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Experiment 2: Capacitors

Objectives of the experiment

Getting to know the following components

- Digital multimeter
- Function generator
- Oscilloscope
- Breadboard

electrical-engineering learning outcome in

- generating and displaying periodic signals
- determining capacitances
- measuring the characteristic curve of a diode and a Zener diode

Display of periodic signals on the oscilloscope

Build the following circuit in figure 1 with the function generator and the oscilloscope.

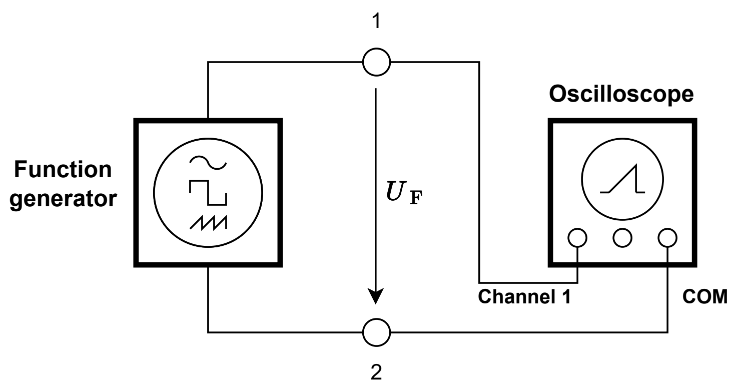


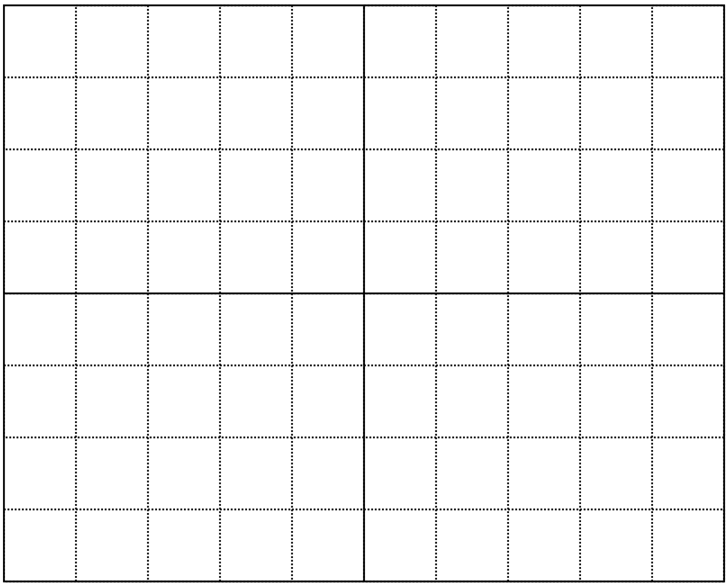
Fig. 1: Periodic signals on the oscilloscope

Set the signals listed in table 1 on the function generator and draw the corresponding oscilloscope screen images. The signal display on the oscilloscope should optimally fill the screen

Signal shape	Frequency	Amplitude
Sine	1.0 kHz	1.8 V
Triangle	4.0 kHz	3.0 V
Square (unipolar)	2.0 kHz	5.0 V
Square (bipolar)	5.0 kHz	2.0 V
Sine DC offset	2.5 kHz	4.0 V 2.0 V

