Exercise 8.

Active electronic components

Required knowledge

- Description of the pn junction
- DC characteristic of diodes
- Transients in diodes
- DC and AC models of transistors
- Transistors in switching mode.

Introduction

The electrical circuits consist of passive (R, C, L) and active (diodes, transistors) components. In many cases these are parts of complex integrated circuits, but in certain applications discrete active components are used. In order to understand the operation of the transistor, learning the properties of junction diodes is of key importance.

Aim of the measurement

You will get acquainted with different semiconductor diodes (Schottky, Zener, LED) and bipolar transistors. You will investigate their static characteristics, small signal- and dynamic parameters.

Keywords

PN junction, semiconductor, diode, transistor.

Web links

http://www.allaboutcircuits.com/vol_3/chpt_3/1.html

http://en.wikipedia.org/wiki/Diode

http://en.wikipedia.org/wiki/Transistor

Measurement instruments

Digital multimeter (6½ digit)	Agilent 34401A
Power supply	Agilent E3631A

Curve tracer   Hameg HM6042
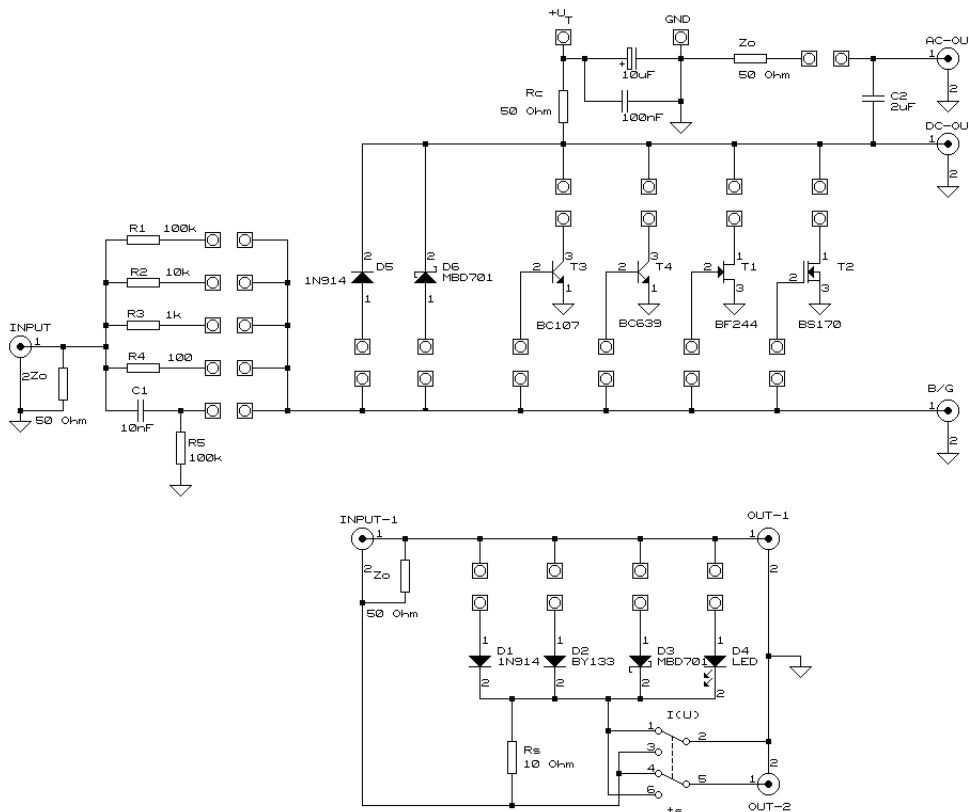
Oscilloscope   Agilent 54622A

Function generator   Agilent 332220A

Test boards

Schematic diagram of the Test board

Theoretical background

Bipolar transistor

Two types of bipolar transistors are defined according to the doping of the different layers of the transistor: type npn and type pnp transistors (the first letter gives the doping type of the collector, the second gives that of the base and the third letter is that of the emitter layer).

The polarities of a bipolar transistor in the so-called normal active region:

Type: npn
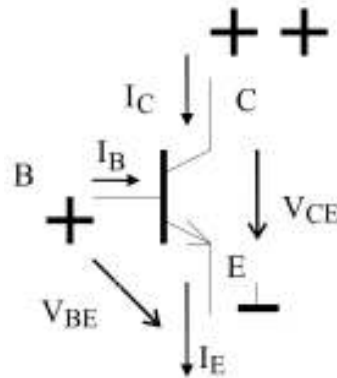
With respect to the emitter as the reference electrode, the voltage of the base must be more positive (by about 0.6 – 0.7V) and the voltage of the collector must be more positive than that of the base.

