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Photoelectrical performances of semiconductor-based devices having CoFe and CoFeNi magnetic interlayers

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Abstract

This study was designed to examine the photoelectric device performances of cobalt-iron (CoFe) and cobalt-iron-nickel (CoFeNi) materials with good magnetic properties, specifically to investigate the effect of the Ni element on the electrical properties. In this context, Al/CoFe/p-Si and Al/CoFeNi/p-Si devices were produced by coating both materials between the semiconductor and the metal using the radio frequency (RF) sputtering method. First of all, to investigate the structural properties of the coated films, the content analysis was carried out by X-ray diffraction (XRD) analysis. To determine the photoelectrical properties of the produced devices, current-voltage and transient photocurrent measurements were performed and analyzed under different light intensities. While the ideality factor (barrier height) values of the devices produced using CoFe and CoFeNi materials were found to be 11.45 (0.487 eV) and 9.86 (0.513 eV), respectively, in the dark, they were obtained as 13.29 (0.446 eV) and 11.02 (0.484 eV) under 100 mW/cm^2 illumination. It was determined that both devices are sensitive to light, with the sensitivity of the device with the CoFeNi interlayer being much higher. In addition, photocapacitance and photoconductivity measurements were carried out to examine the photocapacitor performance of the devices. As a result of the investigations, both current-voltage, photocurrent, and photo-capacitance/conductivity measurements showed that the device with the CoFeNi interface layer showed better performance than the device with the CoFe interface. Therefore, it has been determined that the Ni element has a positive effect on electrical properties. The results obtained show that the prepared materials and produced devices can be used in photovoltaic applications.

Keywords: CoFe; CoFeNi; photodevice; electrical properties; photosensitivity.

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1. Introduction

Semiconductor-based devices have revolutionized the landscape of modern electronics, driving advancements in computing, communication, and sensing technologies [1,2]. These devices rely on the controlled manipulation of electronic charge carriers within semiconductor materials to achieve a wide array of functionalities [3,4]. A critical aspect influencing the performance and efficiency of these devices lies in the design and engineering of interfacial layers between different semiconductor layers or between semiconductors and other materials [5-7]. One of the most important semiconductor-based devices is photodiodes, which are based on the interaction of light with matter [8-10]. The integration of inorganic interfacial layers into photodiodes is seen as one of the very important developments that reshaped the field of optoelectronics [11]. Unlike their organic counterparts, these inorganic layers emerge as a new dimension of possibility that affects charge transfer, absorption, and overall device performance. The deliberate incorporation of inorganic interfacial layers has opened new avenues for tailoring the behavior of semiconductor devices, providing engineers and researchers with powerful tools to optimize performance and address emerging challenges in electronic and optoelectronic applications [12-14].

The materials used can have very different structures or configurations. Nanomagnetic devices have been advanced due to their high potential in magnetic storage, spintronic, and magnetic sensor technologies [15,16]. The ferromagnetic material CoFe has good thermal stability, high permeability, and high saturation magnetization, but is highly brittle and has a low coercivity. The magnetic and mechanical properties of CoFe material can be improved by adding different elements to the CoFe alloy [17-18]. The inclusion of some elements such as copper (Cu) and Ni in the synthesized thin films can lead to improvements in corrosion resistance and a decrease in coercivity [19]. For this purpose, the magnetic and structural properties of alloyed films in different combinations such as CoFeNi, CoFeAlN, CoFeCu, CoNi, and FeCoTiN have been investigated by many researchers [20-25]. Similar to CoFe, CoFeNi alloys exhibit high saturation magnetization, which is beneficial for magnetic applications [26,27].

Thin films can be produced using many different techniques [28-30]. One of the most reliable among these is the RF scattering technique. In the RF sputtering technique, the system allows low-cost deposition, the deposition process implemented is quite simple, plus, toxic gases are not present in the environment during the experiment, and it allows the successive deposition of distinct layers. These advantages are important advantages that take the RF sputtering technique one step forward. In addition, the surface roughness of the coated films is quite smooth (< 5 nm RMS), which is of great importance for electronic devices [31-33].

In this study, CoFeNi material was obtained by adding Ni metal to CoFe material, and the electrical and photoelectric properties of the prepared materials, whose magnetic properties have been studied many times in the literature, were investigated. The most important aim of this study is to investigate the light-dependent electrical properties of the CoFe alloy, whose magnetic and mechanical properties are improved when Ni is added, and to examine its effects on device performance.

