First name .... Date ....

Last name .... Degree program name ....

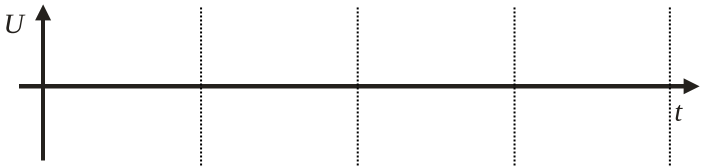
Exercise 146

Study of the Semiconductor Diode

Table I: **Part P46.** Voltage on the diode. Set ....

	Voltage (V) for I = …… mA	Voltage (V) for I = …… mA
Rectifier diode		
Red diode		
Green diode		
Blue diode		

Table II: **Part P47.** AC (alternating current) rectification test.

Type of rectification	Graph of the current time waveform
Without rectification	
A One-way rectification	
B One-way rectification with smoothing	
C Two-way rectification	
D Two-way rectification with smoothing	

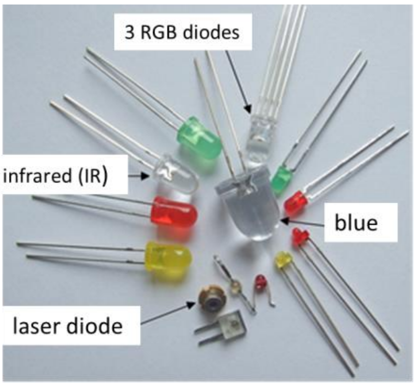
Exercise: Study of the Semiconductor Diode

AIM

The purpose of the exercise is to measure the current-voltage characteristics of a rectifying diode and light-emitting diodes (red, green and blue) - part P46. In the second part of P47, the use of the diode for AC rectification will be studied.

THEORY

Most solids have a crystalline structure, characterized by the fact that the atoms of these bodies are arranged in space in a regular, repeating manner, forming a crystal lattice. Conductors are bodies in which there are so-called free charges that can move inside these bodies. Typical representatives of conductors are *metals*, that is, elements whose atoms have one or two valence electrons. When such atoms join together in larger groups, the valence electrons lose direct contact with their atoms, which as a result become positive ions. These electrons do not occupy specific positions in the crystal lattice, but can move freely between the ions and form what is known as *electron gas*. They are called free electrons or *conduction electrons*. This type of bonding of atoms in the crystal lattice is called *metallic bonding*.



Another type of bonding, called *atomic bonding*, is formed by elements of group IV of the periodic table, such as germanium (Ge) and silicon (Si), which are typical representatives of *semiconductors*. These elements have four valence electrons each, and each of these electrons participates in a bond with the four nearest neighboring atoms. Valence electrons are therefore not free electrons and cannot move around in the crystal. Detachment of a valence electron from an atom is possible, but it requires the supply of an appropriate amount of energy, not less than a certain minimum value called *the activation energy* - E_a. One way to provide energy to the electron is to heat the crystal. The freed electron can already move in the area between atoms and conduct electricity.

Not only free electrons participate in the conduction of current in a semiconductor. As a result of the detachment of an electron from an atom, a free space, known as a *hole*, is created, which can easily be filled by an electron from a neighboring bond. As a result, the holes move in the direction opposite to the movement of the electrons - so the holes behave like free positive charges. If we are dealing with a pure semiconductor and without internal defects, the concentration of holes and free electrons is the same, and then the conduction is called *intrinsic conduction*. The concentration of intrinsic carriers (electron-hole pairs) in a semiconductor is small and changes significantly with changes in external conditions, such as temperature or illumination.

We can increase the number of holes or electrons in semiconductors very easily, not only by changing external conditions, but, for example, by appropriate doping of the crystal. If we introduce a small amount of a pentavalent element (e.g. phosphorus, antimony) into a quaternary semiconductor, we increase the number of free electrons. Such a semiconductor is an **n-type** semiconductor, and ionized dopant atoms that provide one electron are called *donors*. The presence of trivalent atoms (e.g. boron, aluminum) in germanium or silicon increases the number of holes.

