

Introduction to Electronics

Laboratory Manual

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1. The Semiconductor Diode

The equation of an ideal diode is:

$$I = I_0 \left(e^{\frac{eV_{ext}}{kT}} - 1 \right)$$

Where I_0 is the saturation current and V_{ext} is the applied voltage on the diode. If we applied a forward biasing voltage, that means a positive V_{ext} , the 1 becomes negligible in comparison with the exponential, so we will obtain a typical exponential curve. In the case of a reverse biasing voltage, that means negative V_{ext} , exponential vanish rapidly to zero, so we will obtain a constant value of the current, e.g. I_0 . Therefore, we can say that, at reverse biasing voltage the resistance of a diode is infinite, and in conditions of forward biasing voltage the resistance, so called “dynamic resistance”, can be defined by next formula:

$$\frac{dI}{dV} = \frac{e}{kT} I_0 e^{\frac{eV_{ext}}{kT}} = \frac{I_D}{V_T} = \frac{1}{r_D} \quad \text{where } V_T \text{ is so named thermal potential, having at room temperature the value of } 0.026V.$$

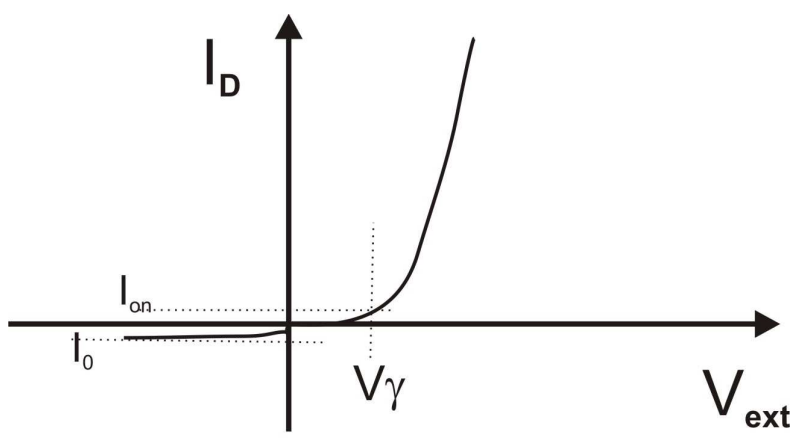


Fig.5

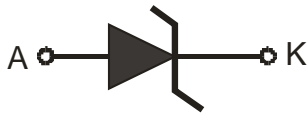
associate his dynamic resistance.

Then, the typical plot of ideal diode equation will be as you can see in Fig.1. The opening voltage of the diode is noted by V_γ . Starting from this value, the current through the diode has values higher than 1mA, and the diode is in so named “active region”, where we can

Typical values for V_γ are: 0.2V on Germanium structure and 0.65V on Silicium structure.

In the case of a real diode, the saturation current doesn't remain constant. At a reverse biasing voltage, named "breakdown" voltage, I_0 increase dramatically while the external voltage applied on the diode remain constant. This effect is used for stabilizing the voltage (voltage regulator) on a load resistor connected as a load resistor on the diode. Such kind of diodes are Zener diodes.

The symbol used for the Zener diode is shown below:



The experimental setup is represented in Fig.6.

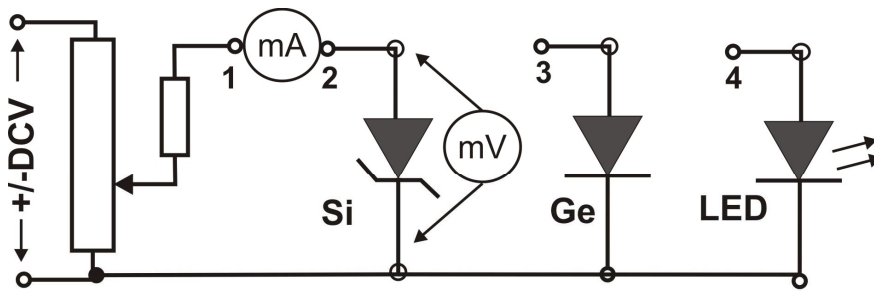
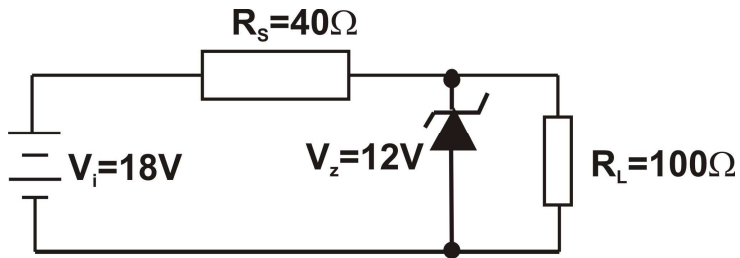


Fig.6

A milliammeter must be connected in series with the each diode, between 1 and 2 jacks, 1 and 3 jacks, 1 and 4 jacks, for each characteristic. Take care on the polarity, depending if you are working in forward or reverse biasing conditions. Use a table as shown below to for writing down your readings.

I_D ($\mu A/mA$)										
V_{ext} (V/mV)										

On the same graph, you must plot the data for all diodes at forward biasing voltage. Plot too, in same conditions, the graph of $\ln I_D = f(V)$. What can you determine from the slope of such graph?



Exercises

Which is the dissipated power on the load resistor?

What is happened if the load resistor has the value of 50Ω ?

Static Characteristics of Bipolar Junction Transistor:

2. Common Base Configuration

3. Common Emitter Configuration

The main configurations for bipolar junction transistors (BJT) are the "Common Base

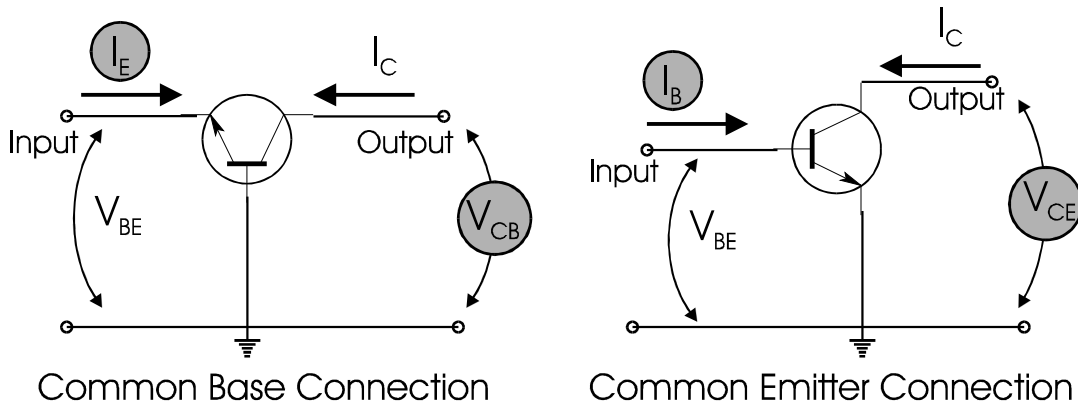
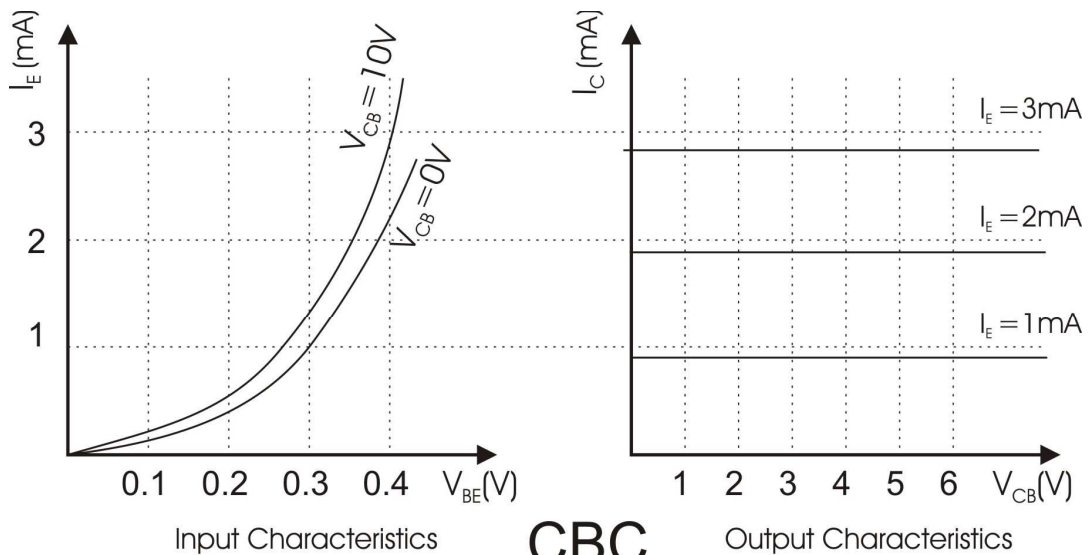


Fig. 1

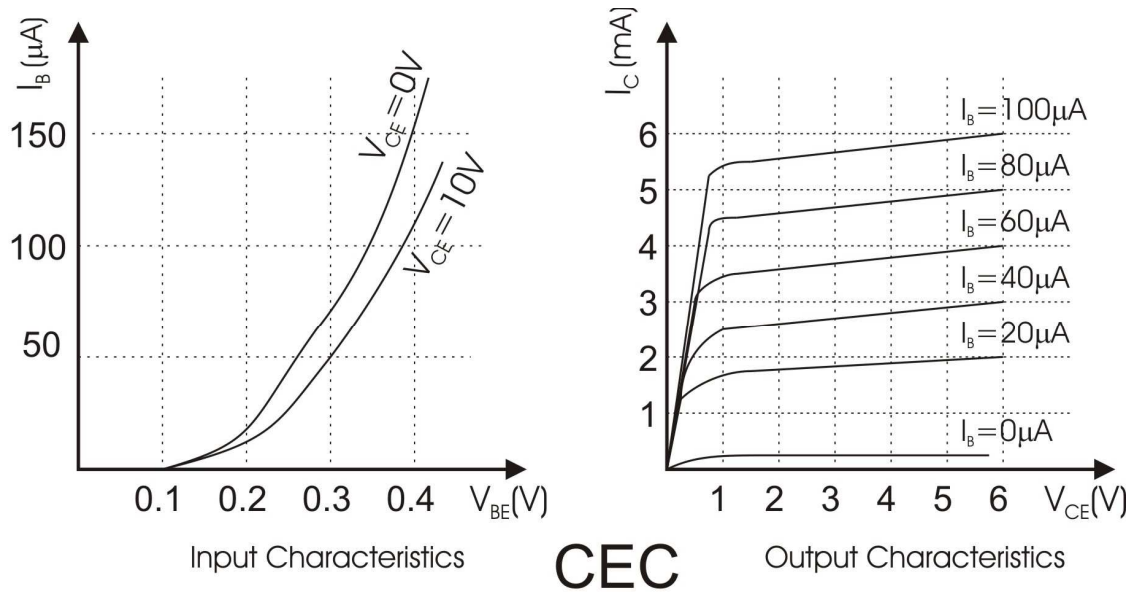


CBC

Fig. 2

Configuration" (CBC) and the "Common Emitter Configuration" (CEC). The naming originates from the fact that the Base, respectively the Emitter, are connected to the Ground of the circuit which is the common connection between one jack of input jacks and one jack of the output jacks. Considering the transistor as a four terminals network (quadripole), we can represent these connections as you can see in fig.1., where the transistors are NPN type. If the transistors should be PNP type, the arrow of the emitter must have reverse direction, e.g. inside the transistor.

Having four variables characterizing the quadripole operation (two at the input and two at the output), in order to plot the static characteristics of the transistor, we choose two of them as independent variables and the represent the other two dependent variables as a function of the independent ones. For instance, we can choose I_E and V_{CB} for CBC, and I_B and V_{CE} for CEC as independent variables, shown as dashed circles in figure 1. Of course, we must operate in the active region of the transistor, that means **forward biasing voltage on the emitter junction and reverse biasing voltage on the collector junction**. Then, the static characteristics of CBC will be as you can see on Fig.2. Please pay attention to the fact that in the output characteristic, I_C is slightly smaller than the I_E . In the case of input characteristic you can see that, for the same V_{BE} , the input current has a little bit higher value if the V_{CE} is different of 0V. This behavior can be explained by the different width of neutral region of the base (Early effect), at different collector-base voltages V_{CB} .



CEC
Fig. 3

In the case of CEC, typical static characteristics are showed in Fig.3. On the input characteristic you can see, in better way, the Early effect. The I_B is smaller if we applied a reverse biasing voltage on the collector. This behavior is done by the decreasing of the recombination phenomena in the neutral region of the base, this

having a smaller width because the depletion region of the collector junction are increasing with the increasing of the reverse voltage applied on the collector.

