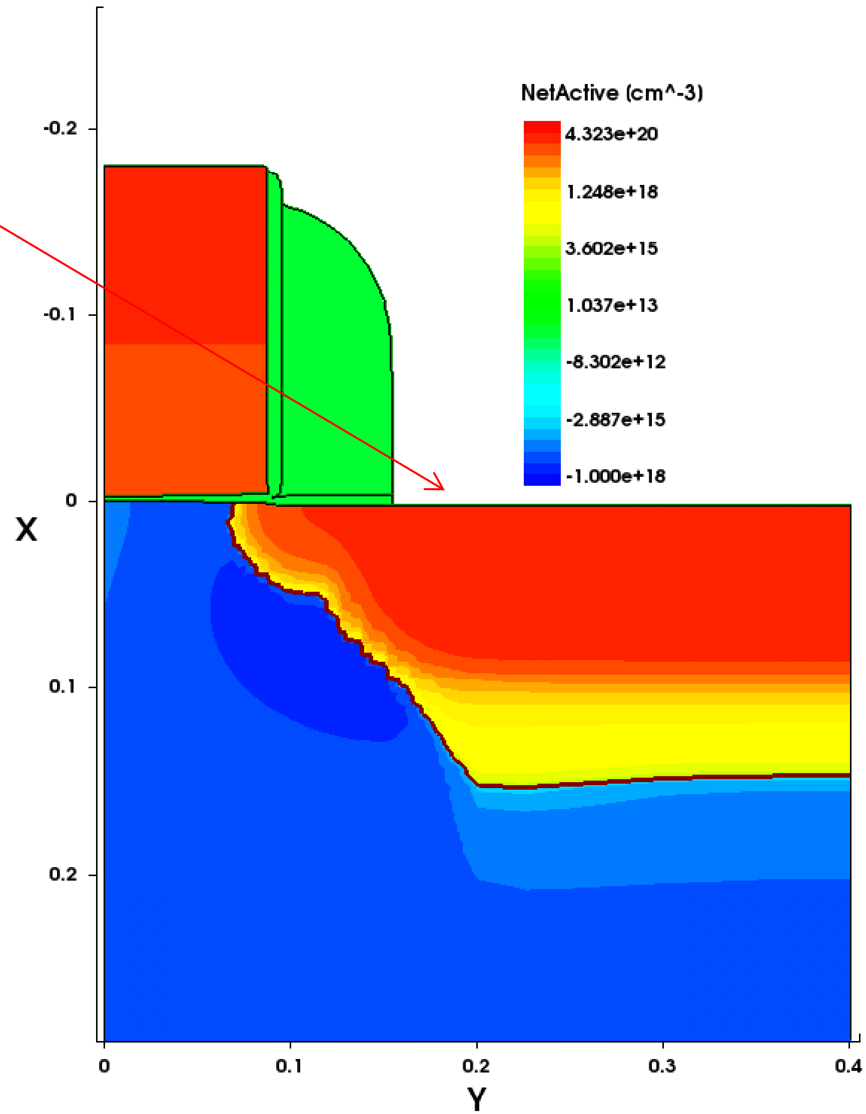
How to fabricate it (5/6)