Tab. 1: Signals

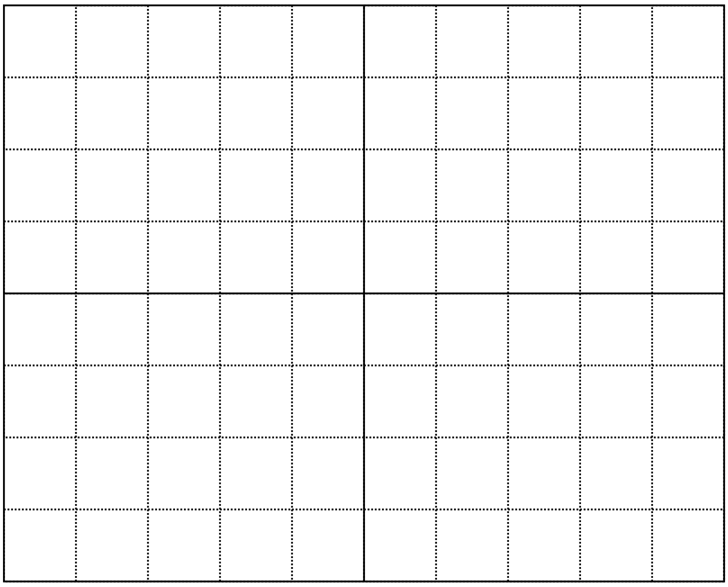
Also document the settings of the used channels, the time base, and the GND () line on the left side of the screen drawings.



