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Analytical Investigation of Co-precipitated SnO_2-CuO Nanocomposite: Synthesis, Characterization, and Performance Assessment

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ABSTRACT

SnO_2–CuO nanocomposites were prepared in the 1:1 molar ratio using the co-precipitation technique followed by calcination at temperatures of 300 °C to 600 °C. The results obtained by XRD analysis revealed the transition from amorphous to highly crystalline nature and an increase in the size of crystallites from 8 nm to 13 nm. Microstrains and dislocation densities were observed to have decreased. The morphology changes from irregular block-like particles to fine-grained particles at higher calcination temperatures were clearly observed using SEM. UV–Vis spectroscopy studies indicated that the absorption edge had shifted towards higher wavelengths and the band gap values had been narrowed with rising calcination temperatures. FTIR studies also confirmed the decrease in O-H vibrational intensity and hence reduced surface hydroxyl group content. The electrical characteristics of the samples also showed significant temperature effects on conductivity. Impedance spectroscopy analysis was performed on all samples and the results showed unique dielectric behaviors. It was noted that only the sample with a calcination temperature of 500 °C showed well-defined semicircular arcs, low dielectric constants and losses, and steady AC conductivities. This result is attributed to the successful formation of p-n junctions in this sample due to strong phase interaction between SnO_2 and CuO phases.

Keywords: SnO_2 CuO Nanocomposite, p-n heterojunction, gas sensing, impedance spectroscopy, band gap engineering

GRAPHICAL ABSTRACT

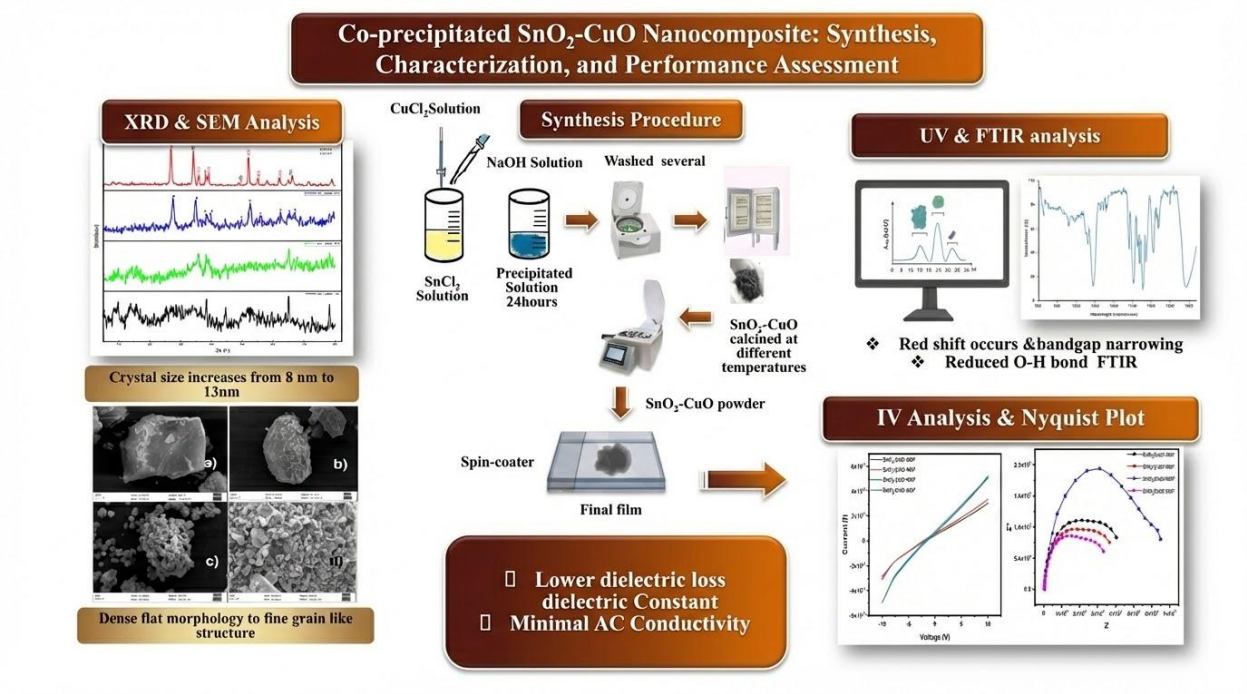


Figure 1: Represents Schematic diagram of SnO_2-CuO Composite Electrical Assessment

1. Introduction

Electronic devices play a crucial role in modern technology, with metal oxide thin films serving as key components in applications such as optoelectronics, sensors and transistors **[1]**. Metal oxides have attracted significant attention due to their low cost, abundance, environmental compatibility and tunable electrical and optical properties, including band gap, charge carrier mobility and luminescence **[2]**. These materials are widely utilized in applications such as energy storage, catalysis, biosensors and gas sensing technologies **[3]**. Among various metal oxides, SnO_2,

CuO, NiO, TiO_2 and WO_3 have been extensively studied due to their versatile functional properties **[4]-[6]**. Semiconducting metal oxides are broadly classified into n-type and p-type materials based on their dominant charge carriers. N-type semiconductors, such as SnO_2, exhibit electron-rich donor defects, whereas p-type materials like CuO possess hole-dominant conduction due to acceptor states **[7]**. The combination of p-type and n-type semiconductors can lead to the formation of p–n heterojunctions, which significantly influence charge transport behavior and enhance device performance **[8]**. Gas sensors based on semiconducting metal oxides have gained considerable interest due to their low cost, fast response, high sensitivity and ease of fabrication**[9]**. These sensors operate based on surface interactions between gas molecules and the sensing material, which modulate electrical conductivity. However, achieving high selectivity remains a challenge **[10]**. Tin dioxide (SnO_2) is a widely studied n-type semiconductor with a wide band gap (~3.6 eV) and excellent chemical and thermal stability. It exhibits high optical transparency in the visible region and has applications in gas sensors, photodetectors, supercapacitors and transparent conducting electrodes **[11]-[13]**. On the other hand, cupric oxide (CuO) is a p-type semiconductor with a narrow band gap (~1.2 eV), known for its high sensitivity to gases and excellent electrical properties **[14],[15]**. The combination of SnO_2 and CuO in a composite system enables the formation of p–n junctions, which can significantly enhance sensing performance through improved charge separation and interfacial interactions. Various synthesis techniques, including hydrothermal, sol–gel and co-precipitation methods, have been employed to prepare metal oxide nanostructures**[16]**. Among these, the co-precipitation method is particularly advantageous due to its simplicity, low cost and ability to produce uniform nanoparticles with controlled size and morphology **[17]**. The use of NaOH as a precipitating agent plays a critical role in controlling pH, nucleation and crystal growth, thereby influencing the structural and functional properties of the