2. Experimental Details

The magnetic thin films (CoFe, and CoNiFe) were fabricated using RF sputtering in a Nordiko NM2000 RF deposition system. The silicon substrates were first cleaned using acetone followed by IPA, to remove any surface dirt, before being put into the Nordiko deposition system. The magnetic films studied were CoFe (power density: 2 $kW.m^{-2}$ and chamber pressure: 4.8 mTorr), and CoNiFe (power density: 1.5 $kW.m^{-2}$ and chamber pressure: 4.5 mTorr). These growth parameters were chosen as they provide a stable plasma, and controlled film growth [34]. For device fabrication, first the 200 nm thick Al layers were evaporated on Si pieces for CoFe/Si and NiFe/Si structures, and then these structures were annealed in the N_2 filled oven for a couple of minutes to achieve ohmic contacts. Then, the CoFe/Si/Al (ohmic contact) and CoFeNi/Si/Al (ohmic contact) structures were transferred into the thermal evaporator to obtain 7.85×10^{-3} cm^2 area Al contacts (100 nm) on the top of CoFe and NiFe layers with the hole array mask. The schematic illustration and measurement system of the Al/CoFe/p-Si and Al/CoFeNi/p-Si photodiode is shown in Fig. 1. The Solar simulator of Fytronix FY-7000 brands as well as a measurement system was employed to collect *I-V* and *I-t* characteristics under different power intensities of light illumination.

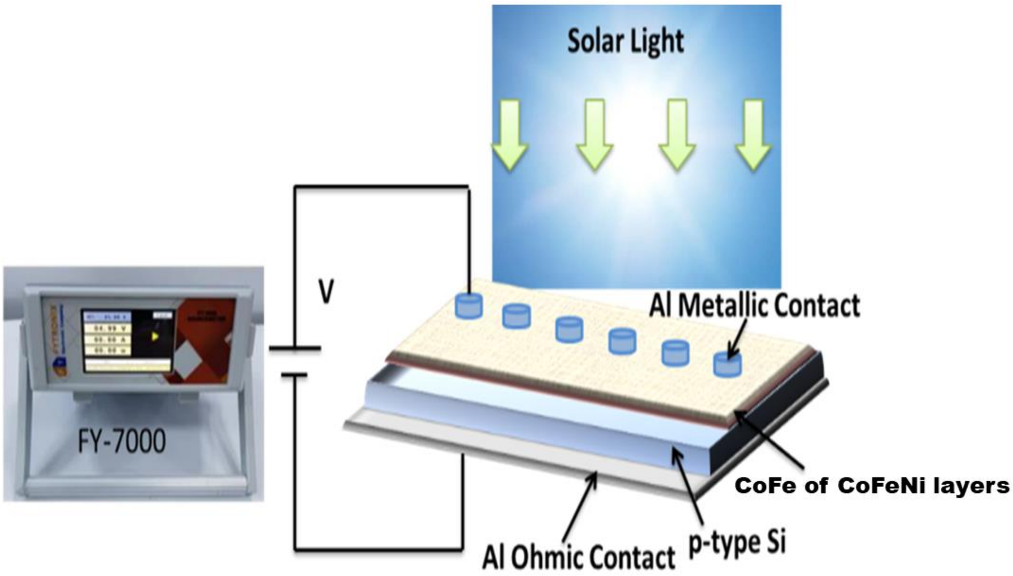

Figure 1. Schematic representation of measurement system and device structure of the fabricated photodiode

3. Results and Discussion

3.1.XRD analysis

X-ray diffraction (XRD) measurements were performed using a Siemens D5000 instrument with a Cu source to determine the phases present within the films. It is observed in Figure 2, that the CoFe film has a peak at 45.031°, which is the bcc <110> peak, and corresponds to a lattice constant of 2.844 Å. Using the Scherrer equation, the size of the crystallites within the film was determined to be d = 14 nm. For the CoFeNi film, there is a broad peak at around 43.2°, corresponding neither to the <111> FCC peak found for NiFe or the <110> BCC peak found for CoFe. The broadness of the peak suggests an amorphous or nanocrystalline phase within the layer.

