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An Educational and Laboratory Device That Demonstrates the Properties of Light as a Stream of Quasiparticles-Photons

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ABSTRACT: In this work a teaching-laboratory device was created for students of secondary schools, academic lyceums and colleges, as well as for students of higher educational institutions to study the phenomenon of internal and external photoeffects and to perform laboratory works in the field of physics optics. The device presents the results obtained on the basis of experiments proving that light consists of a flux of quasi-particle photons. The created device fully demonstrates the most important phenomena of physics, as well as such qualities as safety, ease of use, the possibility of individual work of students, does not require an external energy source and cheapness allow to use this device widely.

KEY WORDS: Electron, Infrared Radiation, Filtrs, Metal, Microammeter, Output Operation, Photon, Phenomenon, Photoresistance, Photoelectric Effect, Semiconductor.

INTRODUCTION

Using the capabilities of semiconductor devices to reveal the essence and under-standing of various physical effects is of great interest. Conducting experiments on the basis of such devices allows students to more fully understand the essence of physical phenomena. It is known from physics that in order to explain and determine the nature of the external photoelectric effect, Einstein proved for the first time that light not only has wave properties, but also consists of a stream of quasi-particles called photons, which have neither mass, nor size, nor charge and have the highest speed [1,2]. These photons have their own specific energy, corresponding to the frequency (or wave-length) of the light. The photon energy is expressed as follows:

$$E_{ph} = h\upsilon = \frac{ch}{\lambda} = \frac{1.24}{\lambda_{\mu m}} \text{ [eV]} \quad (1)$$

Where υ − is the frequency of light ($\frac{c}{\lambda}$); c − is the speed of light (c = 300000 km/h); λ − is the wavelength of light; h− is Planck's constant (h = $6.62 \cdot 10^{-34}$ J·s);

That is, according to Einstein's theory, the energy of a photon takes on different energies depending on the wavelength of light, and its energy is at the same time continuously without changing quantized, that is, it has a discontinuous (discrete) value. However, at present, not only in general education schools, lyceums and professional colleges, but also in physical laboratories of higher educational institutions, there is a need for educational and laboratory devices that demonstrate the properties of light that it consists of a stream of photons [3-6].

MATERIALS AND METHODS

The presence of such laboratory devices: firstly, so that students in laboratory classes are convinced that light consists not only of wave properties, but also of photon-particle fluxes, and secondly, they need the most advanced areas of modern electronics and technology - laser physics and optical fiber data transmission systems and the operation of solar cells also help to fully imagine that light is based on a stream of photonic particles [7-11]. This means that the sunlight coming to us is not only a source of heat, but also an inexhaustible source of environmentally friendly and external energy for the future of mankind, and its use allows for creative research.

The created educational and laboratory device is fundamentally different from other existing devices in that it is equipped with special equipment that facilitates the use of students in studying the phenomenon of the external photoelectric effect [12-14]. The appearance of the laboratory device and its scheme are shown in fig.1.

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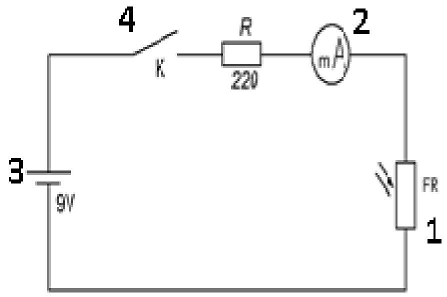

Fig.1. A device for studying the phenomenon of the internal photoelectric effect and its scheme.
Here are 1- a semiconductor photoresistor (silicon-based photoresistor);
2-milli-ammeter; 3-battery; 4-key; 5- filters that transmit various light rays; 6-light source (ordinary lamp or sunlight).

RESULTS AND DISCUSSION

The first experiment. During the experiment, the following is performed: the surface of the photoresistor is covered from above with a black opaque filter and the key is connected. In this case, we determine the strength of the current flowing in the absence of illumination of the semiconductor photoresistor, and set its value to I_0.