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

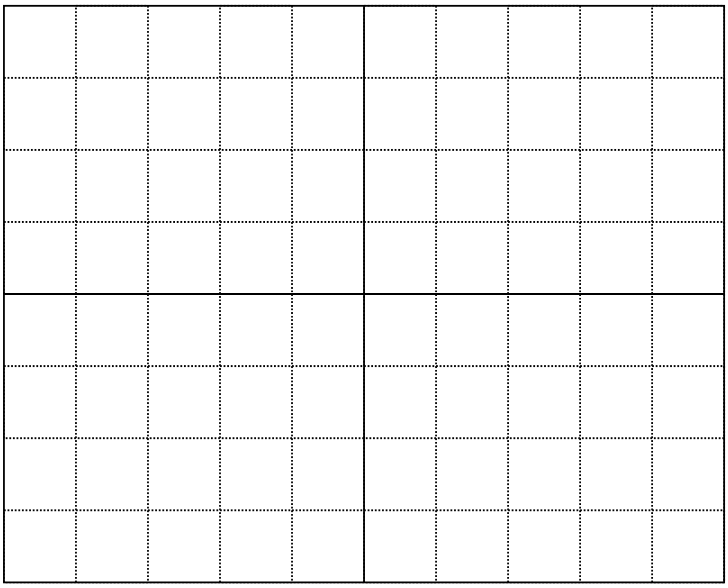
Fig. 2: Sine, f = 1 kHz, U = 1.8V



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

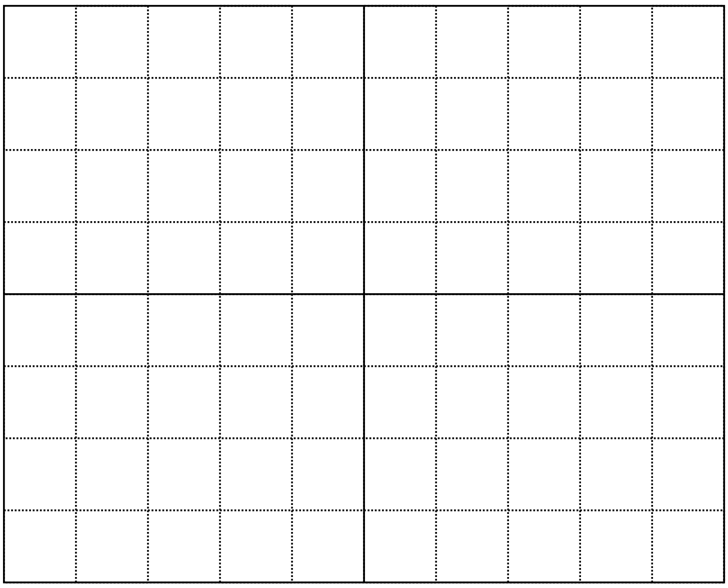
Fig. 3: Triangle, f = 4 kHz, U = 3 V



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

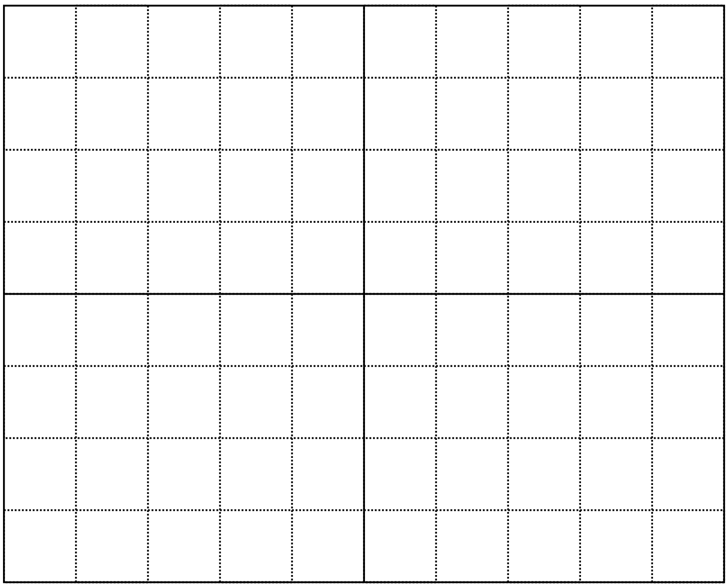
Fig. 4: Rectangle, unipolar, f = 2 kHz, U = 5 V



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

Fig. 5: Rectangle, bipolar, f = 5 kHz, U = 2 V



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

Fig. 6: Sine DC Offset, f = 2.5 kHz, U = 4 V, UDC = 2 V

Capacitors

Direct capacitance measurement

Capacitors are components that allow the storage of electrical energy. In the charged state an electrical charge is present. This charge causes a voltage at the electrical terminals of the capacitor.
Build the following circuit on the breadboard with three capacitors, s. figure 7:

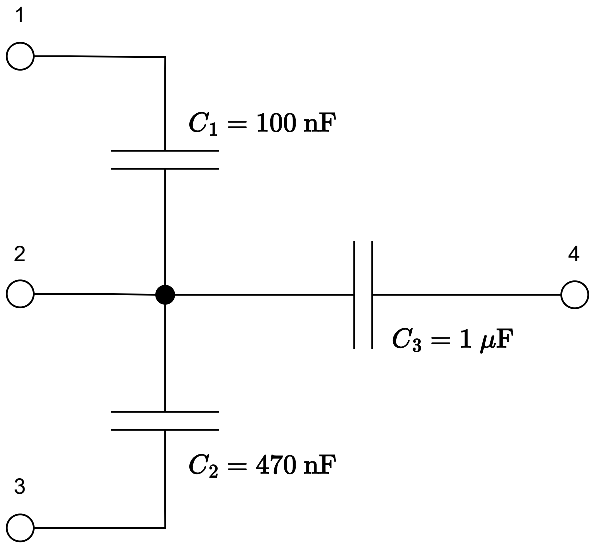


Fig. 7: Capacitors

Measure the capacitance of capacitors $C_1,\ C_2,\ C_3$ with the multimeter and enter the measured values in table 2.

C_1	C_2	C_3

Tab. 2: Capacitors

Capacitors can be connected in series and/or in parallel. The total capacitance of two or more capacitors in parallel is calculated as:

$$C_{\text{total}} = C_1 + C_2 + \ldots + C_{\text{n}}$$

The total capacitance of capacitors connected in series is calculated as:

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_{\text{n}}}$$

Series connection:

- $C_1 + C_2$ (measured between terminals 1 and 3)
- $C_2 + C_3$ (measured between terminals 3 and 4)

Parallel connection:

- $C_1 \,||\, C_3$ (measured between terminals 1 and 2; wire bridge between 1 and 4)
- $C_1 \,||\, C_2$ (measured between terminals 1 and 2; wire bridge between 1 and 3)

Series/parallel connection:

- $C_1 + (C_2 \,||\, C_3)$ (measured between terminals 1 and 3; wire bridge between 3 and 4)

Enter the measured and calculated values in table 3.

	$C_1 + C_2$	$C_2 + C_3$	$C_1 \| \| C_3$	$C_1 \| \| C_2$	$C_1 + (C_2 \| \| C_3)$
Measurement					
Calculation					

Tab. 3: Capacitor meas. vs. calc.

