Structural, Optical and Electrical Properties of Cu$_{0.6}$Co$_x$Zn$_{0.4-x}$Fe$_2$O$_4$ (x = 0.0, 0.1, 0.2, 0.3, 0.4) Soft Ferrites

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Abstract: A series of cobalt-inserted copper zinc ferrites, Cu$_{0.6}$Co$_x$Zn$_{0.4-x}$Fe$_2$O$_4$ (x = 0.0, 0.1, 0.2, 0.3, 0.4) having cubic spinel structure were prepared by the coprecipitation method. Various characterization techniques, including XRD, FTIR, UV-vis and I–V were used to investigate structural optical and electrical properties, respectively. The lattice constant was observed to be decreased as smaller ionic radii Co$^{2+}$ (0.74 Å) replaced the higher ionic radii Zn$^{2+}$ (0.82 Å). The presence of tetrahexedral and octahedral bands was confirmed by FTIR spectra. Optical bandgap energy was determined in the range of 4.44–2.05 eV for x = 0.0 to 0.4 nanoferrites, respectively. DC electrical resistivity was measured and showed an increasing trend (5.42 × 10$^7$ to 6.48 × 10$^7$ Ω-cm) with the addition of cobalt contents as cobalt is more conductive than zinc. The range of DC electrical resistivity (10$^8$ ohm-cm) makes these nanomaterials potential candidates for telecommunication devices.

Keywords: ferrites; Co; Zn; electrical properties

1. Introduction

Ferrites, a group of familiar magnetic materials with general formula MFe$_2$O$_4$, are used extensively in electronic, electrical, medical, and industrial applications due to their chemical constancy, economical production cost and, improved electric, magnetic and thermal characteristics. Soft ferrites are attractive materials with modest magnetization, larger anisotropy and fine electrical insulation. Many researchers have explained the optical, electrical and magnetic properties of zinc doped ferrites. Ferrites behave like insulators at room temperature and are semiconductors at a higher temperature. The electrical and magnetic properties of zinc ferrites can be improved through partial insertion of divalent ions like Cu, Co, Ni, Mn and Mg. Santosh Bhukalet al. reported the copper-doped CoZn ferrites prepared by sol–gel auto combustion technique and found that all nanomaterials have semiconducting nature [1]. K. Anu et al. synthesized Zn-doped cobalt ferrites by applying a two-step process and investigated the variations in electrical and magnetic properties [2]. B. B. V. S. Vera Prasad al. reported the fabrication of Cu-inserted copper zinc ferrites by auto combustion method [3]. They determined the decrease in saturation magnetization with the addition of copper contents. Muhammad Farooq Warsi et al. fabricated erbium-doped NiCo spinel ferrites by using a coprecipitation route and found a decrease in DC electrical resistivity in the range of 6.20 × 10$^7$–0.03 × 10$^7$ ohm-cm [4]. They observed that these materials are potential candidates for various technological devices. Sandeep B. Somvanshi et al. designed magnesium-inserted soft zinc ferrites and resolved...
thermal, structural, optical and spectral characteristics [5]. They concluded the increase in optical bandgap energy in the range of 1.96–2.39 eV. Structural, optical and electrical properties of La$^{3+}$-inserted ZnMgNi soft ferrites were discussed by M. S. Hasan et al. [6].

The materials inserted in the current composition enhance the electrical and optical properties. Also, the DC electrical resistivity in the range of $10^8$ ohm-cm makes Cu-Co-Zn ferrites potential candidates for telecommunication devices. The synthesis route, size of particles and distribution of metal ions on tetrahedral and octahedral sites play vital role in determining the characteristics of soft ferrites. Zinc occupies a tetrahedral site, while the rest of metals, copper and cobalt, partially occupy tetrahedral and octahedral sites. A careful study of the literature shows that various methods have been used by researchers to synthesize the nanomaterials, such as coprecipitation, sol–gel, hydrothermal, microemulsion, mechanical milling etc. [7,8]. Coprecipitation is a popular, emerging, and economical synthesis method having enormous potential [6]. Limpidness and homogeneity are the significant properties of materials synthesized by coprecipitation that provides better impacts to this technique. In recent research work we have fabricated Co$^{2+}$-inserted Cu$_{0.6}$Co$_x$Zn$_{0.4-x}$Fe$_2$O$_4$ soft ferrites where $x = 0.0, 0.1, 0.2, 0.3, 0.4$ applying coprecipitation technique. Furthermore, structural, optical and electrical parameters of Co-inserted Cu-Zn-Ni soft ferrites were examined.