Experiment

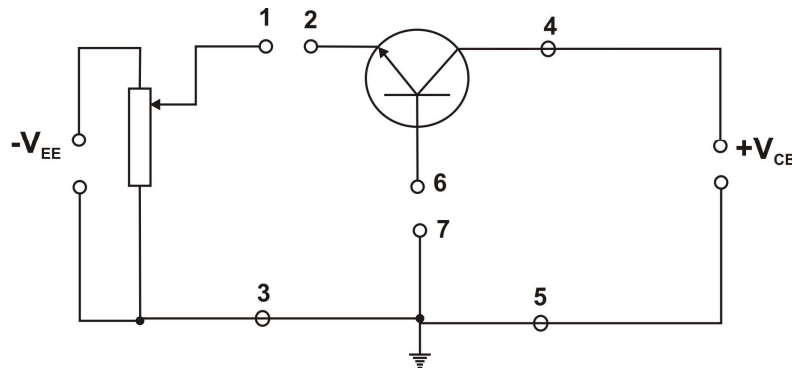


Fig.4

In Fig.4 is represented the experimental setup. Between 1 and 2 jacks you must connect a milli-ammeter, in the aim to measure I_E . Between 2 and 3 you must connect a milli-voltmeter, in the aim to measure V_{BE} . Between 6 and 7 you must

connect a micro-ammeter, to have I_B . We remember you that $I_C = I_E - I_B$, then you can have the true value of I_C . Of course, between 4 and 5 you must connect a voltmeter to measure the V_{BC} voltage. Using this setup, you can plot static characteristics of the transistor as in Fig.2. For input characteristic you can take $V_{CB} = ct.$ at 0V and 12V. Take care to don't increase I_E current more than 10 mA. For output characteristic it is enough to have a family of characteristics for $I_E = 1; 2; 3; 4$ mA. Taking into account that the device formula is $I_C \approx \alpha I_E$, you can compute

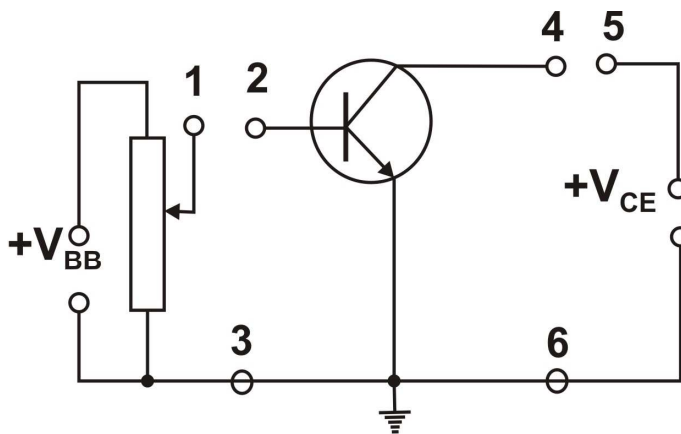


Fig.5

current gain α from output characteristics.

In the aim to plot static characteristics of CEC, you have at your disposal the setup represented in Fig. 5.

Between 1 and 2 you must connect a micro-ammeter, to get the value of I_B . For V_{BE} you must connect a milli-voltmeter between 2 and 3 jacks. I_C will be measured using a milli-

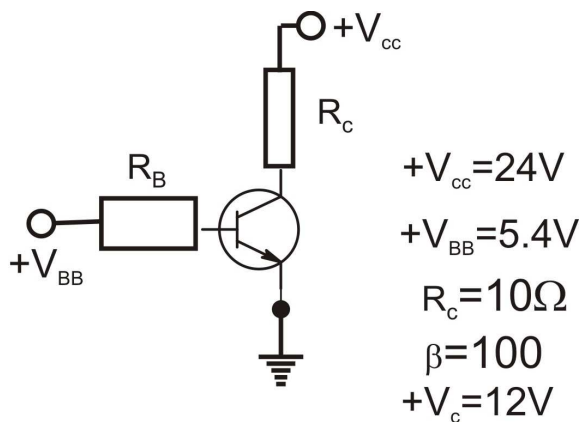
ammeter connected between 4 and 5 jacks. Of course, for V_{CE} measurement you must connect a voltmeter between 4 and 6 jacks. As in the case of CBC, for input characteristics you must take $V_{CE} = ct.$ at 0V and 10V. Take care don't increase I_B more than the value when I_C becomes 10 mA. For output characteristics take $I_B = 20, 30, 40, 50 \mu A$. From device formula $I_C \approx \beta I_B$ you can compute current gain β . For

output characteristics take care to start by small steps (0.1V) of V_{CE} . After first 3 or 4 steps you can go 1 to 1 volt.

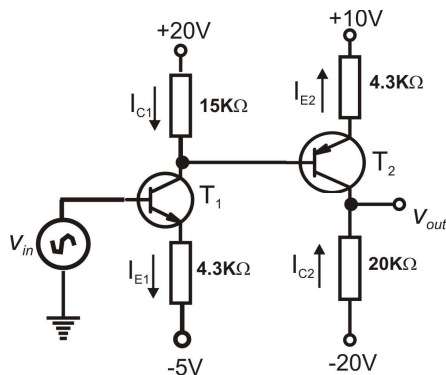
To have good results, we advise you to use a table such this one:

$I_B/I_E/I_C$ ($\mu A/mA$)										
$V_{BE}/V_{CB}/V_{CE}$ (mV/V)										

Exercises



Calculate I_C , I_B , and R_B . Which is the principal conclusion?



T_1 is NPN transistor, having $\beta=100$;
 T_2 is PNP transistor, having $\beta=100$;
 opening voltage $V_{BE}=\pm 0.7V$;
 compute V_{B1} , V_{E1} , V_{C1} , V_{B2} , V_{E2} ,
 V_{C2} ; you can approximate

$$I_E \cong I_C$$

$V_{B1}=0V$ (being connected to the ground); $V_{BE1}=-0.7V$, then

$V_{E1}=-0.7V$; drop voltage on R_{E1} resistor is: $-0.7V - (-5)V=4.3V$;

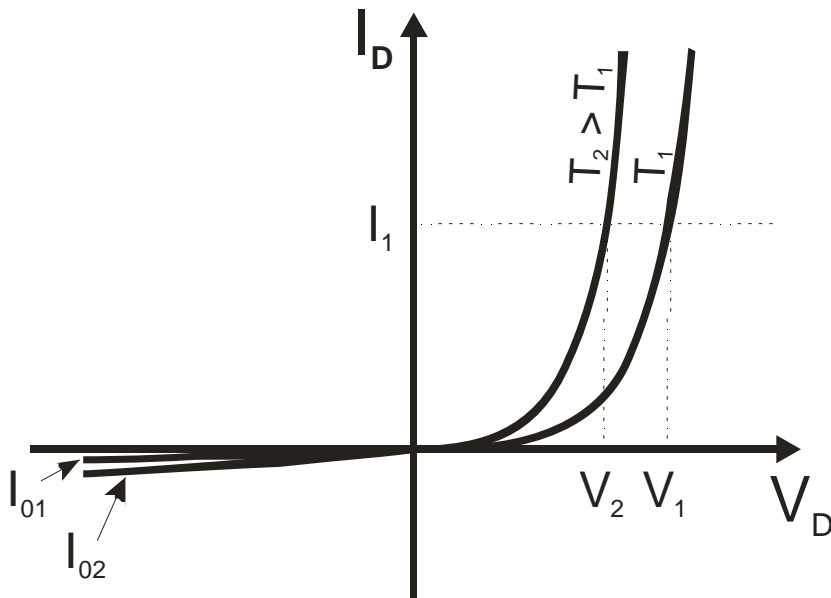
$I_{E1}=4.3V/4.3K\Omega=1mA=I_{C1}$; then the drop voltage on R_{C1} resistor is: $1mA \times 15K\Omega=15V$;

then $V_{C1}=20V-15V=5V=V_{B2}$

$V_{BE2}=+0.7V$; then $V_{E2}=V_{B2}+V_{BE2}=5V+0.7V=5.7V$; then the drop voltage on R_{E2} is $10V-5.7V=4.3V$; then $I_{E2}=4.3V/4.3K\Omega=1mA=I_{C2}$; finally $V_{C2}=-20V - 20K\Omega \times 1mA=0V$

4. Temperature dependence of semiconductor diode and bipolar junction transistor characteristics.

The semiconductor diode has a temperature dependence that changes with temperature as shown in the figure below:



The most sensitive factor to temperature variations of the I-V characteristic of an actual p-n junction is the saturation current I_0 .

$$I = I_0 \left(e^{\frac{eV_{\text{ext}}}{\eta kT}} - 1 \right)$$

For real devices, η is the diode ideality factor ($\eta \approx 1.5-2$) and I_0 matches the reverse bias current.

I_0 primarily depends on the concentration of minority carriers that have a combined power-law and exponential dependence on temperature, such that the saturation current I_0 follows with temperature the equation:

$$I_0 \propto T^3 e^{-\frac{E_g}{kT}}$$

where E_g is the band-gap of the semiconductor ($E_g \approx 1.1\text{eV}$ for Si), $k = 8.62 \times 10^{-5} \text{ eV/K}$ and T is the absolute temperature.

Therefore at reverse bias, the current through the diode strongly increases with temperature. Even at forward bias, the current through the diode will increase with temperature, for the same applied voltage, as the variation of the saturation current will be stronger than the one in the opposite direction of the exponential term in parantheses.

For the bipolar junction transistors (BJT), in the most common configurations, e.g. CE and CB, the output current is I_C . This current depends on I_{C0} , β and V_{BE} , which are dependent on the ambient temperature. Strongest dependence of temperature has I_{C0} , because this current is given by the density of minority charge carriers, which are generated via band to band transition. In most practical situations, the temperature dependence of this current is given by the following formula:

$$I_{C0}(T) = I_{C0}(T_0) \times \left(\frac{T}{T_0} \right)^3 e^{-\text{const.} \cdot \left(\frac{T_0}{T} \right)}$$

where T_0 is room temperature, taken at $300 \text{ }^0\text{K}$.

Germanium has the strongest dependence of temperature because the width of forbidden bend has only 0.7eV , in comparison with Silicium which has this width of 1eV , then, the probability to have a jump from valence band to conduction band is higher for Germanium.

The temperature dependence of current amplification factor β can be approximated by the following formula:

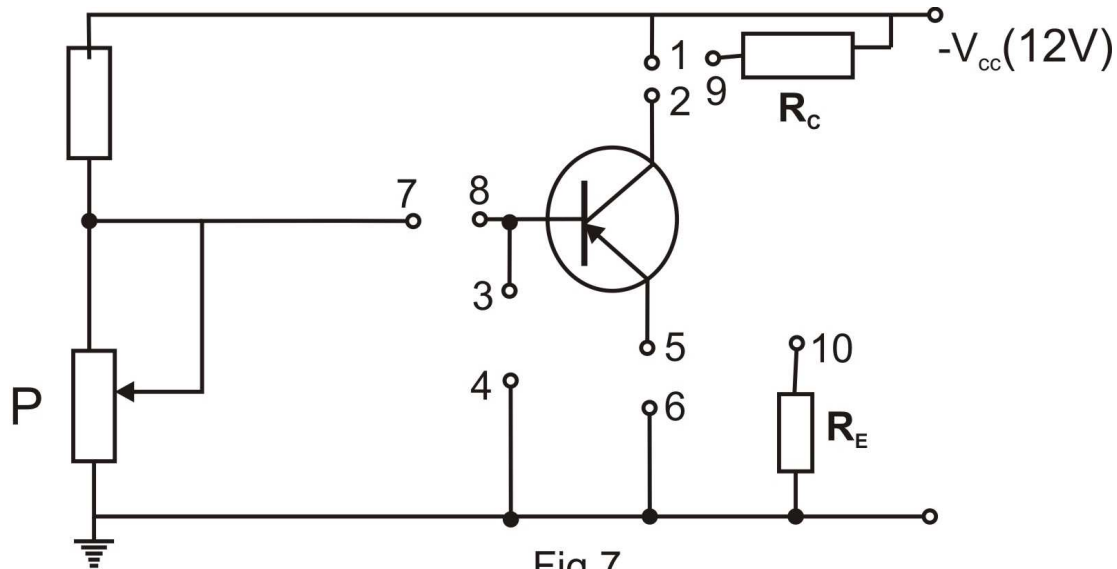
$$\beta(T) = \beta(T_0) \cdot \left[1 + \frac{T - T_0}{K} \right]$$

Where K is a constant having the value 100 for Ge and 50 for Si.

For V_{BE} , the dependence of temperature in a Si transistor is:

$$\frac{\partial V_{BE}}{\partial T} = -2.2\text{mV}/^{\circ}\text{C}$$

This dependence of V_{BE} with temperature is frequently used in integrated circuit temperature sensors.



Experiment

In the laboratory, a Germanium PNP transistor is being used, having residual currents in the μA range, that can be easily measured with an analog DVM. The transistor is mounted in a small oven which has inside a thermistor as temperature sensor. The laboratory setup is shown in Fig.7.

Connect the thermistor to an ohmmeter and the heating wire of the ceramic mini-oven to a DC supply at 2-3 V.

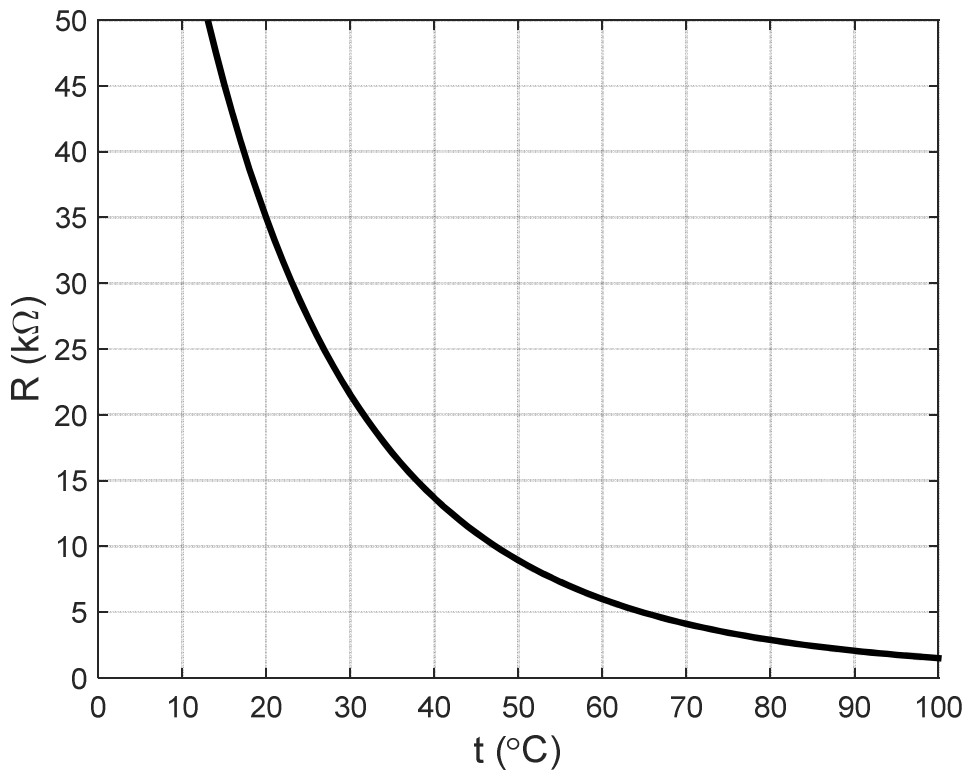
To begin with, the values of R_C and R_E resistors have to be measured using an ohmmeter. After performing that measurement, the ohmmeter has to be connected to the terminals of thermistor.

