



Electrical and dielectric properties of hard/soft $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_x\text{Zn}_y\text{Fe}_2\text{O}_4$ ($x, y \leq 0.5$) spinel ferrite nanofibers

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ABSTRACT

Hard–soft $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_x\text{Zn}_y\text{Fe}_2\text{O}_4$ ($x, y \leq 0.5$) spinel ferrite nanofibers (H/S CFO/CuZnFO SFNFs) were synthesized via electro-spin. The main aim of this study is to investigate effect of co-substitution of transition metals of Cu and Zn on the dielectric features of H/S CFO/NiFO SFNFs. The microstructure and morphology of all products were studied by XRD, SEM along with EDX, TEM and HR-TEM. The dielectric features of all products were evaluated as a function of frequency, F (1 MHz–3 GHz), and temperature, T (20–120 °C). The T -dependent AC and DC conductivity of all products improved with T , in agreement with the semiconductor behavior. While AC conductivity revealed two regions as F -dependent and F -independent, DC conductivities exhibited Arrhenius-type behavior above and below the transition T . Thermally stimulated charge transfer model produced activation energies before and after transition T ranging between $E_a = 78$ and 297 meV, which is consistent with AC and DC conductivities. The dielectric loss, dielectric constant and dielectric loss tangent of all nanofibers decreased with the increase in F at all T . The Cole–Cole plots were used to analyze the effect of grain and grain boundary on conduction mechanism, and they displayed mainly only one incomplete semicircle

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signifying non-Debye behavior and domination of grain boundaries to the conduction mechanism. The dielectric parameters of all samples vary significantly with compositional ratio. The dielectric behaviors of H/S CFO/CuZnFO SFNFs are correlated with the conduction mechanisms based on grain-to-grain boundaries, clarified by Koop's model.

1 Introduction

As technology progresses, there is a high requirement for electric and dielectric devices due to their low cost and high thermal stability. Ferrites (γ -Fe₂O₃, Fe₃O₄) have a molecular electron density exchange between Fe–O ions, making them appropriate dielectric, electric microwave absorber materials [1–4]. Spinel ferrites (SFs) with the chemical formula of MFe₂O₄ have dielectric, low coercivity (H_c), moderate saturation magnetization (M_s), low anisotropy, low eddy current loss, etc. [5]. SFs have a great impact in many industries, including data storage, photo-catalysts, cancer treatment, medications, microwave, telecommunications and sensors, because of their ease of synthesis, high electrical resistivity and chemical stability. Soft SFs have an essential part in various devices due to their electrical, dielectric and magnetic features [5, 6]. The doping of SFs with metal different cations or rare earth elements can create a product with new SFs with chemical and physical properties [7]. Many researchers deeply investigated intrinsic properties of Ni–Cu–Zn SFs. Mandle et al. [8] synthesized the Ni_{0.2}Cu_{0.2}Zn_{0.6}Fe_{2–x}Ho_xO₄ ($x = 0.00, 0.02, 0.04, 0.06$ and 0.08) and used it as a catalyst for one-pot three-component synthesis of dihydropyrimidinones. Almessiere et al. [9] studied on Dy³⁺ ion-substituted Ni_{0.4}Cu_{0.2}Zn_{0.4}Fe_{2–x}Dy_xO₄ ($x \leq 0.04$) nanoferrites produced via sol–gel method and investigated its magnetic and microwave properties. Almessiere et al. [10] have been used the ultrasonic irradiation approach to improve the dielectric and electrical properties with the doping of La³⁺ and Y³⁺ ions in Ni–Cu–Zn nanospinel ferrites (NSFs). Patil et al. [11] used the oxalate co-precipitation process to observe the impact of La³⁺ doping on the dielectric and electric properties of Ni–Cu–Zn NFs.

Other than NSFs, spinel nanofibers are also importance class of materials. They have an application in tissue engineering, fluid filtration, energy field, military field, sensor and textile field [12].

Other than SFs, the hard/soft (H/S) ferrite nanocomposites (NCs) are also important for various applications. The H/S CoFe₂O₄/(NiSc_{0.03}Fe_{1.97}O₄)_x NCs was synthesized to evaluate their dielectric, structural and electrical properties [13]. Almessiere et al. [14] synthesized the H/S SrFe₁₀O₁₉/_x(Ni_{0.8}Zn_{0.2}Fe_{1.8}Cr_{0.2}O₄) NCs via the one-pot citrate sol–gel process and investigated its dielectric, electric, structural and microwave features. Slimani et al. [15] investigated the impact of sonication time on the structural and magnetic features of CoFe₂O₄/Ni_{0.8}Cu_{0.1}Zn_{0.1}Fe₂O₄ hard–soft NCs.

