Application of the Arduino Computer Platform as a Multimeter in Education

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ABSTRACT

The development of new technologies offers numerous opportunities for the use of electronic devices in education, where there is a wide range of advanced computer tools that offer great potential for enriching the learning process and developing students' skills. For example, the Arduino computing platform allows students to learn physics interactively by participating in the design and construction of innovative measurement devices and experimental setups. In this paper, we have demonstrated the possibility of introducing modern technologies into the classroom laboratory. By combining familiar Arduino codes, we programmed an Arduino board as a multimeter to measure the electrical properties of various diodes, resistors, and capacitors, such as the threshold voltage and diode current in both polarization modes, and to determine the capacitance of capacitors and the unknown value of the electrical resistance of various types of resistors with high accuracy (99%). We also tested different capacitors and semiconductor diodes to determine their functionality. In this way, students can achieve learning outcomes related to the electrical conductivity of conductors and semiconductors as fundamental electronic concepts through the use of modern technology. Unlike traditional experiments, this approach can be tailored to different educational levels: secondary, undergraduate, or graduate.

Keywords: Arduino, Electrical Properties, Experiment, Education, Learning Outcomes, Modern Technologies.

1. INTRODUCTION

The development of modern technologies has greatly promoted the progress of scientific research in the field of electronics, the improvement of electronic power components and their use in various devices used in all areas of human activity [1]. For example, microprocessors are an integral part of various medical devices such as MRI scanners, ECG machines, vital signs monitors, and pacemakers used for diagnosis, disease monitoring, and treatment. New technologies are also used in devices to generate electricity from renewable energy sources, such as solar cells [2], and in electronic devices in various household appliances. They also play a key role in the development of communication systems such as mobile, optical, and satellite networks that make the exchange of data and information faster, more reliable, and more secure [1]. At the same time, modern technologies are ubiquitous in the education system, for example, in the form of online courses and e-learning that use interactive content, computer simulations, and various platforms to tailor learning and teaching to the needs and interests of each student [3,4]. Today's information society is characterized by the wide availability of information and the rapid exchange of data through advanced technologies, which makes further technological development a fundamental resource and driver of progress in modern society [5]. Therefore, it is important that the educational system, by adapting teaching strategies to students, enables the acquisition of relevant knowledge and skills necessary for successful and competitive participation in the labor market [6]. In order for the educational process to be in line with the development of society as a whole, greater integration of modern technologies into the teaching process is needed, as they promote active learning and the development of students' critical thinking and creativity [7]. A good example is the Arduino computing platform, which enables the creation of interactive projects through various research activities [8,9]. It consists of hardware components such as a microcontroller [8,9], and the software development environment uses the C/C++ programming language [8,10]. One of the main advantages of the Arduino development board is its ease of use and accessibility, but also its high accuracy when used as a measurement device [9,11,12]. This computer tool is used as a modern teaching tool in electronics and programming classes, as well as in teaching various physics concepts [13]. Through Arduino projects, students can learn the basics of electronics, such as how various electronic components and assemblies work, and they also can develop skills and knowledge applicable to specific situations [9]. On the other hand, the Arduino platform can be used in experiments and laboratory exercises to explore abstract concepts such as electric current or the movement of free charge carriers in semiconductors and conductors, which are often incomprehensible to students [14]. Although there are several variants of Arduino boards (uno, due, mega, nano), according to Kondaveeti et al. [9], the most popular board on the market is the Arduino Uno board. We used this very model in a laboratory exercise that can be conducted in a high school semiconductor materials class, but also at the university

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level, e.g., as part of the Introduction to Physics course or within the Physics course II.

The paper shows how to make a multimeter using the Arduino Uno board to determine and test the characteristics of various electronic components, such as the capacitance of a capacitor, unknown electrical resistance values of various resistors, and diode current in the forward and reverse bias.

2. BASIC THEORETICAL CONCEPTS

The study of electronic devices begins with the study of their components and the materials they are made of. Therefore, knowledge of the structure of matter as well as its basic properties, such as electrical conductivity, is an important prerequisite for the further development of electronics [15]. The main function of electronic components such as resistors, capacitors, diodes, and transistors is to transmit, process, and control electrical signals [16,17]. However, the basic properties and operating mechanisms of electronic components are often abstract in nature, and students have difficulty understanding them [14]. For example, knowledge of the rectifier property of a semiconductor diode enables its correct application in various electronic circuits such as the conversion, control, and filtering of electrical signals and is necessary to avoid errors in the design and maintenance of electronic devices [18]. At the same time, educational research [19–24] points to difficulties in understanding the fundamental concepts of semiconductor materials. Their microscopic properties, the impossibility of visualization, and the quantum mechanical models describing the fundamental properties of the materials are most often cited as reasons for this [19,25].