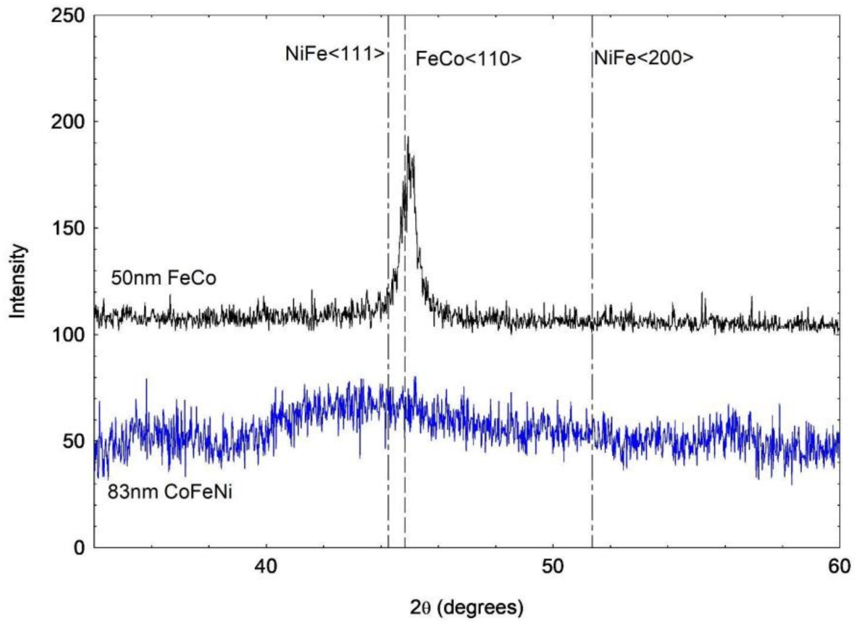

Figure 2. XRD patterns of CoFe and CoNiFe thin films on silicon substrates

3.2. Devices Characterization

Semiconductor-based devices are constantly evolving in parallel with the developments in material technology. Photodiodes, which have a very important place among these devices, have been the subject of much research [35,36]. In this study, CoFe material was coated as an interfacial layer between the metal top layer and the semiconductor. The device performance was investigated by producing a Schottky Diode-based photodiode. In addition, a CoFeNi film was also used as the intermediate layer and the device performance was measured to determine whether the addition of Ni improved the device performance. In order to determine the performances of the two fabricated photodiodes, current-voltage measurements were carried out under different light intensities and dark conditions. There are different approaches that can be effective in the current conduction mechanism in such devices, and the important ones can be listed as follows: thermionic emission, thermionic field emission, and tunneling of electronic charges [37,38]. Some of these are considered insignificant, while others may be dominant. Graphics showing the current-voltage measurements of the produced devices are presented in Figures 3a and b. As seen from the graphs, the measurements were made for a wide applied voltage range and light intensities varying between 20-100 mW/cm^2. When the figures are examined, it is clearly seen that the device exhibits a straightening behavior in all conditions. These characteristics of the produced devices show that the change in current depend upon the voltage and are due to thermionic emission (TE). TE theory states that electrical charges with energy equal to or greater than the barrier height can pass between the metal-semiconductor layers by crossing the barrier, otherwise these transitions cannot occur [39,40]. However, according to the TE theory, the expression that gives the varying current depending on the voltage is formulated as follows [41]:

$$I = I_Z\left[exp\left(\frac{q(V - IR_s)}{nkT}\right) - 1\right] \tag{1}$$

The I_z term given here and formulated as follows is the saturation current at 0 V, known as the intersection point of the linear region on the InI-V curve with the current axis.

$$I_Z = AA^*T^2 exp\left(-\frac{q\Phi_b}{kT}\right) \tag{2}$$

in the given equations, diode area, barrier height, electronic load, ideality factor, Boltzmann constant, and temperature are represented by the abbreviations A, Φ_b, q, n, k and T, respectively. Also, the abbreviation A^* has been used for the Richardson constant and its value is known as 32 A/cm^2K^2 for p-Si [42]. The two equations given above should be arranged to find the barrier height and ideality factor values that are important for diode-based devices. As a result of the simplifications, the following formulas can be obtained to find the relevant parameters [43].