The main focus of this is to both synthesize and examine the conductivity and dielectric properties of H/S CoFe₂O₄/Ni_{0.3}Cu_xZn_yFe₂O₄ ($x, y \leq 0.5$) NSFSS. Due to the similar crystal structure of CFO and NCuZnFO, it is impressive to synthesize core/shell-structured, hard/soft spinel ferrite-based CFO/NCuZnFO nanofibers. The ratios x and y of NiCu NSFSS were varied up to 0.5 to understand its impact on the physical properties of the resultant nanofibers.

2 Experimental

2.1 Synthesis and instrumentations

The H/S CFO/CuZnFO SFNFs were prepared by using electro-spin methodology. The Co(NO₃)₂·6H₂O, Cu(NO₃)₂·4H₂O, Zn(NO₃)₂·4H₂O, Ni(NO₃)₂·6H₂O and Fe(NO₃)₃·9H₂O were used as initial precursors (high-purity Merck products). The stoichiometric weight of nitrate salts and 10 ml C₂H₅OH were mixed in 7 ml DI H₂O. 1.4 g of PVP (polyvinylpyrrolidone with Mw ~1,300,000) was combined with first solution with continuing stirring for 3 h until to get viscous gel. The details of the synthesis have been already presented in Ref [16].

The structure of H/S CFO/CuZnFO SFNFs was clarified by XRD (Rigaku Benchtop Miniflex). The morphology of all products was identified via (SEM/TEM; FEI Titan 80–300 kV FEGS/TEM). The chemical

compositions were verified by EDX analysis. The conductivity and dielectric analyses were done by Novocontrol Alpha impedance analyzer.

3 Results and discussion

3.1 Phase and morphology of H/S CFO/CuZnFO SFNFs

The composition structure of H/S CFO/CuZnFO SFNFs was analyzed by X-ray powder pattern as shown in Fig. 1. The samples exhibited the index peaks of pure cubic SF phase without any undesired phase(s) or impurity. The phase of all ratios was verified by proceeding Rietveld refinement for the XRD experimental data using Match3! and full-proof program according to the cards No. 96-591-10064 for CoFe_2O_4 and 96-230-0290 relevance to NiFe_2O_4 . The refinement approved the combination and existing of both CoFe_2O_4 and NiFe_2O_4 spinel's ferrite. The cell

constants were computed during the refinement and found between $a_o = 8.3905$ and $8.3758 \text{ \AA}$. Moreover, according to Scherrer's formula, the D_{max} (crystallite sizes) were estimated as follow 22, 42, 45, 55 and 90 nm, respectively.

The morphology of H/S CFO/CuZnFO SFNFs was imaged by SEM and TEM as presented in Figs. 2 and 4 which exhibited an overlapping of fiber shape. The images showed the smooth surface and varied cross section. The chemical compositions of H/S $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ SFNSFs verified the existence of Cu, Co, Ni, Zn, Fe and O which is shown in Fig. 3. Additionally, TEM and HR-TEM analysis represented the morphology and structure of H/S $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ SFNFs (Fig. 4). The TEM revealed the assembling of small spherical particles in the form of fiber with different diameters due to the way that the particles accumulation. By calculating the spacing values from HR-TEM images using GATAN software, the formation of spinel phase was confirmed.

