Research Article

Electrical and Photoconductivity Properties of Al/CdFe₂O₄/p-Si/Al Photodiode

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In the present study, we have investigated the effects of illumination intensity on the optical and electrical characteristics of the Al/CdFe₂O₄/p-Si/Al photodiode. A thin film of CdFe₂O₄ was fabricated using the sol-gel spin coating method that allows good thickness control and low-cost manufacturing as compared to alternative techniques. The current-voltage (*I-V*) of the Al/CdFe₂O₄/p-Si/Al photodiode was measured in the dark and under different illumination intensities. The photocurrent increased with higher luminous intensity and its sensitivity has a strong dependence on the reverse bias rising from 1.08×10^{-7} A under dark conditions to 6.11×10^{-4} A at 100 mW/cm² of illumination. The parameters of the photodiode such as ideality factor and barrier height were calculated using the thermionic emission model. The ideality factor of the Al/CdFe₂O₄/p-Si/Al photodiode was found to be 4.4. The barrier height was found to be 0.88 eV. The capacitance-voltage (*C-V*) characteristics measured at different frequencies have strongly varied with frequency, decreasing with frequency. Consequently, the resulting interface density (*D_{it}*) value of the Al/CdFe₂O₄/p-Si/Al photodiode also decreased with higher frequency. Similarly, the fitted series resistance of the Al/CdFe₂O₄/p-Si/Al photodiode has declined with higher frequency.

1. Introduction

In recent years, researchers have gone to significant lengths to prepare and utilize novel semiconductor metal oxides in new device configurations. To this trend, the CdO-based films constitute an important example, as they display n-type semiconductor behavior [1] and attracted great interest due to their optical, chemical, electrical, and physical properties that can be beneficial especially as sensors [2]. Based on this broad interest and high sensing potential, we present in this paper detailed characterization of photodiodes that contain CdFe₂O₄ thin films.

The optical and electrical properties of thin films of nanomaterials are tunable by changing the particulate size, surface chemistry, and shape or aggregation state, providing utility for different applications. Such wide range of tuning parameters helps designers in many advanced applications [2] such as solar cell, gas sensors, and optoelectronic devices [3–9]. In the case of Cd based metal oxides the additional interest

lies in the catalytic behavior [10–12]. The doping behavior of nanoparticles is distinctly different from bulk alloys, including changes by doping concentration. So, thin film photoconductivity behavior can be controlled by carrier localization process [6–9]. In this study, the main aim is to produce new generation photodiodes semiconductor interlayer and to take advantage of this unique control mechanism and prepare Al/CdFe₂O₄/p-Si/Al photodiodes with improved electrical, optical, and photoconductive properties depending on the chemical composition of the CdFe₂O₄ films [10–14]. Thus, not only do we explore a unique metal oxide thin film and its doping behavior, but we also provide practical device data in terms of a major optoelectronic application.

2. Experimental Details

The CdFe₂O₄ film used in this work was synthesized using the sol-gel spin coating method. The Al/CdFe₂O₄/p-Si/Al photodiode was fabricated on a p-Si substrate with resistivity

40–1000 $\Omega\cdot\text{cm}$. Cadmium nitrate, iron chloride, and ethanol were used as precursor materials and solvents, respectively. Firstly, the cadmium nitrate and iron chloride were dissolved in ethanol for 15 min, and then monoethanolamine was added to this solution. The solution was stirred for one hour at room temperature. And then p-Si substrate was cleaned chemically with acetone, methanol, and deionized water using an ultrasonic bath for 15–20 mins. Before further processing, the native oxide on the surface of p-Si was cleaned with buffered HF solution for 20 seconds. After surface cleaning, a low-resistance ohmic contact on the rear of p-Si was formed by thermal evaporation of Al, at a pressure of 4×10^{-5} torr with VAKSIS thermal evaporator system, and then by annealing at 570°C for 5 min in N_2 atmosphere. The CdFe_2O_4 film was deposited onto p-Si substrate by spin coating at a speed of 1500 rpm for 30 seconds. The deposited layer was annealed on a hotplate at 140°C for 5 min followed by a secondary anneal in the oven at 400°C for one hour to obtain a fully cured thin film on the p-Si. Finally, the processing steps concluded with the top Al ohmic contact formation on the CdFe_2O_4 thin film. The electrical characteristics of the Al/ CdFe_2O_4 /p-Si/Al photodiode were determined with 4200 Keithley Semiconductor Characterization System.