Transistor-effect

Because of the thin base layer, the transistor cannot be considered as a simple combination of two diodes. Due to the forward biased base-emitter junction, electrons enter the base layer from the emitter. There, as minority charge carriers, they will be attracted by the positive collector voltage and flow against this reverse biasing voltage mainly towards the collector. Only a small part of the electrons flows to the base electrode. The ratio of the collector current and the base current is called the current gain of the transistor in common emitter connection. The current gain is nearly independent of the amount of these currents. Its notation is B:

$$B = \frac{I_C}{I_B}$$

The typical order of magnitude is: B = 100. The constant current gain makes it possible to control the relatively large collector current (and the related emitter current) by the much smaller base current.

Summary of the transistor-effect: although the collector-base pn-junction is reverse biased, a current flows through this pn-junction, and the amount of the greater collector (and emitter) current can be controlled by the much smaller base current.

Output characteristics of a transistor

Parameter of the characteristics: I_B. $I_{B3} > I_{B2} > I_{B1} > I_{B0}$
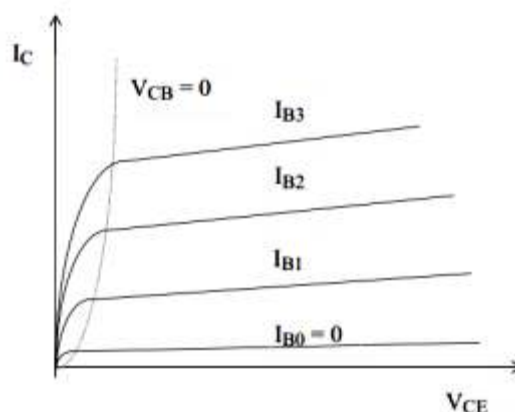
The greater is I_B, the higher runs the corresponding characteristic line. The area between the limit lines with the parameters $V_{CB} = 0$ and $I_{B0} = 0$ is called normal active region. Transistors in amplifiers are operated in this region.

The input characteristic of a transistor is like the characteristic of a diode, giving the relationship of I_B and V_{BE}. In the normal active region with the usual current values in small signal transistors:

$$I_E \approx I_C = 0.1 \ mA \ ... \ 10 \ mA$$

The voltage between the base and the emitter is (just like in case of the diode junctions):
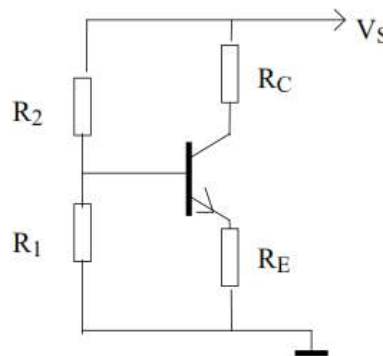
$$V_{BE} = 0.6 \ V$$

This means that the *DC equivalent circuit* of the transistor is:
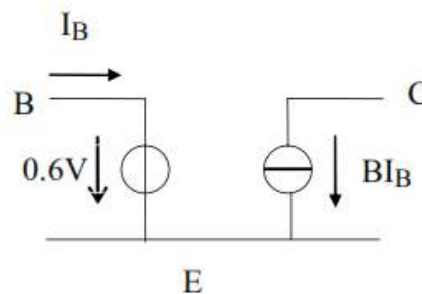
By means of this DC equivalent circuit, the operation point of the transistor can be determined. The operation point data comprises I_C, V_{CE} and sometimes also I_B (if it is not negligible).

General method of the operation point calculation of a transistor

The following circuit is given.