2. Results and Discussion

2.1. XRD Analysis

The XRD patterns of Co-doped Cu$_{0.6}$Co$_x$Zn$_{0.4-x}$Fe$_2$O$_4$ soft ferrites where $x = 0.0, 0.1, 0.2, 0.3, 0.4$ synthesized by coprecipitation technique are shown in Figure 1. The formation of single-phase cubic spinel structure is confirmed by prominent diffraction peaks (220), (311), (400), (422) and (511). XRD pattern confirmed that cobalt is effectively inserted into the spinel structure. By using Scherrer’s relation, the average crystallite size ($D$) was determined as [9]:

$$D = \frac{0.9\lambda}{\beta \cos \theta}$$

(1)

where $\lambda$ and $\beta$ indicate wavelength (1.542 Å) and full width at half maximum (FWHM) of peaks, respectively. Bragg’s law was used to investigate inter planer spacing or distance between crystal planes ($d$) as [10],

$$d = \frac{n\lambda}{2\sin \theta}$$

(2)

where $n = 1$ is the order of reflection for cubic structure and $\theta$ is the diffraction angle obtained from the XRD pattern. Table 1 shows the calculated values of average crystallite size and the lattice constant by using XRD data. Crystallite size confirmed that nanoferrites have a cubic spinel structure. The average crystallite size was determined in the range of 26.74–16.24 nm for $x = 0.0$ to 0.4 nanoferrites, correspondingly. Such decreasing behavior of crystallite size is due to the difference in ionic radii of Co$^{2+}$ (0.74 Å) and Zn$^{2+}$ (0.82 Å). Due to such difference in ionic radii during the replacement of Co by Zn on the lattice strain, some of the Co ions may reside at grain boundaries and generate stress there. Such behavior may cause a reduction in the crystallite size [11]. Lattice constant ($a$) was established by applying the equation as:

$$a = d \sqrt{h^2 + k^2 + l^2}$$

(3)

where $d$ is the interplanar spacing, $(hkl)$ are Miller indices also ($a = b = c$) and ($\alpha = \beta = \gamma = 90^\circ$). It can be observed from Figure 1 that the most prominent peak (311) is shifting towards the right as the value of $2\theta$ is rising. Such rising factors bring diminution in interplanar spacing, as illustrated in Table 1. Lattice constants are observed in the range of 8.438–8.401 Å. It can be examined that lattice parameters have a decreasing style with the enrichment of Co$^{2+}$ contents. This decreasing trend is attributed to the substitution of smaller ionic radii Co$^{2+}$ (0.74 Å) with higher ionic radii Zn$^{2+}$ (0.82 Å). In addition, the shifting of the most prominent peak (311) and decreasing behavior of interplanar spacing causes the decrease
in lattice constant. Furthermore, the doping percentage (0.1%) is very small; hence very small decreasing behavior is shown by the lattice constant. Figure 2 shows the trends demonstrated by average crystallite size and lattice constant with the increase of Cobalt contents. Various other parameters like the volume of the unit cell \( V \), X-ray density \( d_x \) and bulk density \( d_b \) were also determined as enlisted in Table 1 by using the relations as:

\[
V = a^3 
\]

\[
d_x = \frac{8M}{N_A V} 
\]

\[
d_b = \frac{m}{\pi r^2 h} 
\]

where \( M \), \( N_A \) and \( V \) are a molecular mass of compositions, Avogadro’s number is \( 6.0221 \times 10^{23} \text{ g mol}^{-1} \) and volume of the unit cell, respectively. In addition, \( m \) is mass, \( r \) is the radius, and \( h \) is the width of nanoferrites pallets. It can be observed from the Table that the volume of the unit cells for spinel ferrites has the same declining trend as the lattice constant. X-ray density was found greater than the bulk density; however, they are presenting opposite natures by means of an increase in \( \text{Co}^{2+} \) concentration. Bulk density showed a reducing trend because Co has a lower atomic weight (58.93 amu) and density (8.86 g cm\(^{-3}\)) as compared to Zn with atomic weight (65.38 amu) and density (8.91 g cm\(^{-3}\)) [12]. Figure 3 demonstrates the trends of \( d_x \) and \( d_b \) with the increase of \( \text{Co}^{2+} \) concentration. Porosity was determined by using the relation as:

\[
P(\%) = \left[ 1 - \frac{d_b}{d_x} \right] \times 100 
\]

It can be seen from Table 1 that porosity increased with the increase of cobalt contents. This parameter increase is due to the lower atomic mass of cobalt (58.93 amu) than zinc (65.38 amu).

