Effect of low energy ion beam irradiation on the structural and optical properties of flexible PVA/CuO nano composite films

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Abstract

The solution casting production process was used to synthesis the composite PVA/CuO that is consisting of copper oxide nanoparticle (CuONP) with polyvinyl alcohol (PVA) for use in optoelectronic. The PVA/CuO composite were then irradiated with argon fluences of 3×10^{17}, 6×10^{17}, and 9×10^{17} ions.cm^{-2} by cold cathode ion source. The XRD, FTIR, and UV/Vis are employed to investigate the structural, functional group, and optical impacts of PVA/CuO. In addition, the dispersion properties of the investigated films were calculated using the Wemple and Di-Domenico method, which led to the determination of various optical parameters. Pure and irradiated films were estimated for their optical susceptibility and refractive index. At the fluence of 6×10^{17} ions.cm^{-2}, the single oscillator energy $E_o$ rises from 3.25 eV for the un-irradiated film to 3.89 eV and the dispersion energy $E_d$ rises from 0.098 eV to 0.26 eV. Therefore, the results reveal that irradiated PVA/CuO composite are more applicable for optoelectronics.

1. Introduction

Researchers in several fields are looking into the novel and versatile characteristics of nanotechnologies, which have applications in electronics, optics, and sensing [1,2]. Nanoparticles (NPs) have the potential to significantly alter electrical and optical properties of polymer materials [3,4]. A wide variety of applications make use of polymeric nanocomposites, some of which include optical waveguides, antistatic materials, biosensors, batteries, and super capacitors [5]. In addition, polymer nanocomposites can have their optical properties fine-tuned by adding nanoparticles, leading to enhanced transparency [6–8]. Many industries, including those dealing with paper and packaging, rely on adhesives that have PVA bases [9]. In addition, by chemically altering PVA and adding different functional groups, its variety of applications can be much greater [10]. By making these changes, you can get better qualities as water resistant, biodegradable, and compatible with other materials [11]. In order to make nanocomposites, the CuO nanofiller is encouraged to form hydrogen bonds by hydroxyl groups in the PVA chain [12].

Due to its unique properties and many potential applications, CuO nanofiller has recently garnered considerable attentions [13]. The fascinating optical, magnetic, electrical, and catalytic properties of CuO, a transition metal oxide, are revealed at the nanoscale [14]. Among the most notable properties of CuO nanofiller is its high level of electrical conductivity. Because of this, it can be utilized to manufacture conductive sheets, electrodes, and sensors, among other electrical devices [15]. The superior electrical conductivity of CuO nanofiller allows for quicker data transfer and better signal transmission, which in turn improves the overall performance and efficiency of an electronic device [16, 17]. Its optical absorbance in the visible and near-infrared range makes it suitable for application in solar cells, photodetectors, and optoelectronic devices [18, 19].

Moreover, ion beam irradiation process is one approach that demonstrated potential for modifying nanocomposites properties and enhancing their usefulness [20]. The nanocomposite can be tailored to possess desired characteristics using ion beam irradiation, opening up exciting new avenues for numerous potential uses [21]. Ion beam irradiation process alters the molecular and atomic structures of
materials as bombarded with high-energy ions [22, 23]. Different types of ion sources, including electron ionization, charge exchange ionization, and chemical ionization. These modifications in the nanocomposites properties by ion beam were discussed in different works [24–26].

This work aims to develop a PVA/CuO polymer composites for utilizing in optoelectronics applications. Following this, the composite PVA/CuO films were irradiated with argon ion beams of different fluences. The XRD and FTIR techniques were used to investigate the structural properties of the composite. Furthermore, the optical properties of both the pure and irradiated films were examined. The results showed that characteristics of the treated films were improved, which bodes well for a variety of electronic applications.

2. Experimental work

Copper oxide (CuO) with a particle of size 25 nm and PVA with a molecular weight of 85,200 g/mol were supplied by Sigma-Aldrich Co., USA. The method of casting preparation was used to create the polymer composite, as previously mentioned [27]. For 1.5 hours, at 75°C and with stirring, 0.6 g of PVA dissolves in 75 ml deionized water. PVA and CuO solution are combined and agitated for seven hours. After 40 minutes of sonicating the mixes, the CuONPs were evenly distributed throughout the PVA blend. Pouring the finished PVA/CuO slurry onto a glass Petri dish allowed for the necessary drying time. Any air bubbles were blown out using shaking and blowing to create the PVA/CuO composite. A thickness gauge (Mitutoyo 7301) was used to measure the thickness of the produced sheets, which ranges from 0.08 mm.