DC equivalent circuit:
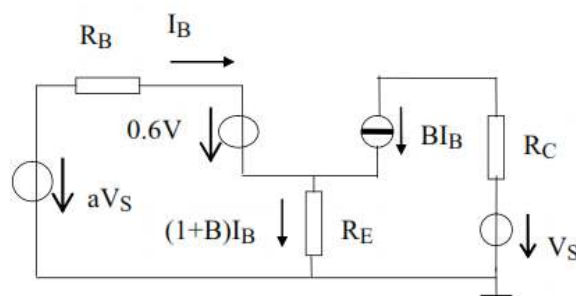
In the equivalent circuit:

- R_B is the internal resistance of the base-divider: $R_B = R_1 \times R_2$
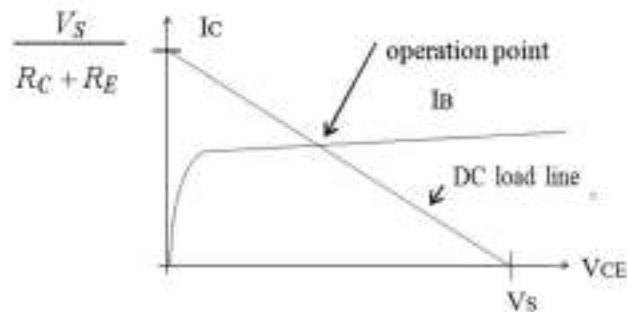
- $a = \dfrac{R_1}{R_1 + R_2}$

By means of the equivalent circuit: $I_B = \dfrac{aV_s - 0.6}{R_B + (1 + B)R_E}$

$I_C = BI_B$

$V_{CE} \approx V_S - (R_E + R_C)I_C$

supposing that: $I_C \approx I_E$

Graphically:

Practical method of the operation point calculation of a transistor

Approximation: $I_B \approx 0$ (verified by whether $[1+B]R_E \gg R_B$ is fulfilled)

With this: $V_B = aV_S$

$V_E = V_B - 0{,}6V$

$I_C \approx I_E$

$I_C \approx I_E = \dfrac{V_E}{R_E}$

$V_{CE} \approx V_S - (R_E + R_C)I_C$

### Plotting the static transistor characteristic using a curve tracer

Instrument: The HM6042 Curve Tracer is a general purpose measurement instrument for displaying the characteristics of semiconductor devices. The instrument is particularly suitable for observation of two and three terminal semiconductors, like diodes and transistors. It provides quick and simple measurement of the main semiconductor parameters after production and in laboratory applications as well. The comparison of two devices are possible by storing one set of parameters in the memory. The measurements can be carried out in 3 voltage ranges (2-10-40V), 3 current ranges (2-20-200mA) and with 3 power limits (0,04-0,4-4W).

The hybrid parameters of the transistor's equivalent circuit can be directly measured with the Curve Tracer.

Static characteristics of the semiconductor diode

(The pn-junction and the diode)

Symbol, characteristic and equation of a diode.
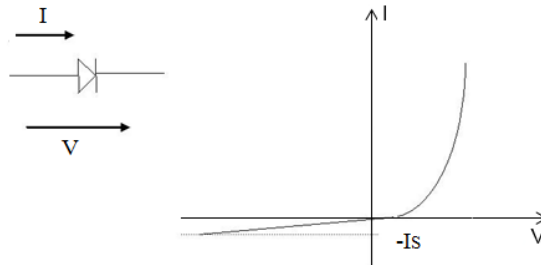
$$I = I_S\left(e^{\frac{V}{V_T}} - 1\right)$$

where I_s is the saturation current and

                V_T is the thermal voltage.

The thermal voltage:

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

where k is the Boltzmann constant,

                T is the temperature in K and

                e is the charge of an electron.

Some numbers to learn:

- The value of the thermal voltage at room temperature ($300\ °\text{K} \approx 27\ °\text{C}$):
  $V_T = 26\ mV$
- At currents between 0.1 mA and 10 mA the voltage drop across a forward biased silicon diode:
  $V_D \approx 0.6\ V$

The *dynamic resistance* of a conducting diode:

$$r_D = \frac{dV}{dI} = \dots \approx \frac{V_T}{I}$$

The static characteristics can be measured using the test panel, setting a switch to the appropriate state. The measurement setup is shown:


$R_G = Z_0 = 50\ \Omega$

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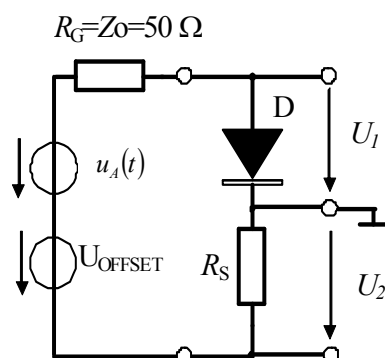
The U-I curve of the diodes can be plotted by the oscilloscope using it in the X-Y mode. The diode voltage can be measured directly by the X channel of the oscilloscope. The diode current can be measured using the series resistance (R_S). By means of the oscilloscope, measure the diode current "$-I_F$ " (the voltage drop on R_s) of the diode and the voltage $[U_F]$ between the anode and cathode.