material **[18]**. Calcination is a key post-synthesis process that significantly affects crystallinity, phase formation, particle size and defect concentration. Increasing calcination temperature generally enhances crystallinity and grain growth while reducing structural defects, which in turn influences optical and electrical properties **[19]**. Therefore, controlling calcination temperature is essential for optimizing material performance. Although several studies have reported SnO_2–CuO composites for gas sensing applications, limited attention has been given to understanding the relationship between calcination-induced microstructural evolution and interfacial electrical and dielectric properties. In this work, we present a systematic investigation of SnO_2–CuO nanocomposites synthesized via co-precipitation and calcined at different temperatures. The study focuses on correlating structural, optical and electrical properties with calcination temperature, highlighting the role of interfacial p–n junction interactions. Our results demonstrate that an optimal calcination temperature of 500 °C leads to enhanced interfacial resistance, reduced dielectric loss and improved charge transport behavior. These findings provide valuable insights into structure–property relationships and establish the SnO_2–CuO nanocomposite as a promising material for advanced gas sensing applications.**[20][24]**

2. Synthesis method

The initial materials used for synthesis were tin(II) chloride monohydrate ($SnCl_2 \cdot H_2O$), copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$), sodium hydroxide (NaOH) and distilled water without further purification. Firstly, 1 g of $SnCl_2 \cdot H_2O$ was dissolved in 20 mL of distilled water and magnetically stirred to get a clear solution. Similarly, 1 g of $CuCl_2 \cdot 2H_2O$ was dissolved in 20 mL of distilled water in another beaker. The pH of both solutions was adjusted to around 9 by adding NaOH solution dropwise. Next, $CuCl_2$ solution was added gradually to the $SnCl_2$ solution under continuous stirring to promote uniform mixing and precipitation. This process was stirred for an

equal time to get a uniform mixture and precipitation. The generated precipitates were separated using centrifugation at 2000 rpm for 10 min. The precipitates were washed three times with distilled water and twice with ethanol to eliminate impurities. Drying was done using vacuum drying at 80°C for 6 h to prepare the precursor powder. Finally, the precursor was heated at different temperatures (300°C, 400°C, 500°C and 600°C) for a predetermined period to produce SnO_2-CuO nanocomposites.

3. Thin film fabrication method

The fabricated SnO_2-CuO nanocomposite powder was suspended in ethanol and sonicated for 30 minutes to produce a homogenous suspension that would be used in coating the glass substrates. Substrates were cleaned before the films were coated on them using the traditional cleaning method. The substrates were fixed onto the vacuum holder of a spin coater machine. Next, the coating solution was applied dropwise on the substrate, followed by spinning it at 3000 revolutions per minute (RPM). The coating process was performed ten times in order to coat the desired thickness of the films. Each of the coatings was dried using a hot plate heated at 100 degrees Celsius to evaporate the solvent. Finally, the thickness of the obtained thin films was measured using a stylus profilometer. The resulting films had thicknesses of 1.07 μm, 1.45 μm, 0.5 μm and 0.04 μm.

4. Material Characterization Tools

The structural characteristics of the obtained SnO_2–CuO nanocomposites were determined via X-ray diffraction analysis (XRD; Shimadzu XRD-6000) to study the crystal structure and crystallite size, with measurements being carried out within a suitable 2θ range. SEM was performed on the synthesized nanocomposites using a scanning electron microscope (JEOL JSM-6390), which

helped in understanding their surface and microstructure characteristics including particle morphology and size distribution. Absorption properties and the optical bandgap of the synthesized nanocomposites were measured by a UV-Vis spectrophotometer (Jasco V-630). Nyquist plot, dielectric constant, dielectric loss and ac electrical conductivity of the nanocomposites were studied using an impedance analyzer (Solartron SI 1260).

5. Results and Discussion

5.1. SEM Analysis

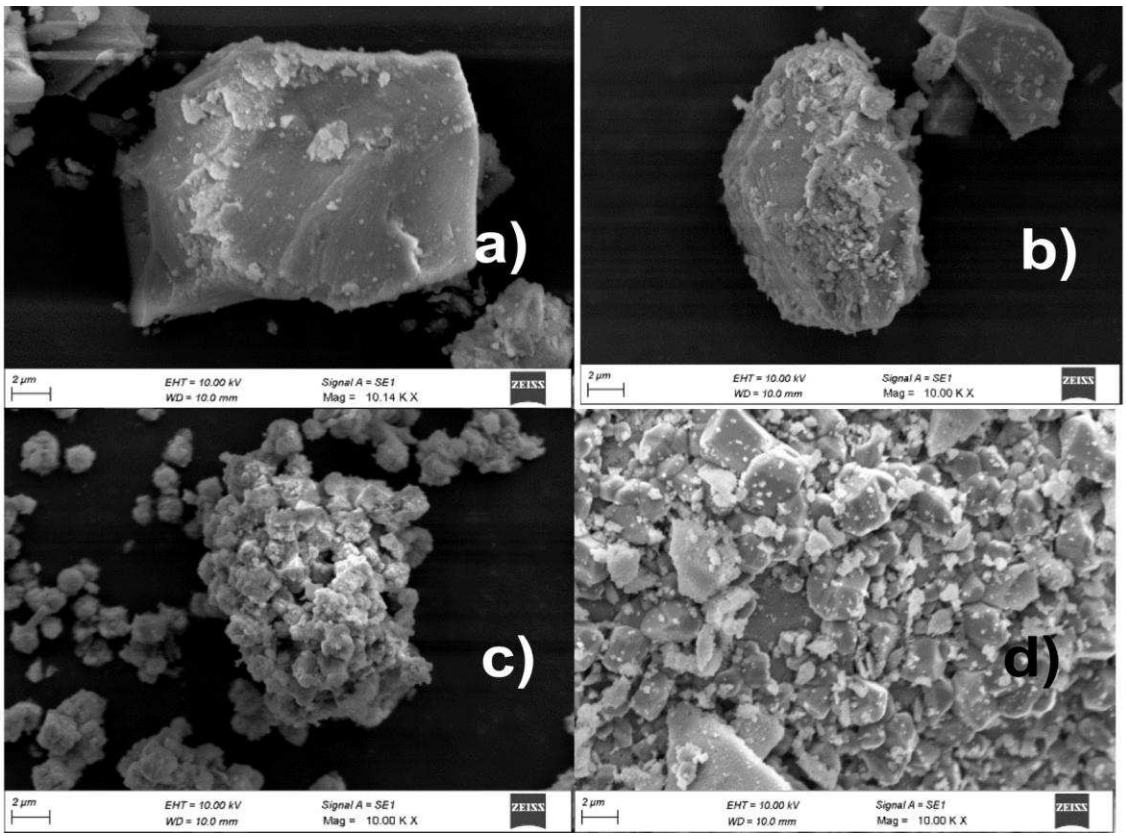


Figure 2: SEM image of the SnO_2–CuO (a-d) nanocomposites Calcinated from 300°to 600° showing its surface morphology.