$$\Phi_b = kTln\left(\frac{AA^*T^2}{I_Z}\right) \tag{3}$$

and

$$n = \frac{q}{kT}\left(\frac{dV}{d(lnI)}\right) \tag{4}$$

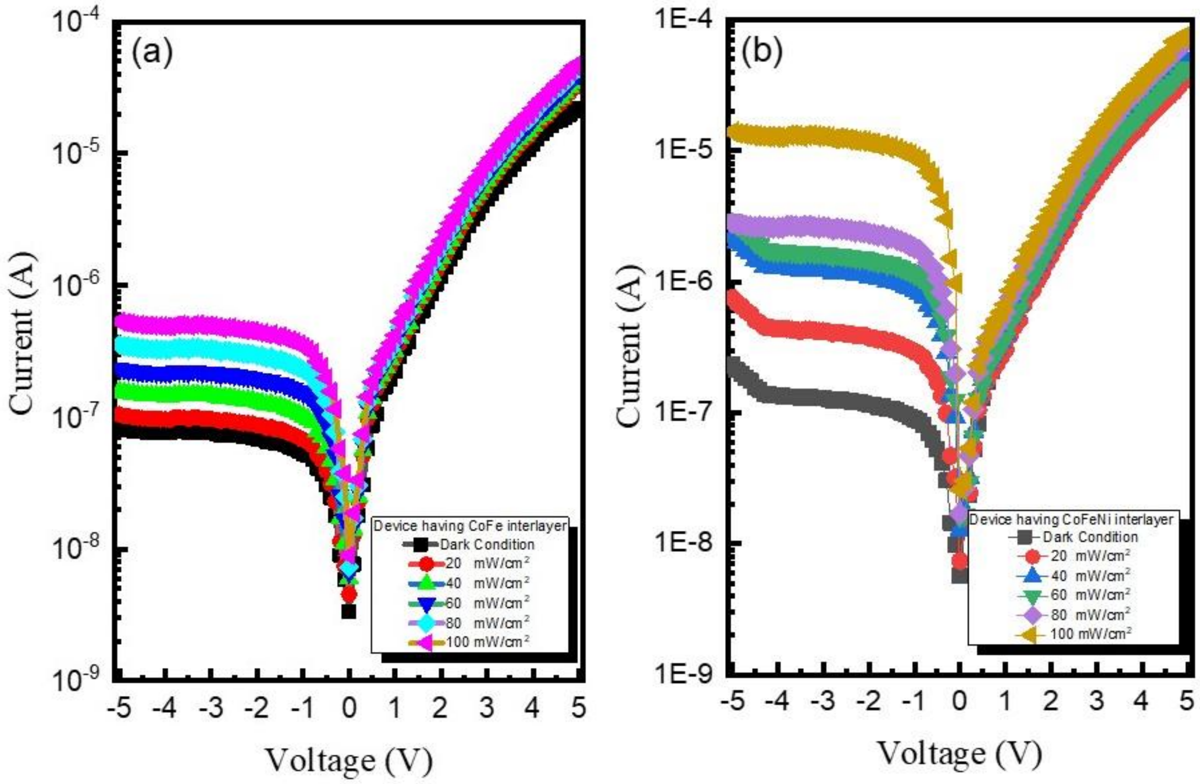

Figure 3. Current-voltage attributes of produced devices with CoFe and CoFeNi interlayers

While the barrier height values of photodiode having CoFe thin film interlayer were found to be 0.487 and 0.446 eV for dark and 100 mW/cm^2 light intensity conditions, respectively, the ideality factor values were calculated as 11.45 and 13.29. For the photodiode having a CoFeNi thin interfacial layer, the ideality factor values were found to be 9.86 for the dark and 11.02 under 100 mW/cm^2 light intensity conditions. The CoFeNi diode barrier height value was obtained as 0.513 eV in the dark environment, and as 0.484 eV under 100 mW/cm^2 light intensity. From the results, it was observed that the ideality factor value increased with the applied light, and the barrier height value decreased for both devices. However, when the obtained results were compared, it was determined that the photodiode produced with a CoFeNi thin film showed better characteristics. In other words, the ideality factor value of the device with CoFeNi interfacial layer is lower and the barrier height value is greater than that of the device fabricated with CoFe interfacial layer. The ideality factor value is theoretically known to be 1 for an ideal diode, but the ideality factor values of the diodes produced in this study are considerably greater than 1, which is essentially as expected. These results can have many different causes, including series resistance, recombination-production effect, irregular border of the barrier or interface conditions [44,45]. Besides these, when the reverse bias part of the current-voltage characteristics is examined, it is seen that the produced devices change depending on the exposed light intensity, that is, they are sensitive to light. This alteration clearly reveals that both of the produced devices have photoconductive behavior. Since the increase in the applied light intensity triggers the number of free charge carriers to increase, it causes an increase in the current in the reverse bias region. This new current, which is formed by the effect of applied light, is called the photocurrent. These findings prove that the fabricated devices exhibit photoresponse features.