Such a semiconductor is **p-type**, and dopant atoms that increase the number of holes are called *acceptors*.

One of the basic components of electronic circuits is *the semiconductor diode*. A semiconductor diode passes current in one direction, a very weak current flows in the opposite direction. A semiconductor diode is made of two semiconductors of different types - a **p-type** semiconductor and an **n-type** semiconductor. If the **p-type** semiconductor is joined to the **n-type** semiconductor, there will be a flow of electrons from the **n-type** material to the **p-type** material and holes in the opposite direction.

As a result, a layer of double stationary space charge is produced at the junction, the so-called barrier layer, which prevents further movement of free charges, Figure 1.

The electric field in a **p-n** junction means that there is a potential difference between the **p** and **n** regions, called *the contact voltage* U_k or *potential barrier*. For germanium junctions, the potential barrier is $U_k = 0,3 \div 0,4\ \text{V}$, and for silicon junctions it is $U_k = 0,7 \div 0,8\ \text{V}$.

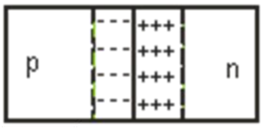


Fig. 1

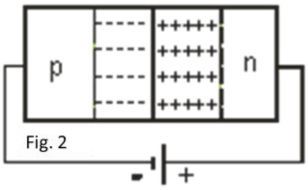


Fig. 2

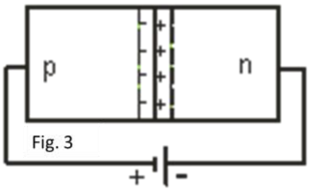


Fig. 3

If a constant voltage is applied to a **p-n** junction so that the positive pole of the battery is connected to an **n-type** semiconductor and the negative pole to a **p-type** semiconductor (Figure 2), holes and electrons will be pulled away from the junction boundary into the interior of the semiconductors, and as a result, the width of the barrier layer increases, its resistance also increases. This direction of polarization of the junction, called the barrier direction, promotes the flow of electrons from the p-semiconductor to the n-semiconductor and holes in the opposite direction. Since electrons in the p-type material and holes in the n-type material are minority carriers, a very weak current will flow through the junction.

If we polarize the **p-n** junction in the opposite direction (Figure 3), the width of the double charge layer is reduced, the resistance of the junction decreases. This direction of polarization of the junction, called the conduction direction, promotes the flow of majority carriers, i.e. electrons from n-type material to **p-type** material and holes from p-type material to n-type material, which gives a rapid increase in current with increasing voltage. The current-voltage characteristics of a diode, i.e., the plot of the current-voltage dependence, for both barrier and conduction polarization, are shown in Figure 4.

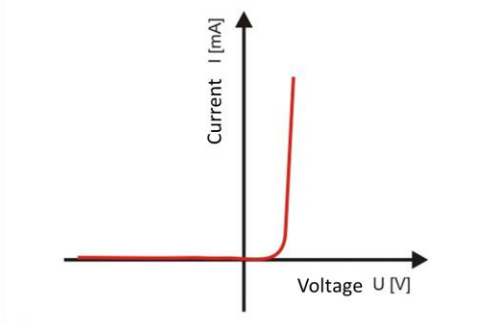
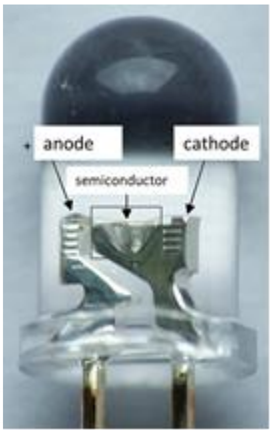


Fig. 4 Current-voltage characteristics of the diode.