The built-in capacitors have values from the E6 series. The E6 series for capacities is shown below. For the measured capacities from table 2, determine the matching value from the E6 series and calculate the respective measurement deviation from the nominal value in %.

$$\text{Deviation} = \frac{C_{\text{meas}} - C_{\text{nom,E6series}}}{C_{\text{nom,E6series}}} \cdot 100$$

Enter your results in the spaces provided below.

$C_1\,(E6) = \ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (Deviation...........%)

$C_2\,(E6) = \ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (Deviation...........%)

$C_3\,(E6) = \ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (Deviation...........%)

The E6 series for capacities in table 4:

100 nF	1 µF	10 µF	100 µF
150 nF	1,5 µF	15 µF	150 µF
220 nF	2,2 µF	22 µF	220 µF
330 nF	3.3 µF	33 µF	330 µF
470 nF	4.7 µF	47 µF	470 µF
680 nF	6.8 µF	68 µF	680 µF

Tab. 4: E6 series for capacitors

RC network

The capacitance of a capacitor is defined as the quotient of charge by voltage:

$$C = \frac{Q}{U}$$

Capacitors must be charged via an electrical source figure 8.

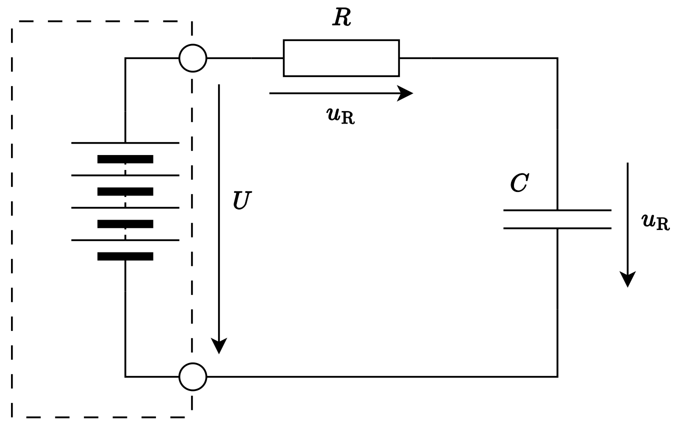


Fig. 8: Capacitor charging

A capacitor charges the faster the smaller the series resistor R is. During charging, the voltage u_C results from a differential equation as:

$$u_\mathrm{C}(\mathrm{t}) = U \cdot (1 - e^{-\frac{t}{\tau}}), \text{with } \tau = R \cdot C$$

The constant τ is called the time constant. After this time, the capacitor is charged to approx. $63\ \%$. The fundamental equation for the relation between current and voltage at a capacitor is:

$$i_\mathrm{C}(\mathrm{t}) = C \cdot \frac{\mathrm{d}u_\mathrm{C}}{\mathrm{dt}}$$

From the two equations, the current through the capacitor is:

$$i_\mathrm{C}(\mathrm{t}) = \frac{U}{R} \cdot e^{-\frac{t}{\tau}}$$

The graphical representation of voltage and current during the charging of a capacitor over time is shown in figure 9.