Various fluences of $3 \times 10^{17}$, $6 \times 10^{17}$, and $9 \times 10^{17}$ ions.cm$^{-2}$ have been used to irradiate the films with argon beam, using a broad beam cold cathode ion source shown in figure (1) as previously investigated [28]. The two main parts of the ion source are the ionization region and the extraction region. The extracted ion beam, of argon energy of 5 keV, a working pressure of $2.05 \times 10^{-4}$ mbar, and a current density of 145 µA/cm$^2$. To analyze the structural properties of both irradiated and un-irradiated PVA/CuO films, the XRD (Shimadzu, CuKα, $\lambda = 0.154$ nm) was used in 2θ range of 4° to 90°. The films’ functional groups were studied using FTIR (Shimadzu FTIR-340) within the wavenumber range of 500–4000 cm$^{-1}$. The UV-Vis reflection and absorption spectra were measured, for the original and irradiated films, in wavelength 200 to 1150 nm using a JascoV-670 spectrophotometer.

3. Results and Discussions

Various parameters that directly related to the ion beam with composite interactions is determined using the SRIM simulation program [29]. Figure 2 displays the outcomes of the SRIM conducted on 5 keV argon with PVA/CuO in dispersed range of 1000 Å. Figure 2 (a) illustrates the incoming ion starts to ionize the surface. The ionization effects that result from the argon ions penetrating the target is some higher than those that come from the recoils target atoms. The findings demonstrate that the penetration ions and recoil atoms have a significant effect on target ionization. Figure 2(b) shows collision events of the argon
ion in the composite vacancies. Consequently, the inbound ions permeate the film and cause the ion-induced alterations by surface-area localized dissipation of heat.

Figure 3 displays the XRD structures of PVA/CuO films that have been exposed to different fluences; $3 \times 10^{17}$, $6 \times 10^{17}$, and $9 \times 10^{17}$ ions.cm$^{-2}$, respectively. The XRD analysis of PVA/CuO revealed that the (101) crystal plane has a peak at $2\theta = 19.5^\circ$, suggesting the semi-crystalline feature of PVA. Additionally, the (111) reflection CuO plane may have a minor peak at $2\theta$ of 38.8° [30]. Due of the increased contact between PVA and CuO for the irradiated samples, the peak's intensity reduced with the ion beam fluence. Moreover, it is evident that the distinct diffracted peaks remain in their original positions following the films’ exposure to ion beams. There is, nevertheless, a variation in peak intensity. This results in an ordered to an unarranged pattern in the crystal structure, which is caused by the chain scission of molecular strings [31]. Furthermore, the generation of defects as a result of increased radiation fluence leads to the development of disordered structures, which is the cause of the intensity drop [32].

The mean size of the crystallite (D) of the CuO in the PVA/CuO composite [33] is given by:

$$D = \frac{0.94 \lambda}{\beta \cos \theta} \quad \text{(1)}$$

where $\lambda$ indicates the wavelength and $\beta$ is the full width intensity of the (111) plane. Moreover, the next formula is used to determine the samples’ particle diameter (R) [34] by:

$$R = \frac{\lambda}{\sin \beta \cos 2\theta} \quad \text{(2)}$$

Consequently, for $9 \times 10^{17}$ ions.cm$^{-2}$ irradiated PVA/CuO, the particle size D and diameter R fall to 11.2 nm and 149.1 µm, respectively, from 16.5 nm and 218.2 µm of PVA/CuO composite. Additionally, the dislocation density ($\delta$) parameter [34] is given by:

$$\delta = \frac{1}{D^2} \quad \text{(3)}$$

As shown in Table 1, for PVA/CuO composite and at a fluence of $9 \times 10^{17}$ ions.cm$^{-2}$, the dislocation density is enhanced from $3.01 \times 10^{-3}$ to $4.75 \times 10^{-3}$ lines/m$^2$. This is due to the changes in inter-planar distance. The strain ($\epsilon$) is given by [35]:

$$\epsilon = \frac{\beta}{4 \tan \theta} \quad \text{(4)}$$

It is observed that the lattice strain increases from $0.072 \times 10^{-3}$ of the pure PVA/CuO composite to $0.085 \times 10^{-3}$ for the fluence of $9 \times 10^{17}$ ions.cm$^{-2}$ irradiated film. These results lead to both the particles’ misalignment and decreased size. Lastly, the distortion parameters (g) is computed by [35].
It is evident that following the fluence of $9 \times 10^{17}$ ions.cm$^{-2}$ irradiated composite, the $g$ rises from 10.7 for the pure PVA/CuO film to 14.1, which further supports the production of a disordered system in the composite.

<table>
<thead>
<tr>
<th>The samples</th>
<th>D [nm]</th>
<th>R [µm]</th>
<th>$\delta$ [10$^{-3}$ lines/m$^2$]</th>
<th>$\varepsilon$ [10$^{-3}$]</th>
<th>g (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA/CuO</td>
<td>16.5</td>
<td>218.2</td>
<td>3.01</td>
<td>0.072</td>
<td>10.7</td>
</tr>
<tr>
<td>$3 \times 10^{17}$ ions.cm$^{-2}$</td>
<td>14.6</td>
<td>195.7</td>
<td>3.04</td>
<td>0.078</td>
<td>10.6</td>
</tr>
<tr>
<td>$6 \times 10^{17}$ ions.cm$^{-2}$</td>
<td>13.1</td>
<td>175.8</td>
<td>4.73</td>
<td>0.082</td>
<td>13.3</td>
</tr>
<tr>
<td>$9 \times 10^{17}$ ions.cm$^{-2}$</td>
<td>11.2</td>
<td>149.1</td>
<td>4.75</td>
<td>0.085</td>
<td>14.1</td>
</tr>
</tbody>
</table>

As seen in Fig. 4, FTIR spectra analysis is used to determine the vibrational bands and functional groups of both pure and irradiated PVA/CuO. The vibrational stretching of PVA is observed as occurring in a broad band at 3275 cm$^{-1}$. An additional band for stretching of C-H at 2925 cm$^{-1}$ is found. The C = O vibrational stretching is detected at 1720 cm$^{-1}$. A Peak is found at 1368 cm$^{-1}$ and is attributed to PVA's C-H bending [36]. The band of absorption detected at 1245 cm$^{-1}$ is determined to be -CH$_2$ wagging. The -CH$_2$ vibrational stretching is seen by the absorption band at 822 cm$^{-1}$. C-O-C vibrational stretching is recognized as the peak at 1092 cm$^{-1}$ [37]. The interaction between PVA and CuO filler is indicated by the lowering of peak intensity for the irradiated PVA/CuO. Additionally, the bands shift following the irradiation process shows how abundant electrons are, which improves the irradiated composite's optical properties [38].

The extinction coefficient (K) is estimated by [39].

$$ K = \frac{\alpha \lambda}{4\pi} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6) $$

Figure 5(a) displays the photon wavelength and the extinction coefficient of both the original and irradiated PVA/CuO films. Because of the defects density increases with irradiation process, the absorbance coefficient (K) grows. The reflectance R of the pure and treated films is seen in Fig. 5(b). The irradiated and un-irradiated films maintain a consistent reflectance at higher wavelengths. In addition, as the irradiation fluence increases, the reflectance rises.

The refractive index (n) [40] is estimated by following equation:
\[ n = \frac{(1 + R)}{(1 - R)} + \sqrt{\frac{4R}{(1 - R)^2}} - K^2 \quad \text{..........................}(7) \]

Figure 6a displays the refractive index \( n \) of the PVA/CuO nanocomposite films before and after the irradiation process. The original film's refractive index is 1.014, meanwhile, after being subjected to 3x10^{17} ions cm\(^{-2}\) and 6x10^{17} ions cm\(^{-2}\), respectively, it increased to 1.020 and 1.030. As a result of the formed free radicals between the various chains of the irradiated samples, the refractive index rises with ion irradiation [41, 42]. The optical conductivity (\( \sigma_{opt} \)) of the pure and irradiated films is given by [43].

\[ \sigma_{opt} = \frac{\alpha nc}{4\pi} \quad \text{..........................}(8) \]

Figure 6b shows the wavelength-dependent shift in optical conductivity for both the un-irradiated and irradiated films. The optical conductivity of the films is enhanced due to a higher absorption coefficient caused by the localized state densities in the band structure.

