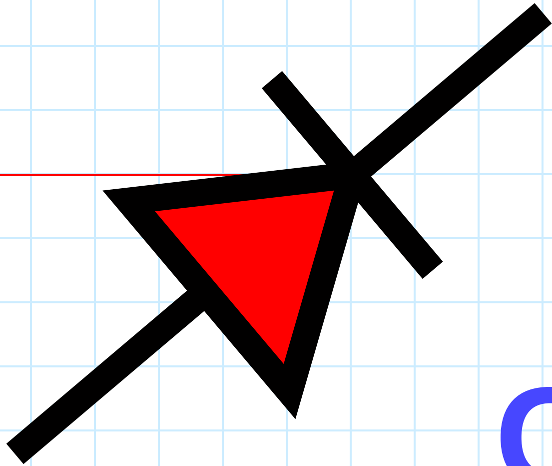
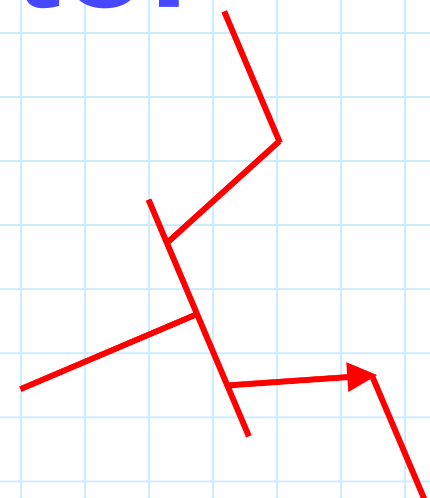


Chapter I:
Basic semiconductor devices



Objectives (1)

At the end of this chapter, the student should:

- Know and understand the basic operation of semiconductor diodes.
- Know the different models of diodes and how to apply them to the analysis of digital circuits with diodes.
- Know and understand the applications of diodes in digital circuits.
- Know and understand the basic operation and some applications of special-purpose diodes, such as Schottky, LEDs and photodiodes.

Objectives (2)

At the end of this chapter, the student should:

- Know and understand the basic operation of bipolar junction transistors (BJTs).
- Know and understand the different regions of operation of a BJT.
- Know and understand the operation of a BJT transistor as a switch.
- Apply the knowledge of BJTs to implement basic logic gates.

Contents

1.1. Bibliography

THEORY:

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- R. L. Boylestad, *Electronics. Circuit theory and electronic devices*, Pearson, 2009. (Chap. 1..3)
- N.R. Malik. *Electronic circuits. Analysis, simulation and design,* Chap. 3, Prentice Hall, 2000. (Cap. 4)
- John F. Wakerly, "*Digital Design. Principles and Practices"*. Prentice Hall; 4th Ed., 2005 (Cap. 3)
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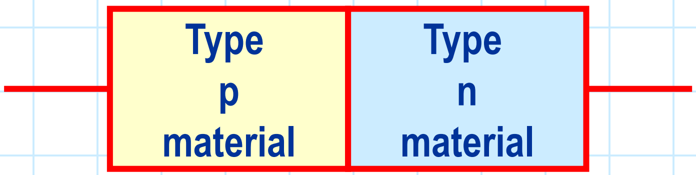
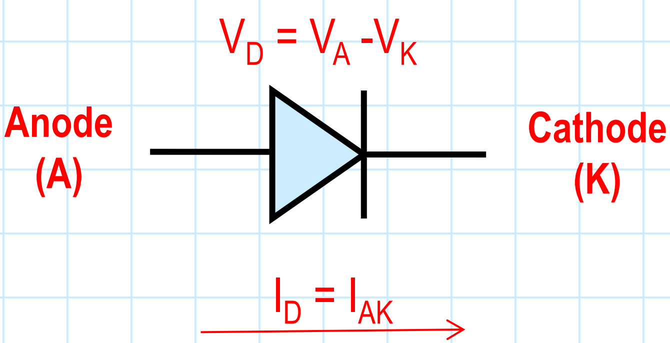
1.1 The junction diode. Foundations



P-N junction



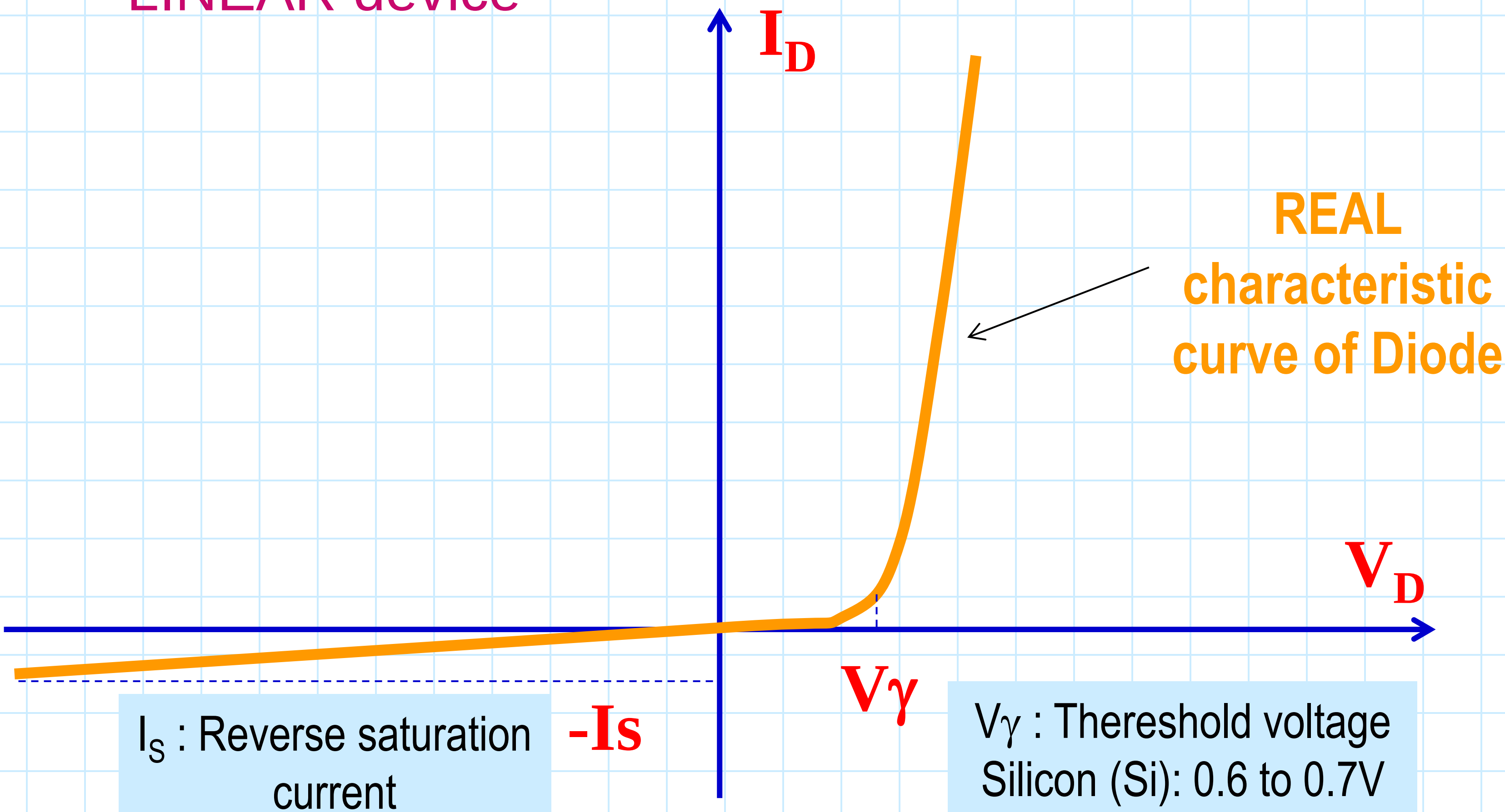
Diode symbol

- The P-N junction conducts more easily in forward (from p to n) than in reverse mode.
- The rectification concept appears
- Device name: DIODE
- Terminals:
  - Anode: type p material
  - Cathode: type n material

1.1 The junction diode. Foundations

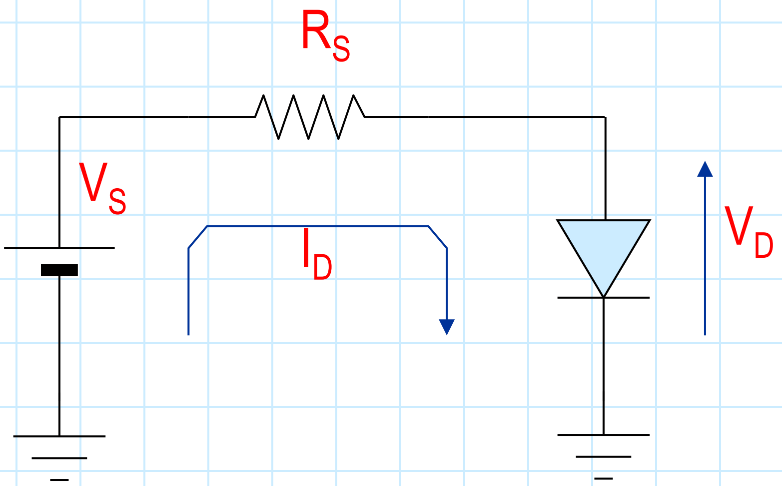
- The Diode is a NON-LINEAR device

$$I_D = I_S\left(e^{V_D/\eta V_T} - 1\right)$$



1.2 Load line

When we connect the diode with a voltage generator (Vs) and a series resistor (Rs), these devices bias the diode, putting it in an operating point.



