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EscIn Estimation of Planck's constant using light-emitting diodes and microcontrollers

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Resumen

En este trabajo estimamos la constante de Plank midiendo las curvas I-V característica de los diodos emisores de luz (LEDs). Para ello utilizamos un microcontrolador, un filtro simple, pasa-baja, de forma de filtrar las frecuencias altas, un método de suavizado de curvas y un promedio de un set de repeticiones para eliminar las imperfecciones en el voltaje entregado por el puerto de modulación de ancho de pulso (PWM) utilizado como fuente de tensión variable. La medición de las tensiones del diodo se realizó mediante los pines analógicos del microcontrolador. La automatización de las dos tareas permitió obtener la curva característica del diodo y el voltaje de umbral (V_0). Utilizando los valores de V_0 y el pico de emisión de 4 LEDs, se determinó la constante de Planck con un error relativo porcentual del 2%.

Palabras claves: Curva característica de LEDs, Microcontroladores, PWM y automatización, Suavización por software.

Abstract

In this work, we estimate the Plank constant by measuring the characteristic I-V curves of light-emitting diodes (LEDs). To do this, we use a microcontroller, a simple low-pass filter to filter out high frequencies, a curve smoothing method, and an average of repetitions to eliminate imperfections in the voltage delivered by the port of pulse width modulation (PWM) used as a variable voltage source. The measurement of the diode voltages was carried out using the microcontroller's analog pin. Automating the two tasks allowed us to obtain the diode's characteristic curve and the threshold voltage (V_0). Using the V_0 values and the emission peak of 4 LEDs, Planck's constant was determined with a relative percentage error of 2%.

Keywords: *Characteristic curve of LEDs, Microcontrollers, PWM and automation, software smoothing.*

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Introduction

The presentation of the bulb diode in 1904 by J. A. Fleming and subsequent advances in semiconductor technology, starting in the 1960s, has been fundamental to the evolution of modern electronics. These developments have found applications in various fields of science (Boylestad, 2009; Angelo, 1985; Serwey & Jewett, 2009). An example is the present work, which seeks the experimental determination of Planck's constant (a characteristic of quantum physics) using light-emitting diodes (LEDs). It highlights the connection between different areas of physics and how, from simple (macroscopic) elements, it is possible to access fundamental constants of the universe, showing the beauty inherent in scientific exploration.

Currently, numerous works try to obtain the characteristic I-V curve of various semiconductors (diodes, transistors, solar cells) (F. Casaburo, 2022; Aryan Jain, 2019; Yu Chen *et al.*, 2023; Abdellah Asbayou, 2021; Vargas-Rodriguez, 2021; Toranzo, Valdez & Ortiz, 2023; Fatih Önder, 2019), where the authors raise the question of finding such a curve and propose a solution. Several of them use microcontrollers accessible to the general public, but they do not mention, to our knowledge, how to solve the noise problem through software.

This work estimates Planck's constant and discusses the results and alternative techniques used in the literature with the same objective, i.e., measuring the characteristic I-V curve of LEDs. To do it, we use a common microcontroller, LEDs, capacitors, and resistors available at any electronics store are used to determine this constant.

The following sections briefly address the theoretical foundations that validate the estimation of Planck's constant with the proposed method, the setup of the experiment, and, finally, the results are presented and discussed, considering the results and methods obtained in other works.

Theory

I-V characteristic curve.- Diodes are composed of two doped semiconductor chips (n-type and p-type) that, when joined together, form a p-n junction and give rise to the depletion region. In this region, the recombination of carriers generates an electric field, establishing the potential barrier $\mathbf{V_o}$ that prevents diffusion, resulting in the absence of current when the applied voltage is less than $\mathbf{V_o}$ (Serwey & Jewett, 2009).