The complicated dielectric constant is separating into two components: real \( \varepsilon_r \) and imaginary \( \varepsilon_i \) that given by the following equation [44]:

\[ \varepsilon = \varepsilon_r + i\varepsilon_i \quad \text{..........................}(9) \]

The \( \varepsilon_r \) is given by [45]:

\[ \varepsilon_r = n^2 - K^2 \quad \text{..........................}(10) \]

Figure 7(a) shows the \( \varepsilon_r \) with wavelength (\( \lambda \)) of the original and irradiated films. It has been observed that the \( \varepsilon_r \) steadily rises with ion irradiation. The formation of bonds of different chains, raises photon energy. Moreover, the imaginary portion (\( \varepsilon_i \)) is given as following [46]:

\[ \varepsilon_i = 2nk \quad \text{..........................}(11) \]

Figure 7(b) displays the \( \varepsilon_i \) with \( \lambda \) of the irradiated and pristine samples. It is noteworthy that the density and refractive index of the PVA/CuO film rise as a result of the \( \varepsilon_i \) steadily increasing with ion fluence.

Wemple and DiDomenico connection [47] is used to estimate the single oscillator by:

\[ \frac{1}{n^2 - 1} = \frac{E_O}{E_d} - \frac{1}{E_O E_d} (h\nu)^2 \quad \text{..........................}(12) \]

The dispersion energy is represented by \( E_d \), and the single oscillator energy is denoted by \( E_o \). As a result, the \((n^2-1)^{-1}\) and \((h\nu)^2\) of the pure and irradiated films is plotted in Fig. 8(a). The linear fit part's intercept and slope can be used to get the \( E_o \) and \( E_d \). Furthermore, the static refraactive index (\( n_o \)) can be calculated [48] as the following:
\[ n_o = \left(1 + \frac{E_d}{E_O}\right)^{1/2} \quad \ldots \ldots \ldots (13) \]

Thus, by using the relation \( \epsilon_\infty = (n_o)^2 \), it is possible to determine the zero frequency dielectric constants (\( \epsilon_\infty \)). Table (2) lists the optical parameters of PVA/CuO nanocomposite, including \( E_o \), \( E_d \), and \( \epsilon_s \). For the irradiated fluence \( 6 \times 10^{17} \) ions.cm\(^{-2}\), it is seen that \( E_d \) rises from 0.098 eV to 0.26 eV and the \( E_o \) increases from 3.25 eV for the pure film to 3.89 eV. The Spitzer-Fan model is used to calculate to the \( \epsilon_l \) and the ratio of \( N/m^* \) by [49].

\[ \epsilon_r = \epsilon_l - \left(\frac{e^2}{4\pi^2\epsilon_s c^2 m^*}\right) \lambda^2 \quad \ldots \ldots \ldots (14) \]

The dielectric free-space is represented by \( \epsilon_s \), the electron charge by \( e \), and the speed of light by \( c \). Consequently, the relationship of the dielectric constant and \( \lambda^2 \) at a greater wavelength is shown in Fig. 8(b). The \( \epsilon_l \) and \( N/m^* \), respectively, can be determined by utilizing the intercept and slope of the straight segments of the detour of Fig. 8(b).

<table>
<thead>
<tr>
<th>The samples</th>
<th>( n_o )</th>
<th>( \epsilon_\infty )</th>
<th>( E_d ) (eV)</th>
<th>( E_o ) (eV)</th>
<th>( \epsilon_l )</th>
<th>( N/m^* \times 10^{39} ) (cm(^3).g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA/CuO</td>
<td>1.014</td>
<td>1.028</td>
<td>0.098</td>
<td>3.25</td>
<td>1.036</td>
<td>0.002</td>
</tr>
<tr>
<td>( 3 \times 10^{17} ) ions.cm(^{-2})</td>
<td>1.020</td>
<td>1.04</td>
<td>0.140</td>
<td>3.86</td>
<td>1.070</td>
<td>0.003</td>
</tr>
<tr>
<td>( 6 \times 10^{17} ) ions.cm(^{-2})</td>
<td>1.030</td>
<td>1.06</td>
<td>0.26</td>
<td>3.89</td>
<td>1.086</td>
<td>0.004</td>
</tr>
<tr>
<td>( 9 \times 10^{17} ) ions.cm(^{-2})</td>
<td>1.007</td>
<td>1.01</td>
<td>0.24</td>
<td>1.67</td>
<td>1.028</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