![Figure 1](image_url)  
**Figure 1.** XRD patterns of Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) soft ferrites where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \).
Figure 2. Trends for crystallite size and lattice constant with the increase of Co$^{2+}$ concentration.

Figure 3. X-ray density and bulk density for Co$^{2+}$-inserted soft ferrites.

Table 1. $2\theta$ of (311) peak, lattice constant ($a_{\text{exp}}$), crystallite size ($D$), unit cell volume ($V$), d-spacing ($d$), X-ray and bulk densities ($d_x$ and $d_b$) and porosity ($P$) for Cu$_{0.6}$Co$_{x}$Zn$_{0.4-x}$Fe$_2$O$_4$ soft ferrites where $x = 0.0, 0.1, 0.2, 0.3, 0.4$.

| Parameter          | $X = 0.00$ | 0.1   | 0.2   | 0.3   | 0.4   |
|--------------------|------------|-------|-------|-------|-------|
| $2\theta$ of (311) peak | 35.32      | 35.34 | 35.40 | 35.43 | 35.48 |
| $a_{\text{exp}}$ (Å)   | 8.438      | 8.434 | 8.420 | 8.415 | 8.401 |
| $D$ (nm)            | 26.74      | 22.28 | 22.97 | 16.24 | 21.84 |
| $V$ (Å$^3$)         | 600.78     | 599.93| 596.98| 595.88| 592.91|
| $d$ (Å)             | 2.544      | 2.542 | 2.538 | 2.535 | 2.533 |
| $d_x$ (g-cm$^{-3}$)  | 5.306      | 5.299 | 5.311 | 5.307 | 5.318 |
| $d_b$ (g-cm$^{-3}$)  | 4.054      | 4.043 | 4.032 | 4.021 | 4.011 |
| $P$ (%)             | 23.59      | 23.70 | 24.08 | 24.23 | 24.57 |

2.2. Fourier-Transformation Infrared Spectroscopy (FTIR)

FTIR is an excellent method to examine cation allocation at tetrahedral and octahedral sites in soft ferrites. Narrow symmetries in crystalline solids and the existence or extinction of Fe$^{2+}$ ions are also determined by this tool [13]. Two major absorption bands $\nu_1$ and $\nu_2$ were shown by the IR spectra of the specimen as in Figure 4. Higher and lower frequency bands ($\nu_1$ and $\nu_2$) are associated with oxygen-tetrahedron (Fe-O) and oxygen-octahedron (O-Fe-O) bending vibrations, respectively [14]. Both $\nu_1$ and $\nu_2$ are mostly ascribed to Fe$^{3+}$-(A/B)-O$^{2-}$ vibrations due to their maximum valency (+3) in spinel structures. The
wave number ranges for $\nu_1$ and $\nu_2$ are 476.62–462.94 cm$^{-1}$ and 540.97–524.32 cm$^{-1}$ correspondingly with Co$^{2+}$ insertion for present fabricated ferrites. The disparity was noticed in $\nu_1$ and $\nu_2$ with the increase in the insertion of cobalt contents. The decreasing trend shown by $\nu_2$ is due to altering size in the octahedron. The shifting of Fe$^{3+}$ with Co$^{2+}$ ions towards the octahedral site causes a decrease in $\nu_2$ size. In the same way, the rest of the Co$^{2+}$ ions reside at the tetrahedral site and cause shrink in $\nu_1$. The alterations in Fe$^{3+}$-O$^{2-}$ bond length at A-site 0.189 nm and at B-site 0.199 nm are responsible for the modifications in-band locations of $\nu_1$ and $\nu_2$, respectively [12]. The inverse spinel structure is signified by bands $\nu_1$ and $\nu_2$, where Fe$^{3+}$ ions are dispersed at A and B sites are based on stoichiometric ratios [15].