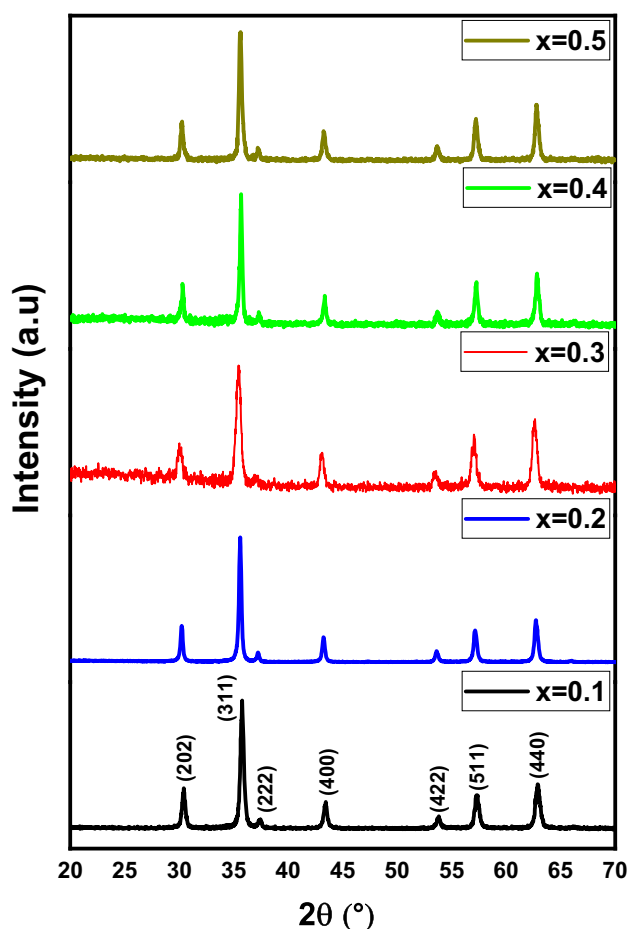


Fig. 1 XRD patterns of H/S CFO/CuZnFO SFNFs

3.2 Electrical and dielectric features

The electrical and dielectric features of H/S CFO/CuZnFO SFNFs have been investigated as functions F and T corresponding to each compositional ratio by means of impedance analyzer in the T range of $20\text{--}120^\circ\text{C}$ and F up to 3.0 MHz . Several parameters such as AC/DC conductivity, complex dielectric constant, dielectric and tangent loss have been studied for all samples.

3.2.1 AC conductivity

The AC conductivity of the SF is basically evaluated by using the following expression

$$\sigma_{\text{ac}}(\omega, T; x) = \omega \epsilon_0 \epsilon' \tan \delta \quad (1)$$

where σ_{ac} is AC conductivity, ω is angular F , ϵ' is relative permittivity of the material and $\tan \delta$ is the dielectric tangent loss. Figure 5 illustrates the variation of AC conductivity of H/S CFO/CuZnFO SFNFs with all compositional ratios calculated between 20 and 120°C and F up to 3.0 MHz . A decrease in AC conductivity with F indicates that the polaron jumping mechanism is more dominant, whereas an increase is associated with slight polaron jumping [17]. In this context, the linear increase in the AC conductivity of H/S $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$