The resonance plasma frequency (\( W_p \)) is determined by [50]:

\[ W_p = \frac{e^2}{\epsilon_o} \times \frac{N}{m^*} \quad \ldots \ldots \ldots (15) \]

Changes in \( \epsilon_l \), \( N/m^* \), and \( W_p \) occurred by the irradiation fluences: \( 3 \times 10^{17} \), \( 6 \times 10^{17} \), and \( 9 \times 10^{17} \) ions.cm\(^{-2}\) are shown as listed in Table 3. The medium oscillator (\( \lambda_o \)) and long-wavelength refractive index (\( n_\infty \)) were evaluated using the single term Sellmeier oscillator [51]:

\[ \frac{n_\infty^2 - 1}{n^2 - 1} = 1 - \left(\frac{\lambda_o}{\lambda}\right)^2 \quad \ldots \ldots \ldots \ldots (16) \]
Thus, as seen in Fig. 8(c), relation \((n^2-1)^{-1}\) and \(\lambda^{-2}\) are used to produce \(n_\infty\) and \(\lambda_o\) from the linear part's intercept and slope, respectively, as given in Table (3). Additionally, the next equation can be used to estimate the values of single oscillator length \(S_o\) by\[52]\:

\[ S_o = \left(\frac{n_\infty^2 - 1}{\lambda_o^2}\right) \ldots \ldots \ldots (17) \]

It is evident that the \(n_\infty\) and \(S_o\) progressively rise as ion beam affects, and conversely, the \(\lambda_o\) values drop for the irradiated films. Meanwhile, the following relation \[53\] links the incident photon wavelength and \(\epsilon_i\) in the Drude model:

\[ \epsilon_i = \frac{1}{4\pi^3\epsilon_o} \left(\frac{e^2 N}{c^3m^*\tau}\right)\lambda^3 \ldots \ldots (18) \]

Plotting the \(\epsilon_i\) and \(\lambda^3\) which are specified in Table (3) as illustrated in Fig. 8(d) yields the relaxation time (\(\tau\)). It is shown that for irradiated 9x10^{17} ions.cm\(^{-2}\), the time relaxation progressively decreases from 21x10^{-15} (sec) for PVA/CuO to 2.9x10^{-15} (sec). These results showed that ion beam irradiation enhanced nanocomposite films, which makes the nanocomposite suitable for use in high-speed optoelectronic devices.

The following formula \[54\] can be used to characterize a material mode's nonlinear optical (NLO) response:

\[ P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 \ldots \ldots (19) \]

Where \(\chi^{(1)}\) is the first linear, \(\chi^{(2)}\) is the second-order NLO, and \(\chi^{(3)}\) is the third-order NLO. \(P\) represents polarization in this example. The relationships shown below are utilized to estimate \(\chi^{(1)}\) and \(\chi^{(3)}\) \[55\].

\[ \chi^{(1)} = \frac{(n^2-1)}{4\pi} \ldots \ldots \ldots (20)\text{, and} \]

\[ \chi^{(3)} = A\left(\chi^{(1)}\right)^4 \ldots \ldots (21) \]

The NLO refractive index \(n(\lambda)\) is given by \[56\]:

\[ n(\lambda) = n_o(\lambda) + n_2(E^2) \ldots \ldots \ldots (22) \]

The refractive index \((n_2)\) can be used to compute the NLO refractive index \[56\].

\[ n_2 = \frac{12\pi X^{(3)}}{n_o} \ldots \ldots \ldots (23) \]

Figures 9(a,b) display the change in \(\chi^{(1)}\) and \(\chi^{(3)}\) with wavelength (\(\lambda\)) for the pure and irradiated films. Ion irradiation increases both \(\chi^{(1)}\) and \(\chi^{(3)}\) values. This is because of the defect centers, which cause
local polarizabilities that rise with radiation [57]. Moreover, the variation in $n_2$ with wavelength is shown in Fig. 9(c). Similar to $\chi(3)$, the $n_2$ increases progressively with the ion beam.