In X-Y mode both inputs of the oscilloscope should be in the DC coupling, with given sensitivity. Rescale channel Y by selecting the ratio 0,1:1 in the Probe Menu and the unit should be Ampere.

The switching time of the diode

The measurement setup for dynamic characteristic of semiconductor diodes is shown below:
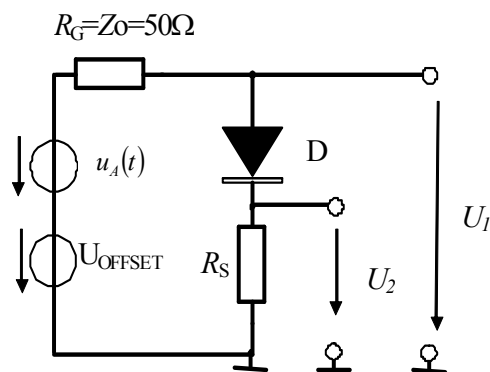
The diodes are characterized by three main parameters: I_{max} (maximum average current) U_{Rmax} (maximum reverse voltage) and t_{rr} (reverse recovery time). The first two parameters relate to the performance of the static power stress, and the third determines the allowed maximum operating frequency.

The diode switching processes depend on the characteristics of the pn junction. The diode switch-off transients are important due to the charge storage. In the ON state of the diode the forward current flows through the pn junction, so the diode stores charges in the boundary layer and the diffusion capacitance is dominant. In OFF state no current flows through the diode. The depletion zone of the pn junction has much smaller than the so-called space-charge capacity.

The switching process can be observed by applying a voltage step on the anode of the diode. During the ON-OFF and OFF-ON transition the voltage and current of the diode can be measured with oscilloscope.

It can be seen in the time diagram below that the diode current does not cease to flow immediately upon reversal of the drive voltage signal, but remains constant ($-I_R$) during the storage time (t_s) and then starts to decrease. The time interval during which the diode current decreases to 10% of its peak value is called fall time. The sum of the storage time and the fall time is the reverse recovery time (t_{rr}).

$$t_{rr} = t_s + t_f$$
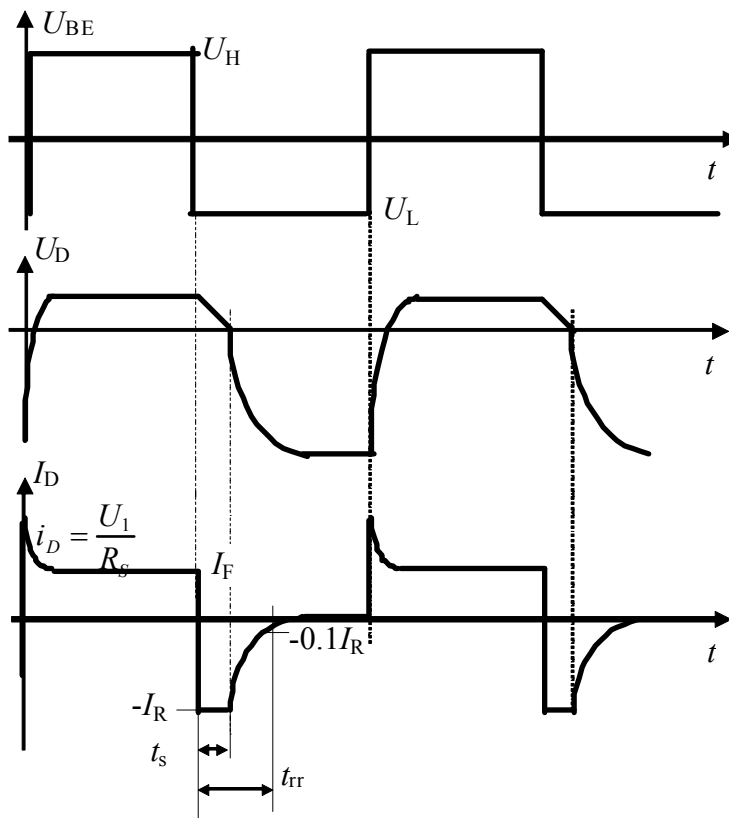
Switching time of the diode. Voltage and current versus time.