On the other hand, electronics is closely related to physics and the laws of physics. For example, the analysis of electrical circuits and electrical circuits is based on fundamental physical laws such as Ohm's law and Kirchhoff's law [17]. Electrical circuits that perform specific functions, such as voltage regulation or amplification and signal conversion, contain components that are connected according to a specific scheme that determines the flow of electrical energy and information [17]. These can be passive (resistors, capacitors,...) or active (diodes, transistors,...) components, and the circuits can be manufactured as single units or as integrated circuits (IC), where the components are miniaturized and integrated on a chip [26]. However, regardless of the structure of electronic circuits, it is necessary to use various physical terms such as current, voltage, resistance, capacitance, etc., to understand the principles of their operation [17]. Therefore, understanding the laws of physics is a basic requirement for a conceptual understanding of the operation of electronic devices.

Semiconductor diode

A semiconductor diode is an active electronic element with a rectifying property, as it conducts electric current in one direction [27,28]. It is formed by connecting two extrinsic P and N type semiconductors forming a PN junction, as shown in Figure 1. At room temperature (T~300 K), due to the difference in the concentration of free charge carriers in P (cavity) and N (electron) type semiconductors, their directional motion occurs, i.e., a diffusion current occurs, I_d. The diffusion current is the cause of the rectifying property of the semiconductor diode [27]. At the contact of P and N semiconductors, recombination of holes and electrons occurs and a PN barrier or depletion zone is formed. The depletion zone is filled with a space charge consisting of uncompensated stationary electric charges: negative ions from acceptor impurities on the P side and positive ions from donor impurities on the N side of the PN junction [27,29].

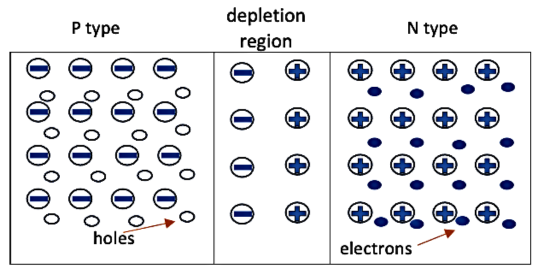

Figure 1. Schematic representation of a PN junction

Under such conditions, a contact voltage *U*, i.e., a potential barrier of the PN junction, is generated at the boundaries of the junction layer, which then acts like a capacitor with capacitance C_{pn}: in case of permeable polarization one speaks of diffusion capacity, in case of impermeable polarization one speaks of space charge capacity, [27].

The voltage generates a new electric field that influences the occurrence of a drift current (I_{drif}) of minority charge carriers generated by the thermal ionization of the semiconductor crystal. A nonpolarized PN junction becomes electrically neutral when the values of the diffusion current of the majority carriers and the drift current of the minority carriers balance. The diffusion current can be regulated by applying an external electric field, while the drift current depends only on the temperature of the semiconductor [16].

In forward bias, as shown in Figure 2, the PN junction is connected to an external voltage source so that the P side is connected to the positive pole of the source while the N side is connected to the negative pole. When the external voltage becomes equal to the voltage generated by the recombination of charge carriers in the depletion region (knee voltage or threshold voltage), the diode becomes conductive [27,29].

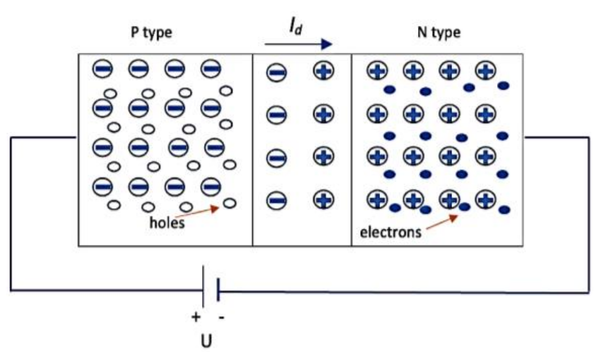

Figure 2. Schematic diagram of a PN junction in forward bias

As a result, the potential barrier decreases and the diffusion current increases [16]. When the bias voltage is reversed, the P side is connected to the negative pole of the source, while the N side is connected to the positive pole of the source. The signs of the applied external voltage and the depleted region voltage are the same, resulting in an increase in the potential barrier that prevents the passage of the main current carriers under these conditions [16,27].