$$I_D = f(V_D)$$

Applying the 2nd Kirchoff law:

$$V_S - I_D R_S - V_D = 0$$

$$I_D = \frac{V_S}{R_S} - \frac{V_D}{R_S}$$

1.2 Load line

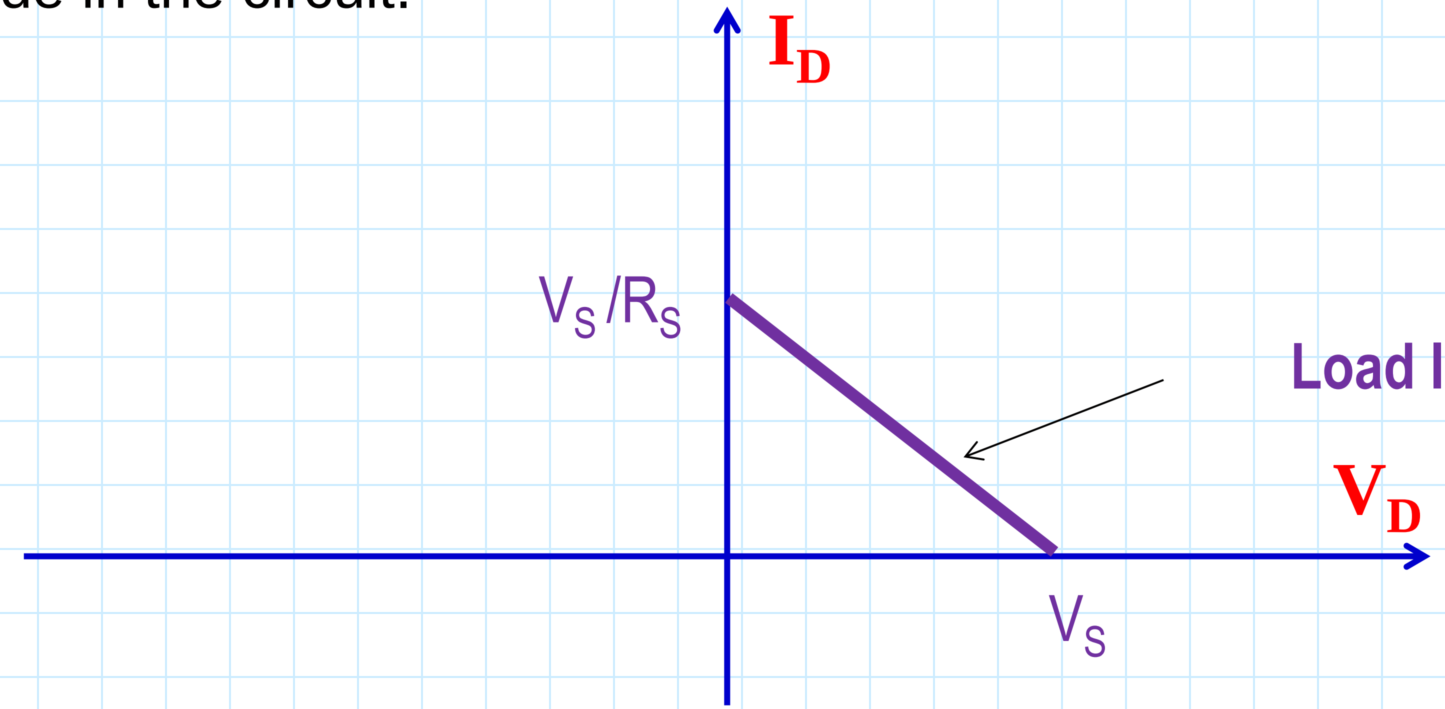
$$I_D = \frac{V_S}{R_S} - \frac{V_D}{R_S}$$

Cross points with the X(V_D) and Y (I_D) axes:

When $I_D = 0 \rightarrow V_D = V_S$

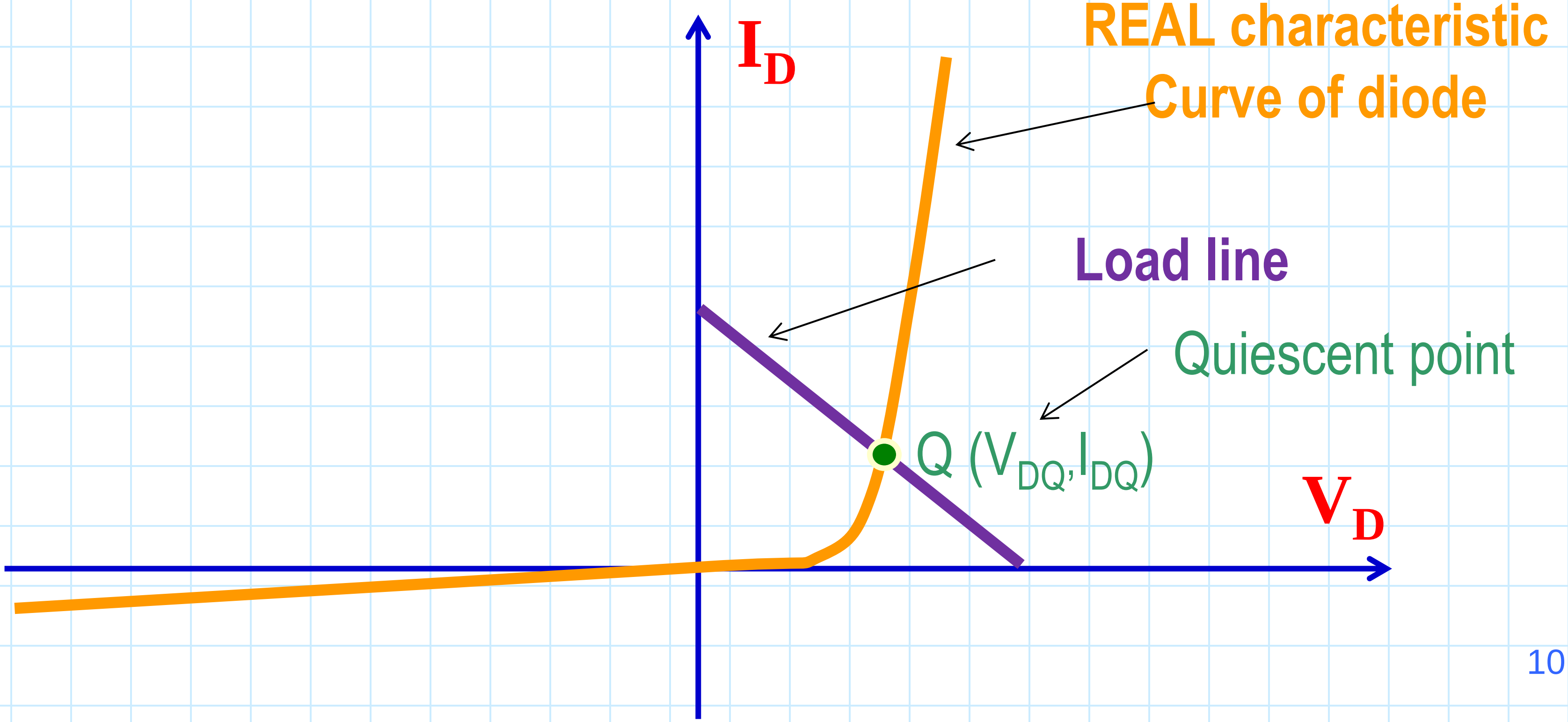
When $V_D = 0 \rightarrow I_D = V_s / R_s$

The LOAD LINE depends only of elements added to the diode in the circuit.



1.2 Quiescent point

- The diode has to met its CHARACTERISTIC CURVE
- The intersection point of the real characteristic curve of diode and the load line defines the QUIESCENT POINT of diode

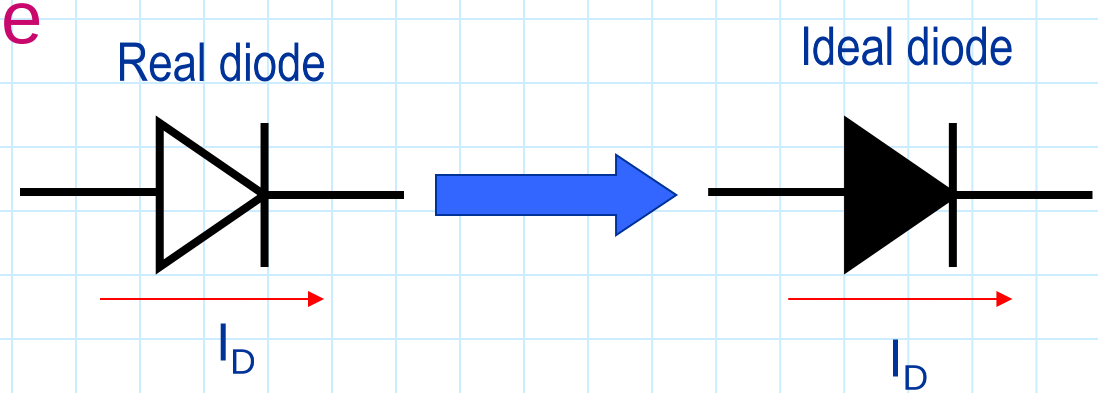


1.2 Diode approximations and models

- We can define diode MODELS that approximate its beviour with an increasing accuracy:
  1. Ideal model
  2. Ideal model with threshold voltage.
  3. …

1.2 Diode models (1)

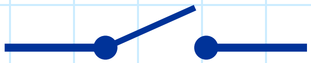
1. Ideal diode

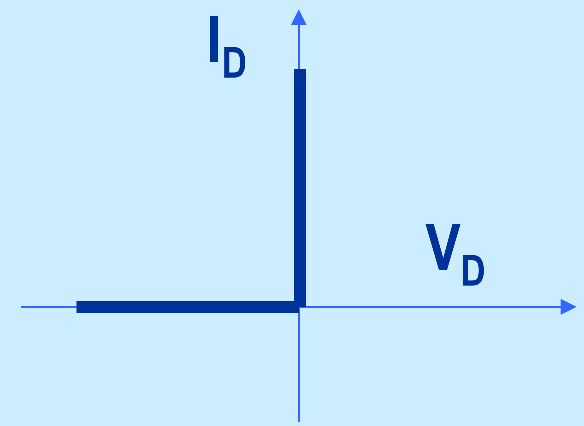


The behaviour is similar to a switch:

- Direct bias: closed (ON)
  - ☞ $V_D = 0$ for all $I_D > 0$

- Reverse bias: open (OFF)
  - ☞ $I_D = 0$ for all $V_D < 0$

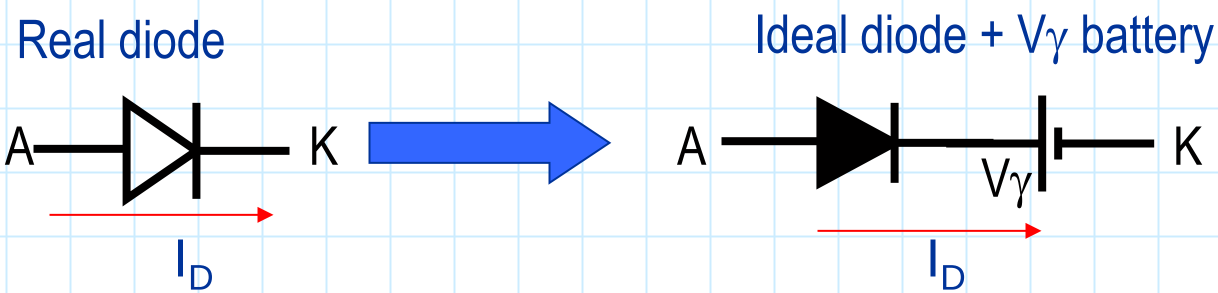




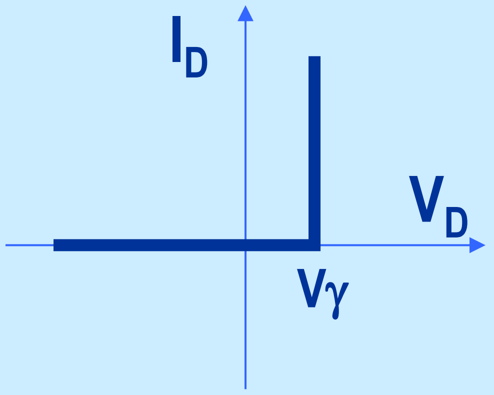
Characteristic curve
1st diode approximation