The first set of measurements refers to plotting the temperature dependence of I_{CB0} . That requires connecting a micro-ammeter between banana jacks 1 and 2 and a short-circuit between jacks 3 and 4.

Next, connect the DC power supply to the oven jacks. As the transistor heats up, you must read quasi-simultaneously the values of I_{CB0} and R_{th} , roughly every 10 °C, in a table like the one below:

I_{CB0} (μA)										
R_{th} ($K\Omega$)										

The resistance-temperature curve of a thermistor similar to the one in the experimental setup, having a resistance of 35 k Ω @ 20 °C is shown below:



Please note that the thermistor may be replaced with one having a different value, therefore consult the resistance-temperature curve provided in the laboratory.

The second experiment refers to measuring the temperature dependence of V_{BE} and his influence on I_C .

For that, the R_C resistor must be connected to the collector of the transistor via a milli-ammeter and the emitter must be connected directly to the ground (short-circuit between 5 and 6 jacks).

Connect a micro-ammeter between banana jacks 7 and 8 and a mili-voltmeter between jacks 3 and 4.

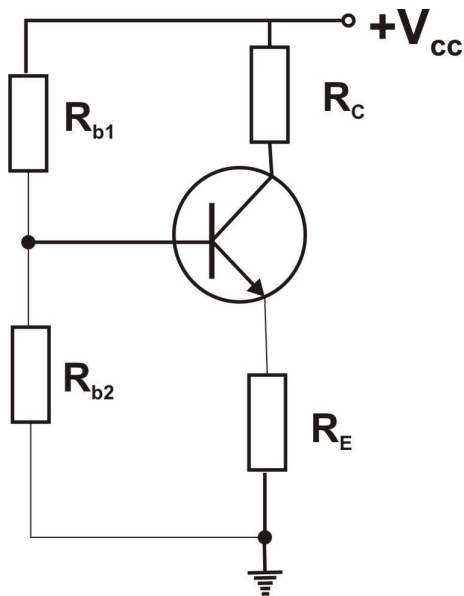
Use the potentiometer P to obtain 4 mA collector current, all measurements taken at room temperature. Note the values of V_{BE} , I_B and I_C .

Start the oven and heat to a temperature of about 10 °C higher than room temperature (e.g. ~35 °C). Note the new values of V_{BE} , I_B and I_C .

Redo these measurements for a new I_C of 7 mA. Repeat the measurements at a temperature 10 °C higher. What are your observations?

Redo the measurements while having a R_E resistor connected in the emitter of the transistor (connect 5 to 10 jack). What are the conclusions?

Exercises



If $V_{CC} = 10V$, $R_C=5k$, $R_E=1k$, $R_{b1}=46k$, $R_{b2}=10k$ compute the static working point (SWP) of the circuit. Which is the approximate value of S_I , taking into account that $S_I = \frac{\beta+1}{1-\beta \frac{\partial I_B}{\partial I_C}}$.

5. Constant Voltage and Constant Current Sources.

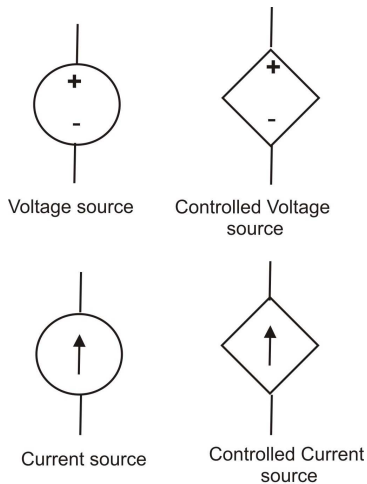


Fig.8

An ideal voltage source has zero ohms internal resistance and is able to apply any value of current which is dependent only by the load resistor. If the voltage across the ideal voltage source is dependent of any current or voltage of the circuit, the voltage source is named “controlled voltage source”.

An ideal current source has infinite internal resistance and is able to apply any value of voltage which is dependent only by the load resistor. If the source current is depending on any voltage or current in the circuit, such source is named “controlled current source”.

Symbols for such sources are shown in fig. 8. Of course, doesn't exist in reality such ideal sources. Then, the aim of this laboratory work is to find in which conditions we can approximate a source as an ideal voltage/current source.

First step consist in the study of a constant voltage source. In Fig.9 you have shown the laboratory setup.

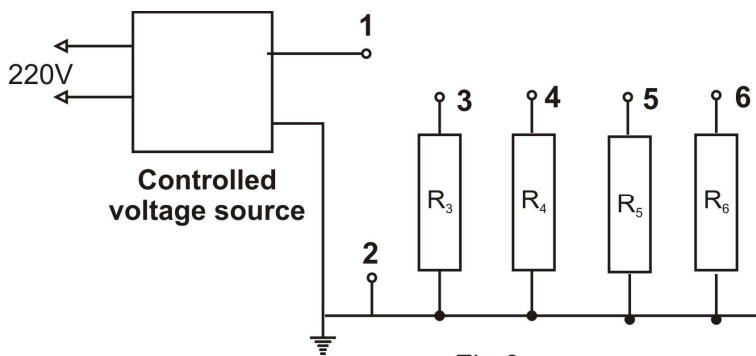
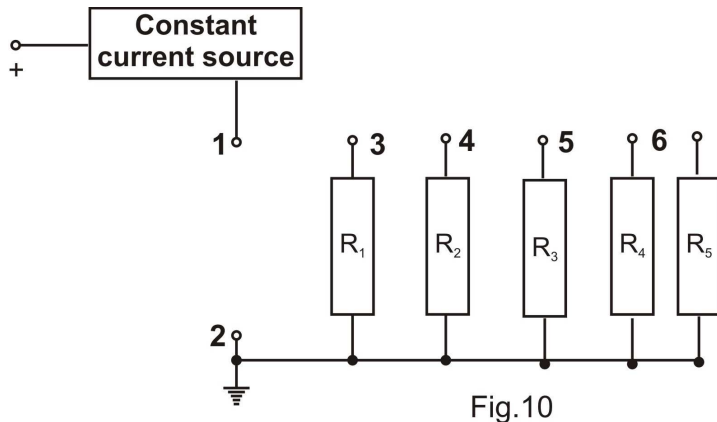


Fig.9

First of all we advise you to measure the values of load resistors using a digital ohm-meter. After that connect the setup to the power line and see, using a digital voltmeter, which is the value of output voltage in open circuit (1 and 2 jacks). After that you must connect a milli-ammeter between 1 and

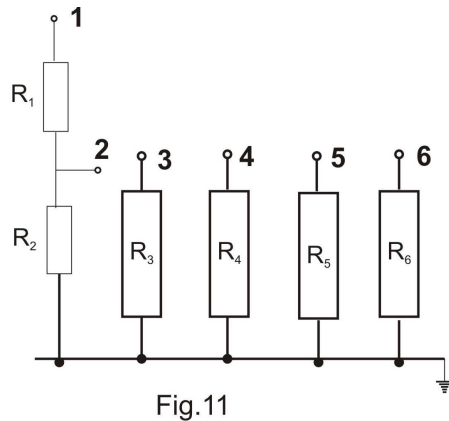
3, 1 and 4, a.s.o., to note the currents through the load resistors. After that you can compute the drop voltage on the load resistor using Ohm's Law ($V=RI$). Is it a constant voltage?

Plot the Voltage function of the current and see which is the region where the source can be considered as a constant voltage source. Don't forget to take into account the open circuit voltage.



On the same setup you have a constant current source, made by a BJT. Be sure that the switch K is on "constant current" position. Now, using a digital/analog mili-ammeter measure the "short circuit" current between 1 and 2 jacks. After that, connecting 1 to 2, or 3 jacks, a.s.o, measure the drop voltage, using a digital voltmeter, on load resistors R_1 , R_2 , a.s.o. Compute the currents which are flowing through resistors using Ohm's Law ($I=V/R$). Plot the dependence of the current to voltage. Which is region where the source can be considered as a "constant current source"?

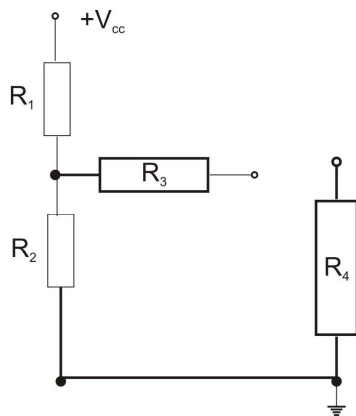
Now, you must see how it's working a voltage divider, see Fig. 11. The voltage divider is made by R_1 and R_2 resistors. Measure the voltage applied on voltage divider between 1 and ground jacks. After that, knowing the values of R_1 and R_2 resistors, compute the output voltage on voltage divider in open circuit. Measure this voltage using a digital voltmeter (2 and ground jacks). Is it a difference between computed and measured values? Why?



Continue by introducing in the circuit the load resistors and measure the drop voltage on everyone and plot the function of these voltages on values of resistors. Can we consider that the voltage divider it's working, approximately, as a constant voltage source? Compute his output resistance using Thevenin's theorem.

Which is the current through the load resistor R_4 ? Which value must have the load resistor to obtain

Exercises.



$V_{cc}=12V$
 $R_1=6K$, $R_2=4K$, $R_3=1K$
 $R_4=0.6K$

Which is the current through the load resistor R_4 ? Which value must have the load resistor to obtain

maximum transfer power to him? Of course, please use Thevenin's theorem to resolve this problem.

5. The Oscilloscope

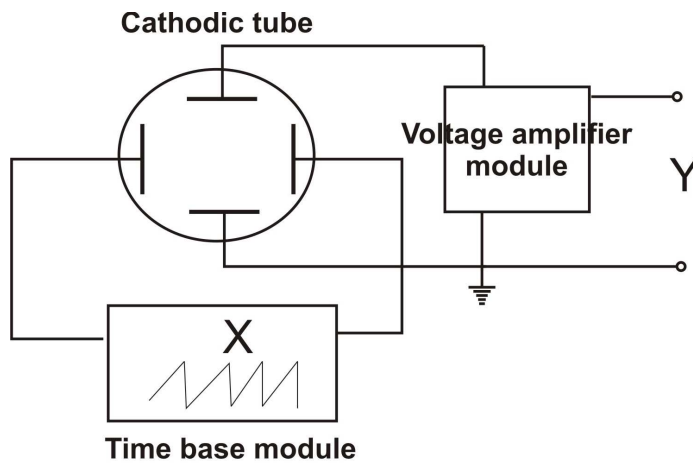


Fig.12

having the sensitivity measured in voltage units (connected to vertical plates of the cathodic tube).

One of the most important tools in a laboratory of electronics is the oscilloscope. The main components of the oscilloscope are: the **cathodic tube**, the **time base** module (his output voltage is applied on horizontal deflection plates of the cathodic tube and has a saw tooth shape of his signal, having a controlled frequencies measured in time units) and the input **voltage amplifier**

Typical representation of all these modules is shown in Fi.12. Depending of the performances of the oscilloscope, the sensitivity of the voltage amplifier module can be between Volts to mili-, micro- or nanoVolts and the range of frequency of time base module can be between seconds to mili-, micro- or nanoseconds. Take into account that $v=1/T$.

Then, using the oscilloscope you can measure the amplitude of a variable signal and his frequency. For that you must be sure that both modules are in the position of "calibrated", as you can see on the front panel of the oscilloscope. A typical front panel of an analogic oscilloscope is shown in Fig.13,

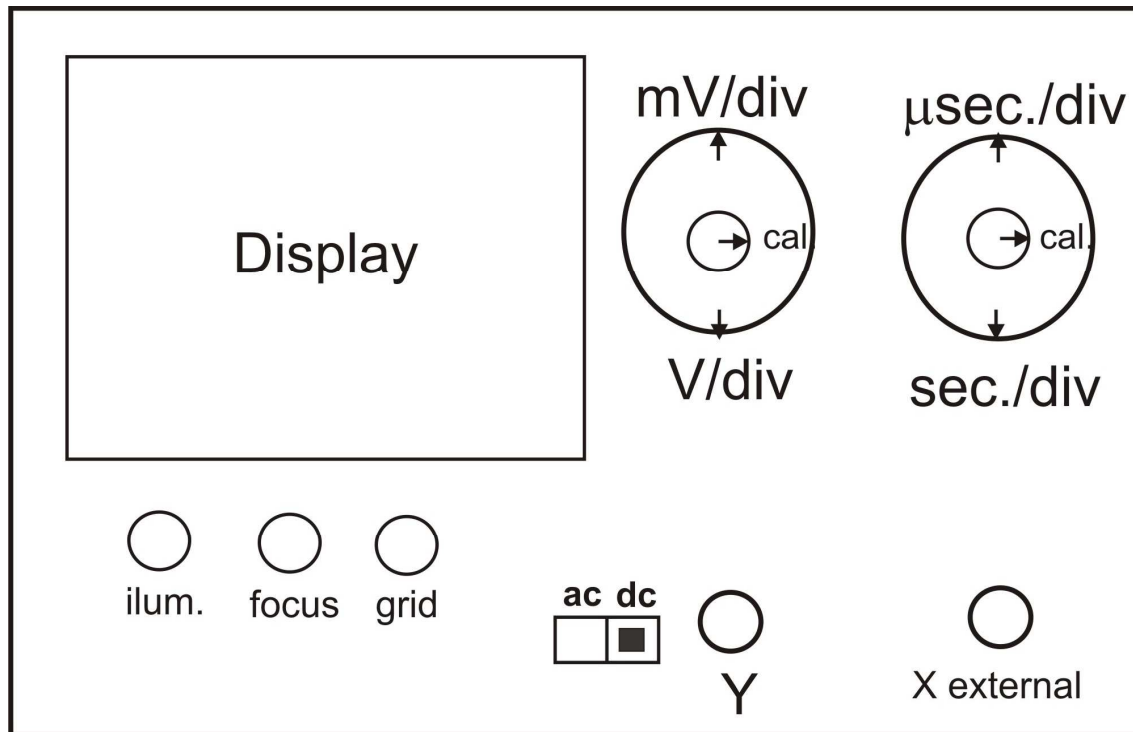


Fig.13

where the principal buttons are: controlled **illumination** of the display, **focus** of the signal shape, **grid** illumination of the display, voltage sensitivity, time base frequency. A BNC input is used for input signal (Y) and, if is necessary, you can use an external time base (X external input on BNC). In the calibrated position, we know how many volts/millivolts are on a division of display on Y axis, or how many seconds/milliseconds are on a division of the display on X axis. Of course, you will discover more buttons on the front panel. Please ask the teacher their utility.