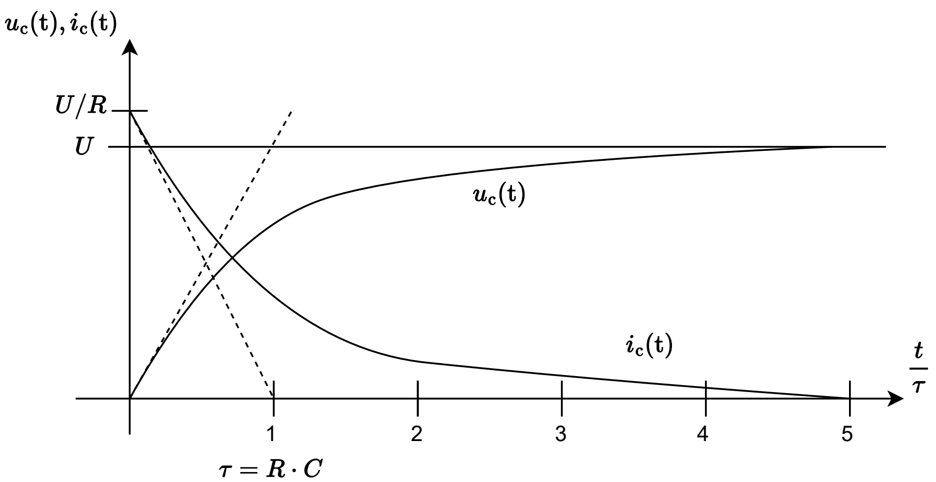


Fig. 9: Voltage/Current in case of charging capacitor

Because of the exponential function, charging is theoretically only complete after an infinitely long time. The capacitor voltage equals $63\ \%\ U$ after $1 \cdot \tau$, $86\ \%\ U$ after $2 \cdot \tau$, $95\ \%\ U$ after $3 \cdot \tau$, $98\ \%\ U$ after $4 \cdot \tau$, and $99\ \%\ U$ after $5 \cdot \tau$. It is assumed that the capacitor is fully charged after a time span $T = 5 \cdot \tau$ and the voltage across the capacitor has reached U. If the charged capacitor C is discharged through a resistor R, the solution of the differential equation for the voltage is:

$$u_{\mathrm{C}}(\mathrm{t}) = U \cdot e^{-\frac{t}{\tau}}$$

For the current accordingly:

$$i_{\mathrm{C}}(\mathrm{t}) = -\frac{U}{R} \cdot e^{-\frac{t}{\tau}}$$

Now build the following circuit. Connect the function generator and the oscilloscope to the circuit as shown in figure 10.

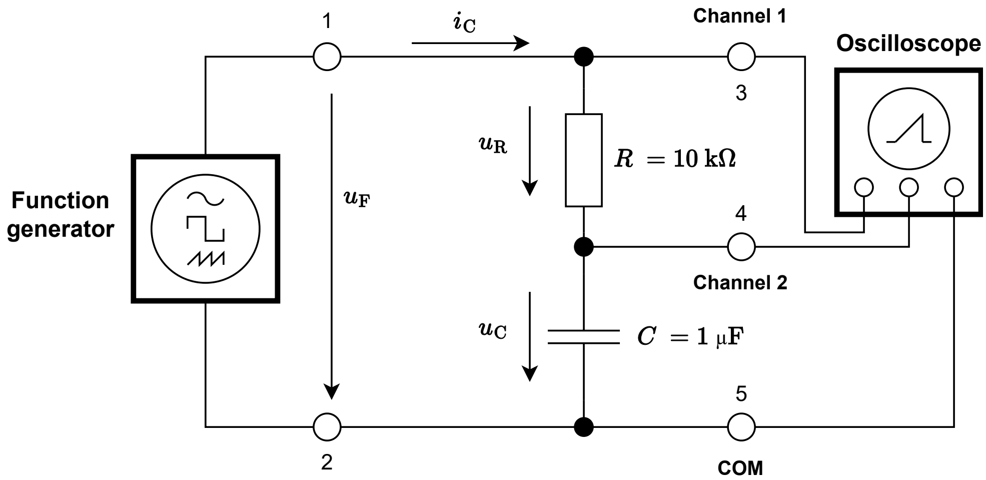


Fig. 10: Circuit with oscilloscope + function generator

Connect the function generator's ground (black) to point 2 and the signal lead to point 1. For the oscilloscope connection use the BNC-banana adapter; the red socket is the signal input and the black socket is the ground connection to the oscilloscope. Connect Channel 1 to point 3, Channel 2 to point 4, and ground to point 5. You only need to make the ground connection to the oscilloscope once, since the ground lines are connected inside the oscilloscope.

Enter in table 5 both the measured values of the components used and the calculated time constant τ.