1.2 Diode models (2)

2. Ideal diode with threshold voltage V_γ



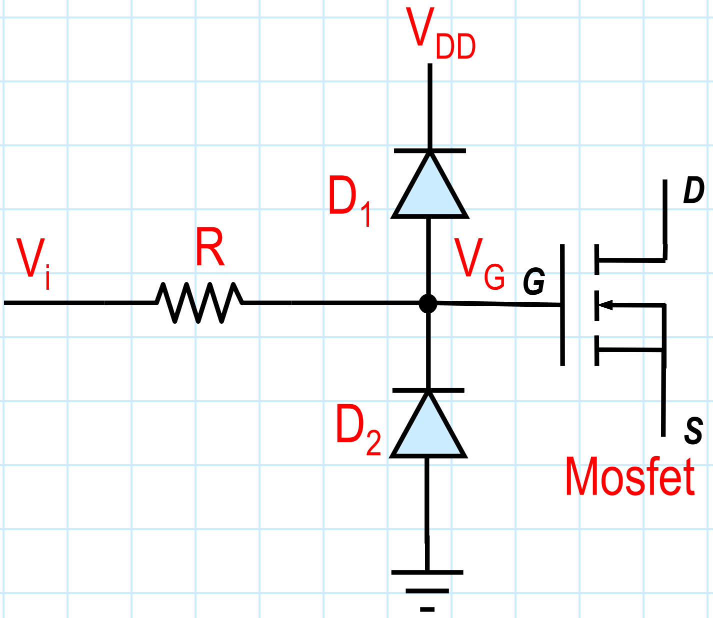
- $V_D = V_\gamma$ for all $I_D > 0$



Characteristic curve
2nd diode approximation

1.3 Diode circuits. Digital inputs protection

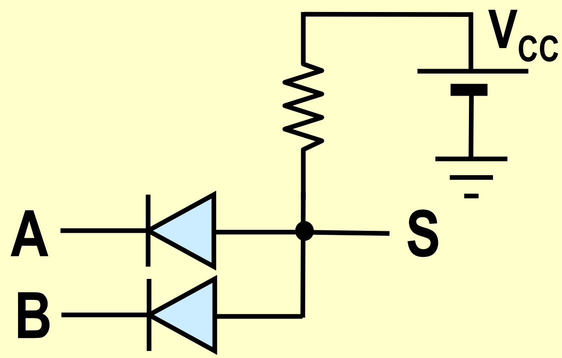
- Clipping diodes: protect the Mosfet inputs of CMOS digital circuits against overvoltages.



- D_1 conducts if $V_i >= V_{DD} + 0.7V$
- D_2 conducts if $V_i \leq -0.7V$
- $-0.7V \leq V_G \leq V_{DD} + 0.7V$

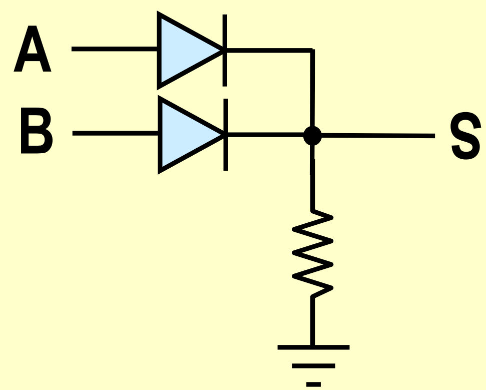
1.3. Diode circuits. Digital applications

AND Gate



A	B	S
0	0	0
0	1	0
1	0	0
1	1	1

OR Gate



A	B	S
0	0	0
0	1	1
1	0	1
1	1	1

1.3 Other applications in digital circuits

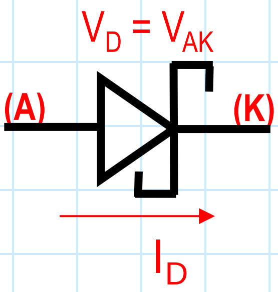
As we will see throughout the course, diodes are present in almost all digital integrated circuits:

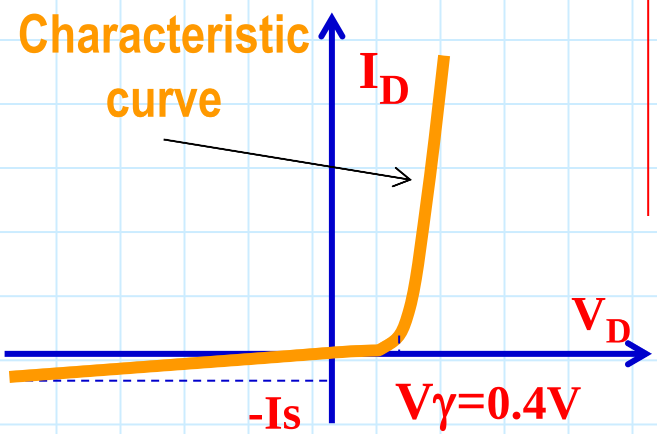
- Digital gates based on bipolar transistors (ex: TTL) use diodes for adjusting the voltage levels.
- Each MOSFET transistor inside NMOS or CMOS digital circuits have implicitely several diodes in reverse mode.

1.4 Special purpose diodes. Schottky diodes

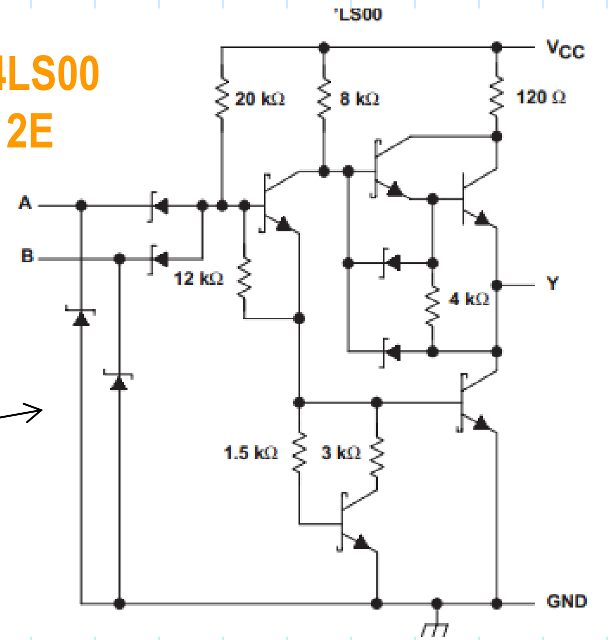
- Special diodes for switching circuits
- Based on a metal (Al)-semiconductor ("n" not many doped) junction
- High Is (1000 times bigger)
- Low Vγ (0,4V approx.)
- Very fast switching
- Application to high-speed digital circuits

Symbol:



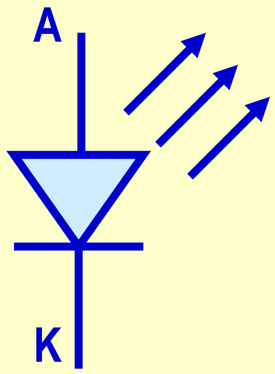


Example: 74LS00
4 * NAND 2E

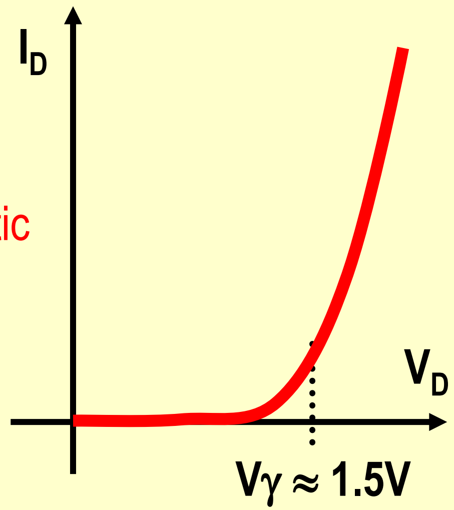


1.4 Special purpose diodes. LEDs

- LED: Light Emitting Diode
- When diode is forward-biased, majority carriers are injected in the P-N junction . The carriers recombinate in order to restore the equilibrium, emitting energy in the form of heat or light.
- This last case (light emitting) is produced only in the case of special semiconductor materials: GaAs, GaAsP, SiC, ...