The decrease in frequency band $\nu_1$ is due to the difference of ionic radii of Co$^{2+}$ (0.74 Å) and Zn$^{2+}$ (0.82 Å) at the tetrahedral site and M-O vibrations [12]. The locations of wave numbers ($\nu_1$ and $\nu_2$), along with the intensities and force constants, are illustrated in Table 2. The force constants were determined by the application of the following relations:

$$K = 4\pi^2 v^2 C^2 m$$

(8)

where $v$, $C$ and $m$ are wave number, speed of light and mass of Fe$^{3+}$-O$^{2-}$ ions ($2.061 \times 10^{-23}$ g), respectively. It can be observed from Table 2 that determined values of force constants for tetrahedral and octahedral bands are demonstrating decreasing trends. Such decreasing trend may be due to the decrease in ionic radii of tetrahedral and octahedral sites. In addition, the change in Fe$^{3+}$-O$^{2-}$ internuclear lengths alters the band positions at A and B sites [16,17].

![Figure 4. FTIR spectra of synthesized nanoferrites.](image)

**Table 2.** FTIR band spectrum showing absorption bands ($\nu_1$ and $\nu_2$), intensities ($I_1$ and $I_2$) and force constants ($K_T$ and $K_o$).

| $X$ (cm$^{-1}$) | $\nu_1$ (cm$^{-1}$) | $I_1$ (%) | $K_T \times 10^5$ (Dyne cm$^{-1}$) | $\nu_2$ (cm$^{-1}$) | $I_2$ (%) | $K_o \times 10^5$ (Dyne cm$^{-1}$) |
|---------------|---------------------|-----------|-----------------------------------|---------------------|-----------|-----------------------------------|
| 0.0           | 540.97              | 62.74     | 2.15                              | 476.62              | 64.05     | 1.66                              |
| 0.1           | 538.73              | 59.73     | 2.13                              | 473.83              | 67.19     | 1.64                              |
| 0.2           | 537.49              | 54.44     | 2.12                              | 472.86              | 62.11     | 1.63                              |
| 0.3           | 524.77              | 62.31     | 2.03                              | 467.87              | 63.14     | 1.60                              |
| 0.4           | 524.32              | 47.46     | 2.02                              | 462.94              | 47.27     | 1.56                              |
2.3. UV-Vis Spectroscopy

Tauc’s relation was used to determine bandgap energy \( E_g \) of Co\(^{2+}\)-doped Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) soft ferrites where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \) as given below:

\[
E_g = \frac{h\nu}{\lambda}
\]

\[
\alpha h\nu = B(h\nu - E_g)^m
\]

where \( h, \nu, B \) and \( m \) are Planck’s constant, frequency and constants, respectively. In this work, \( E_g \) has been obtained by drawing a plot between \( (\alpha h\nu)^2 \) and incident photon energy \( (h\nu) \). \( E_g \) is decreased by the replacement of Zn\(^{2+}\) with Co\(^{2+}\) concentration, as represented in Tauc’s plot of Figure 5. It is due to the fact that Co is more conductive than Zn. The declining trend of \( E_g \) for \( X = 0.00–0.60 \) is shown in Table 3. Furthermore, it can be observed from the figure that by the enhancement of Co contents, the curve is becoming more linear.

![Figure 5. Bandgap energies (\( E_g \)) of Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) soft ferrites where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \).](image)

### Table 3. Bandgap energy (\( E_g \)), electrical resistivity (\( \rho_{DC} \)) and drift mobility (\( \mu_d \)) for nanoferrites.

| Parameters | Results          |
|------------|------------------|
| \( X \)    | 0.0  | 0.1  | 0.2  | 0.3  | 0.4  |
| \( E_g \) (eV) | 4.44 | 4.05 | 3.64 | 3.23 | 2.05 |
| \( \rho_{DC} \) (Ω·cm) | 5.42 \times 10^8 | 5.69 \times 10^8 | 5.90 \times 10^8 | 6.15 \times 10^8 | 6.48 \times 10^8 |
| \( \mu_d \) (cm\(^2\)V\(^{-1}\)s\(^{-1}\)) | 3.07 \times 10^{-14} | 2.92 \times 10^{-14} | 2.82 \times 10^{-14} | 2.70 \times 10^{-14} | 2.57 \times 10^{-14} |