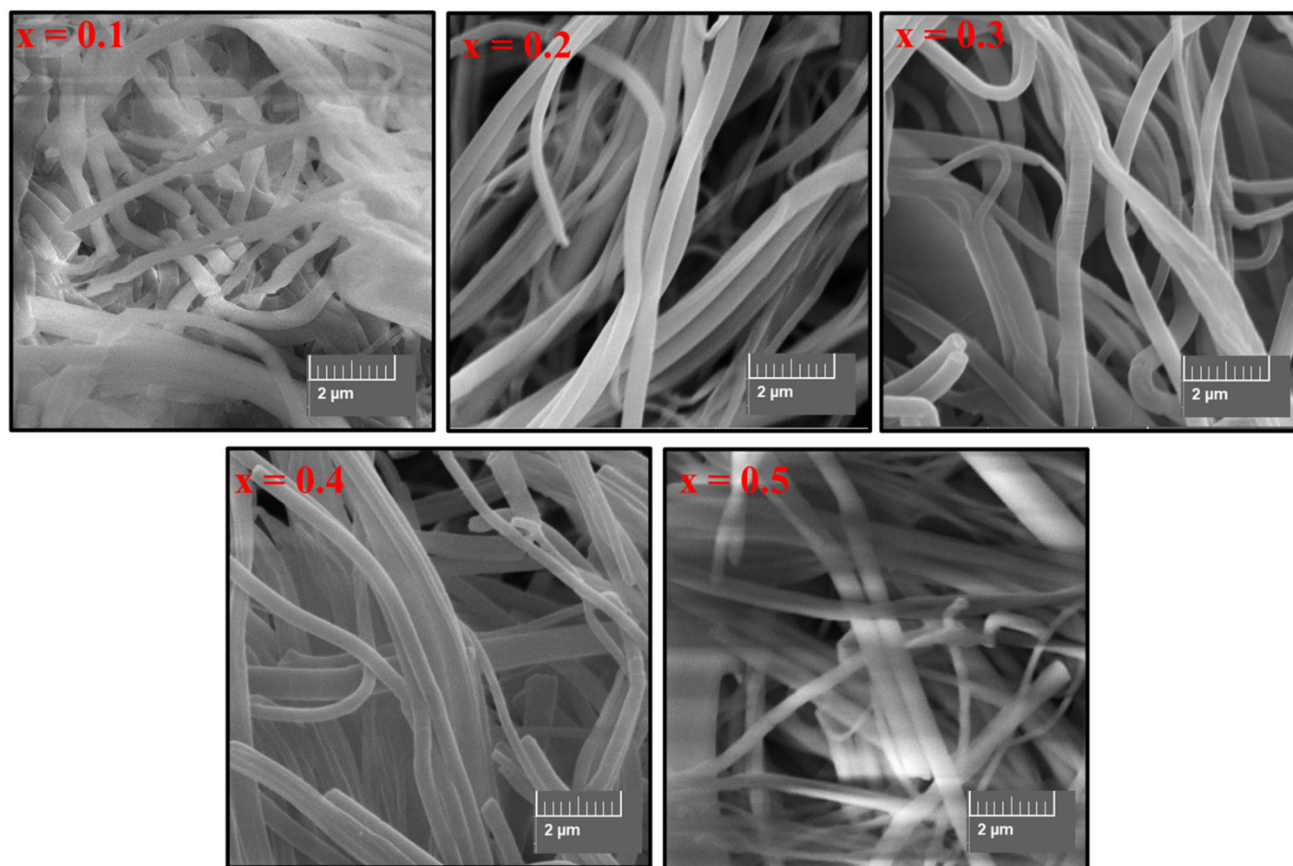


Fig. 2 SEM images of H/S CFO/CuZnFO SFNFs

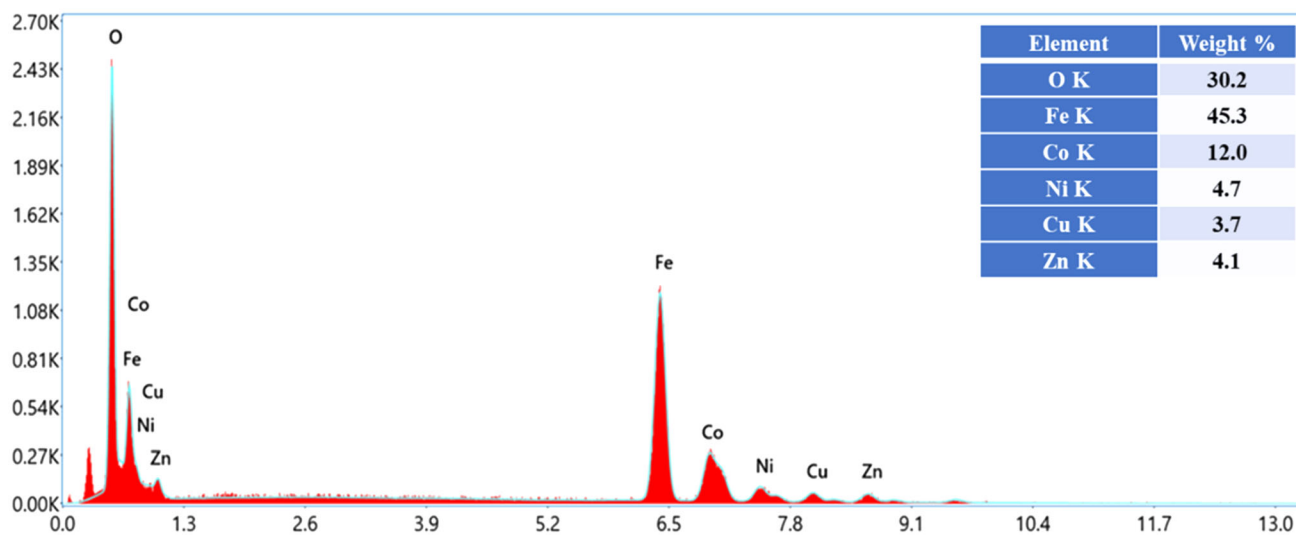


Fig. 3 EDX spectrum of H/S CFO/ $\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ SFNFs

SFNFs, especially at high frequencies, indicates the presence of moderate polaron conduction. The electron hopping between Fe^{3+} and Fe^{2+} ions in tetrahedral and octahedral (Oh) sites is minimal leading to

evaluation of relatively small AC conductivity at low F. In F-dependent region, which shifts to higher frequencies with the increase of x , a linear rise in AC conductivity is primarily due to conduction over