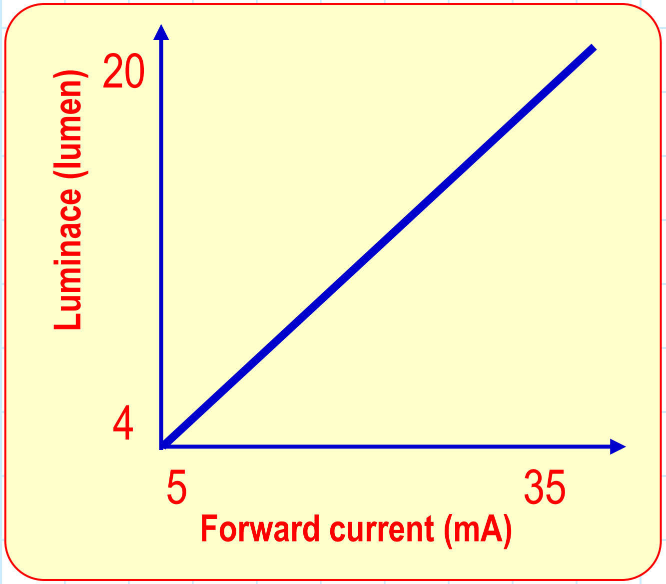


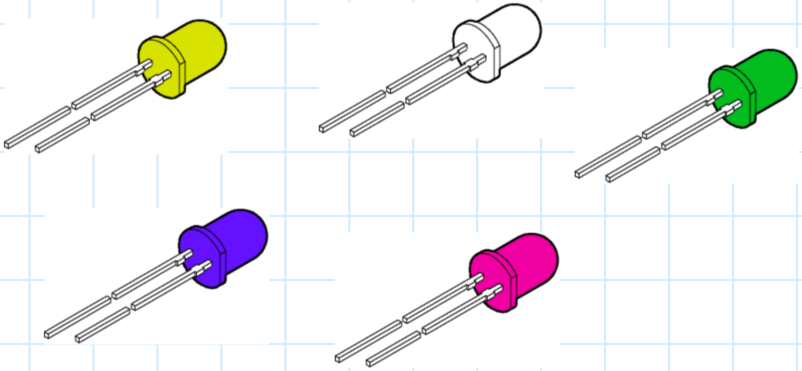
LED symbol



Characteristic curve

1.4 LED features



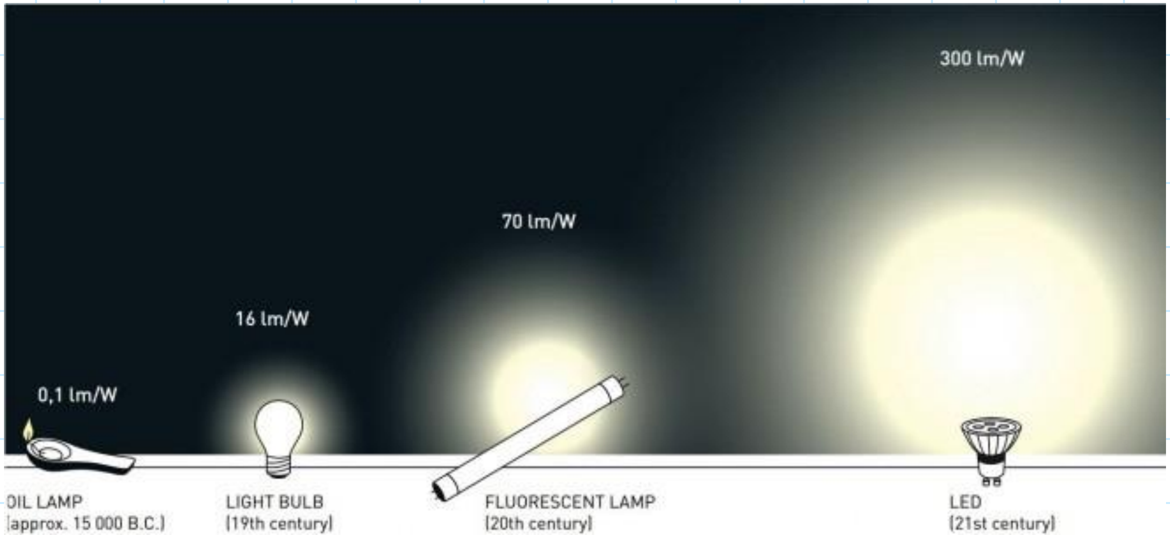


- $V\gamma$ is among **1.5V to 4V**
- The emitted luminace is directly proportional to the forward current
  - (for a good visibility, a forward current from **10 to 20mA** is required)
  - The modern high power LEDs (1 W or more), require more current
- The radiation is almost monochrome (only one color)
- Radiation frequency of LEDs:
  - Infrared (with a lot of applications)
  - Red (the most typical)
  - Yellow
  - Green
  - Blue
  - Ultraviolet

The latest ones

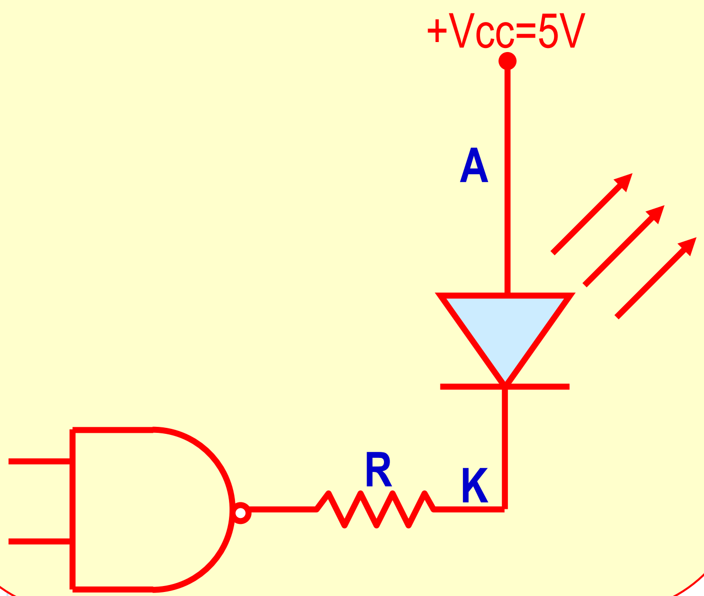
1.4 Blue LED

- In 2014 the Nobel Prize in Physics was delivered to the discoverers of blue LED : Akasaki, Amano and Nakamura.
- To produce white light, blue LED was missing for many years:
  - White light with 3 LEDs: red, green and blue (RGB)
  - White light with one blue (or ultraviolet) LED+ optical filter of Phosphorus
- After several failed attempts, in 1994 they first obtained a "high" efficiency blue LED (for that time).
- They used a semiconductor based on InGaN / AlGaN, and obtained an efficiency of about 2.7% (incandescent bulbs have an efficiency of a 4%).
- Now we have more efficiency:

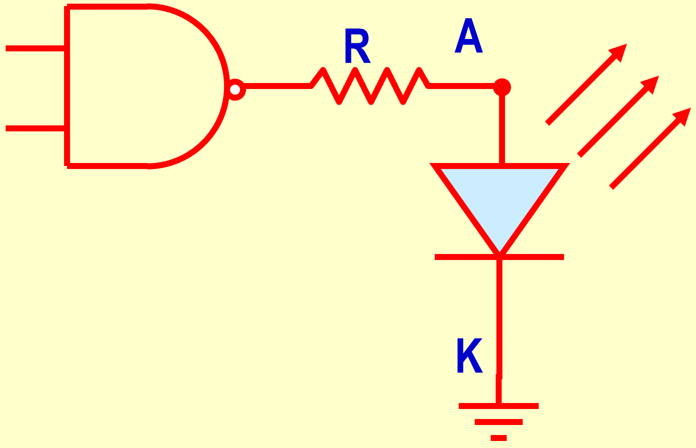


1.4 LED circuits

LED ON with output LOW



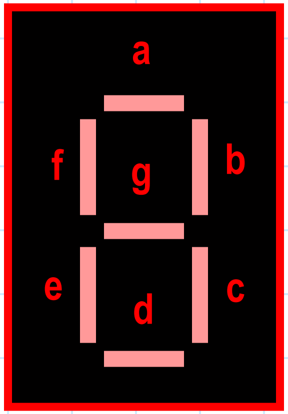
LED ON with output HIGH

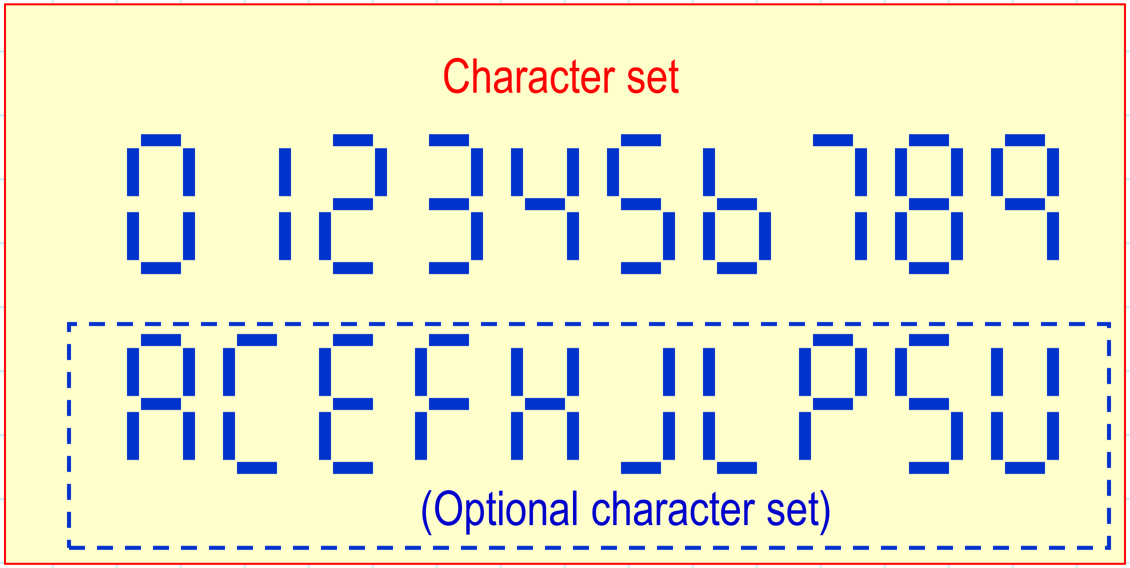


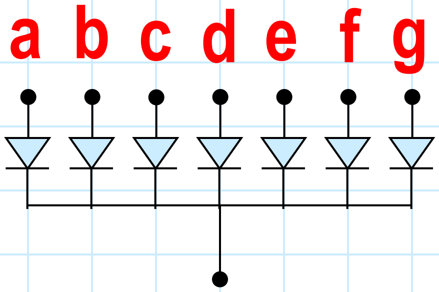
$$R = \frac{Vcc - V_{OL} - V\gamma}{I_{NEEDED}}$$

$$R = \frac{V_{OH} - V\gamma}{I_{NEEDED}}$$

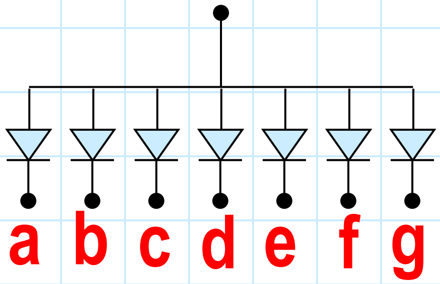
1.4. 7 segment display







Common-cathode configuration

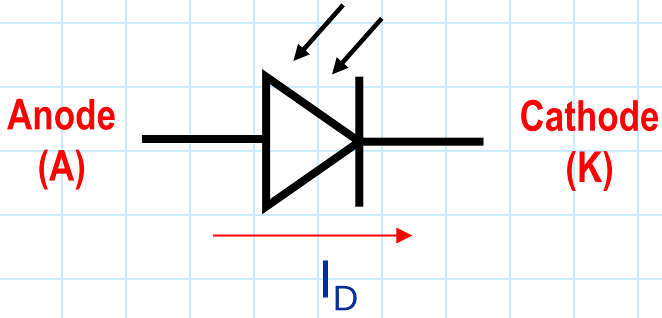


Common-anode configuration

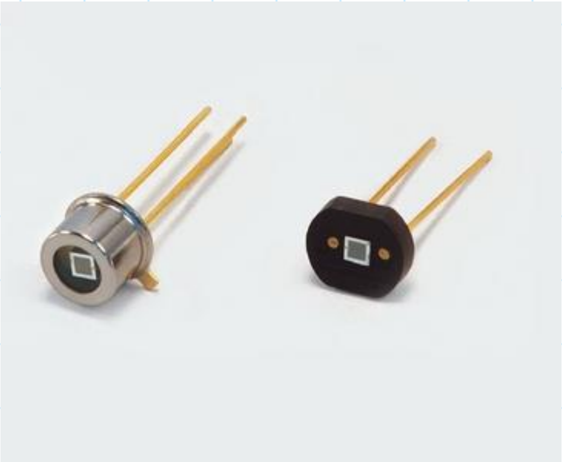
1.4 Photodiodes

- They work in the opposite way to LEDs
  - A reverse current is obtained from light
- The light must reach the diode junction
  - Part of the package is translucent