If a sinusoidally alternating voltage is applied to the diode, current will flow through the diode only for the voltage corresponding to the polarization in the conduction direction. *Unidirectional rectification* then takes place, since only one half of the current sine wave (either the upper or lower half) is used. The direction of such a current is constant, but the value of the current varies periodically. A rectified ripple current is then obtained. Smoothing of the rectified arterial current is carried out with the help of special filters, built from capacitors and chokes (inductors).

The use of circuits, containing a larger number of rectifying elements, gives *bi-directional rectification*, which allows the use of both halves of the current sinusoid. An example of such a circuit is the *Graetz circuit*, discussed next, which consists of four diodes.

Light-emitting diodes are diodes that emit a flux of photons as a result of the conversion of electrical energy into radiant energy. This process is observed in a **p-n** junction, polarized in the conduction direction. Excess electrons and holes are injected into the junction region, where their radiative recombination can take place. This principle is the basis for the operation of light-emitting diodes made of gallium phosphide, gallium arsenide and other compounds of the type A_{III} B_{IV}. Diodes that emit visible radiation are used as optical indicators.

PERFORMANCE OF THE EXERCISE - **FIRST PART OF P46**

Current-voltage characteristics of the diode.

EQUIPMENT REQUIRED	Measurement system for testing diodes. Set A or B (issued by the instructor of the exercise) contains: resistor R = 1 kΩ, from the top a rectifying diode, a red diode, a green diode and a blue diode.
Interface „Science Workshop 700"	
Power Amplifier	
Voltage sensor	Two items
Connecting cables	Two items

Computer Preparation – **don't save changes to files (DON'T SAVE)**

1. Turn on the power of the table (see the dashboard of the table - by your left leg when you sit in front of the computer) - turn the red "knob" in the direction of the arrows (it should pop out), turn the key as in a car and let go. The interface and computer will automatically turn on.
2. The Windows operating system and the "Science Workshop" program will start automatically. Open (File ⇒ Open) in the directory *Library\Physics*, file **P46_DIO1.SWS**. On the screen, you will see the P46_DIO1 basic window, the Diode Current vs Voltage graph window - showing the dependence of current on voltage, and the Signal Generator window, where you set the signal parameters at the output of the power amplifier.

INSTRUCTIONS FOR THE EXERCISE LEADER

The P46_DIO1 base window is in collapsed form. The full form can be restored - as with any window in a *Windows* program. After expanding this window, you should see an interface with the analog inputs **A, B, C** lit up.

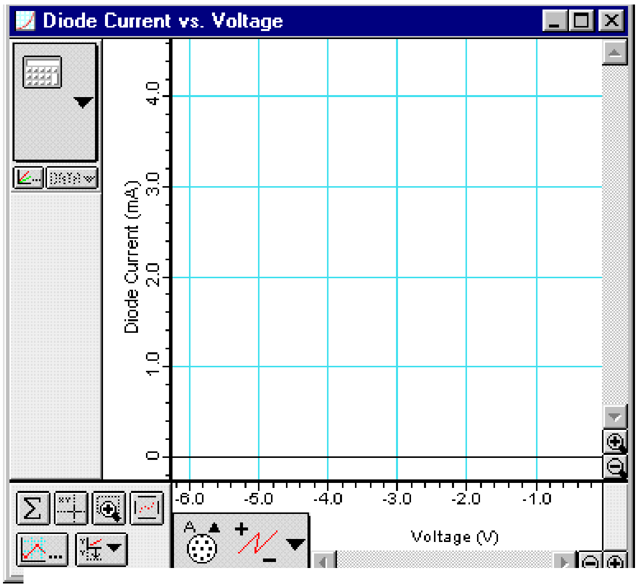
1. Make sure that the signal generator is set to a voltage uniformly increasing from about -6 V to 6 V and with a frequency of 0.05 Hz and that the AUTO option is selected.