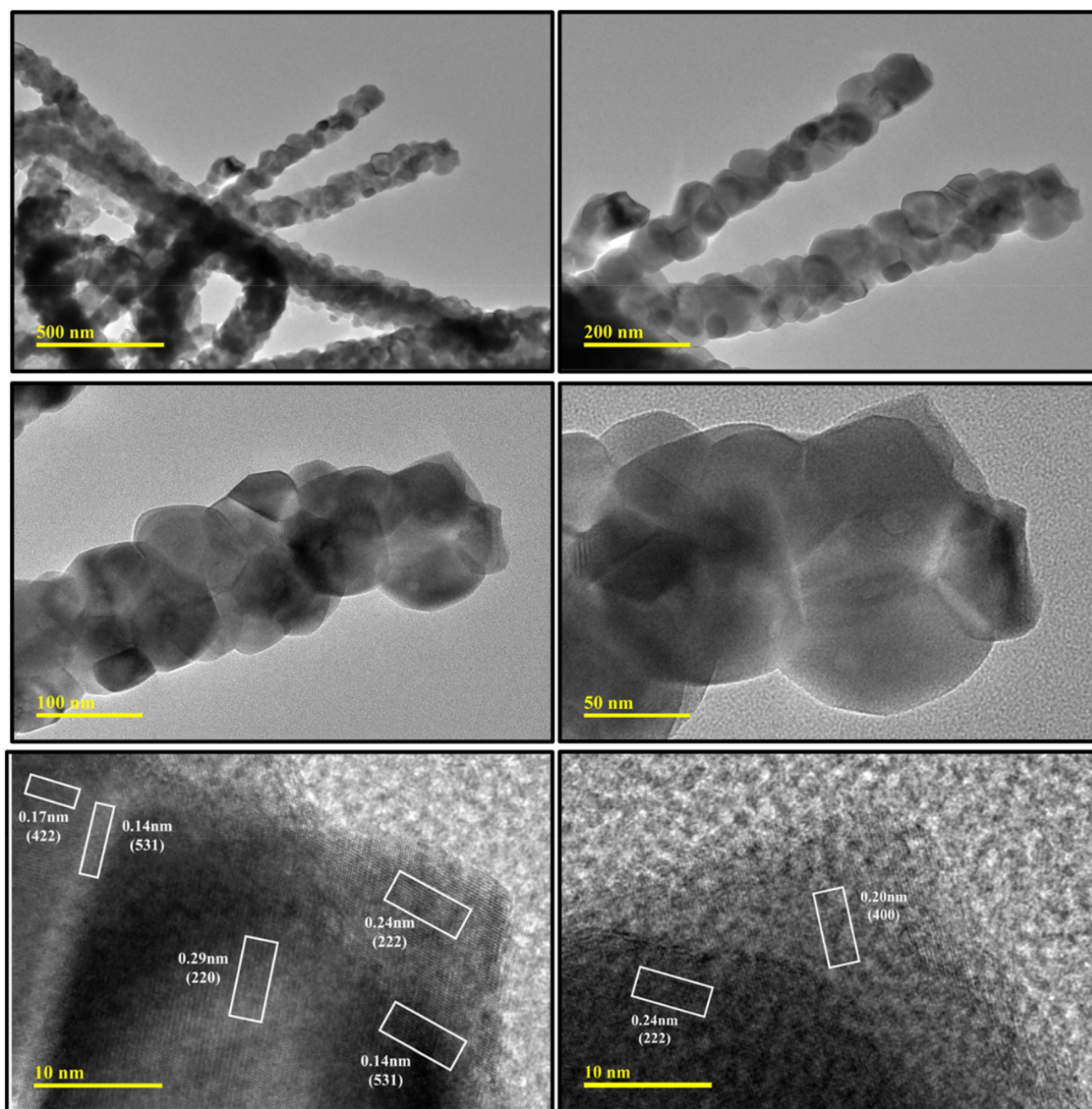


Fig. 4 TEM and HR-TEM micrographs of H/S CFO/Ni_{0.3}Cu_{0.3}Zn_{0.4}Fe₂O₄ SFNFs

electron exchange between the ions of the same atoms [18]. The compositional ratios in NFs can lead to development of structural fluctuations of composites due to their complexity, giving rise to a variation in the conduction mechanism. With increasing F , the electron exchange increases; subsequently, conductivity of NFs improves as compositional ratio x rises. For compositional ratios up to $x = 0.4$, specific trends are observed in conductivity

with respect to any change in both frequencies and T_s . For all compositional ratios, including $x = 0.5$, conductivity is T -dependent in a certain F range, while above this range it is more F -dependent. While the conductivity of NFs at higher frequencies remains nearly constant for compositional ratios of $x = 0.1$ – 0.4 and increases virtually linearly with T in log–log plot at low frequencies, unlike others the one with $x = 0.5$ is both T - and F -dependent at higher frequencies.