3. Result and Discussion

The current-voltage (I - V) characteristics of the resultant Al/ CdFe_2O_4 /p-Si/Al photodiode were studied under darkness and at various illumination intensities as shown in Figure 1. The reverse current under illumination is notably higher compared to the dark condition. The diode indicates a rectifying behavior; its current rises exponentially at low applied voltages. The downward curvature region at high bias voltage in the forward bias I - V characteristics results from the series resistance of the CdFe_2O_4 thin film and the neutral region of the Si semiconductor. The I - V characteristic of photodiode could be analyzed on the basis of thermionic emission model that relates the current to the applied voltage, by the following expression [15, 16]:

$$I = I_0 \exp\left(\frac{q(V - IR_s)}{nkT}\right) \left[1 - \exp\left(\frac{-q(V - IR_s)}{kT}\right)\right], \quad (1)$$

where n is the ideality factor, k is the Boltzmann constant, q is the electronic charge, V is the applied voltage, T is the temperature, R_s is the series resistance, and I_0 is the reverse saturation current that it is given by [16]

$$I_0 = AA^* T^2 \exp\left(\frac{-q\phi_b}{kT}\right), \quad (2)$$

where A^* is the effective Richardson constant that is equal to $32 \text{ A/cm}^2 \text{ K}^2$ for p-type silicon, ϕ_b is the barrier height, and A is the active device area. Using a least squares fit to (1) and (2), the ideality factor and barrier height of the Al/ CdFe_2O_4 /p-Si/Al photodiode were found to be 4.4 and 0.88 eV, respectively. An ideality factor >2 in diodes indicates

FIGURE 1: I - V characteristics of the Al/ CdFe_2O_4 /p-Si/Al photodiode under various illuminations.

surface-mediated leakage, which appears to be the case in this study [17]. The barrier height value calculated appears to be reasonable given the reported values for band gap for CdFe_2O_4 crystals (~ 2.0 eV) [18].

The reverse bias current of the Al/ CdFe_2O_4 /p-Si/Al photodiode increases with the rise in the illumination intensity. Photosensitivity of the Al/ CdFe_2O_4 /p-Si/Al photodiode, photocurrent measured at a bias of -2 V as a function of illumination intensity, is provided in Figure 2. The Al/ CdFe_2O_4 /p-Si/Al photodiode displays a high level of photosensitivity: 6.11×10^{-4} A under 100 mW/cm^2 . This condition has shown that it can be used for different optoelectronic applications. The photocurrent with illumination intensity can be analyzed by the relation given in the following equation:

$$I_{ph} = AP^m, \quad (3)$$

where I_{ph} is the Al/ CdFe_2O_4 /p-Si/Al photodiode photocurrent, A is a constant, P is the illumination intensity, and m is an exponent. The value of m was determined from the slope of $\log(I_{ph})$ and $\log(P)$ plot. It was found to be 1.39, suggesting that the photoconduction mechanism of the Al/ CdFe_2O_4 /p-Si/Al photodiode exhibited a supralinear behavior.

The effect of applied voltage and frequency on the capacitance of the Al/ CdFe_2O_4 /p-Si/Al photodiode was also studied. Frequency dependence of capacity-voltage scans is shown in Figure 3. According to this figure, the capacitance of the Al/ CdFe_2O_4 /p-Si/Al photodiode is independent of

FIGURE 2: Photosensitivity of the Al/CdFe₂O₄/p-Si/Al photodiode. Both linear (left) and logarithmic (right) characteristics are shown.

FIGURE 3: C-V plots of the Al/CdFe₂O₄/p-Si/Al photodiode at the various frequencies.

frequency at the forward bias region, while at the reverse bias region the capacitance varies strongly with the AC frequency, diminishing to very low values as the frequency increases. Assuming that the reverse bias region induces mainly the minority carriers (holes in this case) in the thin film, it is indicative of short lifetimes of holes in our material or high defect density.

The Al/CdFe₂O₄/p-Si/Al photodiode's capacitive properties may also be affected by the interface properties. The interface states are very sensitive to the AC signal at low frequency, but their sensitivity is reduced at high frequency. This may also explain the observed reduction of the capacitance at higher frequencies [19]. Since charge trapped at the defects that may be formed at grain boundaries, around the contacts or at the metallurgic junction between Si and CdFe₂O₄ used to form the device, can lead to space charge distribution, hence strong frequency dependence can also be related to various defects.

The conductance-voltage characteristics of the Al/CdFe₂O₄/p-Si/Al photodiode at different frequencies are provided in Figure 4. The conductance-voltage scan of the film shows a similar behavior as the capacitance: it shows a strong dependence only at the reverse bias voltage region. However, as clearly seen in Figure 4, the step-like increase in the conductance of the photodiode at the reverse bias voltage region grows with frequency, which is the opposite of capacitive response.

The abovementioned decrease in the measured capacitance of the Al/CdFe₂O₄/p-Si/Al photodiode is indicative of a nonideal behavior because of series resistance. To correct for the effect of series resistance on the capacitance and conductance, the following equations can be used [19–22]:

$$C_{adj} = \frac{(G_m^2 + (\omega C_m)^2) C_m}{a^2 + (\omega C_m)^2}, \quad (4)$$

$$G_{adj} = \frac{(G_m^2 + (\omega C_m)^2) a}{a^2 + (\omega C_m)^2}, \quad (5)$$

where C_{adj} is corrected capacitance, G_{adj} is corrected conductance, C_m and G_m are measured capacitance and conductance, ω is angular frequency, and a is variable parameter and

FIGURE 4: G - V plots of the Al/CdFe₂O₄/p-Si/Al photodiode at the various frequencies.