I_0- is the value of the current density $j = env$, according to Ohm's law, flowing through the photoresistor. Where e – is the charge of the electron ($e=1.6\cdot10^{-19}$ K), v is the speed of the electrons, and at T = 300° K $\upsilon = 10^7$sm/s, n-electron concentration, i.e. (number of electrons per unit volume – cm^{-3}). Now, having removed the black filter, we put a filter on the surface of the photoresistor that transmits only infrared light (wavelength $\lambda = 2 \div 4$ μm)), and turn on the lamp at a certain distance from the photoresistor. In the experiment, we make sure that the value of the flowing current does not differ from I_0. At the same time, we make sure that the current value of the silicon photoresistance current does not increase even in the case of incident photons with an energy $h\nu = 0.12 \div 0.3$eV, i.e. no extra electrons are generated. Now, without changing the position of the lamp, we put the second filter, which transmits photons with an IR wavelength ($\lambda = 1.5 \div 2$ μm) and an energy $h\nu = 0.6 \div 0.8$ eV. This means that even if a photon flux with a much higher energy ($h\nu = 0.8 \div 0.62$ eV) falls on the photoresistor, the current does not change, which indicates that no additional electrons are formed in the silicon photoresistor.If the situation does not change, now we put the third filters that transmit infrared rays with a wavelength ($l = 0.7 \div 1.1$ μm) ($h\nu=1.77 \div 1.13$eV). We see that the value of the current in the microammeter increases sharply by 10–12 times relative to I_1.This indicates that additional electrons were formed in the photoresistor, and for their formation the energy of the incident photons must be greater than $h\nu > 1.12$ eV. To understand this result, let's look at the formula that Einstein explained in the phenomenon of the external photoelectric effect:

$$h\nu = A + \frac{mv^2}{2} \qquad (2)$$

Here $h\nu$– is the photon energy, A – is the work function of the metal (the energy required to release electrons from the metal into vacuum) $\frac{mv^2}{2}$ – is the kinetic energy of an electron released from the metal in vacuum.

Hence the condition is shown that in the presence of the external photoelectric effect for the appearance of free electrons in a vacuum the energy of the photon, E_f, falling on the metal must be greater than A, the work of output ($E_f > A$) (Fig. 2).

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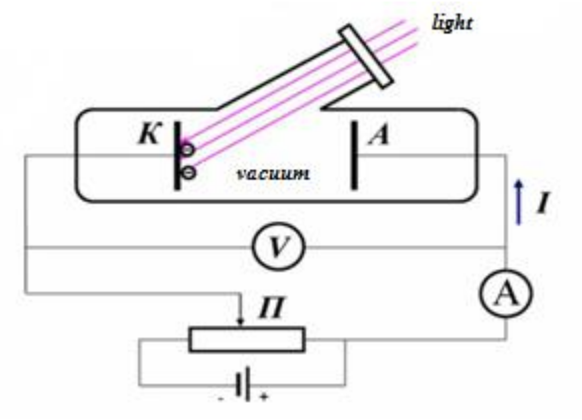

Fig.2. Scheme of a device that studies the phenomenon of the external photoelectric effect.

Now we will try to apply formula (2) to the experiment we are doing. In our experiment, firstly, we use a semiconductor material – silicon, not metal, and secondly, electrons from a semiconductor material do not go into vacuum, but remain inside the semiconductor material. In this case, the value of energy A in formula (2) should be considered as the energy E_0 required for the formation of an additional free electron in the semiconductor. Therefore, to understand the nature of E_0, let us consider the relationship of atoms in the structure of a silicon semi-conductor crystal (fig.3).

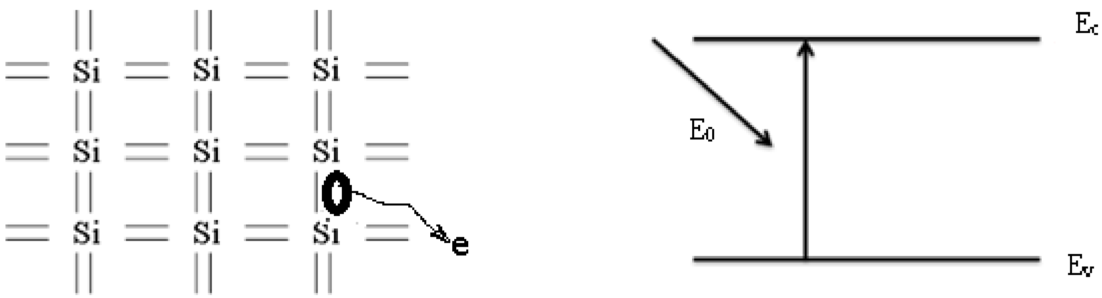

Fig. 3. The relationship of atoms in the structure of a silicon crystal and the energy diagram for incident light.