2.4. Electrical Properties

2.4.1. DC Electrical Resistivity

In Co\(^{3+}\) substituted Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) soft ferrites where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \) synthesized by coprecipitation technique. DC resistivity (\( \rho_{DC} \)) was carried out by application of four-probe methods at 313 K temperature. \( \rho_{DC} \) was investigated by employing the equation below as:

\[
\rho_{DC} = \frac{\pi}{\ln 2} \left( \frac{V}{T} \right) \cdot t
\]

where \( V \) and \( I \) are current, and voltage and \( t \) is the thickness of nanoferrite pallets. Table 3 shows inspected values of DC electrical resistivities for Co\(^{2+}\)-doped nanoferrites. The DC electrical resistivity (\( \rho_{DC} \)) of Co\(^{2+}\) is \( 5.6 \times 10^{-8} \) ohm-cm, while the resistivity (\( \rho_{DC} \)) of Zn\(^{2+}\) is \( 5.5 \times 10^{-8} \) ohm-cm. It can be observed that \( \rho_{DC} \) of cobalt is greater than the zinc. Hence, the overall behavior of resistivity must be increased. It can be examined that \( \rho_{DC} \) is increasing with the increase of Co\(^{2+}\) contents for \( x = 0.0 \) to 0.4. The hopping of electrons is responsible for the conduction process in nanoferrites. This conduction process occurs due
to the hopping of electrons among Fe$^{2+}$ and Fe$^{3+}$ electrons. As Fe$^{2+}$ ions partially occupy both tetrahedral A-site and octahedral B-site whereas, Co$^{2+}$ and Zn$^{2+}$ also partially occupy A-site and B-site. Hence, at A-site, with the increase in Co$^{2+}$ contents, the Zn$^{2+}$ contents at B-site decline. Hence, the movement of iron ions from A-site to B-site fulfills the lack of Zn$^{2+}$ ions at B-site. The decrease in conduction mechanism is because of enhancement in divalent and trivalent iron ions at B-site in soft ferrites, causing the decrease in DC electrical resistivity. Hence, the decrease in DC resistivity confirms the semiconducting behavior of fabricated nanomaterials [18].

The demonstrated behavior of $\rho_{DC}$ is also because of factors like grain size and grain boundaries. The grains are superior conductive to the grain boundaries. The incessant series of ions makes the mobility of charge carriers easier. In addition, the resistivity has an inverse relation with the square of grain size. The reduction in grain size may increase the grain boundaries and increase the resistivity [3,19].

2.4.2. Effect of Co on DC Resistivity

The increase of Co concentration in the Co-Cu-Zn ferrites from 0.0–0.4 the DC resistivity ($\rho_{DC}$) was found to increase in the range of $5.42 \times 10^8$–$6.48 \times 10^8 \, \Omega \cdot \text{cm}$, as illustrated in the Arrhenius plot of Figure 6. The observed behavior of $\rho_{DC}$ with the increase of Co concentration can be described by Verwey and De Boer’s hopping principle [17]. This principle states that the hopping of electrons among the ions of similar elements in different valence conditions, e.g., Fe$^{2+}$ and Fe$^{3+}$ ions, scattered erratically over crystallographic lattice sites and create electronic conduction in ferrites [20]. The distances among the ions due to hopping and activation energy are two factors involved in the probability of hopping. The exchange interactions Co$^{2+} \leftrightarrow$ Co$^{1+} + e^{1-}$, Cu$^{2+} \leftrightarrow$ Cu$^{1+} + e^{1-}$, Zn$^{2+} \leftrightarrow$ Zn$^{1+} + e^{1-}$, Fe$^{3+} \leftrightarrow$ Fe$^{2+} + e^{1-}$, etc. are caused for p-type charge transporters in ferrite phases. Co is partially distributed on A and B sites and is responsible for partially replacing the Fe$^{3+}$ ions on the B-site. Hence, the increase in Co ions replacement at B-site causes the decrease in Fe$^{3+}$ ions on the B-site. Furthermore, the decrease in activation energy with the increase of Co concentration causes the few Fe ions to relocate from A to B site and reducing the Fe ions at B-site. Hence the cations switching level among Fe$^{2+}$ and Fe$^{3+}$ enhances. As a result, resistivity increases with the increase of Co contents in Co-Cu-Zn nanoferrites. In addition, the illustrated resistivity range ($10^8 \, \Omega \cdot \text{cm}$) of fabricated ferrites is highly applicable in telecommunication devices [21,22].