Since the height of the potential barrier has no effect on the minority charge carriers, the current of impermeable polarization, called the reverse saturation current, is constant and very small. At room temperature, it is of the order of a few µm (for germanium diodes) or a few nm (for silicon diodes) [29]. The total current of the PN junction depends on the type of polarization, it is determined by Shockley's equation (1) and can be represented graphically by the current-voltage characteristic in Figure 3, [27].

$$I = I_r \cdot (e^{\frac{Q \cdot U}{k \cdot T}} - 1) \quad (1)$$

(where I_r is the reverse saturation current)

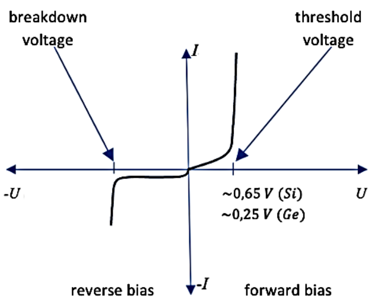

Figure 3. Graphical representation of the current-voltage characteristic of a semiconductor diode

When the bias voltage is above the threshold voltage, which is ~0.7 V for silicon and ~0.3 V for germanium, the diode current increases sharply and the semiconductor diode is considered to conduct current [27].

At reverse bias, voltages above the threshold voltage, ranging from tens of volts to several thousand volts depending on the diode type, cause breakdown of the PN junction and a significant increase in drift current [17,29]. This is caused by a strong external electric field that leads to the breaking of covalent bonds in the semiconductor and a sudden increase in minority charge carriers, i.e., reverse saturation current [16]. Diode breakdown results from: (i) the tunneling of electrons in heavily contaminated extrinsic semiconductors from the valence layer of the P-side to the conducting layer of the N-side of the diode, or (ii) an avalanche effect in the semiconductor in which each released electron ejects two adjacent electrons from the covalent pair, each of which ejects two new electrons, etc. [29]. Semiconductor diodes have a wide range of applications, whether as AC to DC converters, voltage stabilizers, protection for electronic circuits, or signal processing and detection in radio receivers [27]. To ensure their correct application, it is necessary to know their electrical properties (I_d, I_{drif}, U_p, C_{pn}, ...), [30].

Resistors

Resistors are passive electronic elements most commonly used to control and limit current, reduce voltage, and match electrical signals [31]. The basic characteristics of any resistor are: (i) its electrical resistance, expressed in ohms (Ω), which depends on the internal structure of the material that makes up the resistor; (ii) the tolerance, which indicates the deviation of the measured value from the specified, i.e. nominal, value; (iii) the temperature coefficient (α), which describes the change in the value of the electrical resistance due to the temperature change [27,32].

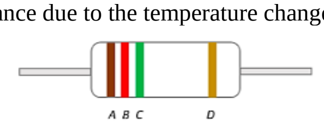

Figure 4. The resistor

The electrical resistance of cylindrical permanent resistors shown in Figure 4., is calculated using the resistance table with codes shown in Figure 5. [33]. Their electrical resistance value is read according to algorithm (2).

For example, the resistor in Figure 4 has a total value of electrical resistance:
$R = 12 \cdot 10^5\ \Omega \pm 5\%$ or 1200 kΩ