The transition of electrons from the valence band to the conduction band, with an energy $\mathbf{E_g}$, results in various ways of releasing energy, such as the emission of a photon with frequency $\boldsymbol{\nu = E_g/h}$. Light-emitting diodes are highly efficient at this form of energy release. When the voltage applied between the terminals of the diode exceeds the threshold voltage $\mathbf{V_o}$, an electric field is induced through the p-n junction that exceeds the internal one, originating a current and resulting in the emission of photons by the excited electrons with an energy $\mathbf{q_e V_o \approx E_g}$, whit $\mathbf{q_e}$ as the charge of the electron; the latter is because the LED emission occurs in a narrow spectral band (Romano & López, 2001; Artuso & Satz, 2007; Casaburo *et al.*, 2022).

Shockley's theory describes the current-voltage (I-V) relationship in a diode, including LEDs, by the equation:

$$I(V) = \left(Ae^{\frac{-E_g}{\eta k_B T}}\right) \cdot \left(e^{\frac{q_e V}{\eta k_B T}} - 1\right) (1)$$

With positive values of V the first term of the equation (1) will grow rapidly allowing the second term to be neglected:

$$I(V) \approx A \cdot e^{\frac{q_e V - E_g}{\eta k_B T}} (2)$$

where **I** is the diode current, **A** is a proportionality constant related to the saturation current, **V** is the voltage across the diode, **η** is the ideality factor (varying between 1 and 2, with 1 for direct diffusion and 2 for recombination, as in LEDs), $\mathbf{k_B}$ is the Boltzmann constant, and **T** is the absolute temperature of the diode. This equation is based on the diffusion of electrons in the material, following a Fermi-Dirac statistic and considering the potential barriers the carriers must overcome (Serwey & Jewett, 2009; Romano & López, 2001; Artuso & Satz, 2007; Casaburo *et al.*, 2022). By measuring the current and voltage values, the value of Eg for a particular diode can be inferred.

The characteristic curve has an exponential behavior, and there is a threshold voltage Vo (different for each LED) for which the current is no longer zero. According to the proposal of O'Connor (1974) and used by studies (Romano & López, 2001; Artuso & Satz, 2007; Casaburo *et al.*, 2022; F. Casaburo, 2022), $\mathbf{V_o}$ is determined by projecting a tangent line to the I-V curve in its linear region. The value of $\mathbf{V_o}$ is the intersection of this tangent with the abscissa axis. Therefore, as seen above, the gap energy $\mathbf{E_g}$ can be inferred from the graphic as $\mathbf{q_e}$Vo for the threshold voltage, and the value of Planck's constant is straightforwardly obtained as the slope of the relation $\mathbf{E_g = h.\nu}$. This method is widely applied in experiments with results that agree well with theory.

Noise reduction.- When applying this procedure, an extended number of points is necessary to minimize the uncertainty of $\mathbf{V_o}$. It is also required to repeat these measurements to minimize statistical error through averaging, reducing the impact of individual fluctuations.

Another practical strategy to achieve better results in obtaining the I-V curve is to reduce the sensitivity of the data set to noise, that is, to values that deviate considerably from the immediately previous ones. To do this, a usual method in this variety of situations is applying exponential smoothing, known for attenuating noises and highlighting underlying patterns (Ivan Svetunkov, 2022). Its first function is to assign greater weight to more recent data points, exponentially

$$S_t = \alpha X_t + (1 - \alpha) S_{t-1} \quad (2)$$

decreasing the influence of older observations. The general formula for calculating exponential smoothing is:

where St is the smoothed value at position **t.** $\mathbf{X_t}$ is the value measured at position t. $\mathbf{S_{t-1}}$ is the smoothed value at the previous position t-1, and α is the smoothing factor, with $\mathbf{0<\alpha<1}$.

The formula indicates that the smoothed value at a given time, $\mathbf{S_t}$ is a weighted combination between the current observed value $\mathbf{X_t}$, and the smoothed value in the previous period $\mathbf{S_{t-1}}$. The factor **α** determines the proportion of influence of the actual observation on the smoothed value. An **α** closer to **1** gives more weight to the current observation, resulting in smoothing that is more sensitive to recent changes. Moreover, an **α** closer to **0** gives greater importance to past observations, generating slower smoothing and less sensitivity to changes.