Now, start to use the oscilloscope as voltmeter and frequency meter. For that use a digital signal source generator, but don't display the value of frequency and rms/pp voltage. You must use only the oscilloscope. At list 10 input signals, having different shapes and frequency, you must measure. To prove that you did it, take a photo of the oscilloscope display for everyone using your own mobile phone!

After that you can use a second signal generator, connected to X external, to obtain Lissajous figures. Don't forget to switch out the internal time base of the oscilloscope for that. Can you discover the rules of Lissajous figures?

Please imagine yourself another experiment in which you must use the oscilloscope!

7. The rectifier and voltage stabilizer.

In most important applications of solid state electronics we need to have a system which can convert the alternative voltage coming from power line into a dc voltage.

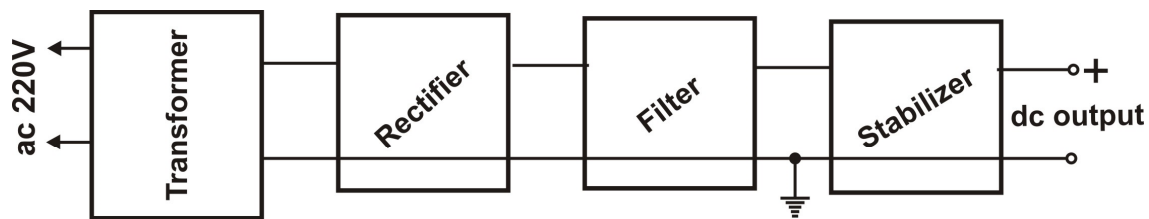


Fig.14

Such a system has, as you can see in Fig.14, a down voltage transformer, a rectifier, a filter and, optional, a voltage stabilizer. Are two types of rectifiers, full wave rectifier and half wave rectifier. First one transforms the sinusoidal voltage of 50Hz period in two half positive alternating voltage. For such alternative signals important is to know which is, so named, root mean square (rms) of the signal. The root mean square of the signal is linked to the same power dissipated on a resistor by a dc signal (voltage or current) and alternative signal in a period. Then, RI^2 must be equal with $\int_0^T Ri^2(t)dt$, where $i(t)$ is the instantaneous value of the signal (e.g. current in this

case). Then I_{rms} is given by $I_{rms}^2 = \frac{1}{T} \int_0^T i^2(t)dt$. A similar formula is for V_{rms} . Should be a

good exercise for you to compute the rms for a full wave rectified signal, taking into account that $u(t)=U_{max}\sin\omega t$ where $\omega=2\pi/T$.

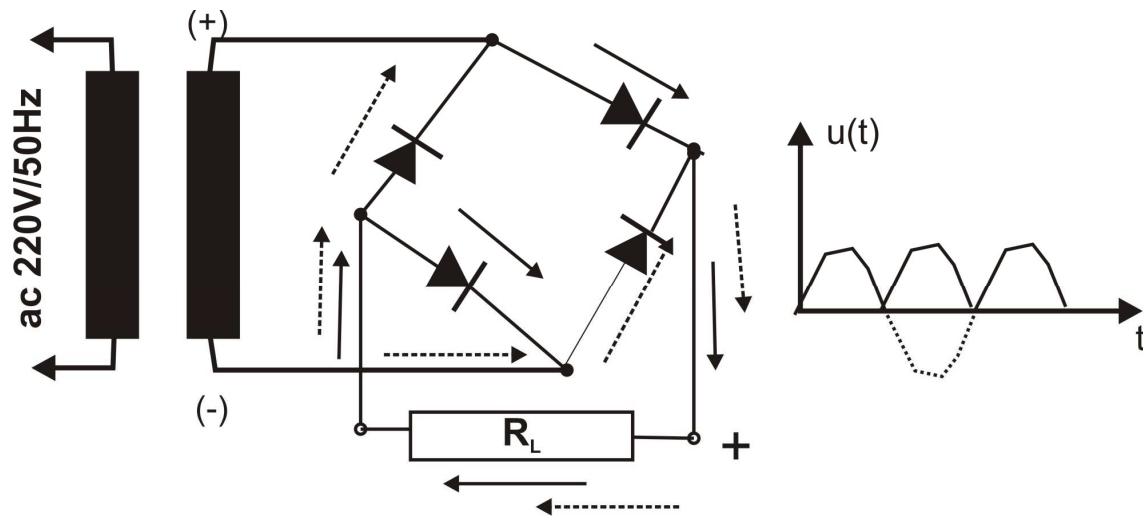


Fig.15

A typical full wave rectifier is made by 4 diodes (bridge of diodes) connected as in Fig. 15. As you can see, through the load resistor R_L all the time the current will flow from right to left, then it is “rectified”! By dashed arrows is indicated the current flow if the output of the transformer change his polarity.

Now, as you can see, on the load resistor we have a drop voltage having the same shape as the current shape, i.e. half wave of a sinusoid. But we need to have a dc voltage! We can obtain something more as a dc voltage if we connect in parallel with the load resistor a capacitor. As you can see in Fig. 16, the capacitor will be charged to the maximum value of the voltage and after that will discharge through the load resistor until the next half sinusoid will charge him again, a.s.o.

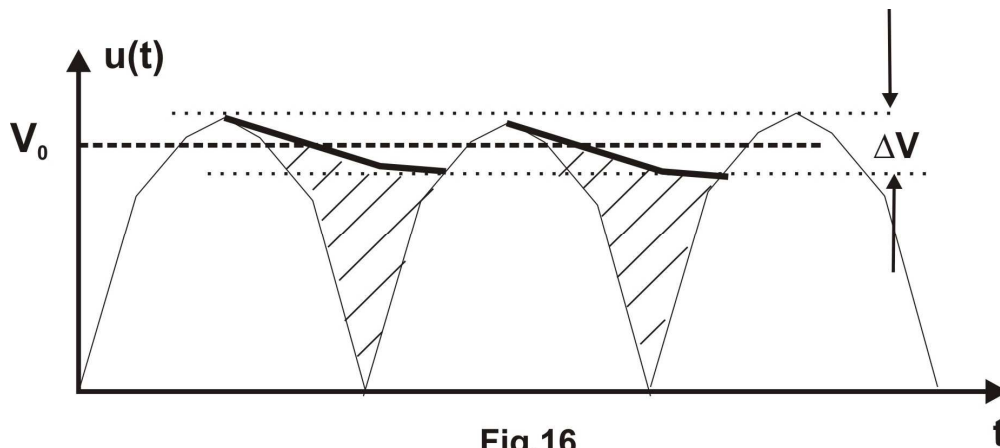


Fig.16

Then, the capacitor will “fill” the space between two half sinusoid and on the load resistor we obtain a dc voltage component, having value V_0 and an ac voltage component having ΔV peak to peak value. The good rectifier must has the “smoothing factor” smaller than 10^{-3} . The definition of “smoothing factor” is:

$$\gamma = \frac{\Delta V}{2V_0}$$

Of course, the γ factor can be improved increasing the value of the capacitor or by replacing the capacitor with a Π filter, as is shown in Fig.

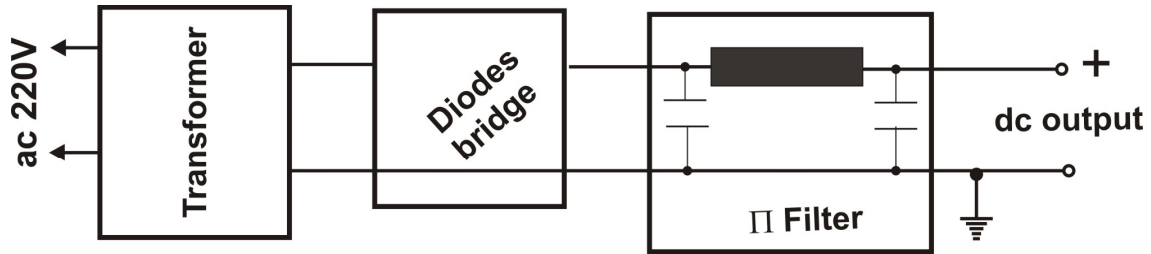


Fig.17

17.

The Π filter is made by two capacitors and an inductance/resistor. First capacitor it is working as we explained before, and the second one together with inductance/resistor are working as a short circuit to the ground for ac component ΔV .

You will start this laboratory work by the study of half wave rectifier and full wave rectifier. The setup is shown in fig. 18.

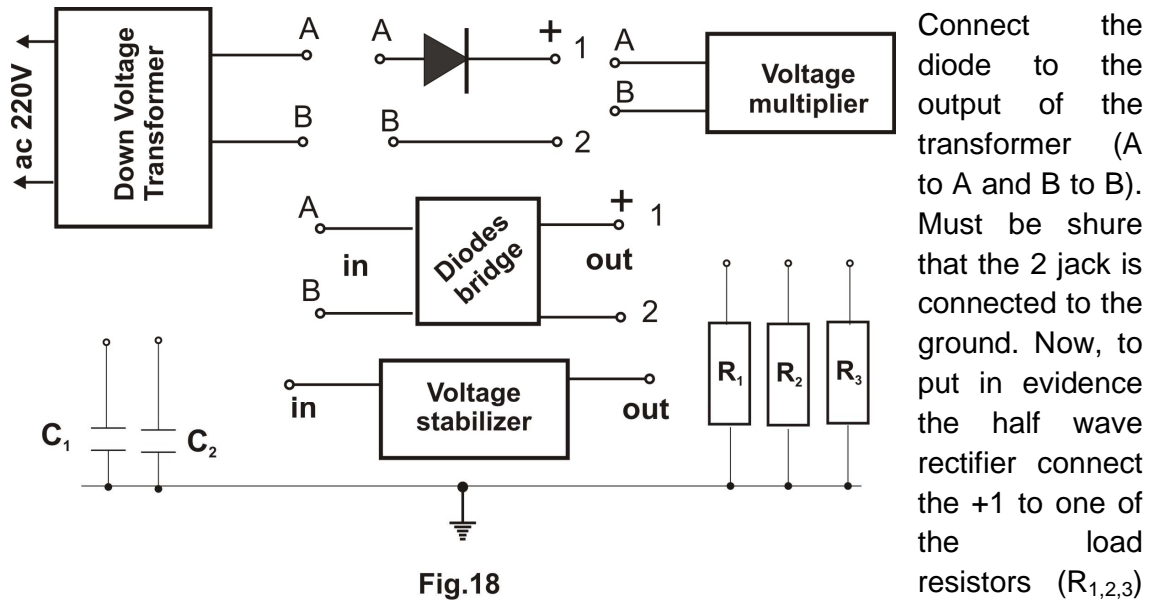


Fig.18

and the resistor to the Y input of the oscilloscope. Be sure that the oscilloscope is in calibrated position and in ac regime. Keeping all these connections measure the effective value of the voltage (rms) using a digital voltmeter. Now, if you connect one of the capacitor ($C_1=0.47\mu\text{F}$ and $C_2=4.7\mu\text{F}$) you can read the new value of the voltage V_0 (rms) and ΔV by oscilloscope. You must determine all values (V_0 and ΔV) for all possible combinations between R and C in the aim to compute the γ factor. For that we advise you to use such a table.

	V_0 (V)	ΔV (mV)	$\gamma = \frac{\Delta V}{2V_0}$	C
R1				
R2				
R3				

The same things you must do for the full wave rectifier, connecting the diodes bridge to the output of the transformer, keeping the same procedure as before.

In the aim to obtain the best γ factor a "voltage stabilizer" is necessary. The circuit of this is shown in Fig.19. Connect to the transformer the diode bridge, as you did it

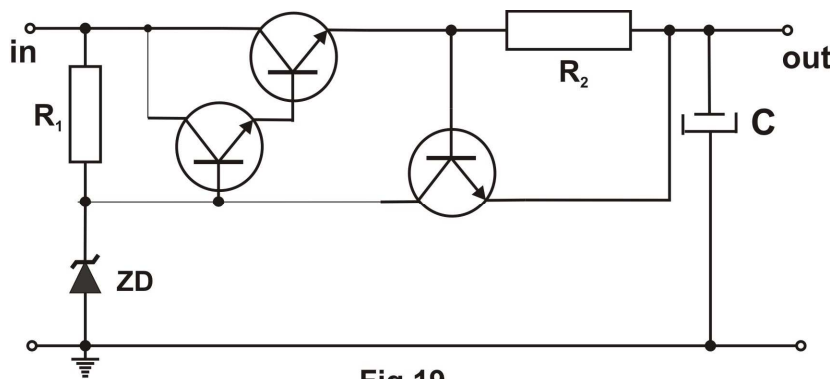


Fig.19

until now. Connect the **out** of diode bridge to the **in** of voltage stabilizer. The **out** of the voltage stabilizer must be connected to the load resistors, as in previous work. Note the values of V_0 and ΔV (no capacitor

connected to the **out** of diode bridge). Do the same thing connecting the C_2 to the **out** of diode bridge. Which is the difference of γ in these two situations?