2. In the main window of the program, press the Sampling Options button and check that the measurement frequency (Periodic Samples) is set to 5 Hz (Fast), Start Condition - none, Stop Condition - 100 samples. Press OK.

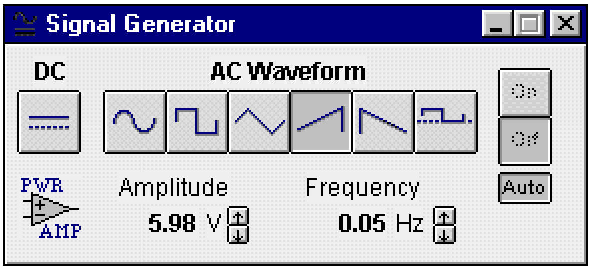
Exercise windows

Basic window **"P46_DIOD1"** - contains control buttons

"Diode Current vs. Voltage" graph window - shows the relationship between voltage and current.



"Signal Generator" window - allows you to adjust the supply voltage.



The measurement system

The wiring diagram of the measurement system is shown in Figure 5.

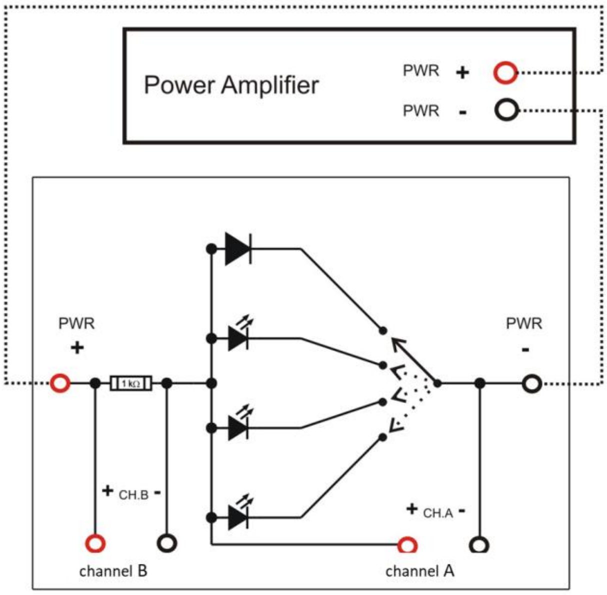


Fig. 5 Diode circuit wiring diagram. Part P46.

Preparation of the measurement system

1. Check that the voltage sensors are connected to the correct channels.

2. One voltage sensor should be connected to analog channel A of the interface, and the other to channel B.

3.The power amplifier should be connected to the analog channel C of the interface (gray wire coming out of the back of the power amplifier).

4. Connect the voltage sensor wires of channel A to the diode (red wire to CH.A "+", black wire to CH.A "-"). Use the switch to select one of the four diodes - to start with, switch to the first one from the top.

5. Connect the wires of the voltage sensor of channel B to the 1 k resistor (red wire to CH.B "+", black wire to CH.B "-").

6. Connect the wires of the power amplifier to the measuring circuit (red output of the amplifier to PWR "+" of the circuit, black output of the amplifier to PWR "-" of the circuit).

7. Ask the instructor to check the connections.

Course and recording of measurements - diode and 1 kΩ resistor

1. Turn on the power amplifier - Power Amplifier.

2. Press the REC button in the P46_DIO1 window - a small flashing blue rectangle should appear under the button, indicating that the measurement has started The measurement will finish automatically.

3. Observe the graph on the screen. For light-emitting diodes: observe the graph and the diode in parallel. Evaluate at what point it begins to "glow".