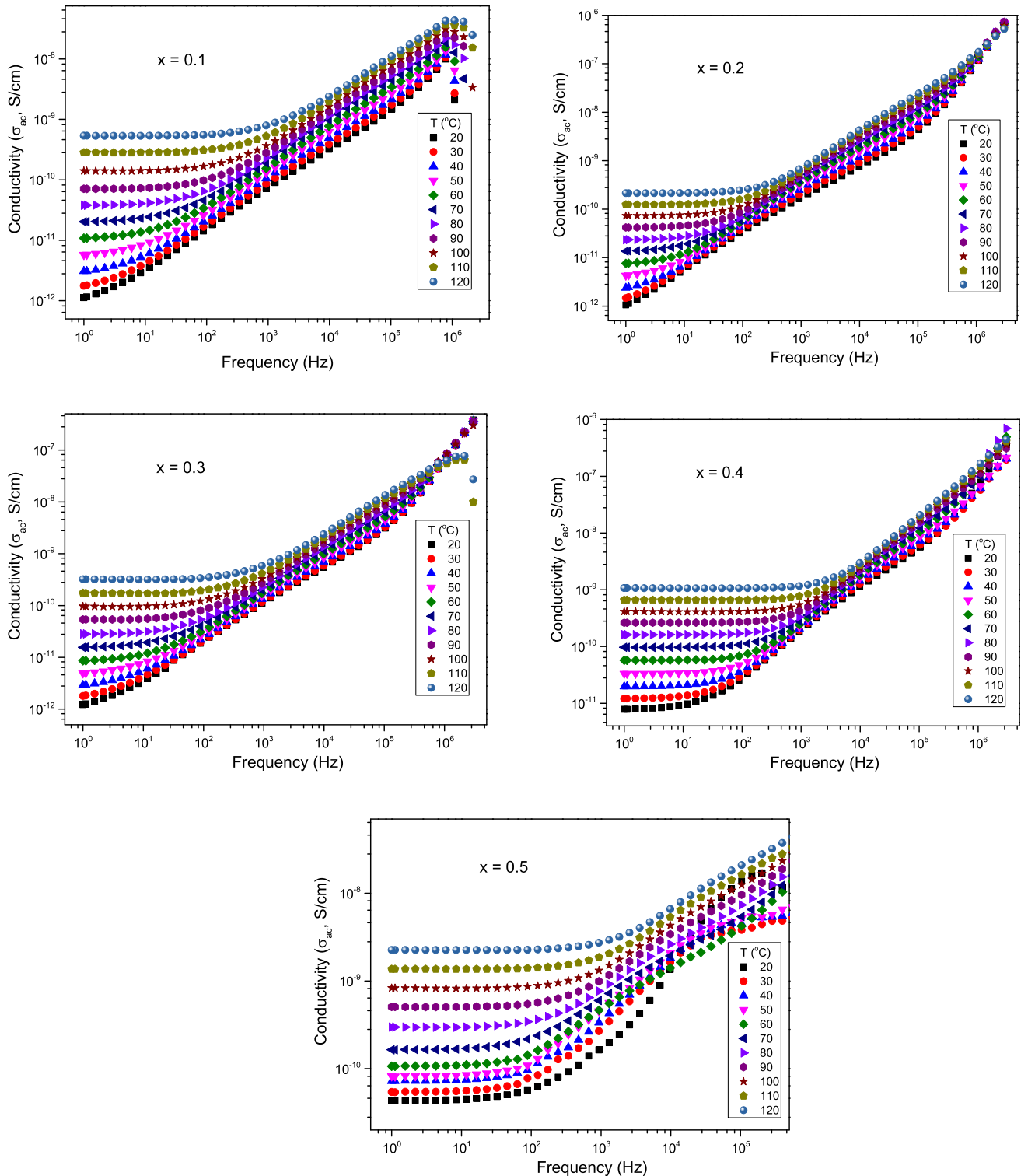


Fig. 5 Variation of log AC conductivity with F for H/S CFO/CuZnFO SFNFs

This may suggest that the sample with $x = 0.5$ composition has a greater effect on the structural change in NFs. The variation of the compositional ratios causes a change in electron jumping between Fe^{2+}

and Fe^{3+} ions in the tetrahedral and Oh regions, and hence the AC conductivity of H/S CFO/CuZnFO SFNFs [19].