Another circuit which you can find in the laboratory setup is a half wave voltage multiplier. A half wave voltage doubler is in Fig. 20. If on the first diode (D_1) is applied the negative half sinusoid from signal generator, having 100V amplitude, the capacitor C_1 will be charged at this maximum value of the voltage.

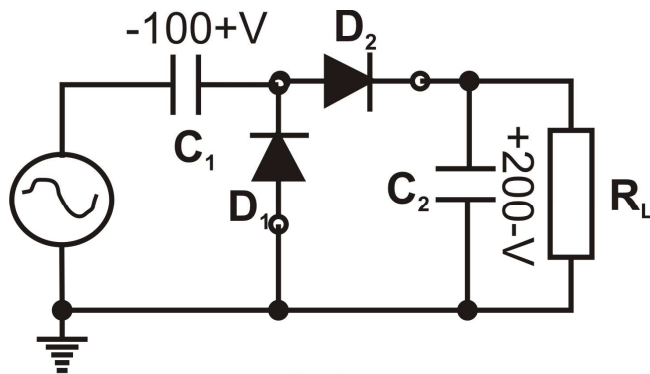


Fig.20

capacitor C_1 will be charged at this maximum value of the voltage. The second half sinusoid been positive this will open the second diode (D_2), first one been blocked. Then C_2 will be charged at 200V which are applied on the load resistor R_L . Using a series of such circuit we can obtain the multiplication of the input signal $2n$ times, if n is the number of such

circuits. The last experiment on this laboratory setup is the study of such doubler. In

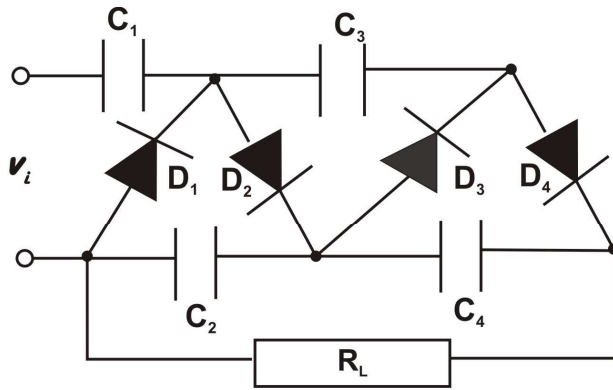


Fig.21

Fig.21 it is shown a two series of doubler. Then, on load resistor you must find 4 times the effective value of the input signal. Use digital voltmeter and measure input signal (ac) and the values of voltages to every nod (dc).

8. Junction Field Effect Transistor (JFET).

By contrast with Bipolar Junction Transistor, JFET it is a monopolar device. Its structure is shown in Fig.22a.

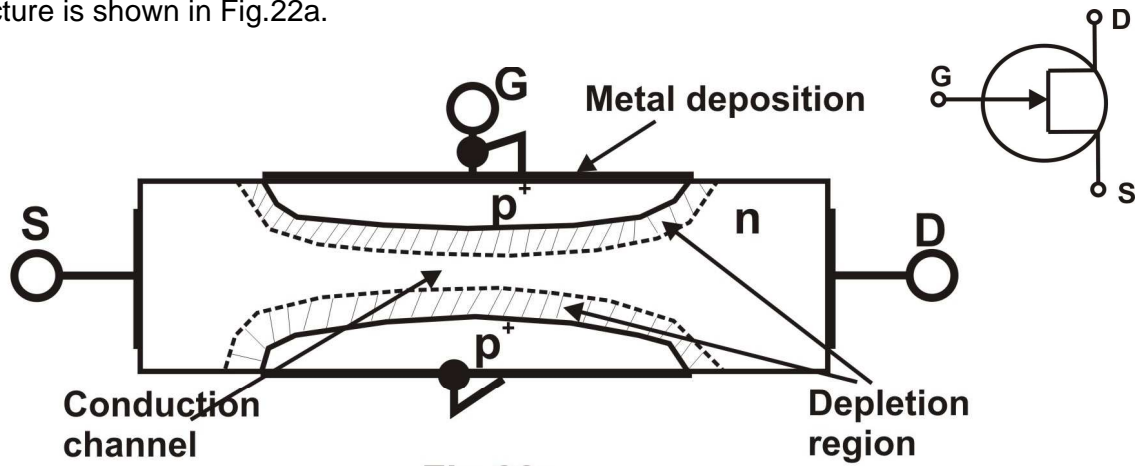


Fig.22a

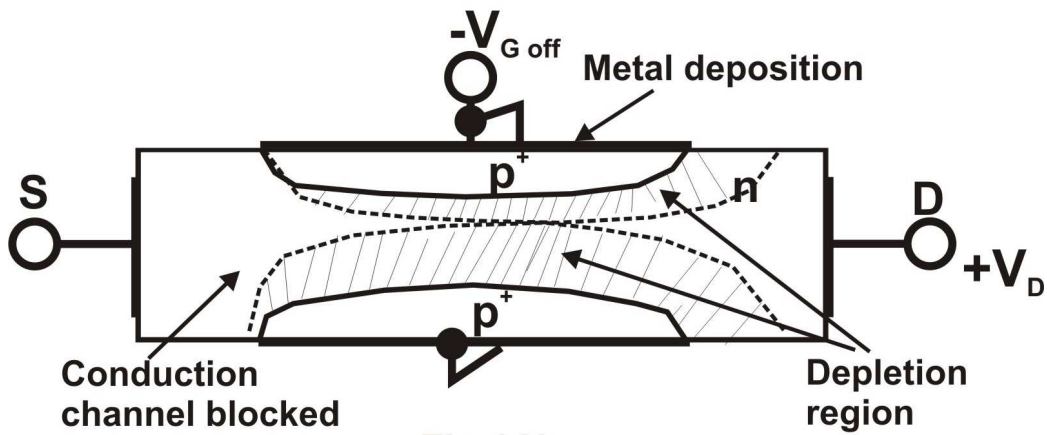


Fig.22b

As it can be seen, in a n-type semiconductor are implanted two islands of p type semiconductor, strongly doped. Then, the depletion region is more extended in n type semiconductor. A metallic film deposition is made on both heads of the structure becoming the Source (S) and the Drain (D) of JFET. Another metallic film deposition is made on the external edge of p type semiconductor, becoming the Gate (G). Now, if we apply a positive voltage on the Drain, a current made only by electrons (majority charge carriers in n type semiconductor) will be established between Source and Drain (I_D) via the conduction channel. Now, if we apply a negative voltage on the Gate, this voltage will be as a reverse biasing voltage applied on a PN structure, then the depletion region will extend in n type semiconductor and the cross area of the conduction channel will decrease. Then, the total number of charge carriers which give us I_D will decrease too! When, by increasing the negative Gate voltage, the depletion regions are in contact, the conduction channel is blocked and the I_D current become zero. This V_G voltage is named the **cut of** voltage (Fig.22b). Then, one of the most important static characteristic of a JFET is given by:

$I_D = f(V_G)_{V_D=ct.}$ named transfer characteristic.

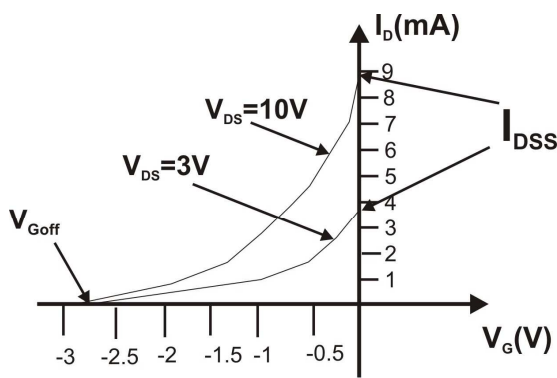


Fig.23

The plot of such function is given in Fig.23.

Where for $I_D=0$, $V_{GS} < V_{Goff}$ and for

$$I_D \sim (V_{GS} - V_{Goff})^2, \quad V_{GS} < V_{Goff}.$$

A better approximation is given by next formula:

$$I_D \cong I_{DSS} \left(\frac{V_{GS}}{V_{Goff}} - 1 \right)^2 \quad \text{where } I_{DSS} \text{ is } I_D$$

current at $V_G=0$.

You must plot such characteristic, point by point, for $V_D = 12V$, $8V$, and $4V$. Use such a table to note the values of I_D function of V_G .

I_D (mA)										
V_G (V)										

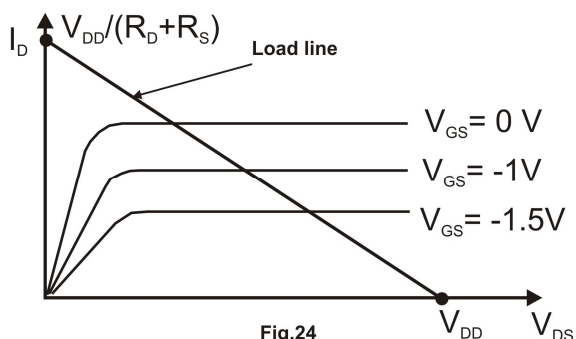


Fig.24

The output characteristics of JFET, taking V_G as constant parameter, are shown in Fig. 24. Using the same procedure as in the case of transfer

characteristics, plot the output characteristics, taking as constant parameter $V_G = 0V, -0.5V, -1V, -1.5V$. Take care on the scale of milli-ammeter when you change the voltage on the gate. In the beginning of the plot have, at least, 3 small steps of the V_D (0.1 to 0.1V). The symbol of JFET is shown in next figure.

The biasing circuit for a JFET must take into account that the potential of the Gate must be negative in comparison with the potential of the Source. A typical circuit for that is shown in Fig. 25. $V_{GS} = V_G - V_S$, but $V_G = 0$ (no current through R_G) and $V_S = R_S I_D$, then $V_{GS} = 0 - (R_S I_D)$. From this point of view, the JFET it's working as an old classical triode. Another biasing circuit is shown in Fig.26, having a self-biasing circuit as in the case of BJT.

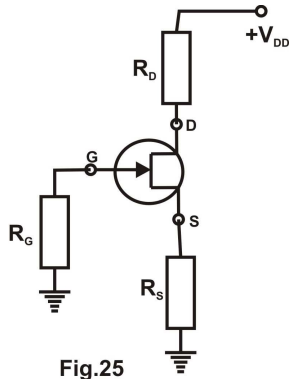
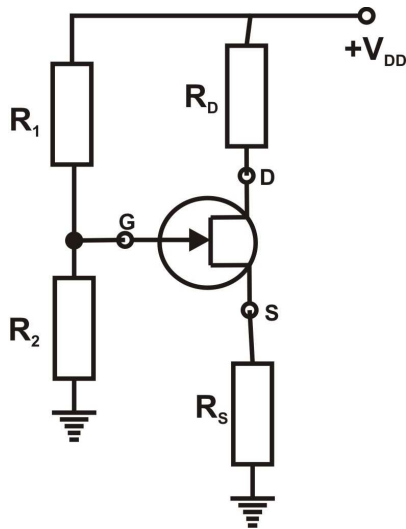


Fig.25

Because the current through the Gate is zero, R_1 and R_2 resistors can have high values (M Ω).



Exercises.

If $V_{DD} = 20V$, $V_{GS} = -2V$ and $R_D = 1K\Omega$, $R_S = 4K\Omega$, $R_1 = R_2 = 1M\Omega$, compute V_G , V_S , V_{DS} .

$$V_G = \frac{V_{DD}}{R_1 + R_2} R_2 = \frac{20}{1 + 1} 1 = 10V$$

$$V_S = V_G - V_{GS} = 10 - (-2) = 12V$$

$$V_S = I_D R_S \rightarrow I_D = \frac{V_S}{R_S} = \frac{12V}{4K} = 3mA$$

$$V_D = V_{DD} - R_D I_D \rightarrow 20V - 1K \cdot 3mA = 17V$$

$$V_{DS} = V_D - V_S = 17 - 12 = 5V$$

9. MOS Field Effect Transistor (MOS-FET).

The MOS-FET transistor has the structure shown in Fig. 26a. As you can see, on a

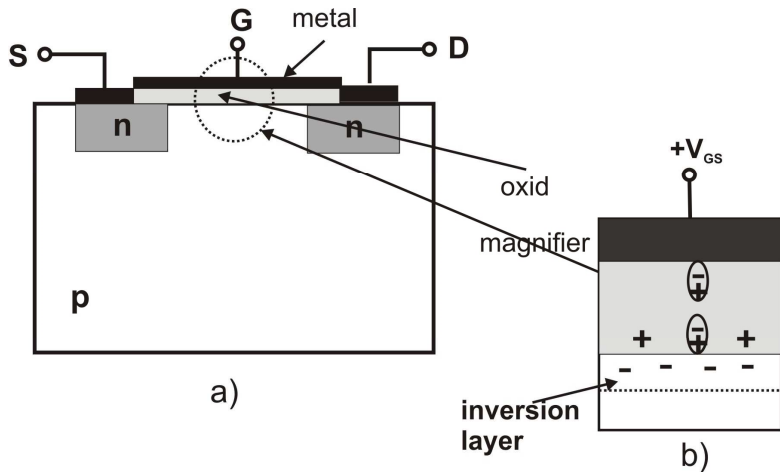
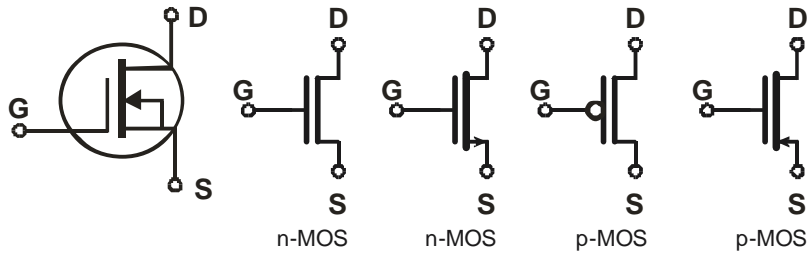


Fig.26

substrate of p type semiconductor are implanted two island of n type semiconductor. These two islands have ohmic contacts to the exterior, one been the Source, and other one been the Drain. Doesn't exist a conduction channel between them because these

islands are separated by a p type semiconductor, where majority charge carriers are holes. On the upper side of this structure is realized a thin film of oxide (SiO_2) between the two islands of n type semiconductor and a thin film of metal will cover the oxide, having a ohmic contact to the exterior, the Gate. Now, if we apply a positive potential on the Gate, the oxide, been an isolator, will be polarized as you can see in Fig.27b. Then the boundary between oxide an p type semiconductor will be charged by positive charges. These positive charges will reject the majority charge carriers of p type semiconductor and will attract the minority charge carriers (electrons). Then, between the two islands will be established an "inversion layer", having as majority charge carries the electrons. Then a conduction channel between Source and Drain will be established. This type of MOS-FET is named "induced channel MOS". The symbols commonly used for this device are shown below:



The biasing circuits are similar with the circuit presented for JFET. As in the case of JFET, the transfer characteristic is very important. In Fig. 29 is presented a family of such characteristics for different V_D .