Experiment

Figure 1 shows the circuit scheme we use to characterize the LEDs (see *Appendix A1*, which contains an illustrative diagram of the circuit and a detailed photograph of the experimental setup). The circuit design integrates pulse width modulation, or PWM, as a variable voltage source with low-pass filtering through a passive device to improve the stability of the direct current signal. It is in line with previous proposals (Aryan Jain, 2019; Vargas-Rodriguez, 2021; Toranzo, Valdez & Ortiz, 2023), which have demonstrated the efficiency and effectiveness of obtaining such a source.

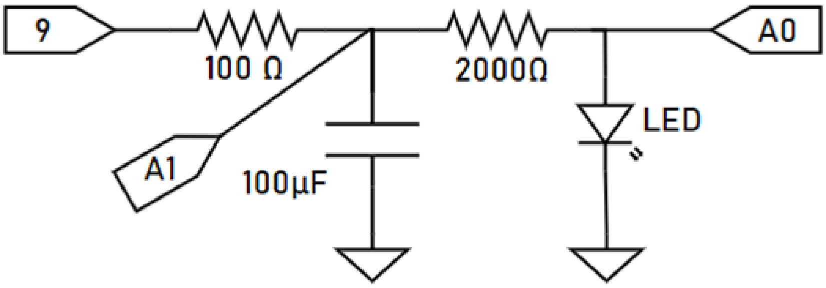

Fig. 1. *Electrical diagram of the implemented circuit.* ***Pin 9*** *is used as a PWM generator and the analog pins* ***A1*** *and* ***A0*** *as voltmeter.*

As mentioned in the previous paragraph, the pulse width modulation plus the passive filter in Figure 1 is equivalent to a variable voltage source automatically regulated by the microcontroller in a range between 0V and 5V, in intervals of (1/51)V. Figure 2 shows the equivalent circuit diagram. We use the capacity of the analog pins of the microcontroller to measure the voltage drop across the resistor R = 2000Ω to obtain the value of the current flowing through the LED.

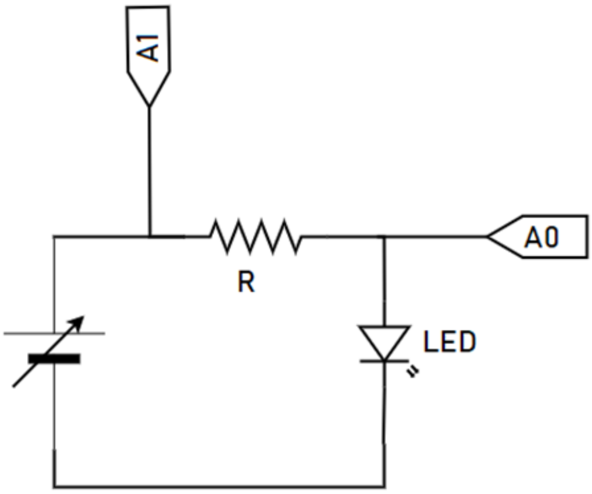

Fig. 2. *Equivalent circuit to the one shown in Fig. 1.*

The code developed for this experiment is included in Appendix A2 and provides for exponential smoothing with a smoothing factor of 0.95. This method attenuates oscillations due to variations in voltage measurements due to pulse width modulation, reducing noise in experimental data (Ivan Svetunkov, 2022).

Once the voltage variation and data collection were automated, in the present case were taken 175 different voltages controlled by Arduino, the experiment was repeated automatically a certain number of times (100 times), and in the end, t he average values were recorded (see Table 1). Following the procedure explained in the theoretical framework, the threshold voltage ($\mathbf{V_o}$) for each LED was determined. The latter was used with the maximum emission of the LED (given by the manufacturer) together to calculate the value of **h** using a linear fit. The Arduino microcontroller allowed the automation, collection, and statistical management of large volumes of data.