4. Turn off the power amplifier - Power Amplifier.

DATA ANALYSIS

1. Press the autoscaling button , located in the lower-left corner of the graph to scale the graph according to the range of measured values. The vertical axis of the graph shows the current in mA, calculated by measuring the voltage across a 1 kΩ resistor. The horizontal axis shows the voltage on the diode.
2. Press the zoom button (the button with the plus sign in the circle). The cursor will turn into a magnifying glass. Use this cursor to frame a section of the graph where the current is between 0.2 and 1.5 mA.
3. Press the precision cursor button 

in the lower left corner of the chart. Move the cursor to the chart area. The cursor turns into a cross of spider threads. The x and y coordinates of the cursor's position are displayed next to the horizontal and vertical axes, these are voltage (x) and current (y), respectively. Move the cursor on the graph to the point where the current reaches 0.5 mA and 1 mA. Record the value of voltage and current in the data table for the corresponding diode.

   Attention. The amperage does not have to be exactly 0.5 mA and 1 mA. You can choose other intensities close to 0.5 mA and up to 1 mA.

4. Carry out identical measurements for the remaining light-emitting diodes.

5.The instructor records the obtained data and prints the selected graphs.

6. After completing this part of the exercise, disconnect the circuit from the sensors and remove the voltage sensor from channel **A**. The others will be useful in the next part of the exercise.

PERFORMANCE OF THE EXERCISE - **SECOND PART OF P47**

The diode as an AC rectifier.

I. Rectifying sinusoidal alternating current with a diode.

EQUIPMENT REQUIRED	The circuit contains: resistor R = 100 Ω, 1N-4007 diode, capacitor 470 μF
Interface „Science Workshop 700”	
Power Amplifier	
Voltage sensor	One item
Connecting cables	Two items

*Computer Preparation – **don't save changes to files (DON’T SAVE)***

Open (File ⇒ Open) in the directory *Library\Physics*, file **P47_DIO2.SWS**. On the screen, you will see (after closing the Experiment Notes window) the P47_DIO2 window, the oscilloscope Scope window - showing the time waveforms of the voltages from the B channels and the input voltage, and the Signal Generator window, where you set the parameters of the signal at the output of the power amplifier.