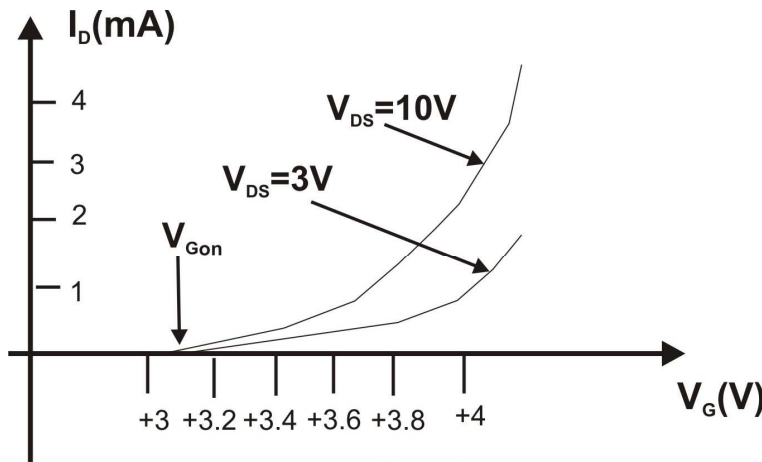


Fig.27

As in the case of JFET, the transfer characteristics for $V_{GS} > V_{Gon}$ can be approximated by a parabolic function:

$$I_D \cong (V_{GS} - V_{Gon})^2$$

The laboratory circuit is presented in Fig. 30. A differential DC power supply has to be used.

One channel for the biasing of the Gate ($+V_{GG}$) and other one for the biasing of the Drain ($+V_{DD}$). A milli-ammeter must be connected in series with the drain and R_D resistor and a voltmeter must be connected in parallel with the MOS-FET, as you can see in Fig.30.

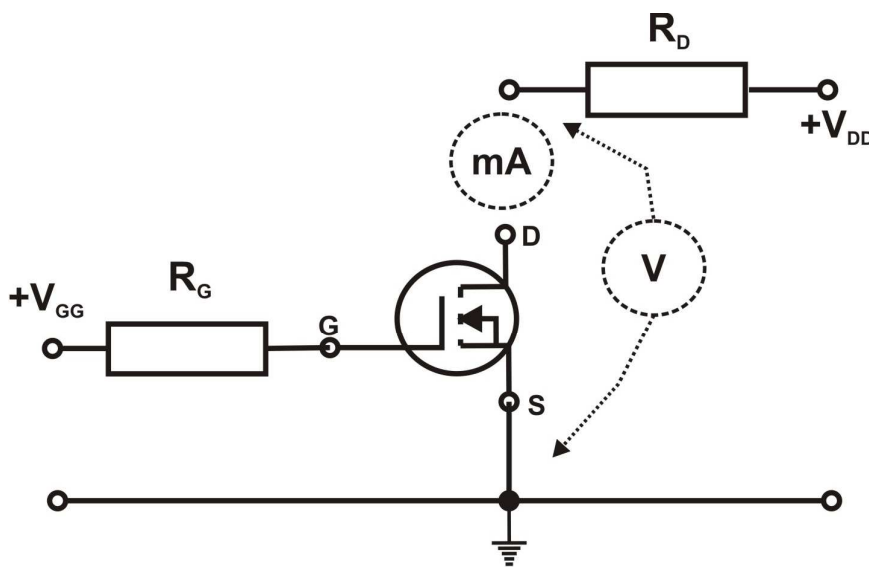


Fig.28

It is not necessary to connect a second voltmeter to read V_G , because the DC power supply has one on the front panel. Use a similar table as in the case of JFET to plot, point by point, the transfer characteristics for

V_D as parameter ($V_D=12V$ and $V_D=6V$).

I_D (mA)										
V_G (V)										

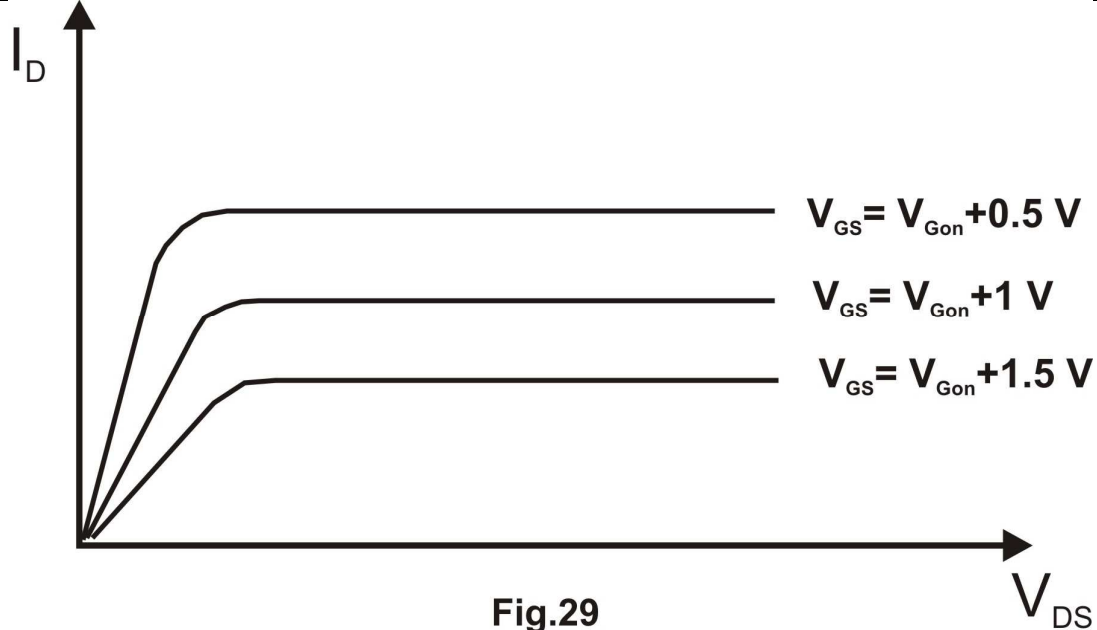
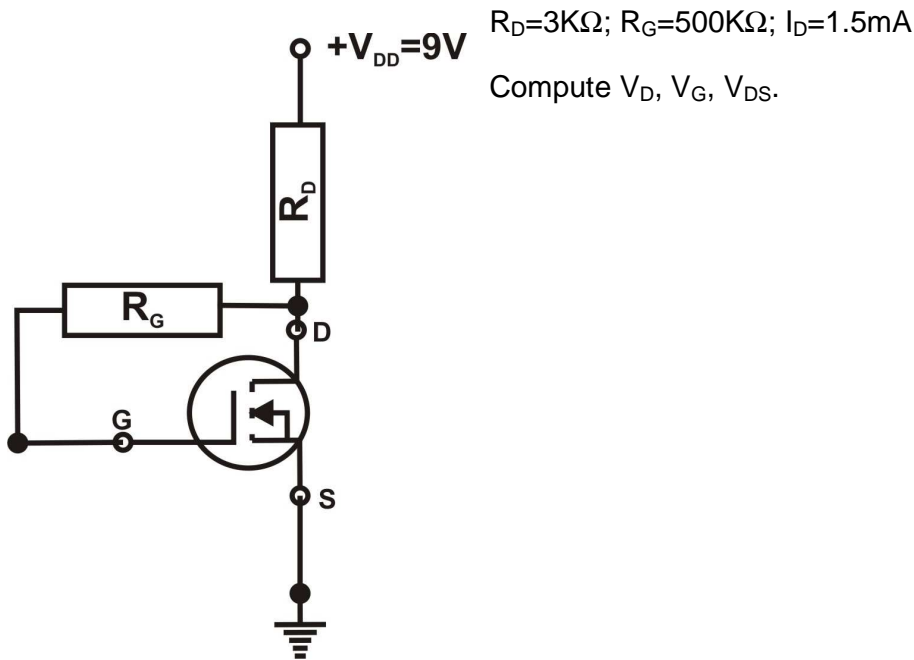


Fig.29

The output characteristics of MOS-FET are presented in Fig.29.

Now, taking V_{GS} as parameter you must plot, point by point, the output characteristics for $V_{GS} > V_{Gon}$. A similar table as you used before it is necessary to plot output characteristics. Of course, must replace V_G by V_D . Take care in the beginning of plotting to have small steps 0.1 to 0.1V, to put in evidence the linear dependence of I_D current function of V_D , until the saturation region. At least a family of three characteristics you must plot.

Exercises.



10. Unijunction-Transistor (UJT).

UJT has a very simple structure. On a bar of n type semiconductor is implanted an

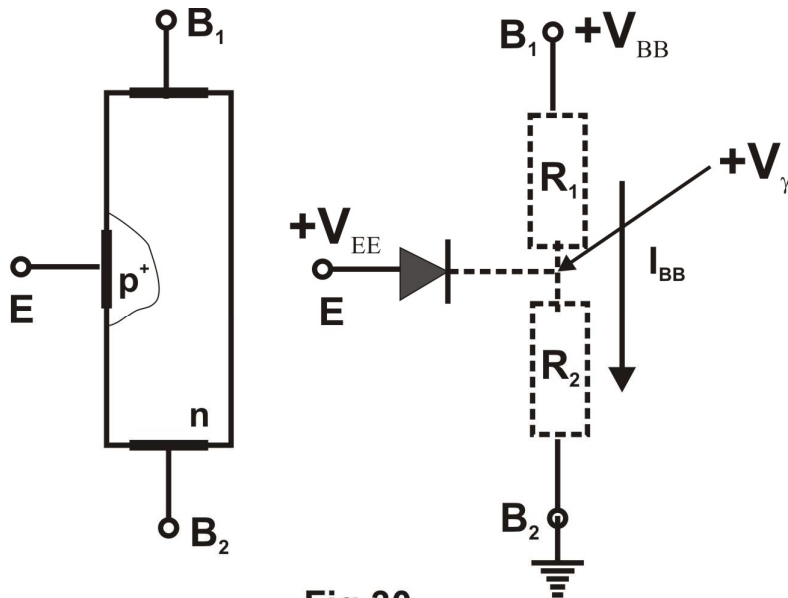


Fig.30

island of p type semiconductor both heads of the bar having ohmic contacts, named Bases. The p type semiconductor has too an ohmic contact named Emitter (see Fig.30). Then, if we apply a positive voltage V_{BB} between the Bases will flow a current I_{BB} through the n type bulk semiconductor.

Because the semiconductor has his

own intrinsic resistance, in the region of p type implant will have a drop voltage as in the case of a voltage divider. Then, the potential in the region of p type semiconductor will be a positive one, V_γ , towards the ground. Then the junction PN of the Emitter is pre-biased in reverse biasing conditions. In such conditions, if we apply a forward biasing voltage on the emitter, V_{EE} , the associated diode will be open only if $V_{EE} > V_\gamma$ where $V_\gamma = V_{BB} \times R_2 / (R_1 + R_2)$. In this case, the input characteristic will be as in Fig. 31.

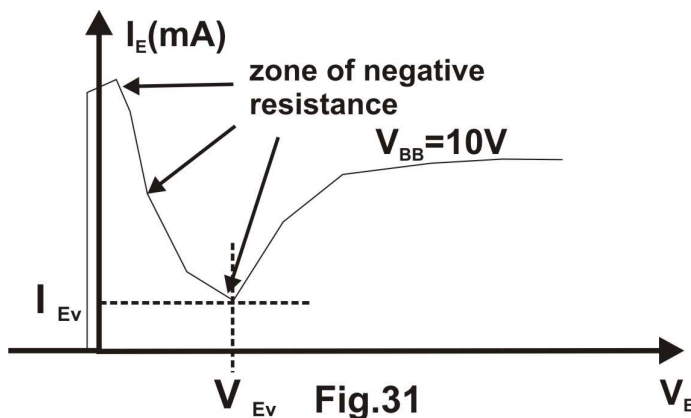


Fig.31

The minimum values of the current and voltage, established when the Emitter diode is open are named "valley current/voltage". Of course these values are depending on the value of external resistance of the

Emitter. In this laboratory work you must see which these “valley values” are function of R_E and V_{BB} .