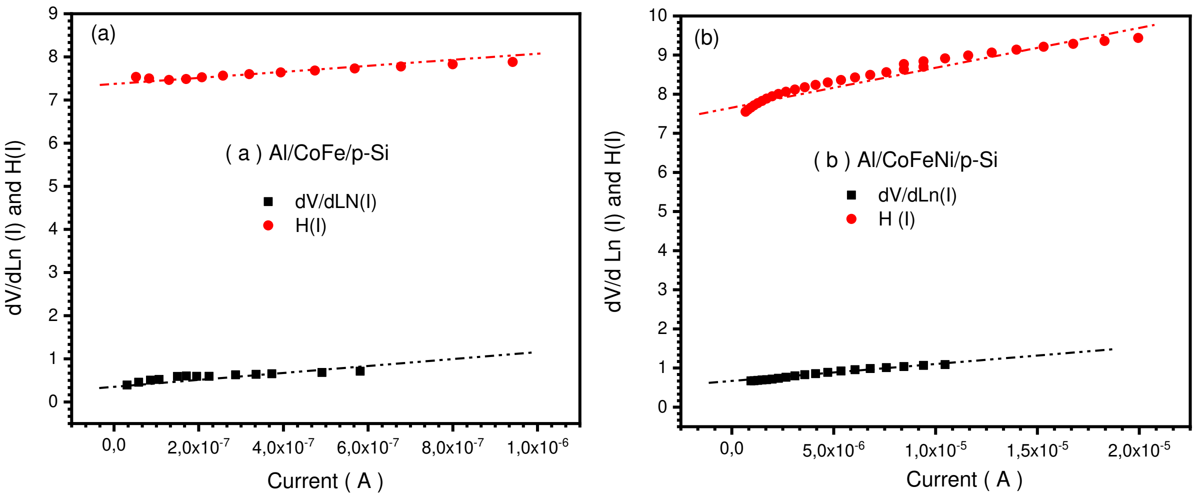

Figure 4. dV/dln(I) and H(I)-current attributes of produced devices with CoFe and CoFeNi interlayers (dashed lines show fit curves made to the relevant data.)

Another approach used to calculate the barrier height, series resistance, and ideality factor, which are among the very important electrical parameters, was presented in the literature by Cheung [46]. In this approach, unlike the thermionic emission approach, the current values in the high voltage region, called the series resistance region, where the current value deviates from linearity are taken into account. Cheung functions used in these calculations are based on this approach are given below [47, 48].

$$\frac{d(V)}{d(lnI)} = \frac{nkT}{q} + IR_s \qquad (5)$$

and,

$$H(I) = n\Phi_b + IR_s \qquad (6)$$

Graphs containing the values obtained using the equations given above are drawn for devices with CoFe and CoFeNi interfacial layers and are presented in Figures 4a and b. The given equations express linearity and therefore the curves drawn should also be linear, as in Figures 4a and b. The ideality factor value calculated with Equation 5 was found to be 12.76 for the device with the CoFe layer, while it was 11.03 for the device with the CoFeNi layer. In addition, the barrier height values, which were calculated using equation 6, were found to be 0.421 eV for the device with CoFe layer and 0.449 eV for the device with CoFeNi. These values obtained are slightly different from the values found from the thermionic emission. These differences arise are a result of the evaluations due to the different regions where the data included in the calculation are taken from. In addition to the values given above, series resistance values that directly affect device performance were also calculated separately using both equations. For the device with the CoFe layer, the series resistance value calculated with the help of Equation 5 is found to be 7274 ohms, while the value calculated with the help of Equation 6 is 8648 ohms. However, for the CoFeNi layered device, these values were obtained as 6422 ohms (calculated with equation 5) and 7735 ohms (calculated with equation 6). Another method to be used in calculating electrical parameters was presented by Ocaya and Yakuphaoğlu [49].