Results and discussion

In this work, we have used four LEDs with different colors, namely, red, amber, blue, and (ultra) violet. Figure 3 shows the I-V characteristic curves of each diode.

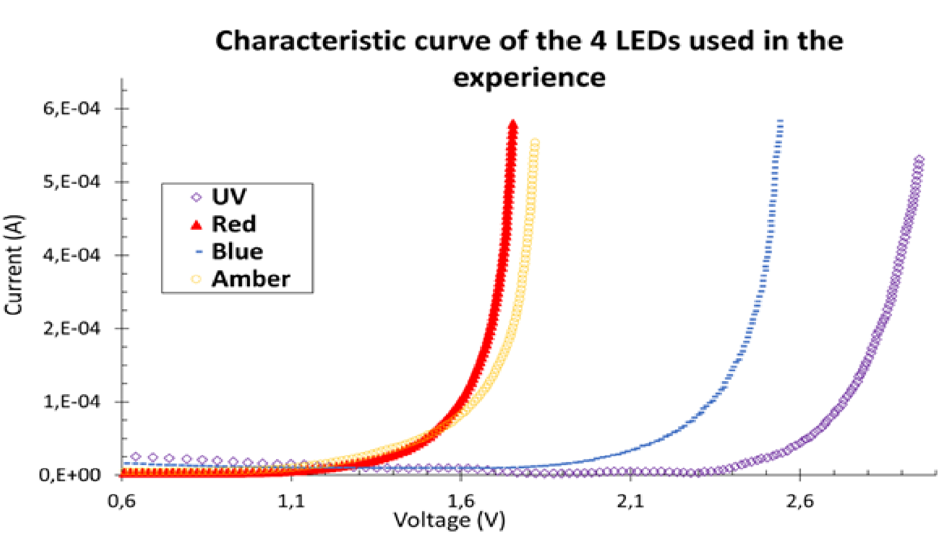

Fig. 3. *Characteristic curves obtained from the current and voltage experimental data through each light-emitting diode. Their shape is similar to that discussed in the theoretical framework.*

For each LED, we determine $\mathbf{V_o}$ through the tangent to the I-V curve considering the last points of the characteristic curve and using least squares, the equation of the tangent I(V)=mV+b was determined. As discussed in the theory, the intersection of it with the abscissa axis allows us to know the threshold voltage, $V_o = \frac{-b}{m}$. Its uncertainty is obtained through error propagation of this last equation. The results are shown in Table 1, alongside the values given by the manufacturer for the emission peak **λ** of each LED:

Table 1. *Data obtained from the LEDs used for the experience. The threshold voltage and emission peak, λ, are given by the manufacturer. Each LED shows its brand and model.*

Diode	Model	Vo (J/C)	σVo (J/C)	λ (nm)
Red	HLMP-EH8-T0000	1.75	0.03	626
Blue	SCY-Led-010-55027	2.50	0.04	457
Ultraviolet	SCY-Led-010-65062	2.80	0.10	400
Orange	HLMP-EH08-10UX000	1.83	0.03	605

Using the values in Table 1, we calculated $\mathbf{E_g}$ (in Joules) and the frequency ν (in Hertz) of the photons emitted by each LED. By considering a linear relationship between the barrier energy as a function of the frequency of each LED, we obtain Planck's constant **h** from the slope of such a plot (see Figure 4). The uncertainty in the energy gap, $\mathbf{E_g}$, was calculated as $\mathbf{q_e \cdot \sigma V_o}$, with q_e as the electron charge.