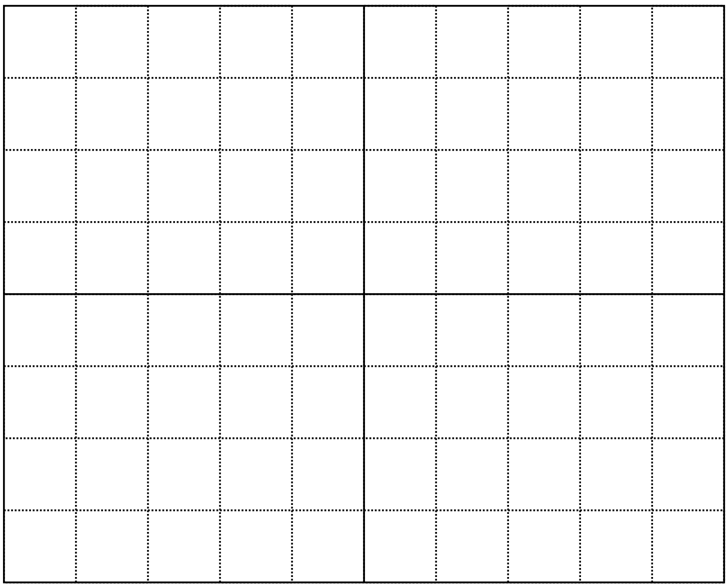
R	C	$\tau = R \cdot C$

Tab. 5: Capacitor meas. + time constant τ

Set the voltage u_{F} generated by the function generator to a unipolar square with amplitude 5 V (i.e., no negative signal voltages occur!). The frequency on the function generator must be chosen so that the capacitor just fully charges and then fully discharges again.
Calculate the frequency to be set:

$f_1 = \ \ldots\ldots\ldots\ldots\ldots$

Sketch the voltages measured with the oscilloscope for u_{F}, u_{C}, and u_{R} in the following screen diagram. Also enter alongside the screen drawings the set $\frac{V}{\mathrm{DIV}}$ of the channels and the $\frac{T}{\mathrm{DIV}}$ of the time base.



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Channel 2: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

Fig. 11: u_F, u_C, u_R

Draw **tangents** in the screen diagram for the start of charging and the start of discharging.
What is the charging current or discharging current at the beginning?

The circuit is now to be operated at higher frequencies. Set the frequency to:

- $f_2 = 10 \cdot f_1$
- $f_3 = 100 \cdot f_1$

Measure the waveforms for u_F, u_C and document the results in the following table 6:

Frequency	Amplitude u_F	Duration of charging	Max value u_C	Min value u_C

Tab. 6: Voltage curve u_F u_C

Explain your observations for the measurements with f_2, f_3:

General information on diodes

The diode (also called rectifier diode) is a semiconductor device with two terminals that has a nonlinear current-voltage-characteristic. It can be regarded as a voltage-dependent switch. The function of a rectifier diode in normal operation can most easily be imagined as a check valve, s. figure 12. If pressure (voltage) is applied to this valve (diode) in the blocking direction, the current flow is blocked. In the opposite direction the pressure must become large enough to overcome the spring pressure of the valve (blocking voltage). Then the valve opens and current can flow. The voltage needed in this mechanical model to overcome the spring pressure corresponds to the so-called forward voltage. A certain forward-direction voltage must first be present for the diode to go into the conducting state. For ordinary silicon diodes this necessary forward voltage is approx. 0.7 V for currents in the mA range.