I looked at the surface of nanocomposites that were heated to different temperatures. 300 °C, 400 °C, 500 °C and 600 °C. Using a special tool called scanning electron microscopy. You can see the results in **Figure *2***(a–d). It is clear that the surface changes a lot when the temperature is increased. When the temperature was 300 °C (**Figure *2***A) the sample had chunks that were stuck together with smooth surfaces. This means that the crystals were not fully formed and there were still some leftover parts from the start. I think this happened because the temperature was not high enough to help the crystals grow properly. At 400 °C these big chunks started to break and I saw some weirdly shaped particles. This shows that the crystals were starting to form and the atoms were moving around more which made the big chunks fall apart. When the temperature went up to 500 °C the surface changed to have particles that were spread out evenly. This means that the crystals were getting better and the particles were growing. The higher temperature helped SnO_2. Cuo work together better which made the particles stick together more and form special interfaces.**[25]** At 600 °C the particles stuck together to form clusters. I think this happened because the particles were moving around more and bumping into each other which made them stick together. The size of the particles got bigger.**[26]** From around 150 nm to 490 nm. When the temperature was increased. I used ImageJ software to estimate this. This growth happened because smaller particles disappeared and stuck to particles, which made the surface smoother. Also when the temperature was higher, SnO_2 and CuO worked together more which made the particles stick together and form crystals. This is what I saw in the XRD results, which showed that the structure was better, at temperatures.**[27]**

5.2. XRD Analysis

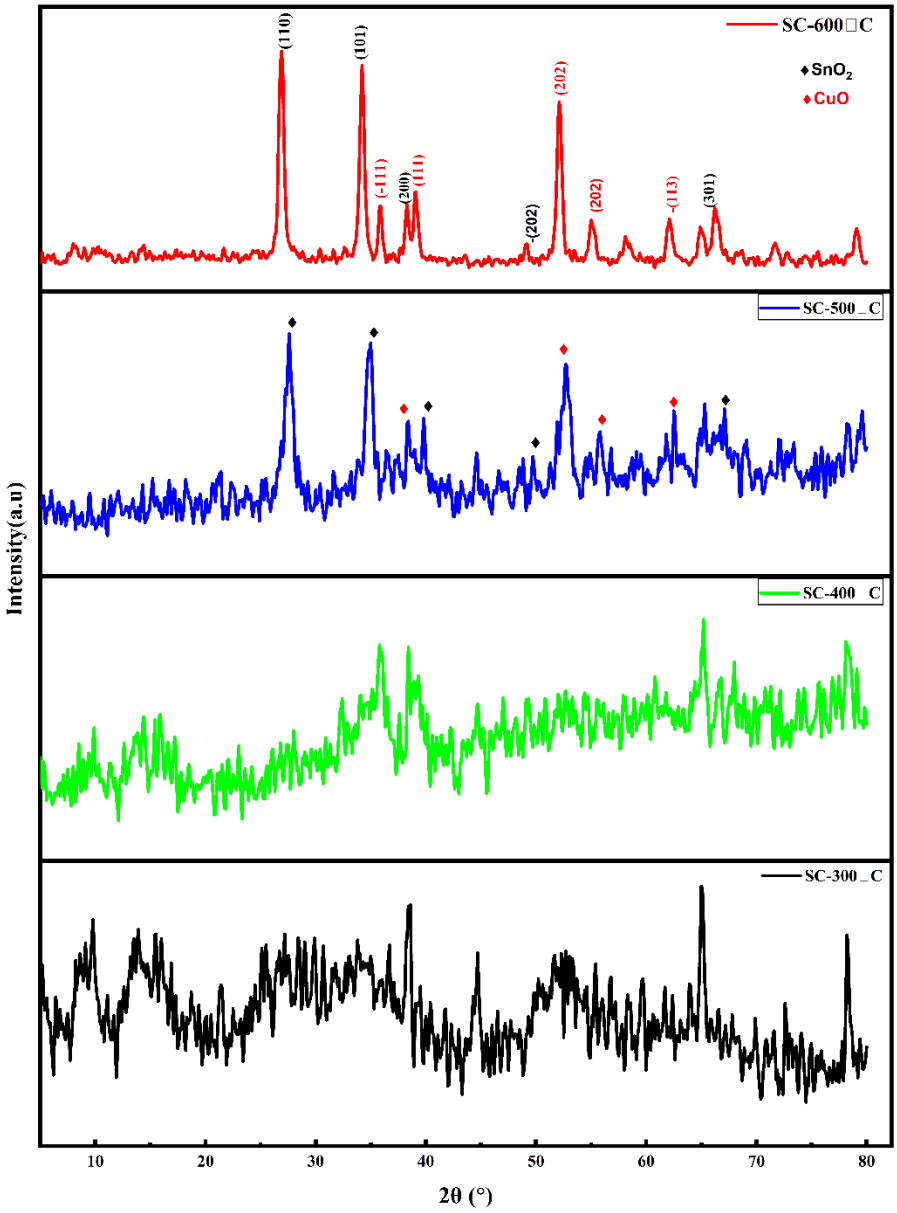


Figure 3: Crystal structure of the SnO_2–CuO nanocomposite analyzed by X-ray diffraction.