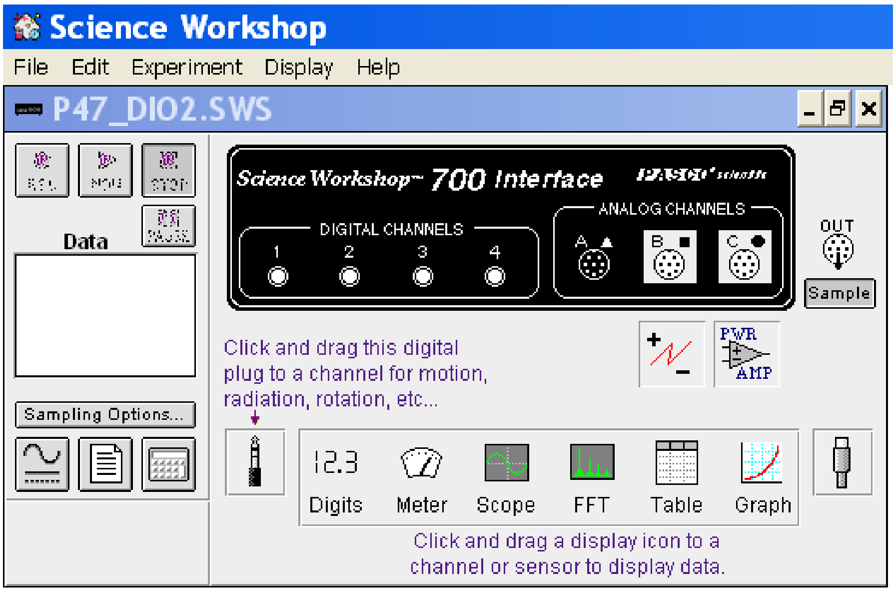
INSTRUCTIONS FOR THE EXERCISE LEADER

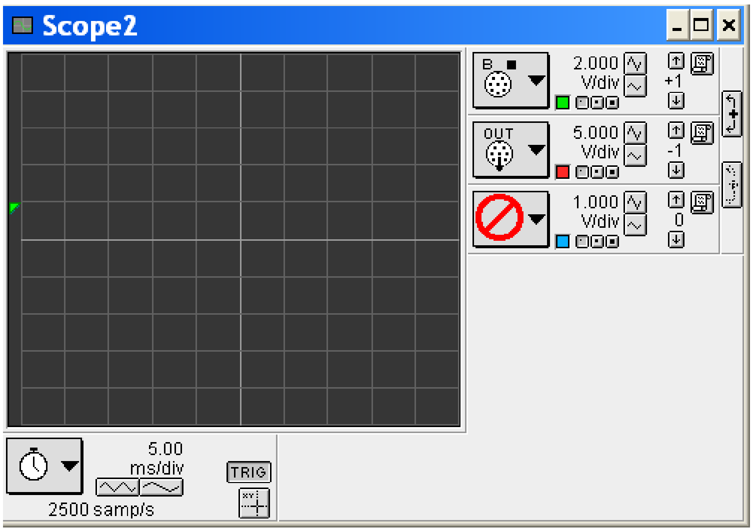
1. The P47_DIO2 base window is in collapsed form. The full form can be restored - as with any window in a Windows program. After expanding this window, we see the interface with the analog inputs B, C highlighted.
2. Check that the signal generator is set to a sinusoidal alternating voltage with an amplitude of about 4 V and frequency of 50 Hz. The AUTO option should be selected, which means that measurements start automatically when the REC or MON button is pressed, and end when the STOP or PAUSE button is pressed.
3. Check that the settings in the oscilloscope window are as shown in the figure on the previous page.

Exercise windows

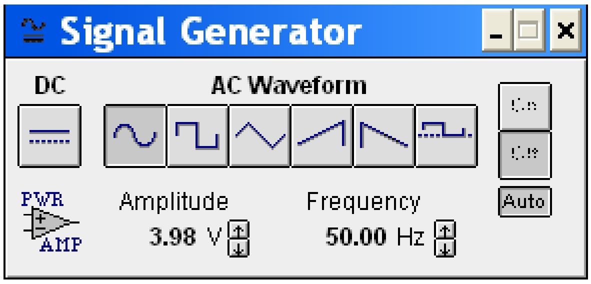
Basic window **"P47_DIOD2"** - contains control buttons

"Scope" window - shows the time waveforms of the voltage across the resistor and the input voltage.





"Signal Generator" window - allows you to adjust the voltage of the power generator.



The measurement system

The measurement system for the first part of the P47 exercise, is shown in Figure 7.

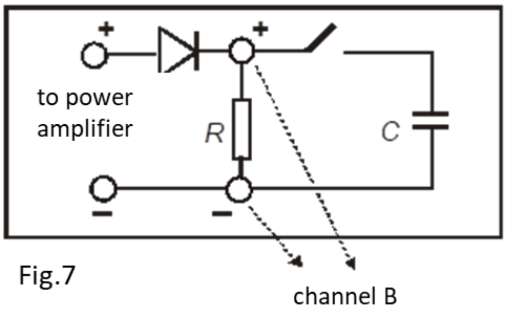


Fig.7

A. Obtaining pulse current - diode and resistor 100Ω

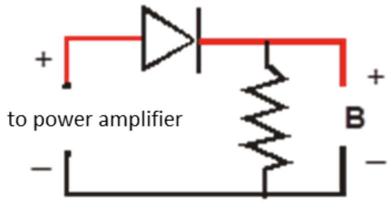


Fig. 8

The measurement system

The pulse current is obtained in the circuit, the diagram of which is shown in Fig.8; (in the measuring circuit to **P47** in Fig.7, the key (on/off switch) must be opened, so that the capacitor is disconnected). Position "left".