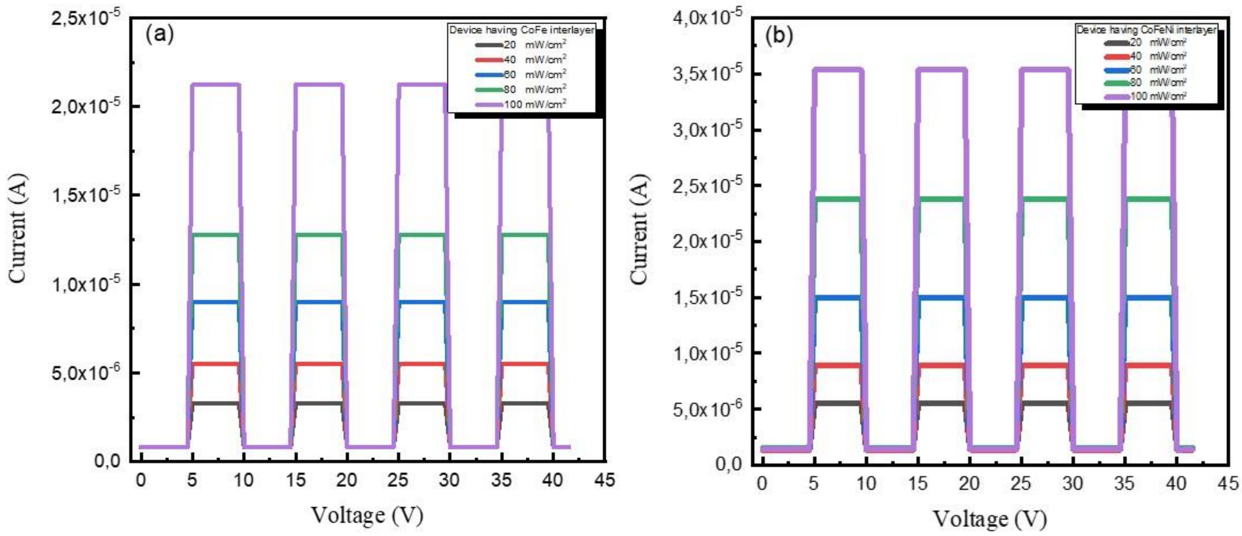

Figure 5. Transient photocurrent measurements for produced devices with CoFe and CoFeNi interlayers

Transient photocurrent measurements were carried out to determine the sensitivity to light for the produced photodiodes having CoFe and CoFeNi thin film interlayers. The graphs showing the values obtained as a result of the measurements are imparted in Figures 5a and b. When the results are examined, it can be clearly stated that the produced photodevices in parallel with turning the light on and off switch from high to low conductivity, and then shift to high when turned on again. As soon as the light is turned on, it creates a photocurrent, causing a marked increase in the number of charge carriers, so that the current increases up to a certain point and remains constant. Then the energy of the light source is cut off and the current drops again quickly towards the starting current. The rapid decrease in photocurrent may be due to the trapping of charge carriers at deep levels. There are two very important parameters in the evaluation of the measurements made, which are the photoresponse value and the duration of this photoresponse. While the photoresponse value expressed as I_{on}/I_{off} was 24 for the fabricated device having CoFe interfacial layer, it was found to be 101 for the device with CoFeNi interlayer. From the obtained data, it has been determined that the photoresponse value of the device produced using CoFeNi thin film interfacial layer is much better than the device produced using CoFe. In this study, it was concluded that the electrical and photoelectric characteristics of the device with CoFeNi thin film interfacial layer formed with Nickel transition metal are better and that the produced devices can be used especially as photodiodes in optoelectronic technology.

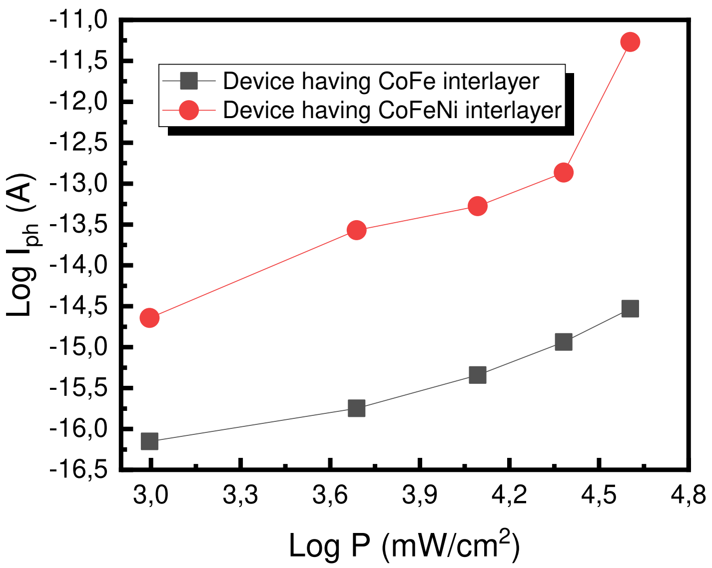

Figure 6. The values of $LogI_{ph}$ against Log P for produced devices with CoFe and CoFeNi interlayers at -4 V

Another important variable that needs to be known in analyzing a produced photodiode or photodetector is the photoconductivity mechanism of the device. In order to determine the dominant mechanism in the transmission of the photocurrent, the photocurrent value should be evaluated and analyzed for each light intensity to which the device is exposed. The graph of photocurrent values against exposure light intensity is presented in Figure 6. In order to describe this graph, the following formula, which gives the relationship between illumination intensity and photocurrent, can be utilized [50,51].

$$I_{ph} = NP^c \tag{7}$$

In equation 7, the term P is used instead of the applied luminous power, and the term I_{ph} indicates the measured photocurrent depending on the power. Also, the terms c and N are the exponent and a constant, respectively. This equation was evaluated by considering the c values obtained by the slope of the graph. The c value can be greater than or equal to 1, or be positioned between 0.5 and 1. From these values the mechanism that is effective in the transmission of the photocurrent [51] can be obtained. The c values of the semiconductor-based photodiodes produced in this study with CoFe and CoFeNi thin film interfacial layers were obtained as 1.01 and 1.31, respectively. The obtained values are greater than 1, denominating that the localized states are properly situated in the mobility gap. Otherwise, if it was less than 1, it would indicate the presence of localized traps [52]. It can also be seen from the graph that the photocurrent increases with increasing light intensity, which proves that photogeneration is related to the counts of photons absorbed by the structure [51].