Figure 3 shows the X-ray diffraction patterns of nanocomposites that were heated at different temperatures. These temperatures ranged from 300 °C to 600 °C. We can see that the nanocomposites change from an amorphous to a crystalline structure as the temperature

increases.**[28]** When the temperature is 300 °C the diffraction pattern has low-intensity peaks. This means that the SnO_2–CuO nanocomposites are mostly amorphous and do not have a ordered structure.**[29]** As the temperature increases to 400 °C the diffraction peaks become more defined. This shows that the nanocomposites start to form a crystalline structure and their atoms become more ordered.**[30]** At temperatures, such as 500 °C and 600 °C we can see clear diffraction peaks that correspond to both SnO_2 and CuO phases. This confirms that the SnO_2–CuO nanocomposites form a system. The peaks at $2\theta \approx 26.9°$, 34.3° and 66.3° match the (110) (101) and (301) planes of tetragonal SnO_2. Similarly the peaks at $2\theta \approx 35.9°$, 39.1° 49.2° and 52.1° match the (−111) (111) (202) and (020) planes of CuO. The fact that the peaks do not shift significantly means that SnO_2 and CuO retain their crystal structures.**[31]** This confirms that the SnO_2–CuO nanocomposites form a heterojunction than a solid solution. The broad diffraction peaks also suggest that the composites are made up of small crystals.**[32]** The average size of these crystals also known as the crystallite size was estimated using a formula. The formula is:

$$D = \frac{K\lambda}{\beta \cos\theta} \ldots\ldots\ldots (1)$$

Where K is a shape factor λ is the X-ray wavelength β is the full width at half maximum and θ is the Bragg angle. The crystallite size increases from 8 nm to 13 nm as the temperature increases. This means that the crystals grow larger as the temperature increases. The microstrain and crystallite size were also analyzed using another method. The method is:

$$\beta_{hkl} \cos\theta = 4\theta\epsilon \sin\theta + K\lambda \ldots\ldots (2)$$

The results show that the peak broadening decreases at higher temperatures. This means that the lattice strain and defect density decrease due to relaxation and improved crystallinity, **Table *1***.

The dislocation density,**[34]** which represents the number of defects in the crystal lattice was calculated using:

$$\mathbf{D} = \frac{\mathbf{1}}{\boldsymbol{\delta^2}} \ldots\ldots (3)$$

The results show that the dislocation density decreases as the temperature increases. This can be attributed to the atomic diffusion and grain boundary migration, which lead to defect annihilation and lattice stabilization. Overall the XRD analysis shows that higher temperatures improve the crystallinity and structural stability of the nanocomposites. The peak sharpening, increase in size and reduction, in microstrain all confirm this. The SnO_2–CuO nanocomposites have a crystal structure and are more stable when they are heated at higher temperatures.

Table 1: Represents the XRD Crystal Size, Dislocation density, Micro Strain

SnO_2 – CuO	**Crystallite Size (nm)**	**Dislocation Density ($\times 10^{-3}$ nm^{-2})**	**Micro Strain**
300°C	8	0.01	3.7×10^{-3}
400°C	9	0.0069	3.1×10^{-3}
500°C	10	0.0030	1.1×10^{-3}
600°C	13	0.00226	0.8×10^{-3}

5.3. U-V Analysis

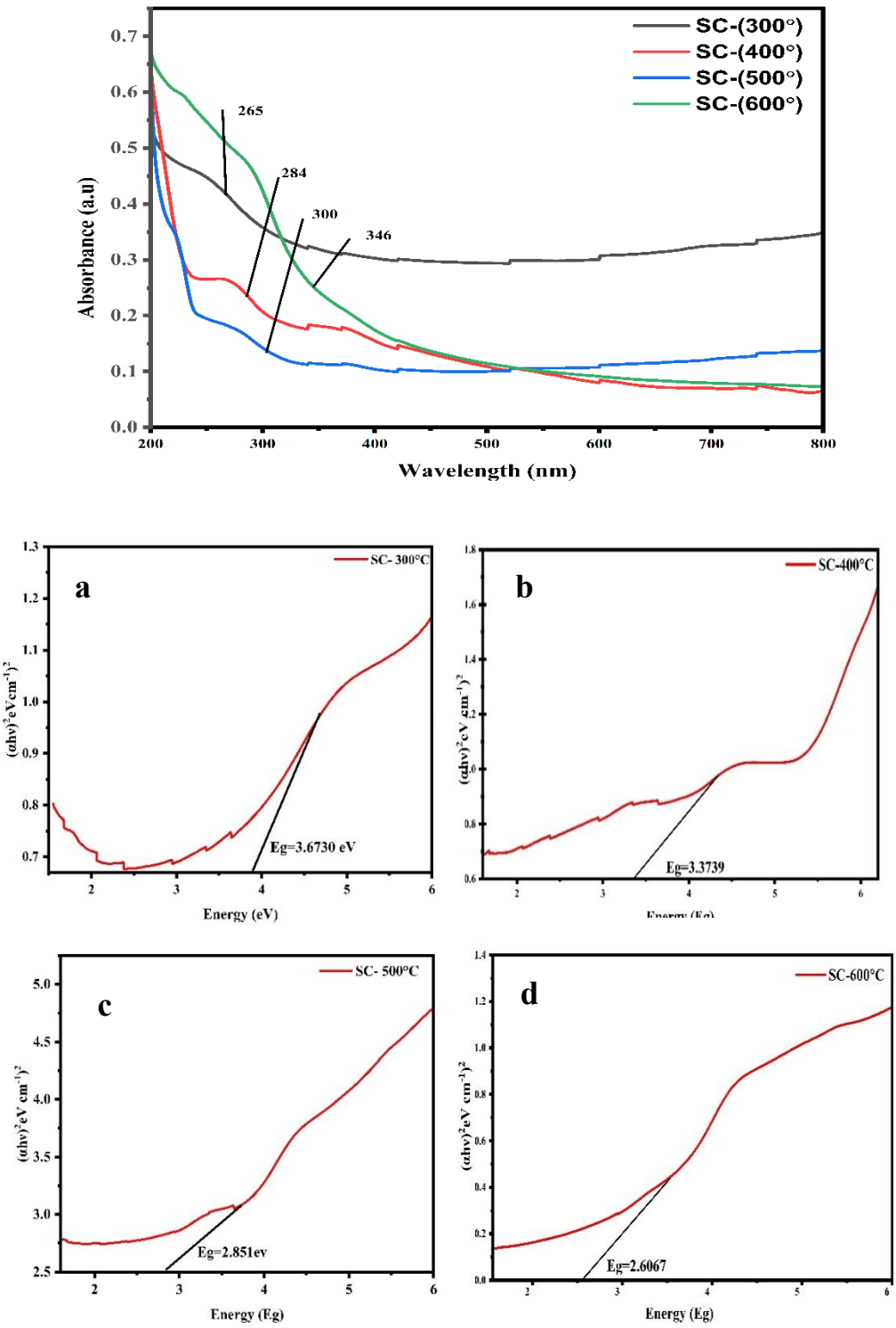


Figure 4: UV–Vis absorption spectra and optical band gap analysis of the SnO_2–CuO nanocomposite (a-d) calcined at temperatures between 300 °C and 600 °C.