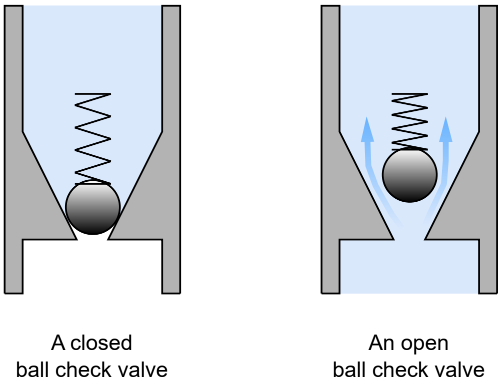


Fig. 12: Valve characterization

Z-diode

Often, the voltage across a load is to be constant; for example in microelectronics, where the allowable operating voltage is mostly between 4.75 V and 5.25 V. This rather narrow range cannot be achieved with simple power supplies. A reference voltage source (regulated voltage) is needed. Z-diodes can be used well for small powers. The Zener effect was discovered in 1934 by Clarence Malvin Zener. Normal diodes are destroyed in reverse operation if a certain voltage threshold is exceeded — one speaks of the diode's breakdown. Zener found that specially doped diodes (Z-diodes) operated in reverse can withstand this breakdown voltage. Since the breakdown voltage (also called Zener voltage) is nearly constant, Z-diodes are suitable as a voltage reference when operated in breakdown. When operated in forward direction or in reverse with voltages below the Zener voltage, Z-diodes behave like normal diodes.

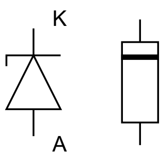


Fig. 13: Circuit symbol for a Z-diode

Inform yourself about Z-diodes and their circuit.

The function generator is to feed a rippled voltage into a circuit consisting of a Z-diode and series resistor. The generator voltage and the voltage at the Z-diode are to be measured with the oscilloscope. Draw the circuit with generator, Z-diode and series resistor as well as oscilloscope with the given values:

- Zener diode: Z 2.4 V / 0.01 W
- Function generator
- Amplitude: 1 V
- DC () offset: +5 V
- Frequency: 50 Hz.

Determine the required resistor for current limiting of the Zener diode under the above condition (document your calculation below!).

Which resistors from the E-series can be used?

. . . .

Is it better to choose a higher or lower resistor? Why?

. . . .

. . . .

. . . .

Build the circuit and set the generator voltage accordingly. Now measure with the oscilloscope the voltage after the generator with Channel 1 and after the Zener diode with Channel 2. Enter the oscilloscope traces in the figure 14 shown below. Label the traces of the corresponding voltages.

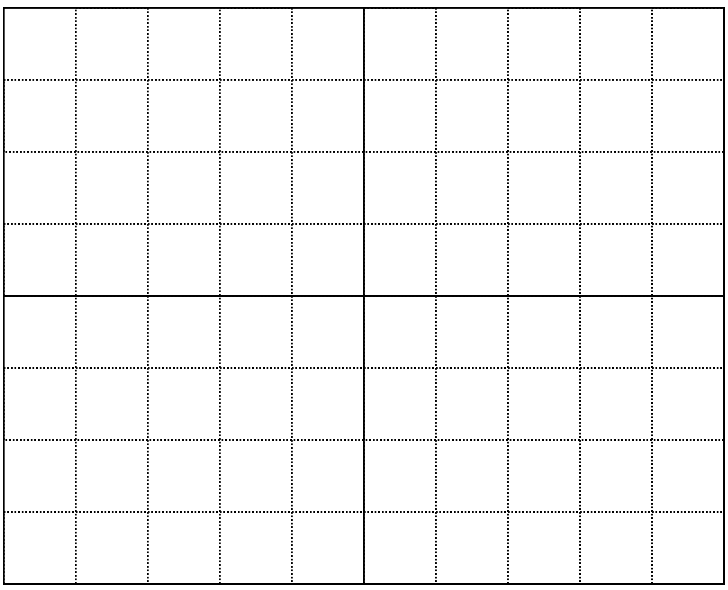


Fig. 14: Screen diagram

Channel 1: $\frac{V}{\mathrm{DIV}} =$

Channel 2: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

Recording a diode characteristic curve with the oscilloscope in X–Y mode

The representation of a diode characteristic on the oscilloscope is done using the circuit in figure 15. As an AC () source for recording the characteristic, the function generator is used, which feeds a sine signal with a frequency of 20 Hz into the circuit. This sine signal must not contain any DC () component (no offset), otherwise the characteristic cannot be displayed correctly on the oscilloscope. The diode voltage u_{D} must be applied to Channel 1. The voltage drop across the resistor u_{R} is proportional to the current through the diode and is applied to Channel 2. The necessary ground connection for the oscilloscope lies between the resistor and the diode. For this reason, Channel 1 must also be inverted for the measurement.