1. Connect the voltage sensor to the analog B channel of the interface. It should remain from the connections in part one.
2. Connect the power amplifier to the analog C channel of the interface. It should remain from the connections in part one.

3. Connect the wires of channel B to both sides of the resistor (red wire to "+", black wire to "-").
4. Connect the wires of the power amplifier with the circuit (red wire to "+", black wire to "-").

Course and recording of measurements

1. Turn on the power amplifier.

2. Press the MON button in the P47_DIO2 window. The data from the **OUT** channel shows the input voltage of the circuit on the oscilloscope screen, the data from the **B** channel - the voltage on the resistor. The time waveforms of the voltages are shifted with respect to each other so that they can be better seen.

3. To get an image of the time waveforms on the oscilloscope screen, press the STOP button when the drawing of the time waveforms covers the entire screen.

4. Turn off the power amplifier.

5. Try to redraw the representation of the time waveforms on the graphs in the table. In this part, you need to complete the "No rectification" graph with the waveform from the lower graph window and the "One-way rectification" graph with the waveform from the upper graph window.

DATA ANALYSIS

From the graph, we can conclude that a unidirectional current flows in the circuit under study. The voltage drop across the resistance varies as does the current flowing in the circuit.

In the course of such a current, we can see the time intervals when the current is not flowing. This is a unidirectional current of varying intensity, the so-called *pulse current*.

When the diode is polarized in the negative direction, current does not flow through the diode, the resistance of the diode is high and then all the voltage applied from the outside is deposited on the diode. On the resistor the voltage is then zero. When the diode is polarized in the conduction direction, a large current flows through the diode, the junction resistance is small. The voltage on the diode is then small, while the voltage on the resistor is large.

B. Smoothing the pulse current - diode, resistor and capacitor

The measurement system

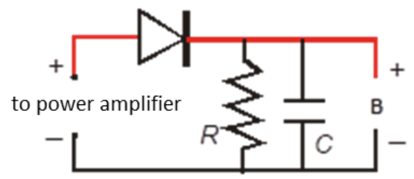


Fig. 9

The smoothing of the pulse current is carried out in the circuit , the diagram of which is shown in Fig.9; (in the measuring system for exercise **P47** in Fig.7, close the key so that the capacitor is switched on).

Preparation of the Computer - is not changed.

Course and recording of measurements

1. Turn on the power amplifier.

2. Press the MON button in the P47_DIO2 window. The data from the OUT channel shows the input voltage of the circuit on the oscilloscope screen, the data from the B channel shows the voltage on the resistor.

3. To get an image of the time waveforms on the oscilloscope screen, press the STOP button, at the moment when the drawing of the time waveforms covers the entire screen.

4. Turn off the power amplifier.

5. Try to redraw the representation of the time waveforms on the graphs in the table.

Notice that the waveform from the bottom window does not change. In this part, you only need to complete the "Unidirectional rectification with smoothing" graph with the waveform from the upper graph window.

DATA ANALYSIS

The capacitor used in the circuit serves as a filter to smooth out changes in current. The time intervals in which the current did not flow are filled by the capacitor's discharge current. When the diode is polarized in the conduction direction, a large current flows in the circuit, which charges the capacitor. When the diode is polarized in the negative direction, no current flows through it, but a capacitor discharge current flows through the resistor.

II. Diode as part of a power supply

EQUIPMENT REQUIRED	The circuit contains: resistor R = 100Ω, four 1N-4007 diodes, capacitor 470 μF
Interface „Science Workshop 700”	
Power Amplifier	
Voltage sensor	One item
Connecting cables	Two items

Preparation of the Computer - is not changed.

The measurement system

The universal measurement system for this part of the exercise, is shown in Figure 10.