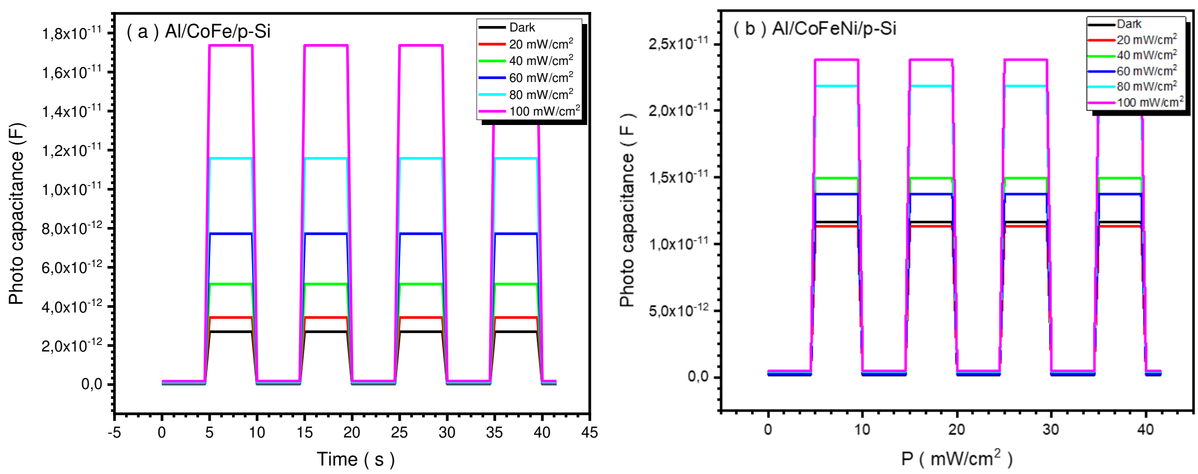

Figure 7. Transient photocapacitance measurements of produced devices with CoFe and CoFeNi interlayers

This device, which is a structure formed by layers placed between two metal contacts, appears as a natural capacitor. For this reason, another issue that can be analyzed is to investigate the capacitance and conductivity values of the device under the influence of light. Figures 7 and 8 show the measured capacitance and conductivity values depending on time under the influence of light. This analysis, in which different light intensities are used, shows the change in the capacity and conductivity performance of the device depending on the light. It can be seen that when the light is off, the capacity and conductivity values are at their minimum, and when the light is turned on, both of them increase and reach a constant. In addition, it is clearly seen that both values increase with increasing light intensity. From the data obtained, it can be stated that both devices produced have photocapacitor and photoconductor properties. However, it is seen that the device with CoFeNi interlayer gives better results than the device with CoFe interlayer.

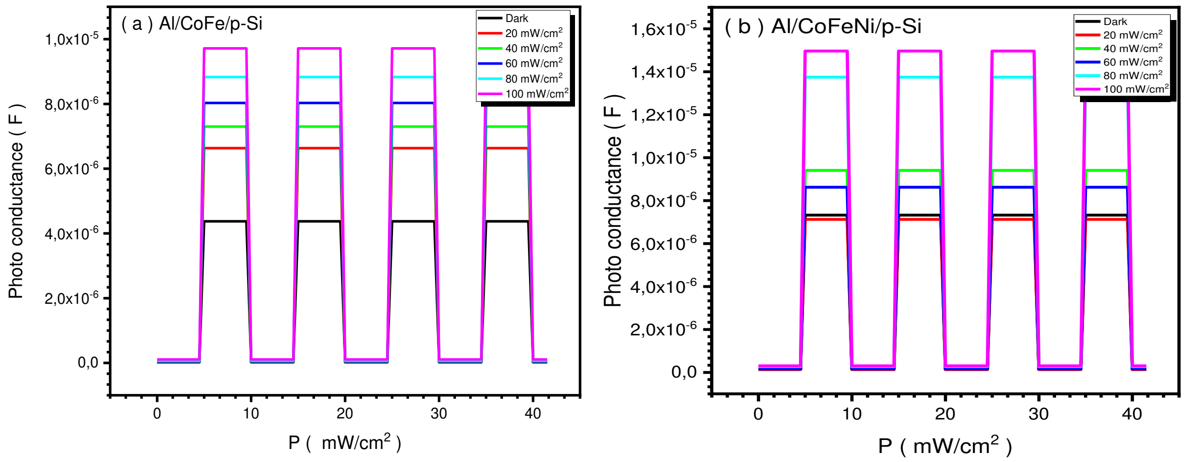

Figure 8. Transient photoconductance measurements of produced devices with CoFe and CoFeNi interlayers