- Symbol

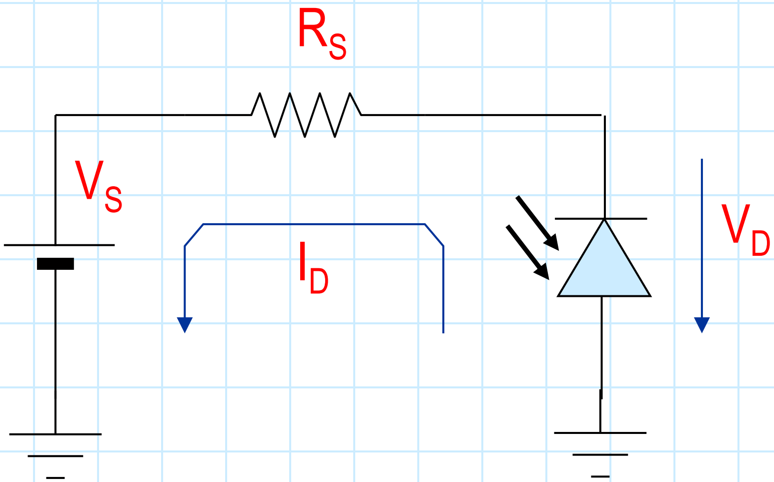


- Real photodiodes

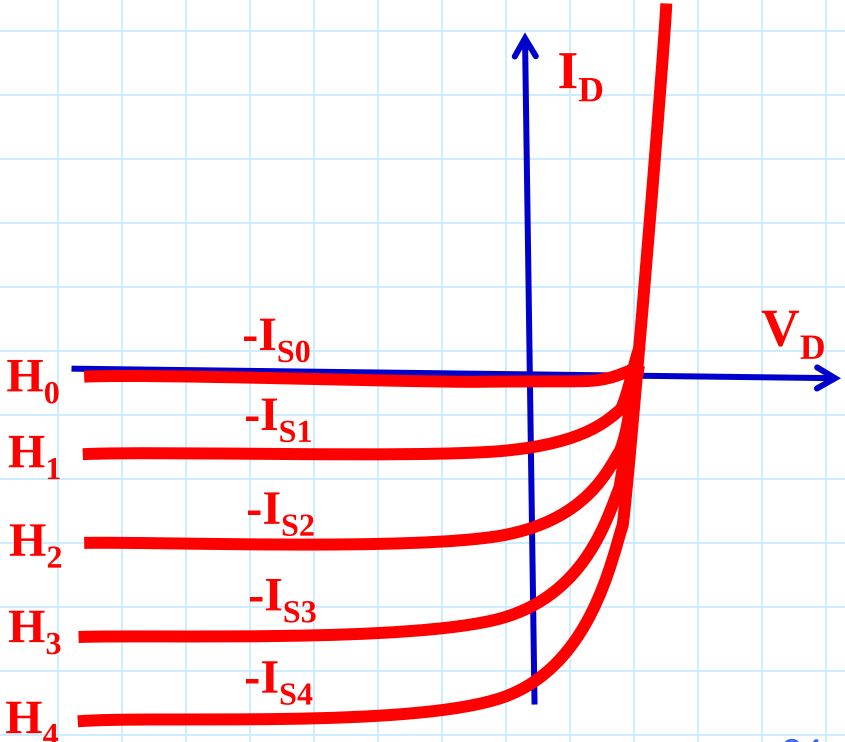


4. Photodiodes

- The photodiode must be in reverse bias mode
- Reverse current (I_D=-I_S) is proportional to brightness of the received light .
  - H: Light brightness [fotons/s] [mW/cm^2]
- Test circuit:



Characteristic curves

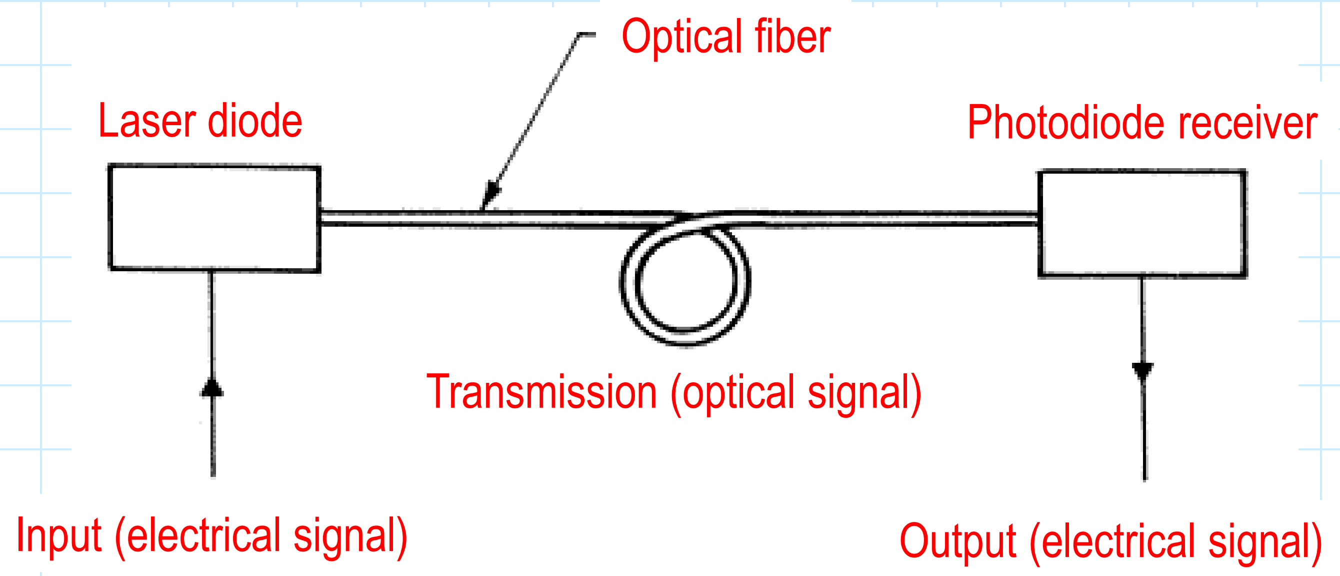


1.4 LED and photodiode apps.

- Displays (TV, computer monitors, panels, markers, multimedia projectors …)
- Optical communications
- Li-Fi network (https://en.wikipedia.org/wiki/Li-Fi)
- Lighting systems (domestic, urban, automotive …)
- Traffic lights
- Optical disks readers
- Peripherals …

1.4 Applications of LEDs and photodiodes (I)

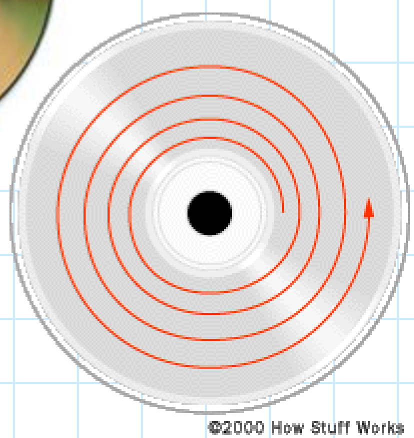
- Application to data transmission by optical fiber



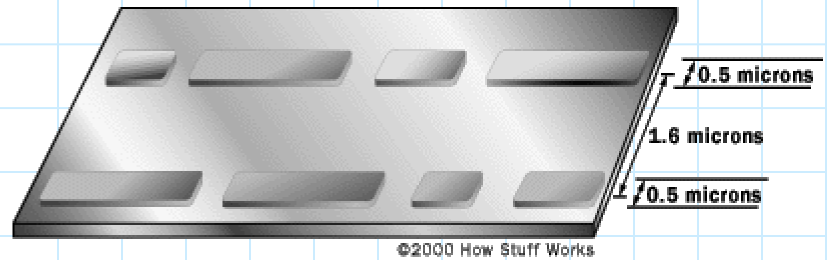
1.4 Applications of LEDs and photodiodes (II)

- **Reading CDs, DVDs and Blu-ray**

◆ Information placement



◆ How the bits are recorded:



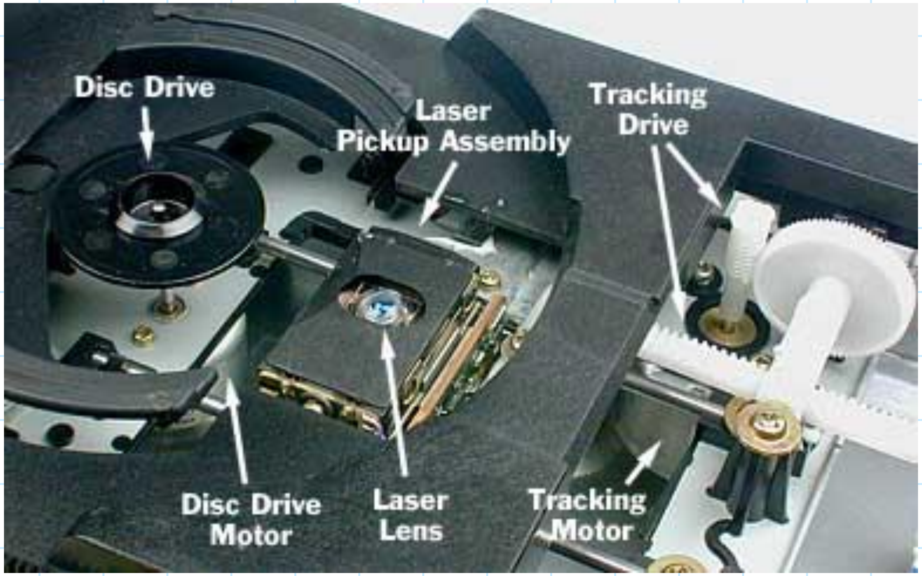
◆ "*Pits*" :
  - 0.5 μm wide
  - 0.83 μm long (mín.)
  - 125 nm high
  - In DVD y Blu-ray these values are lower

◆ "*Lands*"

1.4 Applications of LEDs and photodiodes (II)

- **Reading CDs, DVDs and Blu-ray**

◆ Reading system:



◆ How the reading system work?

http://static.howstuffworks.com/flash/cd-read.swf

1.5 The bipolar transistor. Foundations

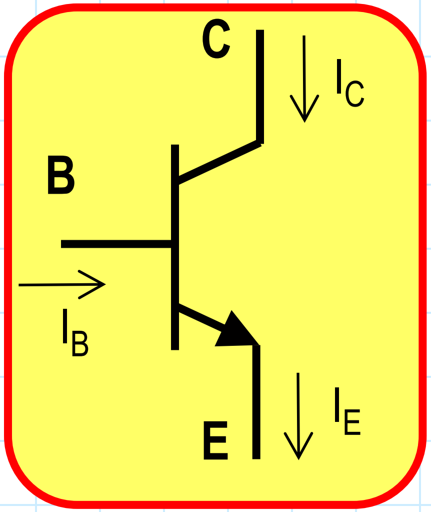
BJT: **B**ipolar **J**unction **T**ransistor

- A Bipolar Junction Transistor is a three-terminal device that, in most logic circuits, acts like a current-controlled switch.