Color	1st Band (1st Digit)	2nd Band (2nd Digit)	3rd Band (3rd Digit)	Multiplier	Tolerance	Temperature Coefficient
Black	0	0	0	$\times 10^0\ \Omega$	N/A	250 ppm/K
Brown	1	1	1	$\times 10^1\ \Omega$	± 1% (F)	100 ppm/K
Red	2	2	2	$\times 10^2\ \Omega$	± 2% (G)	50 ppm/K
Orange	3	3	3	$\times 10^3\ \Omega$	N/A	15 ppm/K
Yellow	4	4	4	$\times 10^4\ \Omega$	N/A	25 ppm/K
Green	5	5	5	$\times 10^5\ \Omega$	± 0.50% (D)	20 ppm/K
Blue	6	6	6	$\times 10^6\ \Omega$	± 0.25% (C)	10 ppm/K
Violet	7	7	7	$\times 10^7\ \Omega$	± 0.10% (B)	5 ppm/K
Grey	8	8	8	$\times 10^8\ \Omega$	± 0.05%	1 ppm/K
White	9	9	9	$\times 10^9\ \Omega$	N/A	N/A
Gold	N/A	N/A	N/A	$\times 10^{-1}\ \Omega$	± 5% (J)	N/A
Silver	N/A	N/A	N/A	$\times 10^{-2}\ \Omega$	± 10% (K)	N/A

Figure 5. Table of resistor codes, (acc. to [33])

multiplier

AB x C ± D% → tolerance (2)

first and second significant digits

Capacitors

Capacitors are passive electronic elements that store electrical energy E (3), in the form of electrical charge q, [27,32,34]. In fact, every capacitor consists of two conducting bodies (electrodes) separated by an insulator. When the electrodes are charged, a potential difference U, i.e. an electric field, is created between them. Due to the existence of electric field forces, work must be invested when charging the capacitor, which is "stored" as electric field energy between the plates of the capacitor [27].

$$E = \int_0^Q U(q)dq \quad (3)$$

The amount of charge stored and the magnitude of the voltage across the electrodes affect the electrical capacitance, which is expressed in farads (F) and is the fundamental property of any capacitor (4), [27,32].

$$u(t) = \frac{1}{C} \int i(t)dt \quad (4)$$

The electrodes are usually separated by an insulator such as air, oil, or ceramic. The type of insulator affects the dielectric strength, dielectric constant, and operating temperature of the capacitor and is selected according to the desired purpose [32]. Capacitors can be permanent (e.g., electrolytic, block, or ceramic, Figure 6) or variable. Ceramic capacitors use a ceramic material as an insulating layer between the electrodes. In this case, the electrodes are made of silver layers with which the ceramic plate is coated.

a) b) c)

Figure 6. Types of permanent capacitors: a) electrolytic, b) block, c) ceramic

Due to their small size, high reliability and wide capacitance range, they are often used in electronic components [27,32]. Block capacitors have many applications in devices where low energy losses must be ensured [27]. The structure o f a block capacitor usually consists of two parallel aluminum plates (sheaths) insulated with wax paper and then twisted together to form a more compact shape. By connecting several block capacitors in parallel in metal cases, capacitors with a capacitance of up to 50 μF are obtained [31]. Due to the very thin oxide layer serving as dielectric, electrolytic capacitors have a large capacitance [31]. This makes them suitable for use in devices for storing and filtering electrical energy [32]. Their main disadvantage is their internal resistance (ESR), which for suitable capacitors should be in the range of typical values calculated as a function of the measured capacitance and the connected voltage [35]. In real capacitors, in addition to capacitance, undesirable parameters such as inductance and the aforementioned equivalent series resistance (ESR) can occur [36]. In addition, capacitors experience energy losses due to dielectric resistance, usually in the form of heating, which may be undesirable in certain applications [27]. Equivalent series resistance (ESR) is usually due to the internal resistance of the electrode material and the electrolyte used in electrolytic capacitors. The ESR can lead to energy losses, heating of the capacitor and reduction of its efficiency [36].

The above-mentioned undesirable properties of the capacitor can be of particular importance in the case of high-frequency and rapid signal changes, since they can lead to losses and changes in the behavior of electrical circuits. Therefore, specially designed capacitors with minimum inductance and low ESR are used in certain applications to minimize these undesirable effects. Capacitors are versatile components with a wide range of applications. They are used, for example, to transmit, receive and filter signals, in audio equipment for noise suppression and signal stabilization, in generators and also in devices for speed control [32].

3. METHODOLOGY

To be sure that the electronic components are correct, you need to test them. There are several standard devices known as multimeters that measure the characteristic values of electronic components such as voltage, current, resistance and capacitance. An example of such a device is shown in Figure 7. For this purpose, we have created a reliable multi-purpose multimeter with an Arduino UNO development board and the appropriate Arduino code (Figure 8).