Series resistance is one of the vital parameters that is of great importance for a manufactured semiconductor-based device and also seriously affects its electrical performance [53-55]. In this context, series resistance values of the devices with CoFe and CoFeNi interfacial layers were calculated as a function of the applied voltage, depending on the changing light intensity. As can be seen from the graphs presented in Figures 9a and b, the series resistance values of the device with the CoFe interface layer are higher than those of the device with the CoFeNi interface layer. However, another important experimental result is that as light intensity increases, the effect of series resistance decreases. Additionally, it is seen that there are peaks in series resistance values in regions close to 0 V. The reason for these peaks can be attributed to the high number of interface states in that region [56,57].

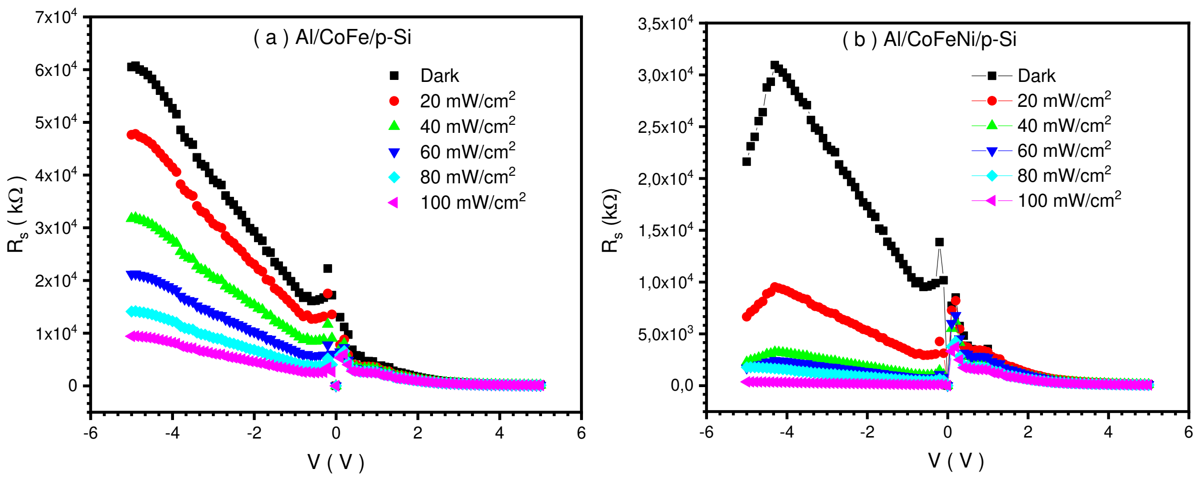

Figure 9. Series resistances-voltage attributes of produced devices with CoFe and CoFeNi interlayers

4. Conclusion

The main purpose of the study was to investigate the healing effect of the material obtained by adding the Ni element to the CoFe magnetic material on the electrical parameters, and indeed the study results were obtained in accordance with the hypothesis of the study. CoFe and CoFeNi materials are materials whose magnetic properties have been extensively researched in the literature and have been reported to exhibit good magnetic properties. XRD measurements of CoFe and CoFeNi materials coated on the semiconductor using the RF sputtering technique were taken and analyzed. The data obtained showed that the materials were successfully coated and turned into films. In this study, the photoelectrical performances of CoFe and CoFeNi materials, which are not included in the literature, were investigated. The electrical performances of the produced Al/CoFe/p-Si and Al/CoFeNi/p-Si devices were investigated under different light intensities and the effect of the Ni element on the device performance was investigated. One of the most important outcomes obtained is that both devices are sensitive to light, and current-voltage and transient photocurrent measurements have shown that the use of the Ni element significantly improves sensitivity to light. It has also been shown that important electrical parameters obtain better values for the device in which CoFeNi material is used. While the ideality factor value of the produced device with CoFe interlayer was found to be 11.45 in the dark, the device with CoFeNi interlayer was found to be 9.86. In addition, the photoresponse value of the device with CoFe interlayer was found to be 24, and the photoresponse value of the device fabricated with the CoFeNi material obtained by doping the Ni element increased approximately 4.21 times and reached the value of 101. In addition, transient photocapacitance and photoconductance measurements were carried out to determine the photocapacitor performance of the produced devices, and the results showed that the device with the CoFeNi interface layer exhibited superior performance. As a result, the produced devices and the CoFe and CoFeNi magnetic materials used in these devices can be used in photovoltaic applications.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Notes

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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