Figure 4 shows the UV-Vis absorption spectra and Tauc plots of nanocomposites calcined at different temperatures from 300 °C to 600 °C. We see that the absorption edge shifts to longer wavelengths as the calcination temperature increases. The absorption spectra show a red shift as the calcination temperature goes up. This means that the nanocomposites absorb light in the visible region. This behavior suggests that it is easier for electrons to move from the valence band to the conduction band with energy.**[35]** The optical band gap values were estimated using Tauc plots. We found that the band gap decreases from about 3.67 eV at 300 °C to 2.60 eV at 600 °C. The band gap narrows as the calcination temperature increases. This is because the crystallites get bigger and more ordered at temperatures, **Table *2***. This reduces the effects of quantum confinement.The interaction between SnO_2 and CuO also gets stronger at temperatures. This forms p-n heterojunctions, which change the electronic band structure. The CuO phase has a narrower band gap.**[36]** So it helps to extend the absorption into the region. There are also defect states, like oxygen vacancies and interfacial defects. These contribute to band tailing near the band edges. This reduces the band gap. Overall, the shift and band gap narrowing with increasing calcination temperature indicate better optical absorption and charge carrier excitation. These are good for applications, like gas sensing and optoelectronic devices.**[37]**

Table 2: UV–Visible absorbance and optical band gap values of the SnO_2–CuO nanocomposite at different calcination temperatures

Material (Temp)	Absorbance (a.u)	Bandgap (eV)
300°C	265	3.65
400°C	284	3.37
500°C	300	2.8
600°C	346	2.6

5.4. FTIR Analysis

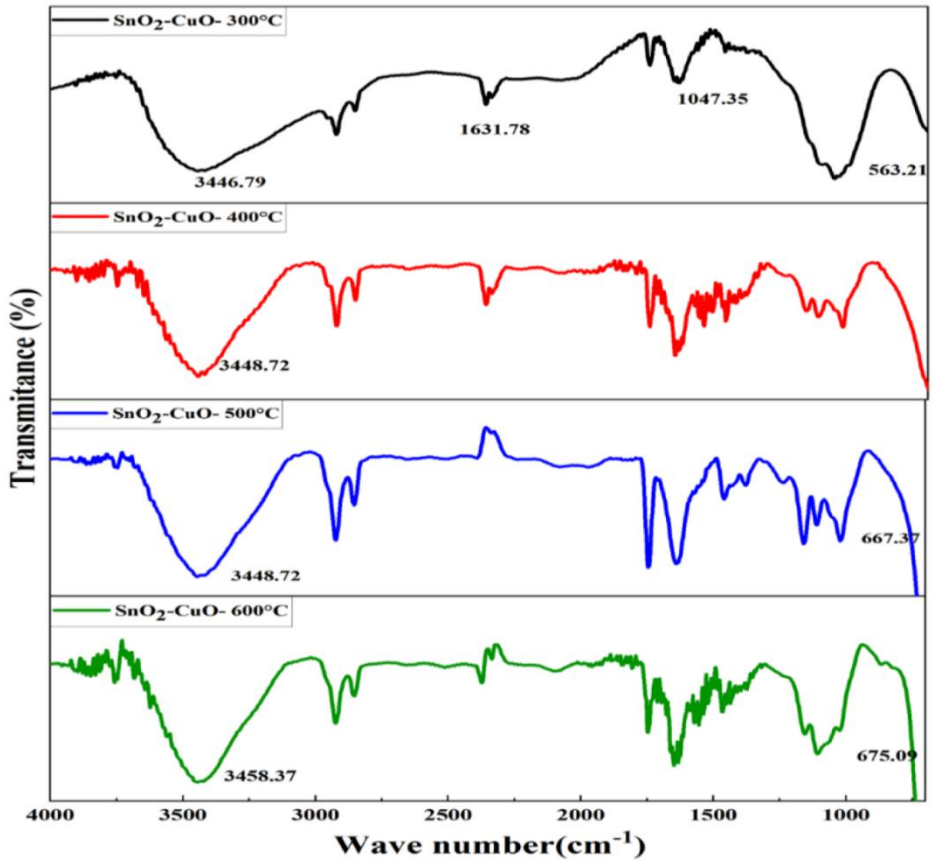


Figure 5: Represents the FTIR - analysis of SnO_2 -CuO composite at different temperature from 300°C to 600°C

Figure 5 shows the FTIR spectra of nanocomposites calcined at different temperatures from 300 °C to 600 °C. The spectra have some absorption bands that show metal–oxygen bonds and surface groups. The low wavenumber region has absorption bands that confirm metal oxide phases. There is a peak at 563 cm^{-1} from Sn–O stretching, which means SnO_2 is present. The band near 675 cm^{-1} is from Cu–O stretching, which confirms CuO in the composite. There is an absorption band at 3446–3458 cm^{-1} from O–H stretching, which shows surface hydroxyl groups and moisture. The peak at 1630–1650 cm^{-1} is, from the bending of H–O–H, which confirms water molecules on the surface. As the calcination temperature increases the O–H related bands get weaker which means adsorbed water and surface hydroxyl groups are removed. This shows thermal stability and fewer surface defects. The metal–oxygen peaks get sharper which reflects structural ordering and crystallinity of SnO_2–CuO. These observations match the XRD results, which show bigger crystallites and better phase formation at higher temperatures. The reduction of hydroxyl groups and better lattice ordering of SnO_2–CuO are expected to improve charge transport, which helps with gas sensing performance of nanocomposites.**[38],[39]**