3.2.2 DC conductivity

Figure 6 depicts the variation of DC conductivity of H/S CFO/CuZnFO SFNFs as a function of applied F recorded in the T range of 20–120 °C and F up to 3.0 MHz. T -dependent Arrhenius plot of DC conductivity is generally interpreted by using the following relation:

$$\sigma_{dc}(T, x) = \sigma_0(x) \exp\left(-\frac{E_a(x)}{k_B T}\right) \quad (2)$$

where $\sigma_{dc}(T, x)$ represents the DC conductivity of SFs, $\sigma_0(x)$ is the pre-exponential factor, while $E_a(x)$ is the activation energy derived from the slope of the $\log \sigma(T)$ versus T^{-1} plot, and k_B is the Boltzmann constant (8.617×10^{-5} eV K^{-1}).

Figure 6 shows that the conductivity increases with T . This behavior is similar to the nature of semiconducting materials [20, 21]. In the DC conductivity graph, two different regions, separated by small bending at certain T_s , are observed. These points of change in the DC curves are known as transition T_s . It is obvious that E_a takes two different values associated with the transition T for each sample with varying compositional ratios. E_a values are presented in Table 1 in detail. The first region of H/S CFO/CuZnFO SFNFs occurred at relatively low T and the E_a was determined from the slope accordingly. The small value of the activation energy in the low- T region proves the existence of hopping of the charge carriers from one site to the other. At low T , the migration of charge carriers from one site to another site is low while the charge carrier mobility improves

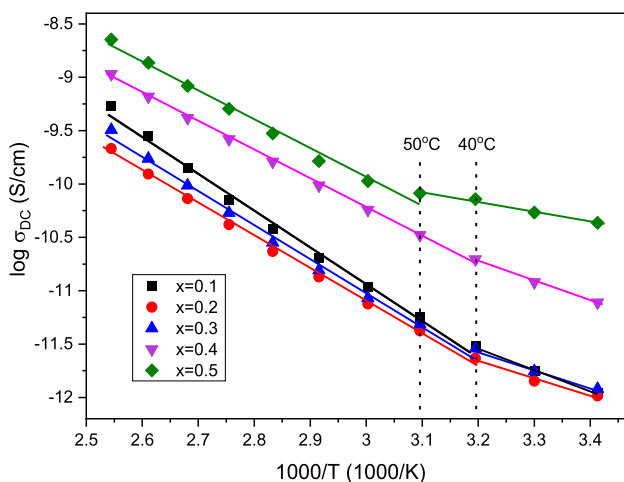


Fig. 6 Variations in DC electrical conductivity with T for H/S CFO/CuZnFO SFNFs

with increasing T . The activation energy of the second region, which appears above transition T , is relatively higher than that of the first region. The observation of high value of activation energy in the second region may suggest that the polaron hopping conduction mechanism is dominating over charge carrier migration. While the compositional ratio of $x = 0.1$ has the highest E_a values both before and after the transition T (172 and 297 meV), the sample with $x = 0.5$ composition has the lowest E_a values (78 and 233 meV). As a result, the composite sample with $x = 0.5$ shows the highest DC conductivity. Substitution of any ion in ferrites can decline or enhance conductivity depending on the change in the charge carrier density and the electrical bond strength developed between the surface charges and substituent ions. Unexpectedly, it is seen that the sample with composition $x = 0.2$ has the lowest DC conductivity value. However, in previous studies, it has been observed that low substitution ratios of Cu and Zn ions generally cause a decrease in conductivity in ferrites, while conductivity improves with increasing substitution ratios [22, 23]. This indicates that at low substitution ratios, stronger bonds are formed between the surface charges and the substituted ions, and accordingly, the movement of charge carriers is impeded. Therefore, localization of free surface charges results in reduced DC conductivity. Above the transition T_s , the activation energies have high values over 200 meV for all SF's compositions. Activation energy and DC conductivity show a good correspondence with the compositional dependence as reported in previous studies [24, 25]. Such a tendency indicates the change of conduction mechanisms, and this phenomenon is more evident with the change of the transition T particularly for the $x = 0.5$ compositional ratio. It is clear that the variation of compositional ratio in H/S $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ SFNFs changes the transition T_s and consequently the E_a values.