For that, please use the next table, for different values of V_{BB} (+12V, +10V, +8V).

$V_{BB} = \dots V$	R1	R2	R3
I_{Ev}			
V_{Ev}			

After reaching the threshold voltage, the Emitter junction will exhibit the behavior of a

forward biasing diode. The region of negative resistance cannot be evidenced entirely, being very steep. The larger the value of the resistor, the more of the negative resistance region can be explored. The laboratory circuit is presented in Fig. 32.

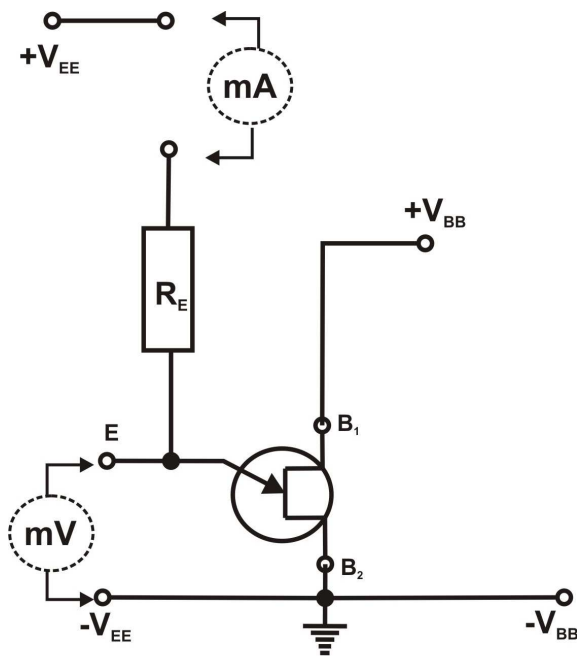


Fig.32

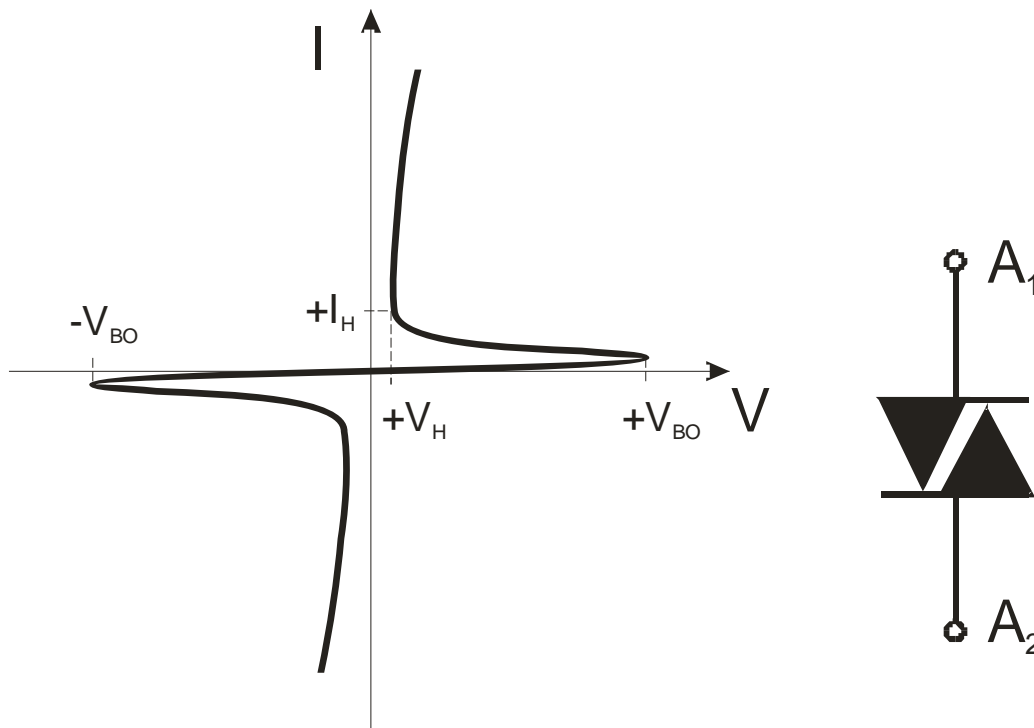
11. Diac, Thyristor, Triac

Introduction

The diac, thyristor and triac are devices that conduct electrical current only after the voltage on their main terminals reach a breakover voltage V_{BO} . The diac is a two-terminal device with a fixed breakover voltage that is symmetrical for positive and negative voltages. The thyristor's and triac's breakover voltage is controlled through a gate electrode. The thyristor differ from triacs in that they can conduct current in only one direction. All these devices have application in the control of high-power devices, operating in AC.

Diac

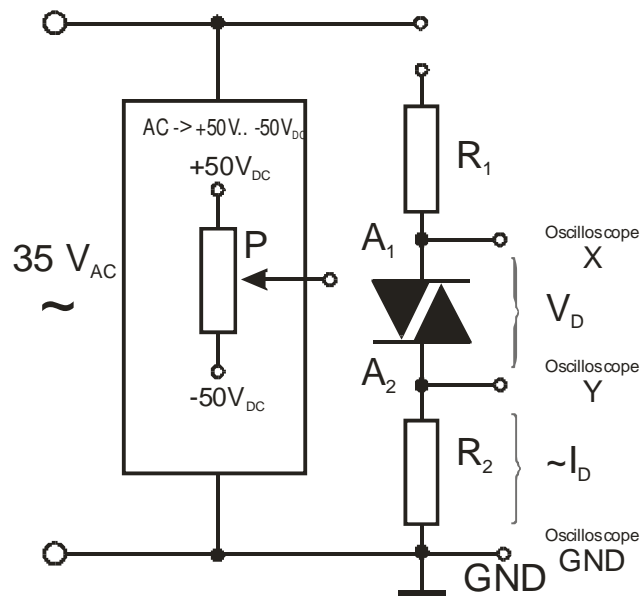
The diac has the symbol and current-voltage characteristic shown below:



For voltages lower than the breakover voltage V_{BO} , the device is in the off state, the current passing through it being very small. After reaching the breakover voltage V_{BO} , the voltage decreases rapidly simultaneously with an increase in the current, corresponding to a negative dynamic resistance. The device remains in conduction until the voltage or the current drop below a minimal value, called *holding voltage* V_H or *holding current* I_H .

Experimental Setup

A circuit board in the lab allowing the visualization of the I-V characteristics of the diac using an oscilloscope has the schematics shown below:



The circuit can be powered using the 35 V AC power supply that is available on the thyristor or triac circuit board (see the triac section later in this document). By connecting a dual-channel oscilloscope that measures the voltage on the diac on the X channel and the current on the Y channel, we can visualize the I-V characteristic of the diac. Since the oscilloscope only has voltage inputs, we insert a resistor R_2 in series with the diac, such that the voltage on the resistor (proportional to the current, $V_R=R_2 \cdot I_D$), connected to the Y input will indicate the I_D current. As the two oscilloscope channels are sharing the same ground connection, the direct measurement of the two voltages with the expected polarity won't be possible, as it will short circuit the series resistor. The alternative to that is to measure the total voltage on the diac and series resistor, as shown in the figure above, and minimize the contribution of the latter by selecting a very small resistor value R_2 . Accordingly, the voltage on the resistor will be negligible, such that the voltage values between A₁ and GND will be very close to the V_D voltage values across the diac.

Static characteristic in DC

Power up the diac circuit board from a ~35V AC power supply on the thyristor circuit board.

Configure the oscilloscope to operate in X-Y mode, and enable trace memory, if available.

Connect the output of the on-board adjustable DC voltage source ($\pm 50V_{DC}$) to the diac series circuit.

By slowly sweeping the DC bias point, observe the breakdown of the diac when reaching the breakover voltage, the negative dynamic resistance, as well as the hold current/voltage.

Visualization of the I-V characteristic in AC

By using an AC voltage to power the diac series circuit, the I-V characteristic of the diac can be visualized, in case the oscilloscope does not provide trace memory functionality.

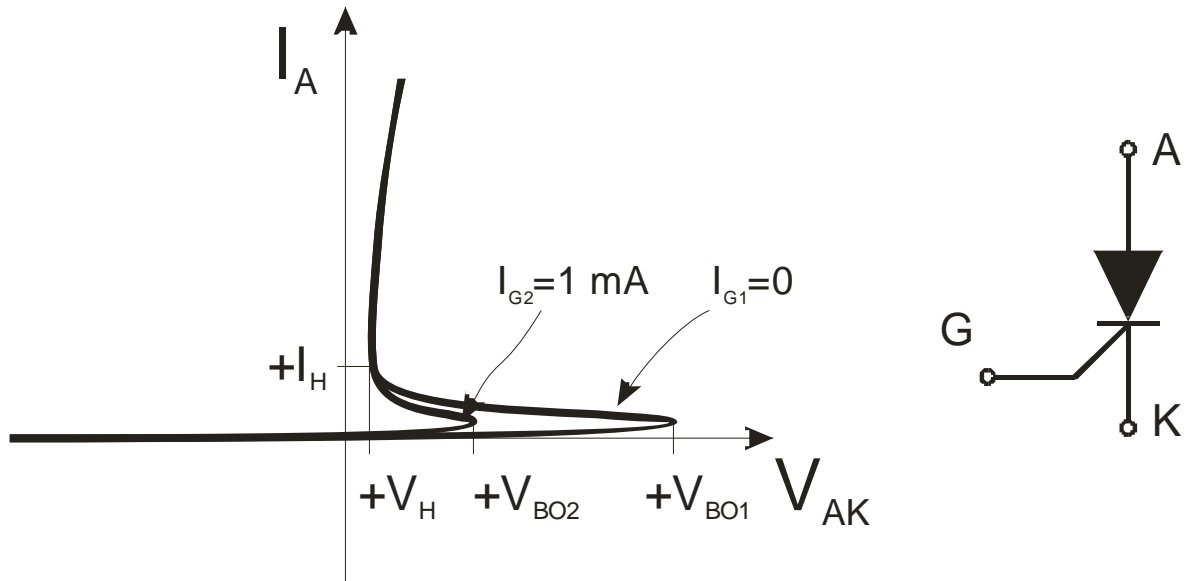
Apply the 50Hz ~35V AC supply voltage directly on the diac series circuit.

While the oscilloscope to operate in X-Y mode, the sweep of the characteristic at a 50 Hz cycle rate (power line frequency) will leave the impression of a still display even on a standard oscilloscope.

Observe the features of the I-V characteristic: breakdown of the diac when reaching the breakover voltage, the negative dynamic resistance, hold current and voltage, nearly symmetrical characteristic in quadrants 1 and 3.

Thyristor

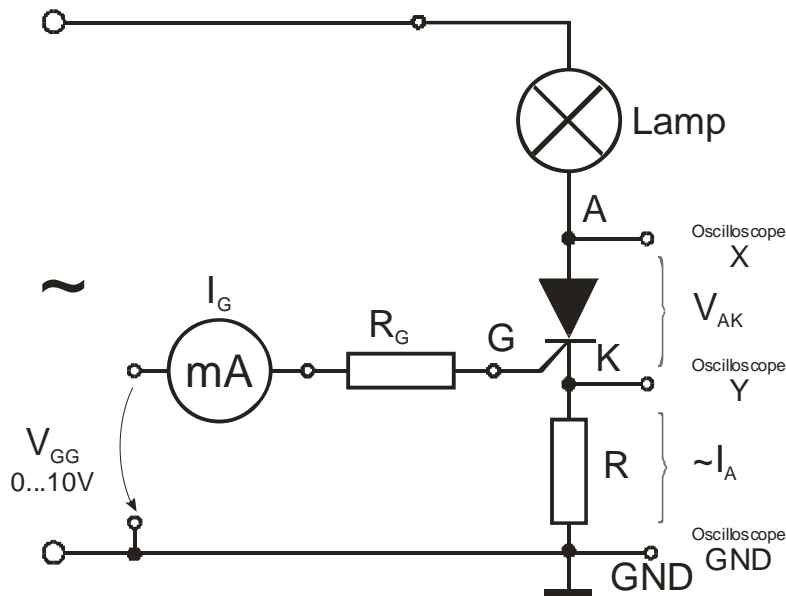
The thyristor is a device that has a I-V characteristic similar to the one of the diac, in the first quadrant (Q1), but has a controlling terminal called GATE for the the breakover voltage. The thyristor is a uni-directional device, i.e. the current in the third quadrant of the I-V characteristic is always very small (negligible), and that's why it is generically called a Semiconductor-Controlled-Rectifier (**SCR**). The typical I-V characteristics and symbol of the thyristor are shown below:



With a null current applied through the thyristor's gate, the A-K current-voltage characteristic in first quadrant resembles the one of a diac. With larger gate currents, the breakover voltage decreases. The device's applications typically include circuit configurations where voltages less the anode-cathode breakover value at null gate current are applied, such that the thyristor's A-K circuit acts as an open switch (it is in the "off" state). By injecting a current through the gate large enough to bring the breakover voltage below the applied A-K voltage, the current through the device increases, such that it can be considered close to a closed switch (in the "on" state). One has to note that once the breakdown has taken place and the instantaneous operating point has moved into the higher current region of the characteristic, beyond the hold point (I_H , V_H), little affected by the injection of a gate current, there is no way to switch off the thyristor by applying a current of any value or polarity on the gate of the thyristor. Switching the thyristor in the off state can happen only by decreasing the current below the minimal value represented by the hold current I_H . Therefore, the thyristor can be turned "on" but not "off" by applying a command signal on its gate terminal. Accordingly, its applications are in AC circuits that periodically "reset" the device by applying a low A-K voltage, near the zero-crossing points of the applied AC waveform.