5.5. I-V Analysis

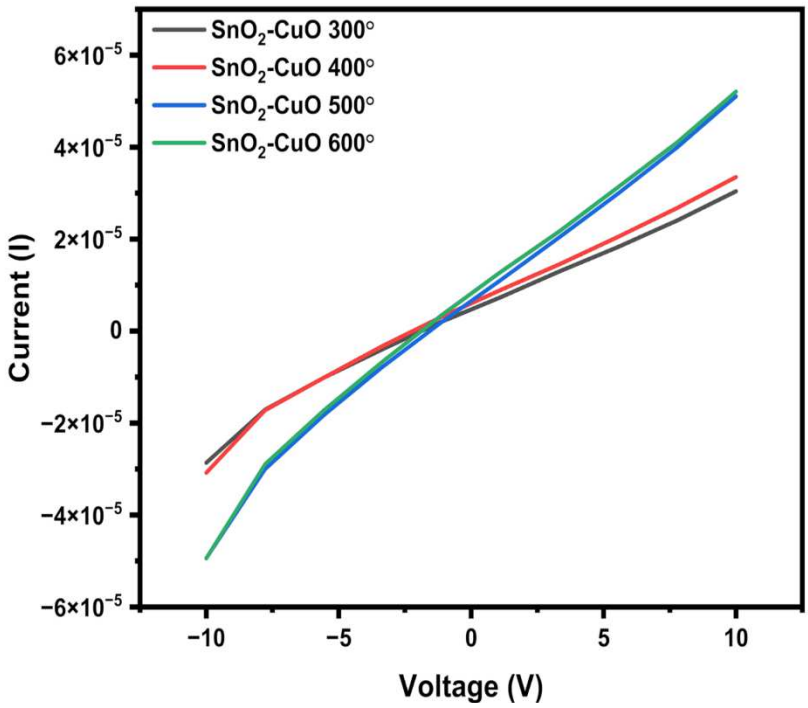


Figure 6: Electrical resistance values obtained from I–V measurements of the SnO_2–CuO nanocomposite calcined at different temperatures (300–600 °C)

The National Instruments system was used to measure the current and voltage of nanocomposite films that were heated to different temperatures from 300 °C to 600 °C. This was done using a setup with four probes and the voltage was varied from -10 V to +10 V as shown in **Figure 6**. All the samples showed a straight line when the current and voltage were plotted against each other. This means that the current and voltage are related in a way. It was also clear that the current increased when the temperature was increased. This shows that the SnO_2–CuO nanocomposite films conduct electricity better when they are heated to temperatures. When the temperature is increased the tiny crystals in the film get bigger. Their structure becomes more perfect. This was confirmed by XRD analysis. Higher temperatures also make the grains in the film grow, which reduces the resistance between the grains and decreases the number of defects. All these changes make it easier for the electrical charge to move through the film.

The electrical resistivity of the films was calculated using a formula:

$$\rho = (R \times A) / L$$

where R is the resistance A is the cross-sectional area and L is the thickness of the film. The electrical conductivity is the inverse of the resistivity:

$$\sigma = 1 / \rho$$

The samples that were heated to temperatures, such as 300 °C and 400 °C did not conduct electricity as well as the others,**[40], Table *3*.** This is because the crystals were smaller there were defects and the grains were more scattered. On the hand the samples heated to 500 °C and 600 °C conducted electricity much better. This is because the crystals were bigger and more perfect and there were defects.**[41]** The formation of the CuO phase also known as tenorite helps the grains to connect and makes it easier for the electrical charge to move through the SnO_2–CuO interface.**[42]** The combination of n-type SnO_2 and p-type CuO also helps to separate the charges and make them move more easily.**[43]** The sample that was heated to 500 °C showed the electrical behavior. This is because it had a balance between the size of the crystals and the surface area. When the temperature was increased to 600 °C the crystals got even bigger. The surface area and the number of active sites decreased. This is important because the surface area and active sites are critical for gas sensing applications. In general the results show that heating the nanocomposite films to intermediate temperatures improves their electrical conductivity. This highlights the importance of optimizing the microstructure of the films to achieve device performance. The SnO_2–CuO nanocomposite films with electrical conductivity can be used to make better devices. The I–V analysis of the nanocomposite films is important, for understanding their electrical behavior.**[44]**

Table 3: Electrical parameters obtained from I–V analysis of the SnO_2–CuO nanocomposite calcined at different temperatures

Materials at different temperature	Resistance $\times 10^6$ (MΩ)	Resistivity $\times 10^4$(KΩm)	Conductivity (µS/m)
SnO_2-CuO 300°C	0.36	7.7	0.1298
SnO_2-CuO 400°C	0.33	7.1	0.1351
SnO_2-CuO 500°C	0.21	4.5	0.2222
SnO_2-CuO 600°C	0.20	4.1	0.2439

Table 3: Electrical parameters obtained from I–V analysis of the nanocomposite calcined at different temperatures

5.6. Impedance Analysis

5.6.1. Nyquist Plot

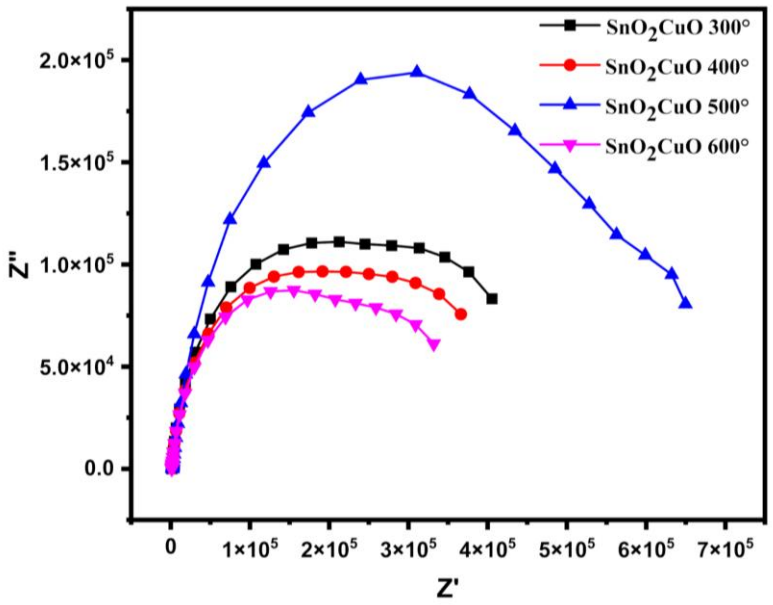


Figure 7: Nyquist plots obtained from NI impedance analysis of the SnO_2–CuO nanocomposite calcined at different temperatures

Figure *7* shows the Nyquist plots of nanocomposite films calcined at different temperatures from 300 °C to 600 °C. These plots were measured at room temperature using a Solartron impedance analyzer. The plots have arcs. These arcs represent the grain boundary resistance and charge transfer processes in the material. The samples calcined at 300 °C and 400 °C have smaller semicircles. This means they have overall impedance. This behavior is because of incomplete crystallization and many defects. These defects help charge transport through defect-mediated pathways not through crystalline conduction.**[45]** At 600 °C the semicircle diameter decreases again. This means there is reduced resistance and better conductivity. This happens because of crystallinity bigger grain size and better connectivity between grains. This reduces grain resistance and helps charge transport.**[44]** In contrast the sample calcined at 500 °C has a defined and bigger semicircular arc. This means it has charge transfer resistance. This behavior is because of the formation of p–n heterojunctions between SnO_2 and CuO. The interface creates a barrier that restricts charge carrier movement and increases resistance. This interfacial resistance is important for sensing applications. It makes sensitivity better by changing charge transport in response to gas adsorption. The developed heterojunction at 500 °C leads to strong interactions, controlled charge transfer and better dielectric behavior. At temperatures 300 °C and 400 °C, higher surface area and defect density may help gas adsorption. The lack of well-defined heterojunctions limits controlled charge transport. At temperature 600 °C too much grain growth reduces surface area and active sites. This can hurt gas sensing performance with better conductivity. Overall the sample calcined at 500 °C has a balance between crystallinity, interfacial resistance and surface activity. This makes it the best candidate, for gas sensing applications.**[46],[47]**