- If we put a small current into one of the terminals, called the base, then the switch is ON:
  - Current may flow between the other two terminals, called the emitter and the collector.
- If no current is put into the base, then the switch is OFF:
  - No current flows between the emitter and the collector.

1.5 The bipolar transistor. Foundations

N-P-N TRANSISTOR



B: Base

C: Collector

E: Emitter

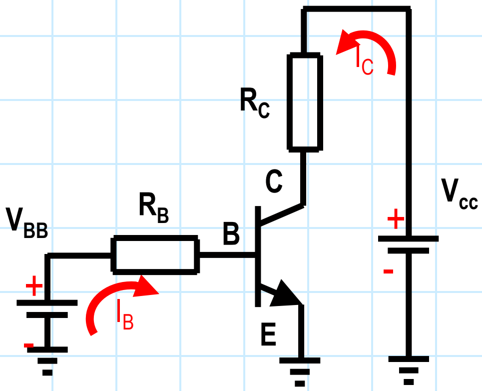
$$I_B + I_C = I_E$$

• Notice that the symbol contains an arrow in the direction of positive current flow (base-to-emitter junction, like in a diode)

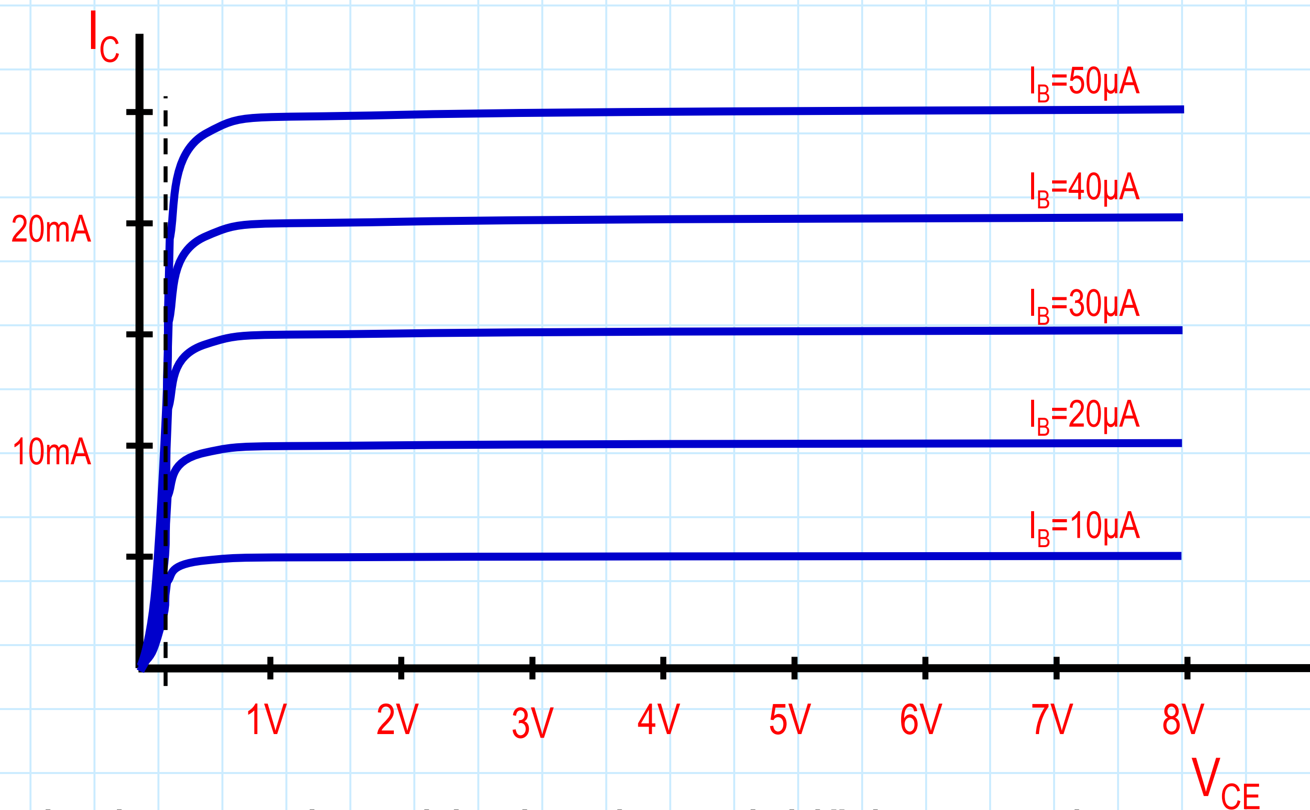
• It is also possible to manufacture a PNP transistor. However, pnp transistors are seldom used in digital circuits.

1.6 Output Characteristic Curves

Current I_C as a function of voltage V_{CE} and current I_B



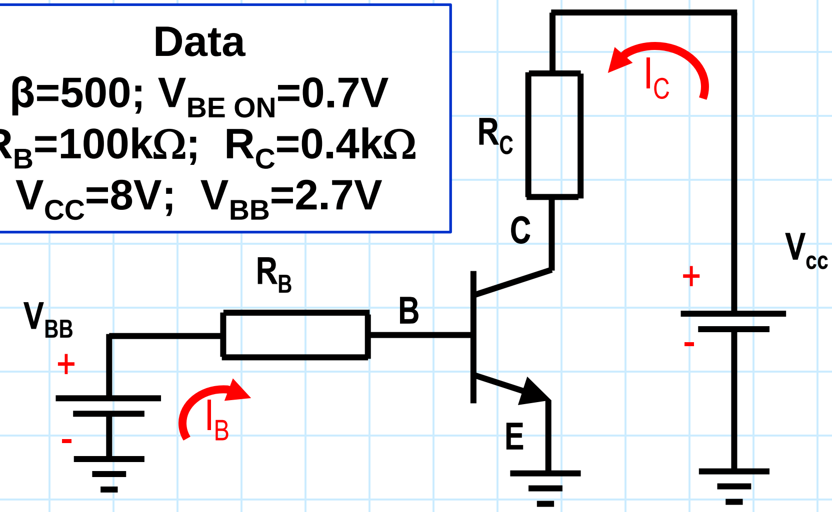
Data:
β=500
(gain of the transistor)
R_B=100kΩ
R_C=0.4kΩ
V_{CC}=8V



Polimedia about "*Bipolar transistor biasing (Spanish)*" (G.Benet):
https://media.upv.es/player/?id=d0a5f9f5-2a3e-a04f-a5d1-d2e6a5028f86

1.6 Static Load Line

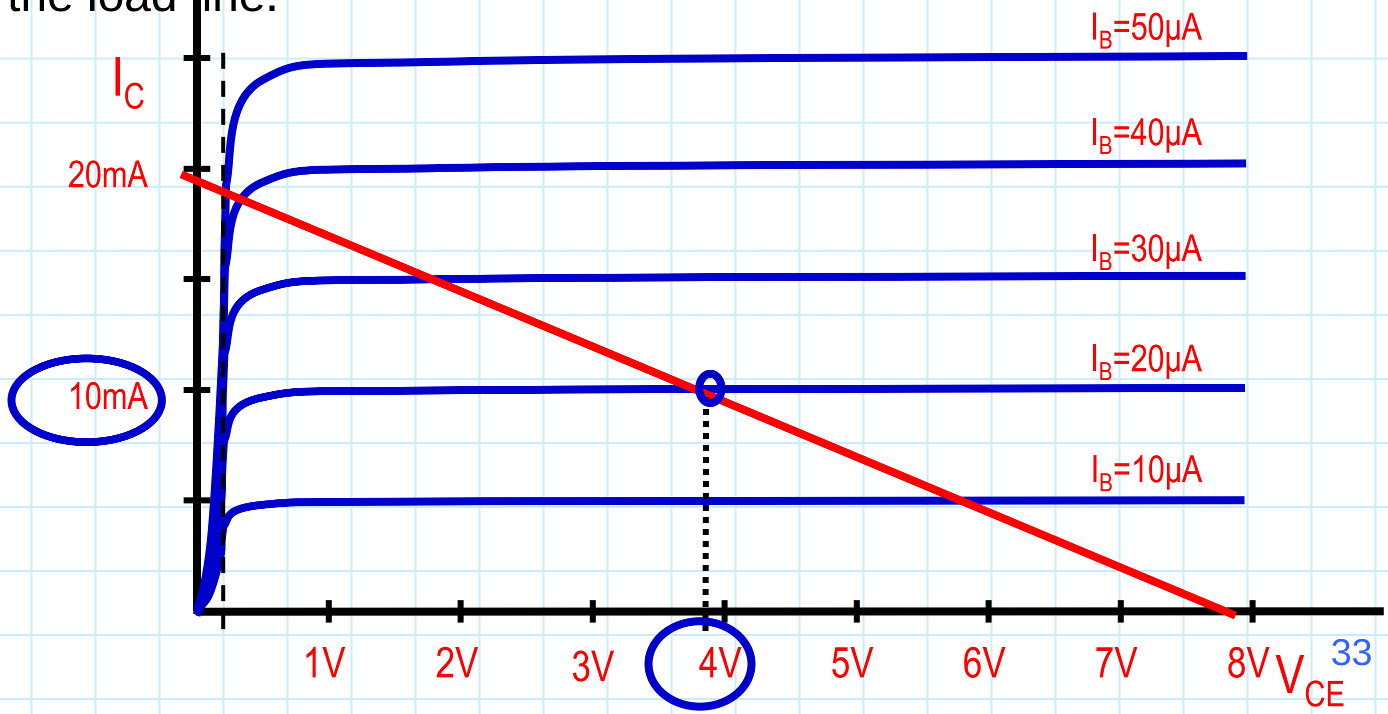
Data
β=500; $V_{BE\ ON}$=0.7V
R_B=100kΩ; R_C=0.4kΩ
V_{CC}=8V; V_{BB}=2.7V