Experimental Setup

A circuit board allowing the visualization of the I-V characteristic of the thyristor and the measurement of the gate threshold current and voltage is provided in the lab. For DC measurement of the gate threshold current and voltage, a DC power supply V_{GG} has to be connected in the gate-cathode circuit, as shown below. To measure the gate current, a milliammeter has to be connected in series with the gate and the current-limiting resistor R_G , as shown below:



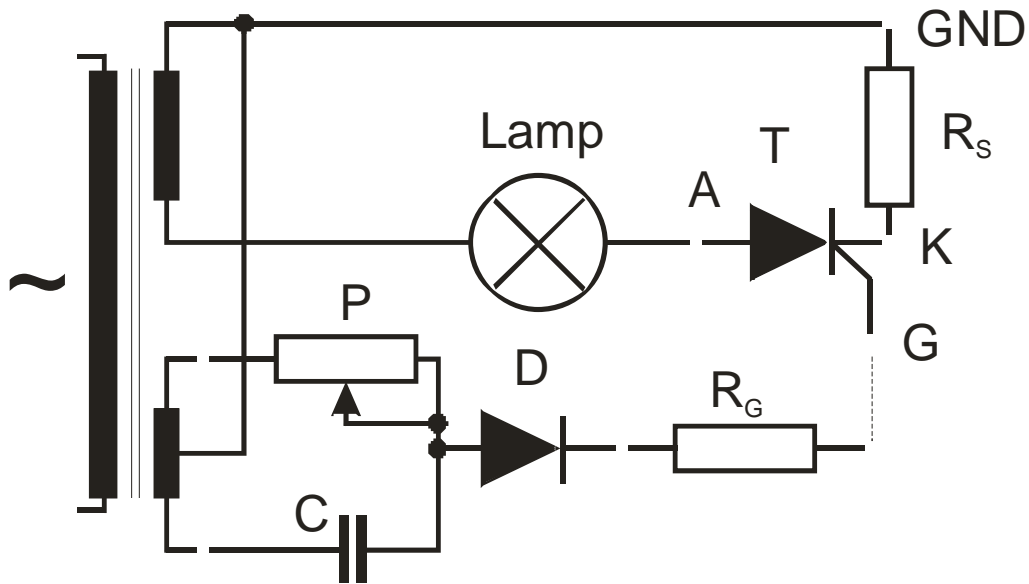
Connect a DC voltmeter between gate and cathode, or use one oscilloscope channel to measure the gate voltage.

Slowly increase the DC power supply voltage V_{GG} , while monitoring the state of the lamp.

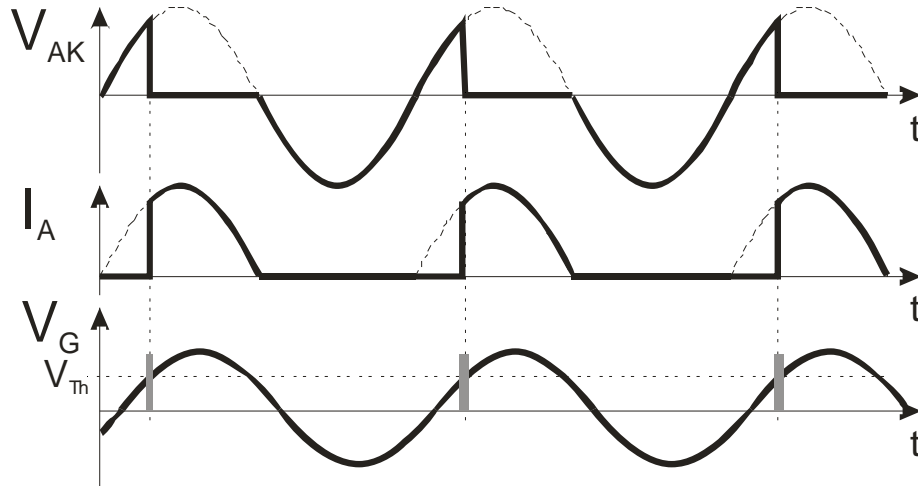
Note the threshold current I_{Th} and V_{Th} voltage at which the thyristor switches on and the lamp illuminates.

Visualize the I-V characteristic of the thyristor, connecting the oscilloscope as in the above figure, at various gate currents in the neighborhood of the threshold value. Note the unidirectional conduction through the thyristor's A-K circuit.

Another circuit board in the lab allows studying the control of power on loads in AC. The circuit has the schematics shown below:



The main circuit containing the load (an incandescent lamp) in series with the controlling element, that is the thyristor and with a current sensing resistor R_s is powered from a separate section of a transformer that provides $\sim 24\text{V}$ AC when its primary is connected to the 220 V AC power line. The gate circuit is powered from another section of the transformer, although an alternate configuration would allow it to be powered directly from the main section, as you will see later, when studying the triac circuit. The operation of the circuit is based on switching on the thyristor at different moments in time during the positive phase of the supply voltage cycle. That is achieved through the gate circuit that contains a R-C circuit that phase-shifts the AC voltage in the secondary section of the transformer and applies it to the thyristor's gate. To prevent damage to the thyristor's gate, a current-limiting resistor R_G and a diode that prevents the application of negative gate voltages are inserted in series with the gate. By varying the position of the cursor of the potentiometer P, the phase at which the gate current reaches the threshold value I_{Th} , changes, switching on the thyristor at earlier or later points during each positive cycle of the AC voltage or current. Thyristor's operation we have described is illustrated in the figure below:



One has to note that as the gate voltage or current decreases below the threshold, the thyristor is not switched off, it remains in conduction state until the next zero crossing of the voltage/current applied on the A-K circuit.

By varying the time during which the thyristor is in the on state, the mean current/voltage/power through the load can be controlled.

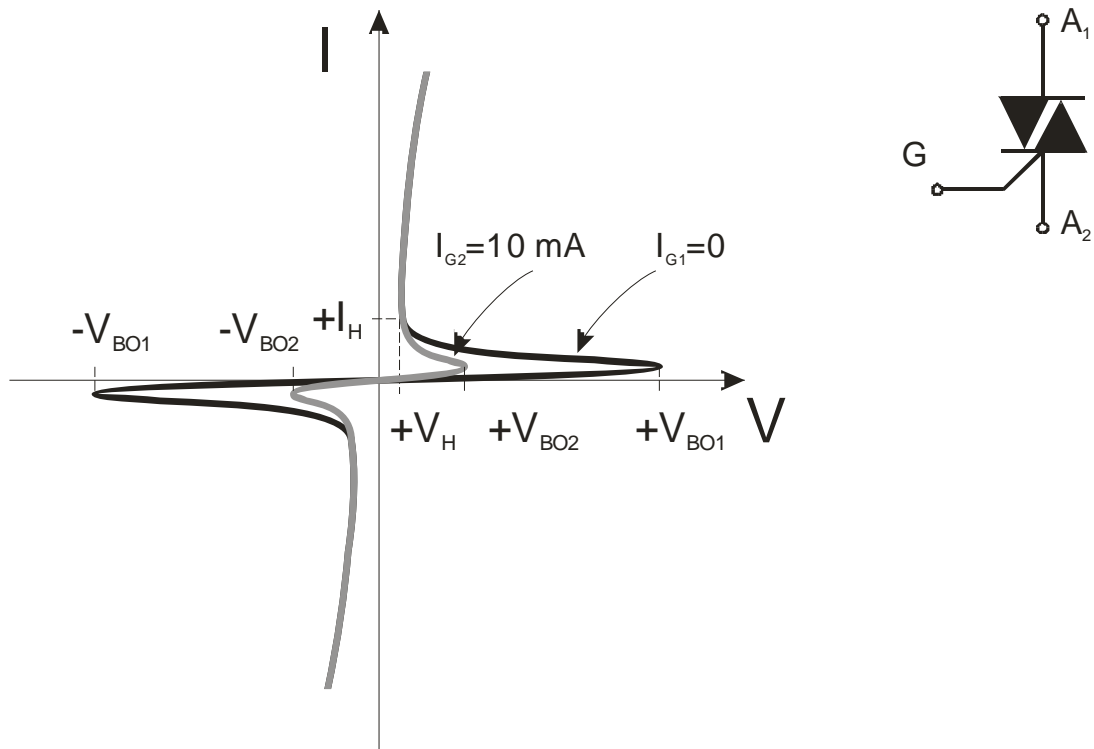
Visualize the waveforms that characterize the AC operation of the thyristor by connecting the oscilloscope as described earlier. Please note the “upside down” physical layout of the circuit in the lab, where the ground is at the top.

By varying the position of potentiometer’s cursor, note the phase shifting of the voltage applied on gate, occurring simultaneously with a modulation of its amplitude. A minimal signal amplitude applied to the gate is required, matching the values previously measured in DC.

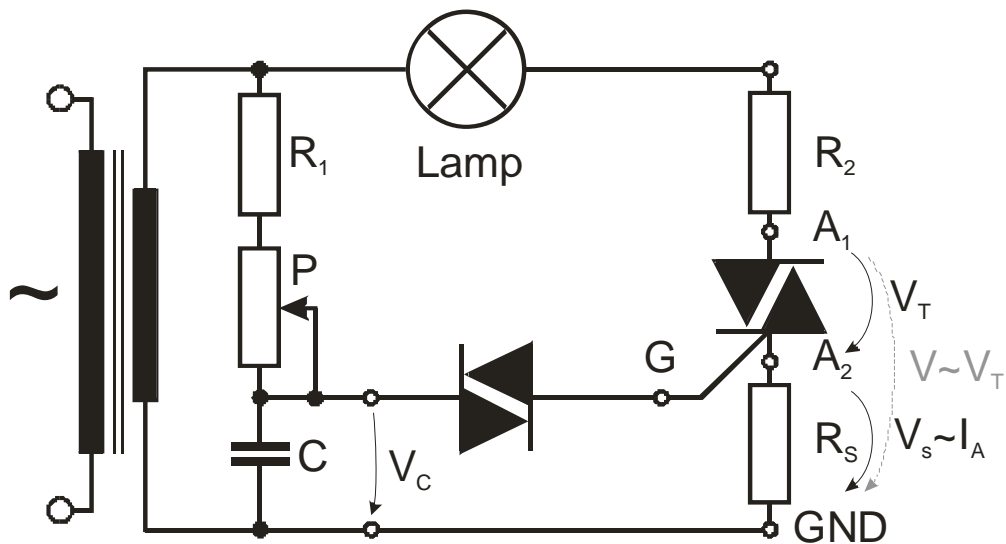
Note the modulation of the lamp’s brightness while acting on the command circuitry.

Triac

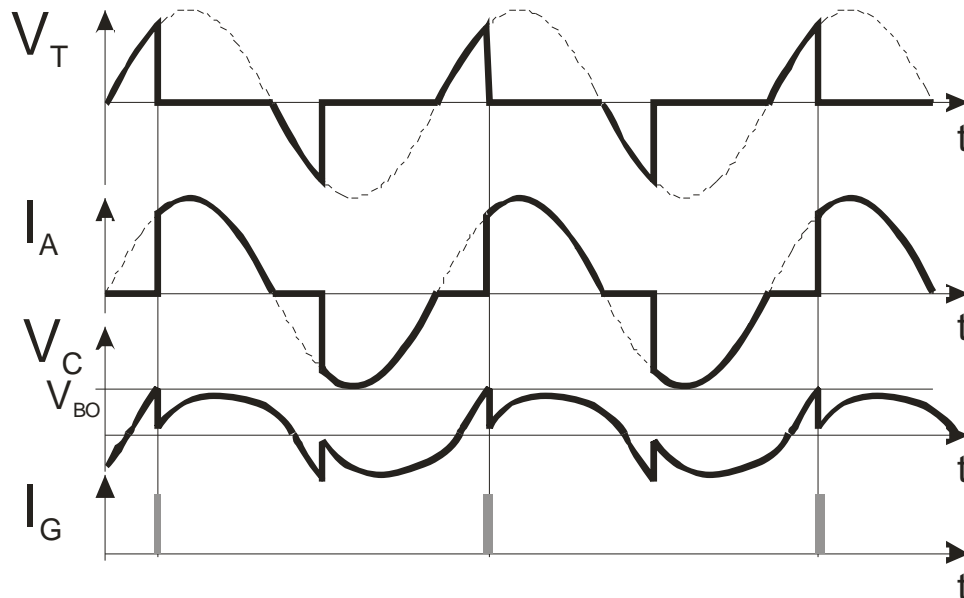
Triac’s operation is very similar to the thyristor’s one, except that its operation in the third quadrant of the I-V characteristic is similar to the one in the first quadrant. Therefore, the triac is a bi-directional device. The gate current required for switching on the thyristor by lowering the breakover voltage is typically significantly larger than the one one of the triac. The I-V characteristics and symbol of the triac are shown below:



To implement a command circuit for the triac, the RC variable-phase circuit can be used, with some modifications required for providing a larger gate current. These modifications include the insertion of a diac in series with the gate and powering the RC circuit from a higher voltage (same as the one powering the A-K circuit), exceeding the breakover voltage of the diac. The circuit's schematic is shown below:



The operation of the command circuit relies on the charge stored on the capacitor as the voltage on it increases, which quickly discharges through the triac's gate whenever the diac's breakover voltage has been reached. When this occurs, a quite large current pulse is applied to the triac's gate, switching it on. The time-course of different variables characterizing the circuit is illustrated in the figure below:



Visualize the waveforms that characterize the AC operation of the triac by connecting the oscilloscope as described in the figure on top of page.

By varying the position of potentiometer's cursor, note the phase shifting of the voltage applied on gate, occurring simultaneously with a modulation of its amplitude. The triac can be switched on only when the voltage on the capacitor C reaches the breakover voltage of the diac in series with the gate.

Please note the discharge of the capacitor C through the diac and the triac's gate. The pulse-like discharge can be better visualized if one channel the oscilloscope is connected directly to the gate G.

Note the modulation of the lamp's brightness while acting on the command circuitry.