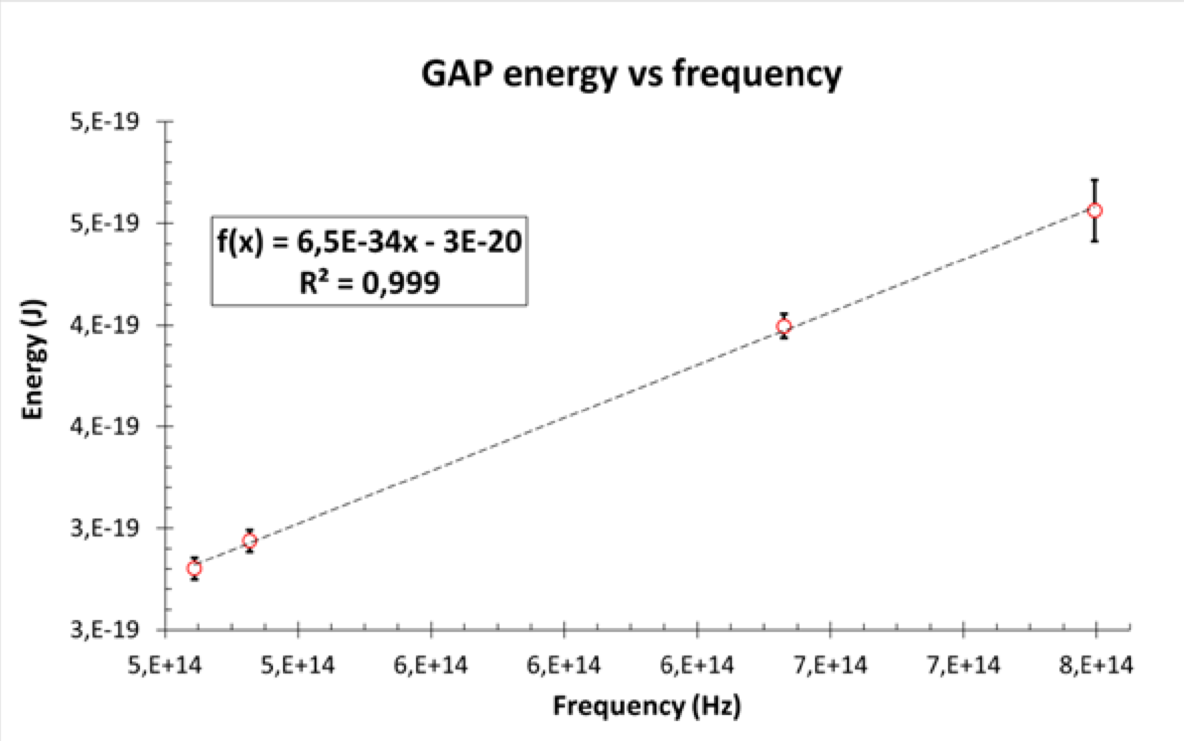

Fig. 4. *Gap energy E_g as a function of the emission (peak) frequency ν of the diodes used in the experiment. Shown is the equation that fits the experimental data, where its slope gives the value of h.*

With the protocol discussed here, we experimentally obtained the value $h=6,5\pm0,1\times10^{34}$ *J.s* for Planck's constant, which presents notable consistency with the value defined by the SI[1] with a discrepancy of less than 2%. In good agreement with Ref. Romano & López (2001), Artuso & Satz (2007) and Casaburo *et al.* (2022).

The proposed methodology was appropriate to achieve our objective. The use of Arduino allowed efficient automation, managing to collect 175 pairs of values (***V, I***) for each LED. This protocol was repeated 100 times and averaged in an automated manner. For an average obtained within a set of 1000 repetitions, the error for **h** drops to 1%, but with the disadvantage of increasing the whole elapsed time in the experiment by a factor of 10. The ability of the microcontroller to handle this extensive data set highlights its value as an alternative to consider in an experimental process, as it not only simplified data recollection but also allowed effective management of voltage variation.

1 In the International System of Units (SI), Planck's constant is defined such that, when expressed in SI units, it has the exact value of 6.626 070 15 × 10^-34 J-s. This value was defined by the Committee on Data for Science and Technology (CODATA) in 2018. The International System of Units (SI), 2019 Edition (nist.gov)

The combination of the methodology used, the use of microcontrollers, the filtering process both by electronic means and by numerical methods, and statistical repetition allowed us to obtain a consistent and precise value of **h**, highlighting the effectiveness of this approach in quantitative research or a simple laboratory experience.