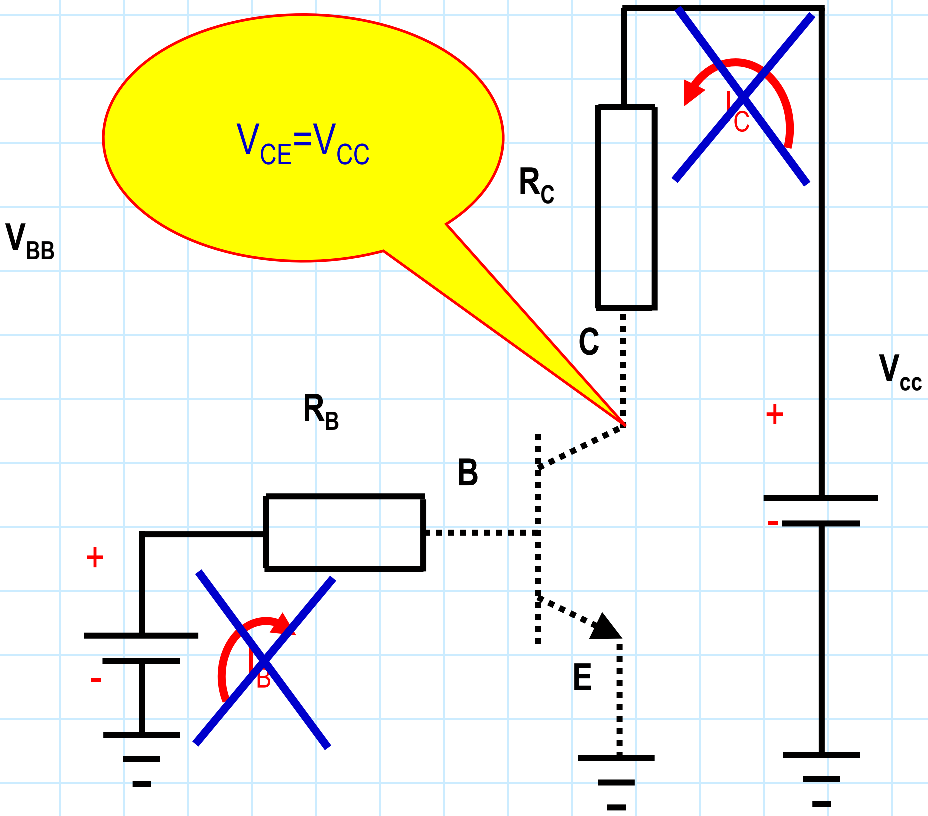
Static Load Line: $V_{CE}=V_{CC}-R_C \times I_C$

$I_B = (V_{BB}-0.7) / R_B = 20\mu A$

The quiescent point is determined by the intersection of the transistor output characteristic curve associated with I_B=20μA and the load line.



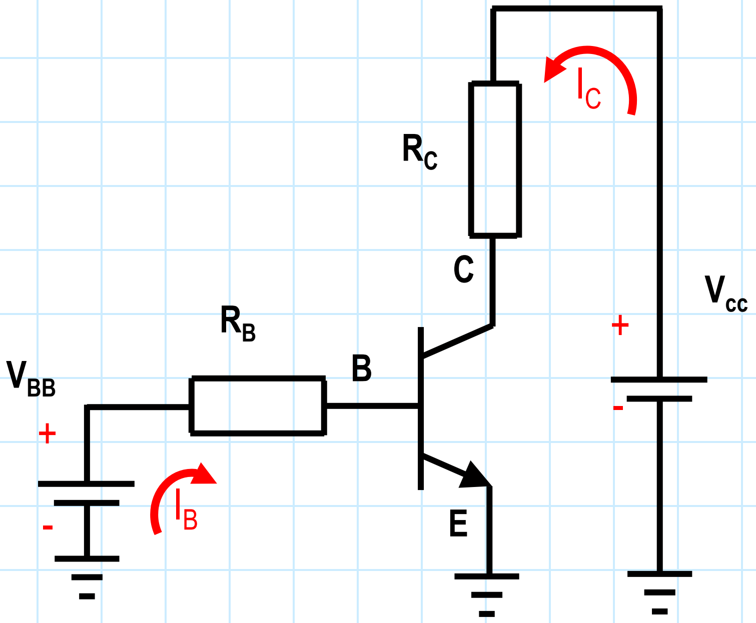
1.7 Regions of operation. Cut-off



$I_B=0,\ I_C=0,\ I_E=0$

The switch is OFF

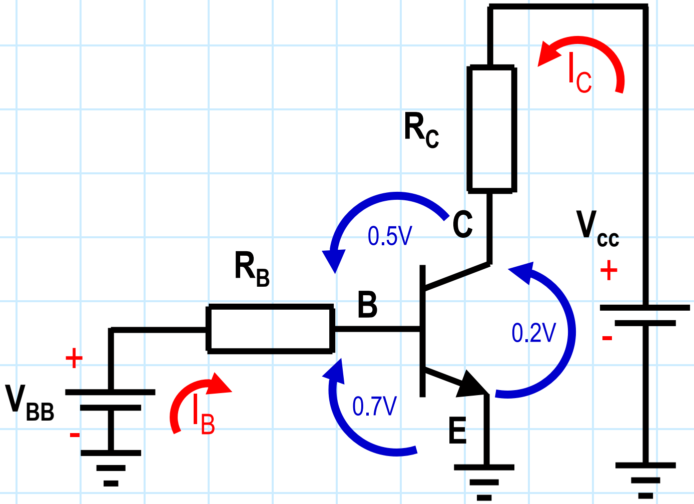
1.7 Operating regions. Active



$$\boxed{I_B > 0 \quad \rightarrow \quad I_C = \beta\, I_B}$$

I_C current is proportional to I_B (linear zone)

1.7 Regions of operation. Saturation



The switch is fully ON

- I_C can not increase more, the transistor is said to be SATURATED

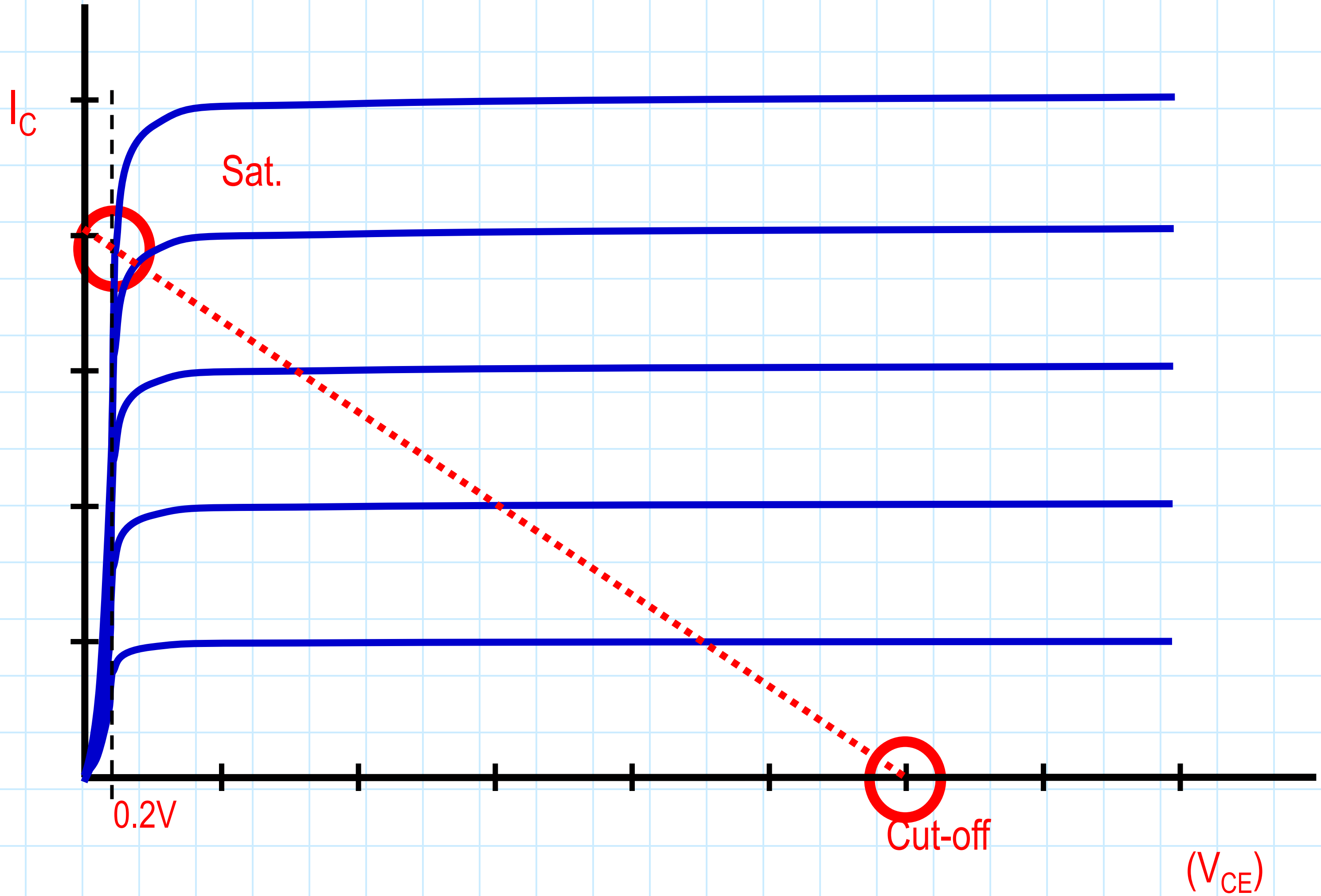
$$I_C < \beta . I_B \text{ ; } V_{CE} \approx 0.2V \text{ ; being } I_B \geq I_{BmínSAT}$$

- Saturation occurs because the output circuit (V_{CC} and R_C) limits I_C to a maximum value.

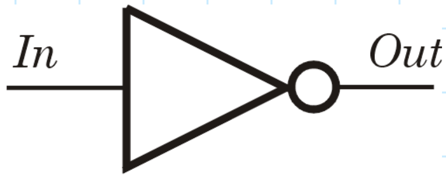
1.8 The BJT in switching mode (1)

- Transistors operate either cut-off (OFF) or saturated (fully ON) :
  - Two very different states
  - Minimum power consumption
  - Very suitable for digital circuits
- The collector and emitter form the switch terminals and the base is the switch handle (control).
- In other words, the small base current can be used to control a much larger current between the collector and emitter.