5.6.2. Dielectric Constant

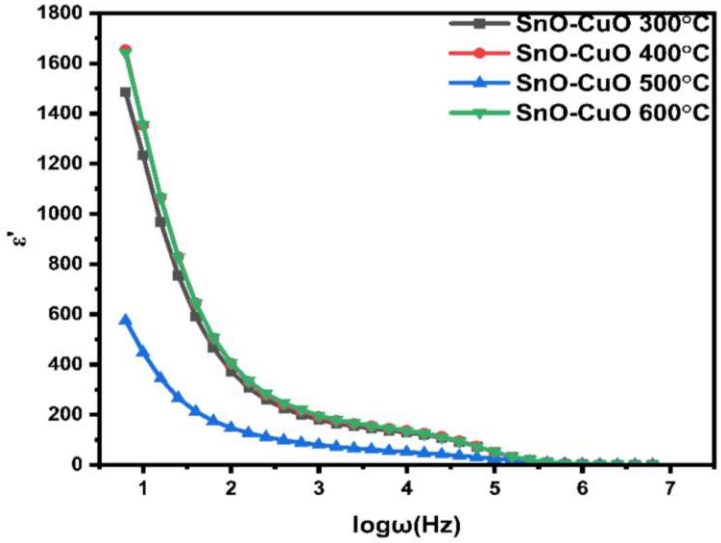


Figure 8: Dielectric constant of the SnO_2–CuO nanocomposite measured at different caicination temperatures

The properties of SnO_2–CuO nanocomposites that were heated to different temperatures (300 °C to 600 °C) were studied at room temperature over a range of frequencies as shown in **Figure *8***. The constant (ε') shows how well the material can store electrical energy when an electric field is applied. All samples have a dielectric constant at higher frequencies. This is behavior for metal oxide semiconductors. At frequencies the dielectric constant is higher because of space charge polarization and interfacial polarization. This happens because charges build up at grain boundaries and interfaces. The samples heated to 400 °C and 600 °C have a dielectric constant at low frequencies. This is because there is polarization due to more defects and charge buildup at interfaces.**[48]** The sample heated to 500 °C has a lower dielectric constant than the others. This is because the grains grew better and the material became more crystalline. This reduces the number of grain boundaries and limits charge buildup at interfaces. As a result space charge polarization is reduced. Also the formation of p–n heterojunctions between SnO_2 and CuO at 500

°C helps control charge transport and reduces dispersion.**[49]** Oxygen vacancies and interfacial defects also affect polarization by changing the electronic structure. The dielectric constant at 500 °C is good for gas sensing applications. It reduces charge trapping. Improves the sensitivity and stability of the sensor. Lower dielectric polarization also improves response and recovery characteristics. This enables charge transfer during gas adsorption and desorption processes. Overall the dielectric analysis shows that the SnO_2–CuO composite heated to 500 °C has the electrical behavior. This supports its performance, in sensing applications.**[50]**

5.6.3. Dielectric Loss

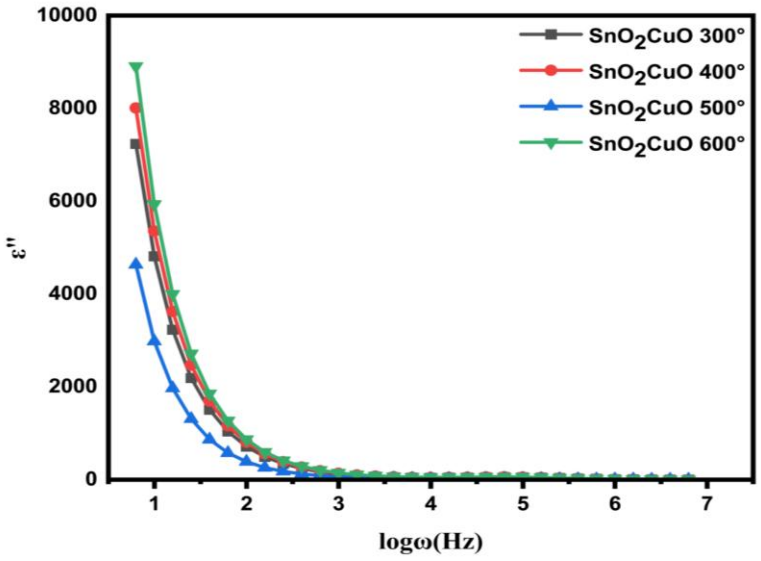


Figure 9: Represents the Dielectric Loss of SnO_2-CuO composite

Figure *9* shows what happens to the loss of SnO_2–CuO nanocomposites when they are calcined at different temperatures. Dielectric loss is the energy that gets wasted as heat when an electric field that keeps changing is applied to the material. All the samples we looked at lose energy as the frequency gets higher which is what we expect from metal oxide semiconductors. When the

frequency is low the dielectric loss is higher because of space charge polarization and charge carriers moving across the boundaries of the grains. The samples that were calcined at 300 °C and 400 °C have a dielectric loss. This is because they have a lot of defects the lattice is strained. The crystals are not well formed. These things make the charge carriers scatter and waste energy. The sample that was calcined at 600 °C also loses energy. This is because the grains got too big and the surface area got smaller. This can cause the polarization to be uneven and waste energy even though the crystals are better formed. On the hand the sample that was calcined at 500 °C has the lowest dielectric loss of all the samples.**[51]** This is because it has a microstructure with crystals that are well formed fewer defects and grains that are the right size. The boundaries between the grains have defects, which reduces the energy that is wasted. When SnO_2 and CuO form a p–n heterojunction at this temperature it helps the charge move better and reduces the dielectric relaxation losses. This makes the material more stable electrically. Reduces noise. The low dielectric loss we see at 500 °C is very good for sensing gases because it makes the signal more stable increases the sensitivity and makes the response and recovery times faster. Also the lower dielectric loss reduces the power that is used and the self-heating effects, which makes the material good for sensing devices that're efficient and stable. Overall looking at the loss tells us that the SnO_2–CuO composite that is calcined at 500 °C is the best, for electrical performance, which is what we saw from the impedance and dielectric constant results.**[52]**