Conclusion

In this paper, we propose a protocol that exploits microcontrollers and LEDs to determine Planck's constant with an error of less than 2%. The results contribute to the understanding of the quantum properties of semiconductors as well as highlight the effectiveness of microcontrollers in scientific research.

The automation and extensive data collection strategy stand out compared to previous studies. Therefore, it adds a new dimension to the experimental precision in determining the Planck constant.

This approach not only has theoretical relevance but also presents practical applications. The circuit and methods used could prove beneficial for the characterization of solid-state electronic devices, addressing the common variability between devices of the same brand and family.

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Appendix

A1: Circuit.

a)

b)

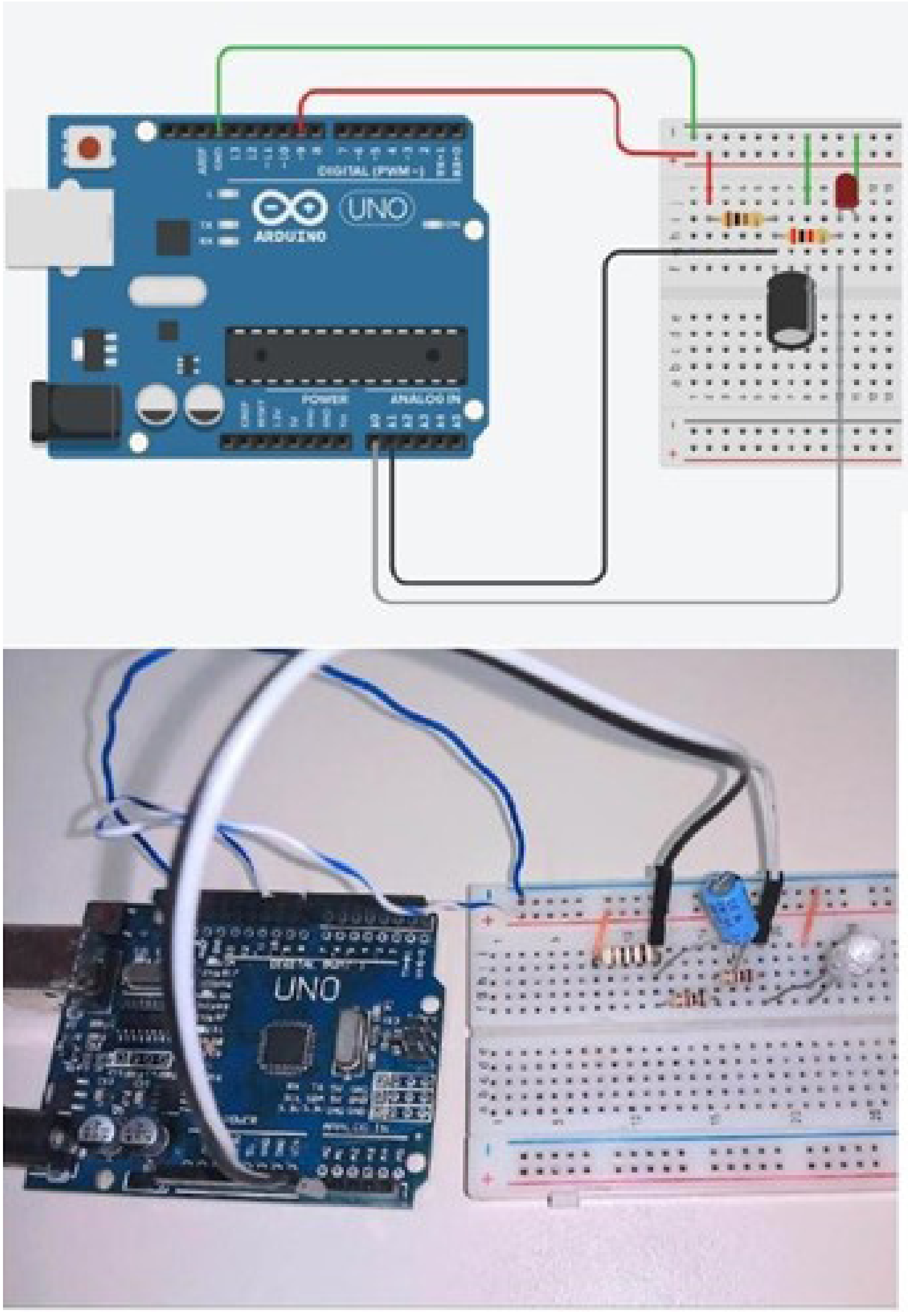

Fig. A1: a) Connections of the device used. b) Photograph of the operating device.

A2: Code programmed in the microcontroller

```
#define NUMERO_PUNTOS 176   //Rango del PWM.
#define BAUDIOS 9600
#define TIEMPO_ESPERA 5
#define PIN_MEDICION_FUENTE A1
#define PIN_MEDICION_DIODO A0
#define PIN_FUENTE 9
#define REPETICION 100      //Número de veces que se repite el experimento.
#define SMOOTHINGFACTOR 0.95
#define FINPWM 255
#define INICIOPWM 80

float caida_tension_resistencia[NUMERO_PUNTOS];   // vector donde se guarda la caída de tensión a través de la resistncia para cada punto del rango del PWM
float caida_tension_diodo[NUMERO_PUNTOS];         // vector donde se guarda la caída de tensión a través del diodo para cada punto del rango del PWM

void setup() {