- 0.18 μm NMOSFET
  - Nitride spacer



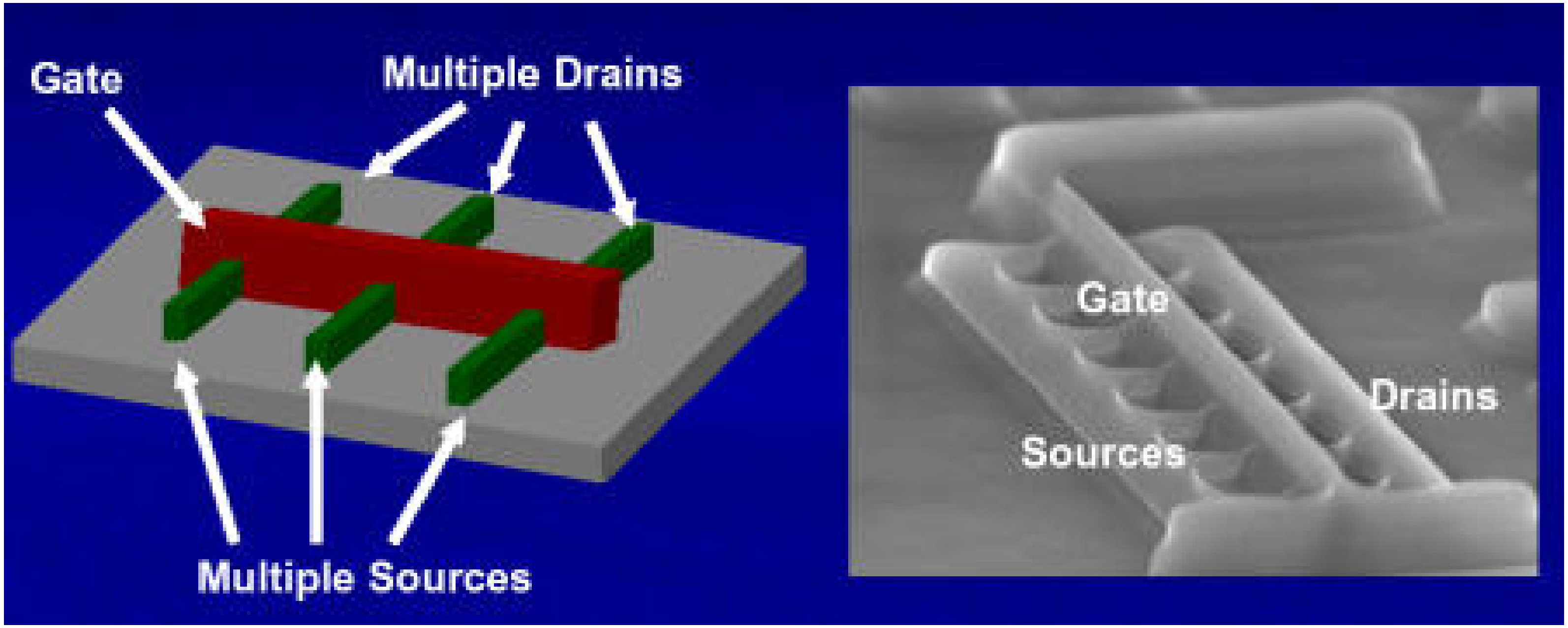
How to fabricate it (6/6)

- 0.18 μm NMOSFET
  - Source/drain implant



Top view

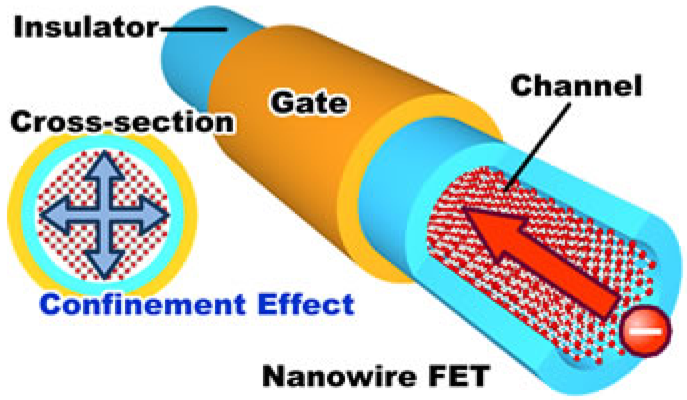
- TEM image of a MOSFET
  - 22nm node
  - (a few years ago…)



(Wikipedia)

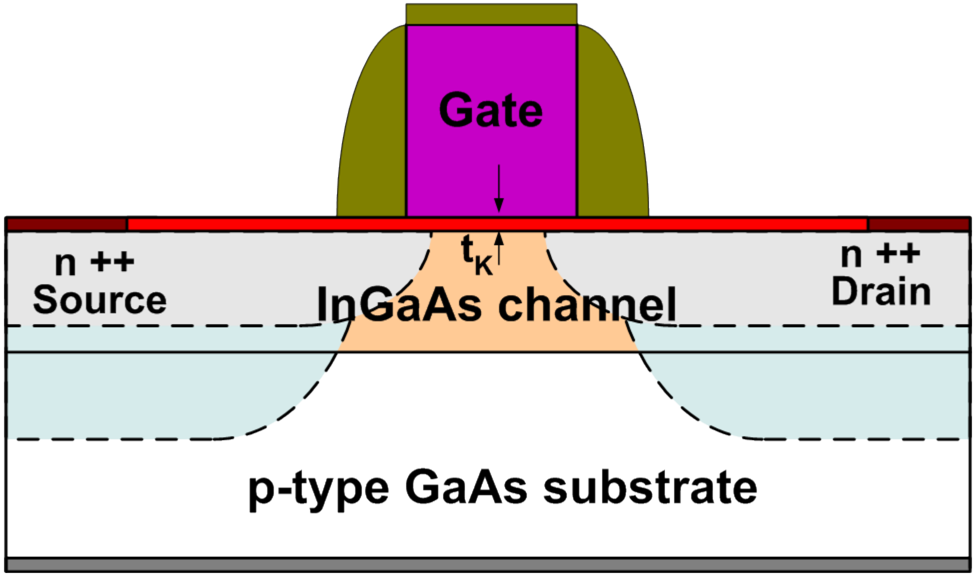
Future

- Nanowire?



(Google images)

- III-V?



(Google images)

Other application

- Up to now, we have seen the MOSFET used for the logic application.
  - CMOS RF

- However,
  - NAND Flash memory
  - Power device
  - Various sensors