2.4.3. Drift Mobility

The following relation was utilized to determine the drift mobility ($\mu_d$) as:

$$\mu_d = \frac{1}{\eta \rho_{DC}}$$  \hspace{1cm} (12)
where \( \eta \) and \( e \) are the concentration of charge carriers and charge of electrons, respectively. The concentration of charge carriers (\( \eta \)) can be established by using the relation as:

\[
\eta = \frac{N_A \rho_b P_{Fe}}{M} \tag{13}
\]

where \( N_A \) is the Avogadro number having value \( 2.022 \times 10^{23} \) mol\(^{-1} \), \( \rho_b \) is bulk density, \( P_{Fe} \) is a number of compositional trivalent iron atoms, and \( M \) is the molecular weight of composed nano ferrites. The determined drift mobility (\( \mu_d \)) values for all Co-doped Co-Cu-Zn soft ferrites were found to increase as enlisted in Table 3. Drift mobility reduced from \( 3.07 \times 10^{-14} \) to \( 2.57 \times 10^{-14} \) cm\(^2\)V\(^{-1}\)s\(^{-1} \) for \( x = 0.0–0.4 \) nanoparticles, respectively. Results indicated that the specimens with greater resistivity have short mobility and vice versa. With an increase in temperature, the \( \mu_d \) decreased. The decreasing trend shown in Figure 7 shows that alteration in charge carrier mobility was due to dissimilarity in resistivity by means of temperature. Thus, with an increase in temperature, the charge carriers started hopping between the sites, illustrating the increase in resistivity and enhancement in drift mobility for nano ferrites.

![Figure 7. Drift mobility for Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) soft ferrites where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \).](image)

### 3. Materials and Methods

\( \text{Co}^{2+} \)-substituted Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) where \( x = 0.0, 0.1, 0.2, 0.3, 0.4 \) nanoparticles were synthesized by coprecipitation method. Nitrates of copper, cobalt, zinc and iron were used to prepare Co-doped Cu\(_{0.6}\)Co\(_x\)Zn\(_{0.4-x}\)Fe\(_2\)O\(_4\) nano ferrites. The stoichiometric ratios of desired salts were dissolved in deionized water. The solutions were stirred at \( 80 ^\circ \text{C} \), and sodium hydroxide (NaOH) mixed in water was added to maintain a pH of 11. The resulting solutions were placed in a water bath at \( 80 ^\circ \text{C} \) for 24 h, followed by filtration. The particles were cleaned with deionized water followed by ethanol until a pH of 7 was achieved. The obtained crystals were dried in the oven and ground into a fine powder. The resulting powder of each sample was sintered at \( 800 ^\circ \text{C} \) for 8 h. The whole synthesis process is shown in Figure 8.

The structures of nano ferrites were determined using various techniques. X-ray powder diffraction (Bruker D8) scheme with Cu K\(_\alpha\) supply having wavelength \( 1.5406 \) Å was used to authenticate arrangements of single-phase spinel cubic formation in all synthesized nano ferrites. Numerous structural parameters, including crystallite size, lattice constant, density (bulk and X-ray), porosity and dislocation density, were computed by XRD analysis. In order to determine the bulk density, pallets of nano ferrites were fabricated with radius \( r = 0.35 \) cm and width \( h = 0.153 \) cm). For this purpose, a hydraulic press machine was used at 13 t pressure for 30 min for each pallet. UV-vis spectroscopy was used to determine bandgap energy (\( E_g \)) of all specimens. Adsorption bands and force constant were calculated...
by (Perkin) FTIR spectroscopy. The four-probe I–V technique was utilized to study the DC electrical resistivity and drift mobility.

Figure 8. Schematic of the experimental setup.

4. Conclusions

Ferrite nanoparticles were prepared by the coprecipitation method. The insertion of cobalt in Cu$_{0.6}$Co$_x$Zn$_{0.4-x}$Fe$_2$O$_4$ ferrites brought novel modifications in structural, optical and electrical characteristics. XRD, FTIR, UV-vis and four-probe I–V techniques were used to characterize the samples. The lattice constant decreased with the increase of cobalt due to the smaller ionic radius of cobalt than the zinc. Crystallite size, X-ray density, bulk density and porosity were also measured. Both absorption bands (tetrahedral and octahedral), along with their corresponding intensities, decreased with the increase of cobalt contents leading to a decrease in force constants for composed nanoferrites. DC electrical resistivity increased with the increase of cobalt concentration, confirming the semiconductor nature of composed nanoferrites. The determined range of DC electrical resistivity indicated that these fabricated materials are highly applicable in telecommunication devices.

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