The storage time can be determined from the charge continuity equation, assuming that during the storage time the diode current is constant (I_R) and the initial amount of accumulated charge in the base at the time of switching off the diode is: $q_{t=0} = \tau \cdot I_F$ (where τ is the recombination time constant). After solving the continuity equation the following simple expression can be obtained for the storage time:

$$t_s = \tau \cdot \ln\left(1 + \frac{I_F}{I_R}\right)$$

By measuring the storage time the τ time constant can be calculated from the above equation.

By the end of the storage time the diode voltage drops from the forward voltage level ($U_F \approx$ 0.7V) to zero. Therefore the diode can be considered as a "voltage generator" during the storage time as its voltage only slightly changes. The diode voltage then decreases to the reverse voltage level when the current decreases.

The fall time of the diode current is determined by the layer capacitance and the remaining charge in the base space after the constant current period.

Bipolar transistor: beta cut-off frequency

Increasing the frequency above a certain value the current transfer ratio of the transistor decreases until the transistor does not amplifies. At the beta cut off frequency (f_β) current transfer ratio is:

$$|\beta| = \beta_0 / \sqrt{2}$$

At frequencies higher than the beta cut off frequency, β decreases by 20dB/decade. The frequency where $\beta = 1$ is called transit frequency.

$$f_T = |\beta_{measured}| \cdot f_\beta$$

The $C_{B'E}$ capacitance can be calculated from f_β, assuming that the base drive is current generator type ($R_B \gg r_E$).

$$f_\beta \cong \frac{1}{2\pi C_{B'E}(1+\beta)r_E}$$

If the series resistance R_B is decreased and the cut-off frequency measurement is repeated ($f_{\beta'}$), the base resistance $r_{BB'}$ can be calculated from the following equation.

$$f_{\beta'} \cong \frac{1}{2\pi C_{B'E}\left\{\left(R_B + r_{BB'}\right) \times (1+\beta)r_E\right\}}$$

Switching times for bipolar transistor

Two operating points can be defined on the output characteristic of the common emitter transistor in switching mode. The operating point of the switched off transistor is given by the $I_B = 0$ curve and the load line, and that of the switched on transistor is in the saturation region, near the maximum collector current point of the load line. In this case the operating point is the intersection of the switch-on base current curve and the load line. Depending on the value of the base current, several operating points can be determined. The most notable is the I_{Blim}, where the operating point is at the boundary of the saturation region. This boundary is defined by definition as $U_{BC} = 0$V.
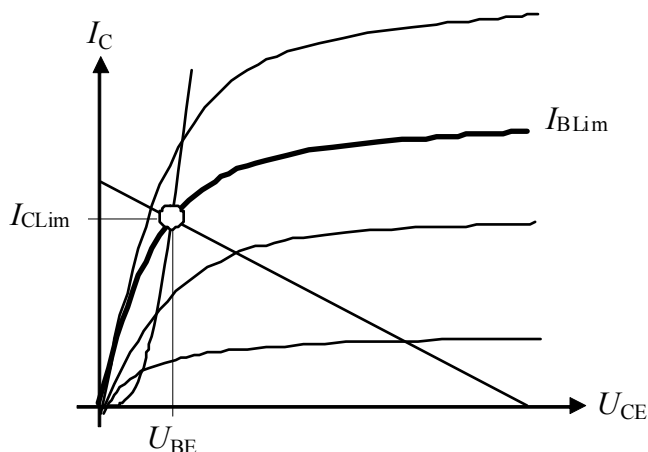
If a generator producing a bipolar square wave signal is connected to the base through R_B, the switching times of the transistor can be determined from the time diagram of the collector voltage (see below).