Table 3
The $W_p$, $n_\infty$, $\lambda_o$, $S_o$, and $\tau$ of pure and treated irradiated PVA/CuO films.

<table>
<thead>
<tr>
<th>The samples</th>
<th>$W_p \times 10^{12}$ (sec$^{-1}$)</th>
<th>$n_\infty$</th>
<th>$\lambda_o$ (nm)</th>
<th>$S_o \times 10^{12}$ (m$^{-2}$)</th>
<th>$\tau \times 10^{-15}$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA/CuO</td>
<td>0.0006</td>
<td>1.015</td>
<td>407</td>
<td>0.63</td>
<td>21</td>
</tr>
<tr>
<td>3x10$^{17}$ ions.cm$^{-2}$</td>
<td>0.0009</td>
<td>1.026</td>
<td>471</td>
<td>0.62</td>
<td>9.1</td>
</tr>
<tr>
<td>6x10$^{17}$ ions.cm$^{-2}$</td>
<td>0.0012</td>
<td>1.032</td>
<td>537</td>
<td>0.47</td>
<td>6.3</td>
</tr>
<tr>
<td>9x10$^{17}$ ions.cm$^{-2}$</td>
<td>0.0015</td>
<td>1.047</td>
<td>834</td>
<td>0.15</td>
<td>2.9</td>
</tr>
</tbody>
</table>

4. Conclusion

The PVA/CuO nanocomposite were manufactured using a solution casing. The XRD pattern clearly indicates the successful production of PVA/CuO nanocomposite films. The greatest intensity of the bombarded film has dropped, as shown by the FTIR tests. This indicates that the chain session process is happened in the irradiation films. Based on the SRIM/TRIM simulation program, the vacancy production behavior for a broad range of incident ion-target interaction were examined. The optical characteristics of PVA/CuO were studied for both pure and bombarded films. The relaxation time decreasesd with the bombarded ions. With no treatment, the dispersion energy of PVA/CuO increases from 0.098 eV to 0.26 eV. In addition, the static refractive index increases from 1.014 to 1.03 for irradiated 6x10$^{17}$ ions.cm$^{-2}$. In order to improve the optoelectronic device's performance of PVA/CuO, the results prove that irradiation improves the optical properties of PVA/CuO, low energy argon ion beam fluence could be utilized.

Declarations

Author Contributions: A. A., M. M. and H. M. wrote the main results, R. A. and M. E. shared the funding. All authors read and approved the final manuscript.

Conflicts of interest: The authors declare no conflict of interest.

Competing interests: The authors have no relevant financial

Availability of data and materials: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

![Figure 1](image)

Figure 1

Broad beam cold cathode ion source with the electrical circuit.
Figure 2

a) ionization of collided argon ions with PVA/CuO b) collisions events of collided ions with PVA/CuO.

Figure 3

XRD of the untreated and irradiated PVA/CuO composite films.
Figure 4

FTIR spectra of pure and irradiated PVA/CuO composite films.

Figure 5

(a) $K$ with $\lambda$, (b) $R$ with $\lambda$, for pure and treated PVA/CuO.
Figure 6
(a) $n$ with $\lambda$, and (b) $\sigma_{\text{opt}}$ with $\lambda$, for pure and treated PVA/CuO.

Figure 7
(a) $\varepsilon_r$ with $\lambda$ and (b) $\varepsilon_i$ with $\lambda$, for pure and irradiated PVA/CuO films
Fig. 8: (a) $(n^2-1)^{-1}$ and $(hv)^2$, (b) $\varepsilon_r$, and $(\lambda^2)$, (c) $(n^2-1)^{-1}$ and $(\lambda)^2$, and (d) $\varepsilon_i$ and $(\lambda)^3$, for pure and irradiated PVA/CuO films.

Figure 8

See image above for figure legend
Fig. 9: (a) $\chi^{(1)}$ with $\lambda$, (b) $\chi^{(3)}$ with $\lambda$, and (c) $n_2$ with $\lambda$, for pure and irradiated PVA/CuO

Figure 9

See image above for figure legend