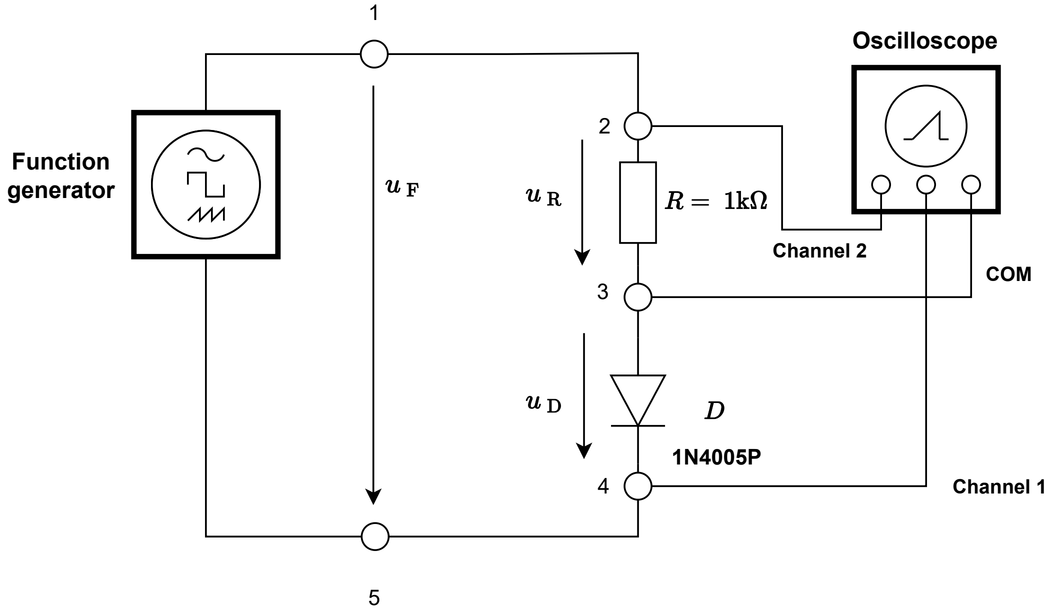
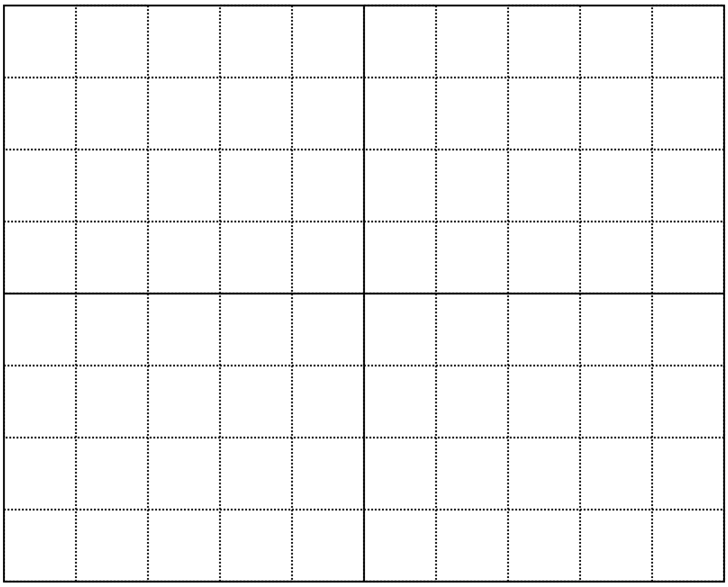


Fig. 15: Diode characteristic with oscilloscope

Record the screen image of the diode characteristic in figure 16 and determine the forward voltage of the diode by placing a straight line in the screen diagram.



Channel 1: $\frac{V}{\mathrm{DIV}} =$

Channel 2: $\frac{V}{\mathrm{DIV}} =$

Time basis: $\frac{T}{\mathrm{DIV}} =$

Fig. 16: Screen image diode characteristic

Give the determined forward voltage of the diode 1N4005P:

. . . .