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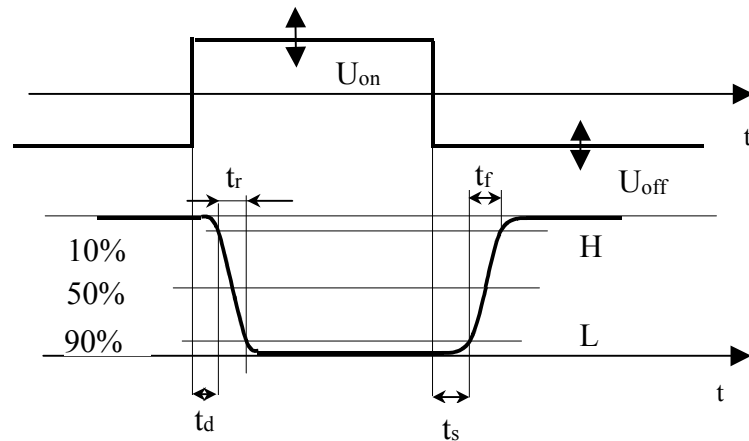
The switching times of the transistor are as follows:

t_d switch ON delay time

t_r current rise time (U_{CE} fall time)

t_s charge storage time (U_{BE} decreases from 0,7V to 0V

t_f current fall time (U_{CE} rise time)

For the switch-on base current: $I_{B_{ON}} = \dfrac{U_{ON} - U_{BE}}{R_B}$. In this case, the E-B junction is open and

$U_{BE} = 0,7$ V can be assumed. For the switch-off base current: $I_{B_{OFF}} = \dfrac{U_{OFF} - U_{BE}}{R_B}$, as long

as the transistor is switched on.

By continuously increasing the amplitude of the switch-on impulse the I_B reaches the critical current (I_{BLim}) where the transistor goes into saturation. This means that the collector-base voltage $U_{CB} = 0$ and the collector current $I_{CLim} = I_{CMAX}$. Therefore, the base current for

saturation is $I_{BLim} = \dfrac{U_{ON} - U_{BE}}{R_B}$.

The switch-on and switch-off overdrive are defined as $m_{ON} = \dfrac{I_{B_{ON}}}{I_{BLim}}$ and $m_{OFF} = \dfrac{I_{B_{OFF}}}{I_{BLim}}$,

respectively.

The base time factor τ_B can be calculated from the following equation:

$t_s = \tau_B \ln \dfrac{m_{ON} + m_{OFF}}{0,9 + m_{OFF}}$.

Connecting a reverse biased Schottky diode between the collector and base pins, the saturation of the transistor can be avoided as the storage time strongly decreases.

Test questions:

1. Draw the $U_D - I_D$ forward characteristic of a diode!

2. Give the characteristic equation of the "ideal diode". What other effects shall be taken into account in case of a real diode!

3. What causes the storage time of bipolar semiconductor devices?

4. Define the f_β, f_α, f_1, f_T and f_{max} frequencies of the bipolar transistor. What is the relation between these frequencies?

5. Draw the output characteristic of the common emitter bipolar transistor. Mark the saturation and normal active regions!

6. Draw the time diagram of the collector current of a bipolar transistor driven by an ideal square wave! Define in your diagram the switching transient times of the bipolar transistor: delay time (t_d), rise time (t_r), storage time (t_s) and fall time (t_f)!

7. What is approximately the maximum current (I_{CMax}) of the given circuit? What is the necessary base current (I_{Blim}) to drive the transistor into saturation?
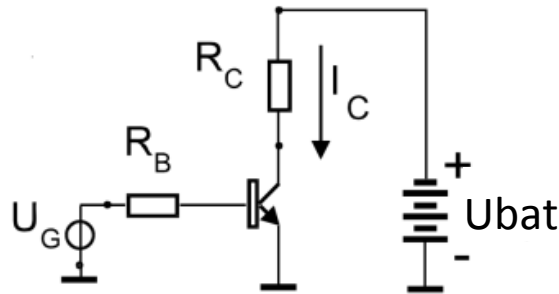
8. What effects cause the charge storage time? Which factors determine the length of the storage time? When does the fall time start?

9. By increasing the switch-on overdrive,

   a.   the rise time: increases, decreases, or remains the same?

   b.   the storage time: increases, decreases, or remains the same?

   c.   the fall time: increases, decreases, or remains the same?

10. By increasing the draw current,

   a.   the rise time: increases, decreases, or remains the same?

   b.   the storage time: increases, decreases, or remains the same?

   c.   the fall time: increases, decreases, or remains the same?

11. Which methods are used to decrease the storage time?

12. Describe the effects of the speed-up capacitor on the switching times.

13. Describe the effects of the protection of the transistor saturation with Schottky diode on the switching times.

14. What are the most important maximum ratings of the power semiconductors?

15. What is the dissipation hyperbole?

16. What is the safe operating area (SOA)?