5.6.4. AC Conductivity

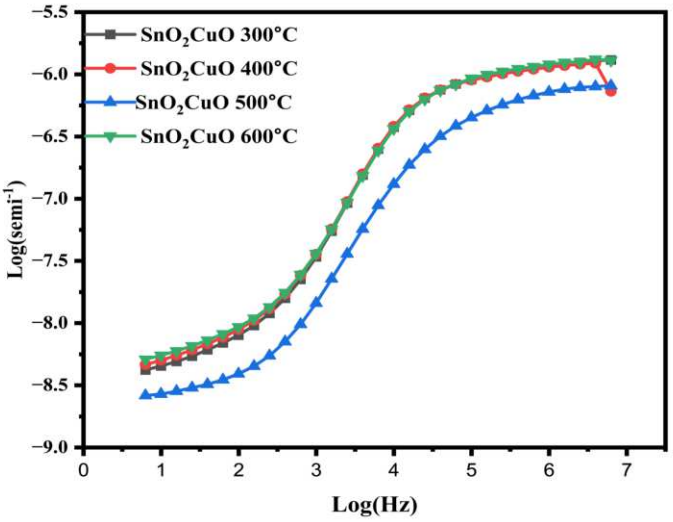


Figure 10: Represents the AC Conductivity of SnO_2-CuO composite

Figure *10* shows how the AC conductivity of SnO_2–CuO nanocomposites changes when they are heated to temperatures from 300 °C to 600 °C. The AC conductivity helps us understand how charge moves around which is affected by the structure of the material any defects it has and how the different parts of the material interact with each other. All the samples we looked at show that their conductivity gets better when the frequency increases, which is what we expect from materials like these. This happens because the charge carriers can jump from one place to another easily. The samples that were heated to 400 °C. 600 °C have relatively high AC conductivity. This is because the material is more ordered there are charge carriers and the grains are better connected. When we heat the material to a temperature the boundaries between the grains have less resistance so it is easier for the charge to move around. On the hand the sample that was heated to 300 °C has lower conductivity.**[50]** This is because the material is not very ordered the crystals are small. There are a lot of defects. All these things make it harder for the charge carriers to move around.

Table 4: Represents the Comparison chart of SnO2-CuO Composite with Other materials

Material	Synthesis method	Crystal Size(nm)	Bandgap (Eg)	Electrical behaviour	Reference
SnO_2-CuO	Hydrothermal method	59	3.5	Shows good electrical conductivity and no frequency dependent dielectric studies	**[54]**
SnO_2-CuO	Sonochemical method	10 &16		Enhanced photocatalytic and electrochemical battery performance by improved surface area	**[55]**
SnO_2-CuO	Wet chemical method	25		Detection of CH_4 space charge restricted current mechanism and n–p junction formed in the composite.	**[56]**
NiO/TiO_2	Sol-gel method	18.5	3.1	p-n type heterojunction formation improves electric properties defects and interfaces improves	**[57]**
TiO_2	Spray Pyrolysis	18.63	3.08	It shows lower band gap, reduced crystal size applied for electrical and impedance studies for memristor application	**[54]**
PVA / rGO 10%	Solvent casting method	17.7		Reduced I-V current and improved dielectric constant	**[23]**
SnO_2-CuO	Co-Precipitation method	8-13	2.7	Dielectric, impedance and AC conductivity behaviour that is based on calcination with optimal interfacial resistance at 500 °C	**Current work**

It is interesting that the sample heated to 500 °C has AC conductivity. This is because the SnO_2 and CuO form a kind of junction which creates a barrier that restricts the movement of charge carriers. This barrier makes the material more resistant. This kind of controlled conductivity is useful for detecting gases because it makes the material more sensitive to changes when gas is

present. The sample heated to 500 °C has the right balance of conductivity and resistance which makes it good for sensing applications. This is consistent with studies we did on the material. Overall looking at the AC conductivity tells us that the temperature we heat the material to's very important for how well it conducts charge. The sample heated to 500 °C has the electrical properties for sensing applications. The AC conductivity analysis of nanocomposites shows that the calcination temperature is crucial, for tuning the charge transport behavior of SnO_2–CuO nanocomposites.**[53]**

5.7. Conclusion

We made nanocomposites in a 1:1 ratio using a co-precipitation method. Then we heated them at temperatures from 300 °C to 600 °C. This helped us see how the heat treatment affects their structure, light absorption and electrical properties. X-ray diffraction analysis showed that as we increased the temperature the nanocomposites changed from being amorphous to crystalline. The crystals also grew from 8 nm to 13 nm. This growth reduced lattice strain and dislocation density. It means the structure became more ordered. When we looked at the morphology, we saw that at temperatures the nanocomposites formed dense block-like shapes. At temperatures they turned into uniformly distributed fine-grained particles. This change shows that the crystallinity improved and the grains refined. UV–Vis analysis showed that as the calcination temperature increased the absorption edge shifted to the red. This shift means the band gap narrowed and the nanocomposites absorbed light in the visible region. FTIR results also supported these findings. They showed a reduction in O– vibrational intensity. This reduction indicates that there were surface hydroxyls and the phase became more stable. The electrical properties strongly depended on the calcination temperature. Higher temperatures improved conductivity. This improvement happened because of

crystallinity and reduced defects. However impedance analysis showed that the sample heated at 500 °C had an electrical response. It had a pronounced Nyquist arc, lower dielectric constant, reduced dielectric loss and moderate AC conductivity. The optimal formation of p–n heterojunctions between SnO_2 and CuO at 500 °C helped regulate charge transport. This regulation improved the sensing characteristics of the composite. The balance between crystallinity, interfacial resistance and charge transport at 500 °C enhanced sensitivity, selectivity and stability in gas sensing applications. In conclusion this study shows that the calcination temperature plays a role in tuning the structure and properties of SnO_2–CuO nanocomposites. The composite heated at 500 °C has multifunctional properties. It is a candidate, for high-performance gas sensing devices.

Author Contribution

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- Performed the analysis
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- Conceived and designed the analysis
- Constant designed
- Verified the analysis
- Corrected the paper

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Conflicts of interest

All authors declare there are no conflicts of interest

Availability of data and material

All data that supports the findings of this study are included within the article (and any supplementary files)

Data availability statement

The data that support the findings of this study are not currently publicly available but will be made available upon reasonable request.

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