It is known that all valence electrons of silicon atoms participate in chemical bonding and have a certain binding energy (E_{bond}) with atoms. In this case, in a semiconductor material at room temperature in an unexposed state, there are very few free electrons corresponding to the kT-thermal energy, i.e. they determine I_0 – the current value in an unexposed silicon photoresistor. If the photoresistor is illuminated with photons with energy $h\nu > E_{bond}$, then the photon gives up its energy to the silicon atom, which breaks the binding energy of the electron participating in the chemical bond, and allows the electrons to go into a free state. Therefore, additional free electrons appear in the photoresistor and, accordingly, current begins to flow through it. Therefore, $h\nu = E_{bond}$ - energy is the binding energy of the silicon crystal or the band gap energy. In this case, the energy required for the transfer of electrons from the valence band to the conduction band must be greater than the band gap energy, i.e. the energy of bound electrons. The invariance of the current value when filters I and II are installed in the experiment indicates the fulfillment of the inequality $h\nu < E_{bond}$ for the energy of photons passing through such filters. Further, when filter III is installed, the energy of the incident photons leads to the formation of free electrons and an increase in the value of the current at an energy $h\nu \geq E_{bond}$. This phenomenon is called the internal photoelectric effect. Its essence is also based on Einstein's theory, which proves that rays consist of a stream of photons with an energy corresponding to their wavelength.

The second experiment. At the same time, the change in the magnitude of the current, which occurs due to the internal photoelectric effect, is studied by controlling the distance between the filter and the lamp, in the case of placing only filter III on the surface of the photoresistor. According to the results of the experiment, we see that with a decrease in the distance between the lamp and the filter (photoresist), the value of the current increases proportionally (Table 1).

Table 1.

Distance between lamp and filter x[sm]	20	15	10	5
Current value I_0 [µA]	80	98	117	135

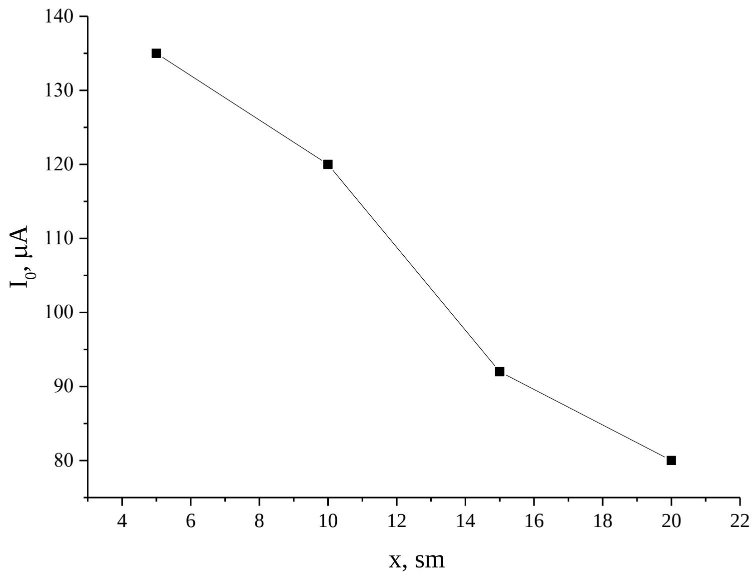

Fig.4. Current value corresponding to the distance between the lamp and the filter.

The results of this experiment also confirm the idea that the number of free electrons generated according to Einstein's theory increases in proportion to the flux of incident photons. To verify this, by simultaneously placing filter I or II on the surface of the photoresistor, we see that no matter how close the lamp is to it, the current value in the milliammeter does not increase.

Using other semiconductor (Ge, CdS, GaAs) photoresistors instead of silicon photoresistors in this experiment, the device based on the phenomenon of internal photoelectric effect fully demonstrates that light is a stream of quasi-particles, called photons. The advantage of our educational and laboratory device that demonstrates the phenomenon of the internal photoelectric effect over the device that demonstrates the phenomenon of the external photoelectric effect is, firstly, that it does not require a special vacuum glass vessel, as well as a spectrometer and external sources to control photon energy. Secondly, the experimental device is completely safe, its structure and capabilities encourage students to science and thinking. In addition to its effective use in all educational institutions, it provides additional information on the physics of semiconductor materials, which is the basis of modern electronics.

CONCLUSION

Using the device provides students with information necessary for their creative research in the field of optics and semiconductor physics, as well as a great opportunity to expand their understanding of modern physics of lasers, LEDs, fiber optic systems. The created device allows you to fully demonstrate the most interesting effects, in which each student can conduct an independent experiment.

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