Figure 7. Multimeter

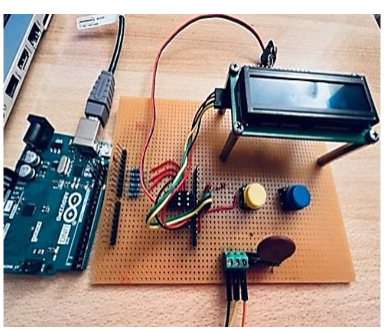

Figure 8. Arduino tester of electronic components

We performed the measurement with analogue-to-digital conversion (ADC) as part of a resistor network consisting of 680 Ω and 470 k Ω resistors connected according to the scheme shown in Figure 9, [37].

Depending on the tested element (resistor, capacitor, semiconductor diode), the part of the Arduino code that measures the corresponding physical quantity (electrical resistance, capacitor capacitance or diode current) is applied.

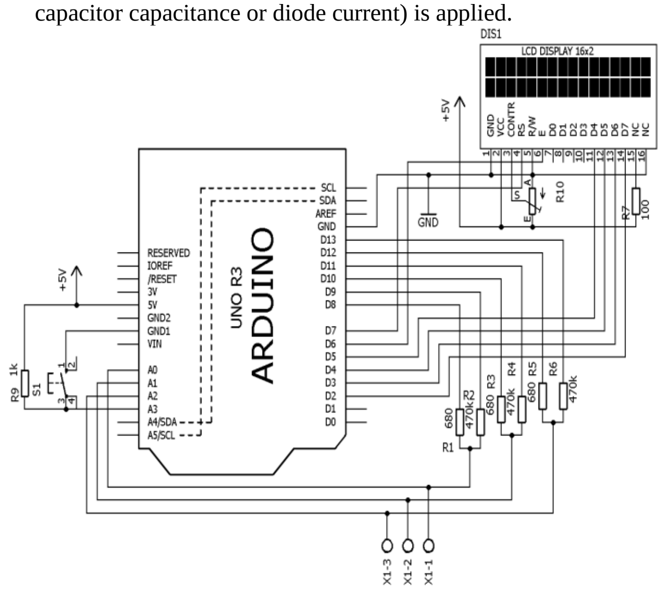

Figure 9. Arduino multimeter scheme, (acc. to Fadli, 2017)

In making a multimeter for testing electronic components and determining their characteristic properties, we used the following experimental setup shown in Figure 10:

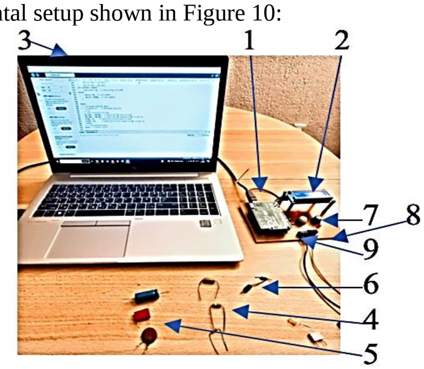

Figure 10. Experimental setup

1. Arduino UNO Rev3 board
2. Arduino LCD display
3. a computer with installed Arduino software
4. resistors with different electrical resistances
5. electrolytic, ceramic and block capacitor
6. semiconductor diodes
7. switch
8. PCB - circuit board for mechanical and electrical connection of electronic components
9. test input

Programming the Arduino board

The Arduino computing platform consists of hardware and software components [8,9]. The hardware is a microcontroller that is programmed for different requirements through a series of input/output pins. The software is a programming environment (IDE) in which the codes we use to program the Arduino development board are written. For this purpose, the C++ [8,9], programming language is used. You can download the Arduino IDE platform for free from the official Arduino site, [38]. Remark: The Arduino code we used can be found at the link: *https://drive.google.com/file/d/13tZX9oe1BjIbzSmFTvuc3LpWBUmukdDi/view?usp=sharing*

4. RESULTS AND DISCUSSION

We used the constructed Arduino multimetar to measure the electrical properties of various diodes, resistors and capacitors. We also tested electrolytic, plate, and block capacitors, as well as semiconductor diodes to determine their functionality.

Semiconductor diode

In the experiment, two diodes were used and the values of diode current, voltage and diode capacitance were measured for both types of polarization. From the results shown in Table 1, we can conclude that the first diode is correct, while the second diode is not, since it has approximately equal current values in both polarizations (I_{d2}= 25nA, I_{r2}= 29nA). The measured forward bias voltage on both diodes is U_d~0.7V, so we conclude that these are silicon diodes.