it is dependent on C_m , G_m , and R_s parameters and it can be defined by the following equation:

$$a = G_m - (G_m^2 + (\omega C_m)^2) R_s, \quad (6)$$

where R_s of the device was calculated using the equation

$$R_s = \frac{(G_m/\omega C_m)^2}{1 + (G_m/\omega C_m)^2} \frac{1}{G_m}. \quad (7)$$

Based on the measured capacitance and conductance values, and (4) through (7), C_{adj} and G_{adj} plot of the Al/CdFe₂O₄/p-Si/Al photodiode at diverse frequencies are shown in Figures 5(a) and 5(b), respectively. Clearly, C_{adj} decreases with increasing frequency at the reverse bias voltage region, but at the forward bias region it does not change. At the same time the corrected conductance increases with higher frequency. Moreover, G_{adj} - V plots exhibit a peak in the reverse bias voltage that increases in intensity with increase in frequency, which indicates that the interface states can follow the AC signal. This is formed because of the presence of interface states and series resistance. The frequency dependence of density of interface states (D_{it}) in the photodiode can be calculated using the following relation [20, 23]:

$$D_{it} = \frac{2}{qA} \left[\frac{(G_{adj}/\omega)_{\max}}{[(G_{\max}/\omega C_{ox})^2 + (1 - C_m/C_{ox})^2]} \right], \quad (8)$$

where $(G_{adj}/\omega)_{\max}$ is the measured conductivity, C_m is the measured capacitance, C_{ox} is the capacitance of the insulator layer, ω is the angular frequency, and A is the contact area of the Al/CdFe₂O₄/p-Si/Al photodiode. D_{it} values of the Al/CdFe₂O₄/p-Si/Al photodiode calculated from G_{adj} - V plots using (8) are provided in Figure 6, which indicates that trap density decreases at higher frequencies, especially after 400 kHz.

The dependence of diode series resistance R_s on the applied bias and measurement frequency is given in Figure 7. These R_s values were calculated from measured capacitance and conductance values of at the accumulation region [21–24]. The R_s plot shows a peak, wherein the peak position changes with increased frequency. This change is due to interface charges following the frequency of applied voltage at relatively low frequencies. However, at higher frequencies, the interface state cannot follow the AC signal, so they do not make an important contribution to interface states.

Finally, a plot of C^{-2} - V is shown in Figure 8, which can be used to estimate built-in potential and carrier concentration in the junction region. For the former the intersection of the resulting curve on the voltage axis is sufficient. For space charge density (N_a) the slope of the plot can be fitted to the following relationship [16, 19–24]:

$$\frac{1}{C^2} = \frac{2(V_{bi} + V)}{A^2 \epsilon_s q N_a}, \quad (9)$$

where V_{bi} is the built-in potential, ϵ_s is the dielectric constant of the p-Si ($\epsilon_s = 11.8$) [20], N_a is the acceptor concentration of the p-Si, q is the electronic charge (1.6×10^{-19} eV). The V_{bi} values of the Al/CdFe₂O₄/p-Si/Al photodiode were found to be 0.53 eV. Now, using these values the barrier height of diode as measured by C - V curves ($\phi_{b(c-v)}$) can be calculated by the following relation [23]:

$$\phi_{b(c-v)} = V_{bi} + \frac{kT}{q} \ln \left(\frac{N_v}{N_a} \right), \quad (10)$$

where N_v is effective density of states in conduction band of the p-Si (1.82×10^{19} cm⁻³). Thus, the barrier height ($\phi_{b(c-v)}$) of the Al/CdFe₂O₄/p-Si/Al photodiode was calculated using (10) to be 0.83 eV. It is worth pointing out that this effective barrier height as measured by C - V curve is in good agreement with earlier barrier height (0.88 eV) calculated from diode I - V relationship. Both values are commensurate with the relatively large band gap of this metal oxide alloy reported to be ~2.0 eV [18].

4. Conclusions

A thin film photodiode of CdFe₂O₄ was fabricated using sol-gel spin coating method on p-type Si substrate. The electrical and optical properties of the Al/CdFe₂O₄/p-Si/Al stack were studied. The photosensitive properties of the Al/CdFe₂O₄/p-Si/Al photodiode were studied under different illumination intensities. The ideality factor and barrier height of the

FIGURE 5: (a) C_{adj} plots of the Al/CdFe₂O₄/p-Si/Al photodiode at the various frequencies. (b) G_{adj} plots of the Al/CdFe₂O₄/p-Si/Al photodiode at the various frequencies.

FIGURE 6: D_{it} plots of the Al/CdFe₂O₄/p-Si/Al photodiode.

Al/CdFe₂O₄/p-Si/Al photodiode were found to be 4.4 and 0.88 eV, respectively. A detailed analysis of frequency dependent behavior of measured diode capacitance, conductance, series resistance, and interface state density is also provided. The electrical and optical results show that the deposited Al/CdFe₂O₄/p-Si/Al stack can be used as a photodiode or photosensor for various optoelectronic device applications.

FIGURE 7: R_s -V plots of the Al/CdFe₂O₄/p-Si/Al photodiode.

Competing Interests

The authors declare that they have no competing interests.

FIGURE 8: Plot of C^{-2} - V of the Al/CdFe₂O₄/p-Si/Al photodiode.

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