  Serial.begin(BAUDIOS);
  TCCR2A = B10100011;
  TCCR2B = B00000001;
  pinMode(PIN_FUENTE, OUTPUT);
  pinMode(PIN_MEDICION_FUENTE, INPUT);
  pinMode(PIN_MEDICION_DIODO, INPUT);
}
void loop() {
  for (int i = 0; i < REPETICION; i++) {
    float smoothCaidaEnResistencia = 0.0;
    float smoothCaidaEnDiodo = 0.0;

    for (int j = INICIOPWM; j < FINPWM; j++) {  // Varía el valor del PWM y recolecta de datos de tensión.
      analogWrite(PIN_FUENTE, j);

      int caidaEnResistencia = (analogRead(PIN_MEDICION_FUENTE) - analogRead(PIN_MEDICION_DIODO));
      int caidaEnDiodo = analogRead(PIN_MEDICION_DIODO);

      // Aplica suavizado exponencial
```

```
        smoothCaidaEnResistencia = SMOOTHINGFACTOR * smoothCaidaEnResistencia + (1.0 - SMOOTHINGFACTOR) * caidaEnResistencia;
        smoothCaidaEnDiodo = SMOOTHINGFACTOR * smoothCaidaEnDiodo + (1.0 - SMOOTHINGFACTOR) * caidaEnDiodo;
        // Guarda los números en los vectores definidos
    int k=j-INICIOPWM;
        caida_tension_resistencia[k] = caida_tension_resistencia[k] + smoothCaidaEnResistencia / REPETICION;
        caida_tension_diodo[k] = caida_tension_diodo[k] + smoothCaidaEnDiodo / REPETICION;
        delay(TIEMPO_ESPERA);
      }
    }
    // Imprime resultados
     Serial.print("Caida de tensión en el diodo \t");
     Serial.println("caida de tensión en la resistencia");

    for (int k = 0; k < NUMERO_PUNTOS; k++) {
      Serial.print(caida_tension_diodo[k], 4);  // Imprimir con 4 decimales
      Serial.print("\t");
      Serial.println(caida_tension_resistencia[k], 4);  // Imprimir con 4 decimales
    }
    Serial.println("\n\n");
    Serial.println("Fin.");
    delay(TIEMPO_ESPERA);
    while (1);
  }
```