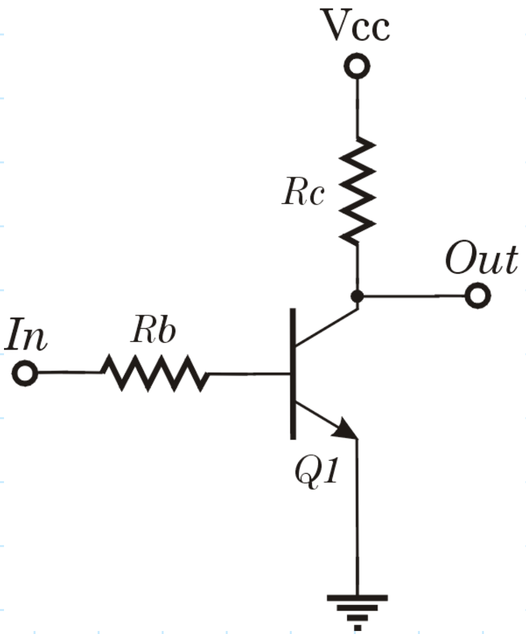
1.8 The BJT in switching mode (&2)



1.9 Transistor-based logic gates : The inverter

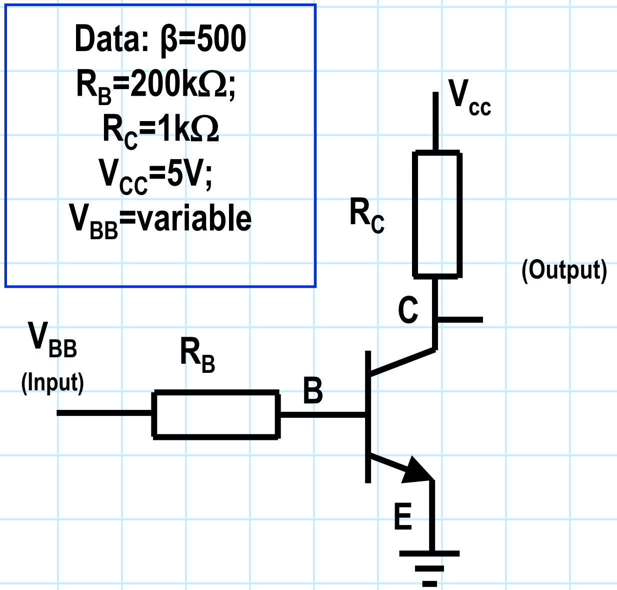


In	Out
1	0
0	1



An inverter can be easily constructed with a properly polarized BJT transistor

1.9 Logic gates. The inverter



Let V_{BB} be a voltage source switching between 0 and 5V, the output will be:

- In the OFF state:

  if $V_{BB} = 0$; $I_C = 0$; $V_C = 5V$ (BJT is OFF)

  - $P = I_C * V_{CE} = 0$

- In the full ON state:

  if $V_{BB} = 5V$; $V_o \sim 0$

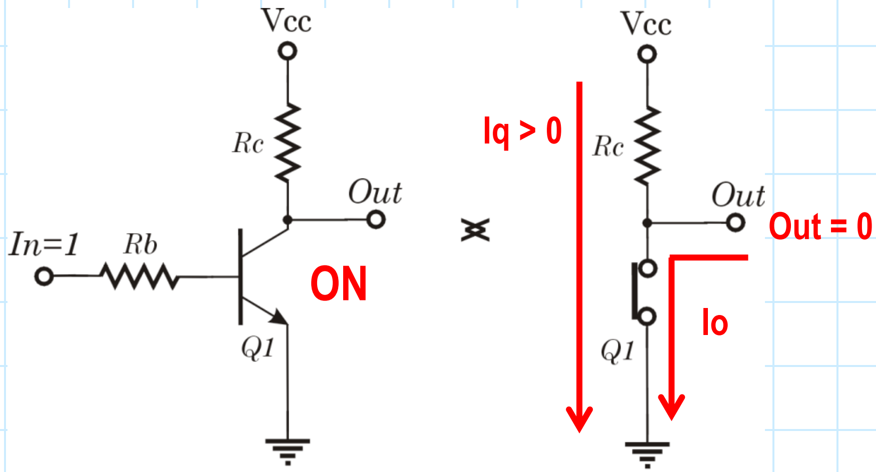
  (provided that BJT is SAT)

  - $P = I_C * V_{CE} \sim 0$

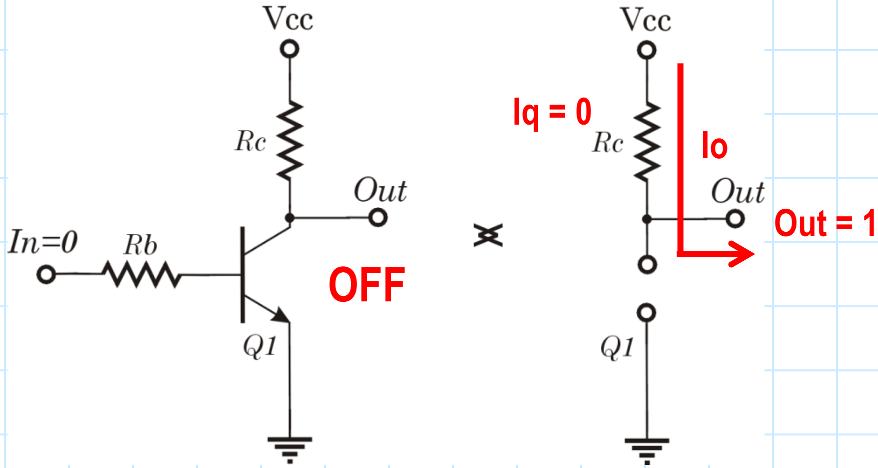
    as V_{CE} is almost 0 so the power is very small

1.9 Logic gates. The inverter

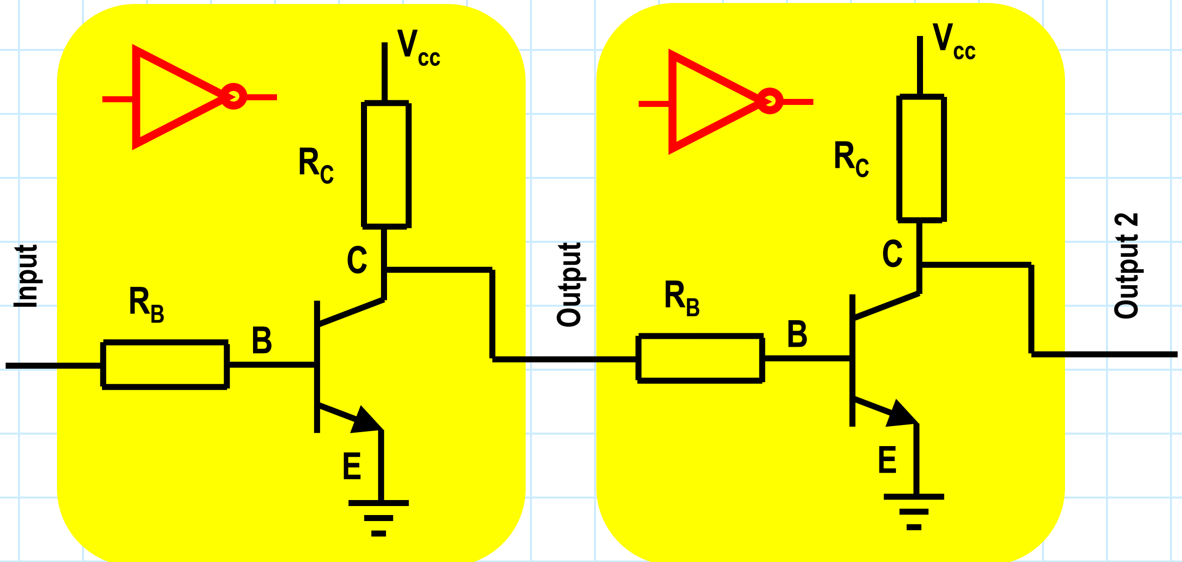
In =1: The input voltage is high enough to saturate Q1 → Q1 ON.
Q1 can be approximated to a short circuit

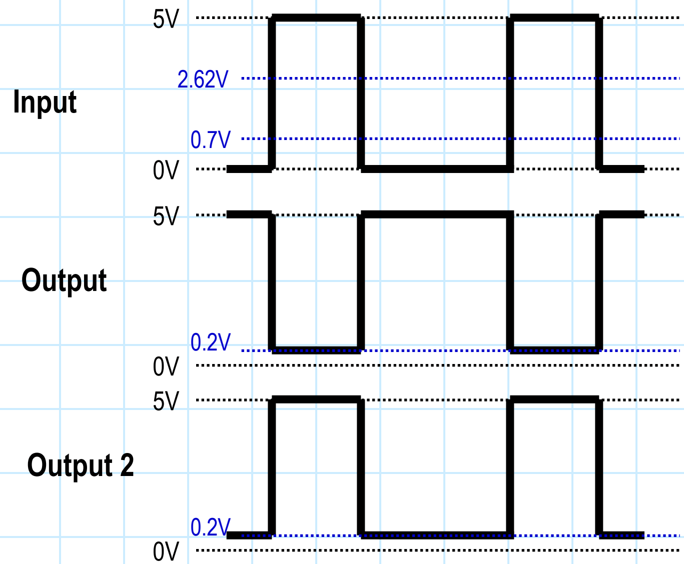


In = 0: The input voltage is very small and Q1 is in cut-off region→ Q1 OFF. Q1 can be approximated to a open circuit



1.9 Transistor-based logic gates





Chapter 1. Summary (1)

In this chapter we first reviewed the operation of the PN junction, which we approximated by different models. These approaches have allowed us to simplify the analysis of diode circuits.

Secondly, we introduced some of the most important diode circuits, used in digital systems. As a examples, we described a circuit for input protection of MOSFET, and various circuits implementing digital logic gates.

Subsequently, we described the Schottky diode, which achieves higher speed and lower V□ than the conventional diode, thereby making it particularly important for switching applications.

Similarly, we described the main characteristics of the LEDs, showing some of their application circuits. As an example, we described circuits that allow us to identify the output logic level of digital circuits. We also described another special-purpose diode, such as the photodiode, which achieves the opposite effect that the LED, as soon as it turns a light radiation into an electrical current.

Chapter 1. Summary (and 2)

After studying the diode, we have focused on the BJT transistor, explaining the basis of its operation and its output curves.

Subsequently, we introduced the operating regions of BJT: cut-off when it does not conduct, and linear and saturation regions when it is conducting current. We also introduced the load line, that is dependent on the external components to the transistor, and determines its quiescent point.

Once known the operating regions of BJT, emphasis has been placed in the two regions used in digital applications (cut-off and saturation). Placing the BJT in these regions makes it to operate in switching (digital) mode.

Finally, we have described several transistor-based circuits for digital applications, with examples related to logic gates, as the logic inverter gate.