Table 1. Values determined for diode current, voltage a capacitance of the PN junction

diode	forward bias	reverse bias
diode 1	I_d = 13,1 mA U_d = 640 mV C_{pn} = 83 pF	I_r = 10 nA U_d = 5,1 V C_{pn} = 127 pF
diode 2	I_d = 25 nA U_d = 595 mV C_{pn} = 29 pF	I_r = 29 nA U_d = 4,3 V C_{pn} = 32 pF

Since each P-N junction has a specific capacitance, we measured both, the space charge capacitance and the diffusion capacitance of the diode. The results indicate a diode with a large capacitance (C~100 pF). Therefore, diode1 can be used in the low frequency range for frequency modulation like a varicap diode.

Resistors

Table 2 shows the experimentally measured electrical resistance values for each ceramic resistor using an Arduino multimeter (R_e) and the theoretical values (R_t) obtained by calculating the codes from the resistance code table shown in Figure 5.

Table 2. Experimentally measured and theoretical values of electrical resistances

resistor	*Re*/kΩ	*Rt*/kΩ
resistor 1	22,59	22±5%
resistor 2	1496	1500±10%
resistor 3	0,099	0,1±2%

Comparison of the experimentally determined values of electrical resistance R_e with the theoretical value R_t leads to the conclusion that the developed device works with a high percentage of accuracy (~99.5%).

Capacitors

Ceramic, electrolytic and block capacitors were used for the experiment. The measured values for the capacitance of the individual capacitors are listed in Table 3.

Table 3. Measured values of capacitor capacitance (C), internal resistance (ESR) and percentage energy loss (U_{los})

capacitor	*C*/nF	ESR/Ω	U_{los}
block	343,1		0,1 %
ceramic	6,8		0,3 %
electrolytic	$1{,}156 \cdot 10^6$	0,68	1,7 %

The block capacitor has a much smaller capacitance than the electrolytic capacitor, although a ceramic capacitor can store the smallest amount of charge (C=6.8 nF). The highest energy loss was measured for the electrolytic capacitor, which is due to the presence of an internal resistance ESR that the other two capacitors do not have. The measured values correspond to the factory values (indicated on the devices) with a deviation of 1%.

5. CONCLUSION

Electronics are constantly evolving, and in modern society, the ability to access, understand, and apply information has become a key skill. Therefore, students should be able to adapt to rapid changes in technology and society and develop innovative approaches and solutions. At the same time, new technologies such as the Arduino computing platform provide a stimulating environment for learning electronics, programming, and physics by promoting hands-on, interactive, and fun learning. Through projects and research activities, students gain skills and knowledge that are applicable in the real world and increase their motivation, engagement, and creativity. In this way, they are enabled to develop a deeper understanding of physical concepts. On the other hand, electronic semiconductor devices are crucial to the development of modern electronics and can be found in various fields such as telecommunications, medicine, transportation, industry and many others. Their application enables the functionality and high efficiency of electrical devices and innovative solutions that meet the demands of the modern world. Understanding the basic properties of electronic components allows us to analyze their behavior in electronic circuits and to properly select and use components when designing electronic systems. For example, knowing the properties of resistors allows us to properly select the resistance value to achieve the desired current-voltage relationship in controlling light intensity in lighting fixtures or volume in audio equipment, while knowing the characteristics of capacitors allows us to select the appropriate capacitance for storing and delivering electrical energy. A conceptual understanding of the functional mechanisms and properties of electronic components is therefore essential for the further development of electronics science.

The paper shows how, using appropriate Arduino components, an Arduino UNO board with microcontroller, and a compatible LCD screen, a multimeter can be built that can be used in teaching electronics and the physical concepts of electrical conductivity of solids. It can be used to test the accuracy and determine the basic characteristics of electronic components such as PN junction voltage, diode current, type of polarization of semiconductor diodes, capacitance of capacitors, ESR values of electrolytic capacitors and others with a high percentage of accuracy. This project-based teaching, using modern technologies can help students better understand complex and abstract physical and electronic concepts. Since the Arduino platform is highly customizable to the specific needs of the teaching process, it can be used at all levels of education.

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