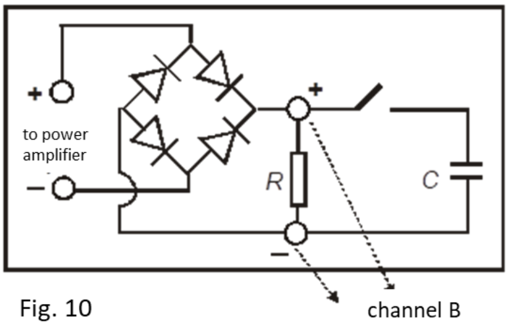


Fig. 10

C. Full current rectification - 4 diodes and a resistor

The measurement system

Full rectification of the current is carried out in the circuit, the diagram of which is shown in Fig.11; (in the measuring circuit in Fig.10, open the key (on/off switch), so as to disconnect the capacitor). "Left" position.
1. connect the wires of the voltage sensor of channel B on both sides of the resistor (red wire to "+",black wire to "-").
2. connect the wires of the power amplifier to the circuit (red wire to "+",black to "-").

Course and recording of measurements

1. Turn on the power amplifier.

2. Press the MON button in the P47_DIO2 window. The data from the OUT channel shows the input voltage of the circuit on the oscilloscope screen, the data from the B channel shows the voltage on the resistor.

3. To get an image of the time waveforms on the oscilloscope screen, press the STOP button, at the moment when the drawing of the time waveforms covers the entire screen.

4. Turn off the power amplifier.

5. Try to redraw the representation of the time waveforms on the graphs in the table.

As before, the waveform from the bottom window does not change. In this part, you only need to complete the "Two-way rectification" graph with the waveform from the upper graph window.

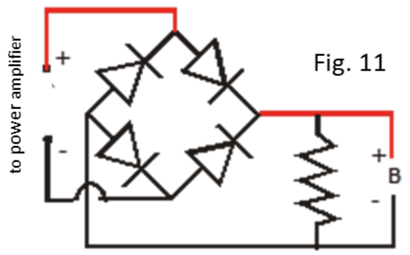


Fig. 11

DATA ANALYSIS

Using a circuit consisting of 4 diodes, bidirectional rectification is achieved. In this case, both halves of the current sine wave are used. During one half of the period, the current will flow through the two diodes opposite each other in the circuit, and during the other half of the period - through the other two diodes.

D. Smoothing of rectified current - 4 diodes, resistor and capacitor

Preparation of the Computer - is not changed.

The measurement system

The smoothing of the rectified current is carried out in the circuit shown in Fig.12; (in the circuit in Fig.10, close the key so that the capacitor is switched on).

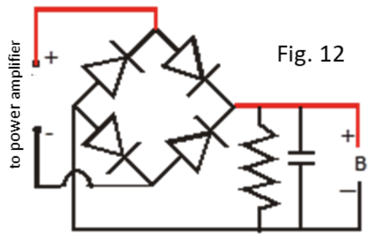


Fig. 12

Course and recording of measurements

1. Turn on the power amplifier.

2. Press the MON button in the P47_DIO2 window. The data from the OUT channel shows the input voltage of the circuit on the oscilloscope screen, the data from the B channel - the voltage on the resistor. The time waveforms of the voltages are shifted with respect to each other so that they can be better seen.

3. To get an image of the time waveforms on the oscilloscope screen, press the STOP button, at the moment when the drawing of the time waveforms covers the entire screen.

4. Turn off the power amplifier.

5. Try to redraw the representation of the time waveforms on the graphs in the table.

As before, the waveform from the bottom window does not change. In this part, you only need to complete the graph "Two-way rectification with smoothing" with the waveform from the upper graph window.

DATA ANALYSIS

The capacitor used in the circuit serves as a filter to smooth out changes in current. In this case, we get a current with a constant direction and almost constant intensity.

QUESTIONS

1. What components are included in an electronic circuit to obtain rectified current:
A. one-way
B. one-way smoothed
C. two-way
D. two-way smoothed?

2. What does the graph of the rectified current look like, respectively? Draw the time waveforms of the currents in the measurement table.