3.2.3 Dielectric constant

The dielectric constant of H/S CFO/CuZnFO SFNFs was measured in F range 1 Hz–3.0 MHz at between 20 and 120 °C. The variation of dielectric constant vs F at various T_s is depicted in Fig. 7. The dielectric constant drops substantially with the rise of F , and subsequently, it achieves virtually a constant value at higher frequencies. A sharp almost linear decline is

Table 1 Activation energies (E_a) of H/S CFO/CuZnFO SFNFs

x	0.1		0.2		0.3		0.4		0.5	
T (°C)	T < 40	T > 40	T < 40	T > 40	T < 40	T > 40	T < 40	T > 40	T < 50	T > 50
E_a (meV)	172	297	139	260	149	273	160	235	78	233

observed in lower-F region particularly at low T_s while it broadens with enhancement of T and slowed down in higher-F region [26]. At low F, the observation of the improved value of dielectric constant for all SF's compositions is essentially due to high polarization. Consequently, the decrease in polarization is responsible for the reduction in dielectric constant at high frequencies. This phenomenon is called as dielectric relaxation/dispersion process, and such type of behavior is described based on space-charge polarization in which materials contains slightly conductive grains separated by highly resistive grain boundaries [27]. According to Koop's explanation, lower F values will create a higher grain boundary's influence. The dielectric constant is obviously associated with conduction mechanism in which the hopping of electrons between Fe^{2+} and Fe^{3+} ions is the primary factor that affects conduction process. The hopping of electrons leads to displacement of local charges giving rise to the polarization at grain boundaries. At the F limit exceeding a certain value, the $\text{Fe}^{2+} \leftrightarrow \text{Fe}^{3+}$ transition does not comply with the variant in an applied field.

It is clear that all the changes in the dielectric constant present greatly dependent on composition ratios and the curvature tendencies show similarities in the graphs apart from $x = 0.4$ at low and 0.5 at high frequencies. Such a typical interaction under the effect of the composition ratio suggests that the dielectric function produces a highly complex structure. On the contrary, the dielectric constant displays quite characteristic T dependency over the variation of F. For all compositions, the dielectric constant increases with T and it becomes more apparent at low frequencies except $x = 0.4$ while the T dependence behavior disappears for all compositions at high frequencies. However, the $x = 0.5$ sample exhibits T-independent behavior as two different groups at high frequencies. In the case of $x = 0.4$, the dielectric constant values are comparable for all T_s at low frequencies, whereas it starts to take quite different values with the increase in F. In other composition

ratios, a fairly stable trend is observed in the dielectric constant along the T axis.

At a given value of compositional ratios, in the present study for $x = 0.4$ and $x = 0.5$, the dielectric constant may display unexpectedly different behavior. It has been observed that electrical and dielectric properties of ferrite composites are significantly affected by various essential factors such as compositional ratios, structural arrangements, charge polarization, cation distribution and measurement T under the impact of various soft phases [28, 29].

3.2.4 Dielectric loss

The dielectric loss of H/S CFO/CuZnFO SFNFs was measured in F range of 1 Hz–3 MHz at various T_s , and the corresponding curves are illustrated in Fig. 8. Significant decrease is observed in dielectric loss particularly at lower frequencies, while the rate of decline lowers with the increase in F. The dielectric loss shows a fluctuation at higher frequencies for all compositional variations except $x = 0.1$ and 0.5. First, it decreases at all T_s and exhibits a F-independent behavior with practically equivalent values and then shows a small growth again. Since the dipole changes is the main factors adjusting the electrical properties of ferrites, it is reasonable to see such a fluctuation in dielectric loss with variations in compositional ratio. In the current SFs, CoFe_2O_4 and $\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ all or most Co^{2+} , Ni^{2+} , Cu^{2+} and Zn^{2+} ions occupy Oh sites (B sites) while the Fe^{3+} ions are on both tetrahedral (A sites) and B sites [30–32]. With the changes of the quantity of SF in the ferrite nanocomposites, the interaction of Fe^{2+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+} and Zn^{2+} ions with adjacent O^{2-} ions varies giving rise to a considerable alteration in dipoles as well as dielectric loss. The dipole interactions are more efficient at low frequencies, and hence, dielectric loss exhibits substantial lessening at high frequencies [33]. For all compositions except $x = 0.5$, the T effect is dominant specifically at low frequencies. An increase in the thermal energy facilitates the

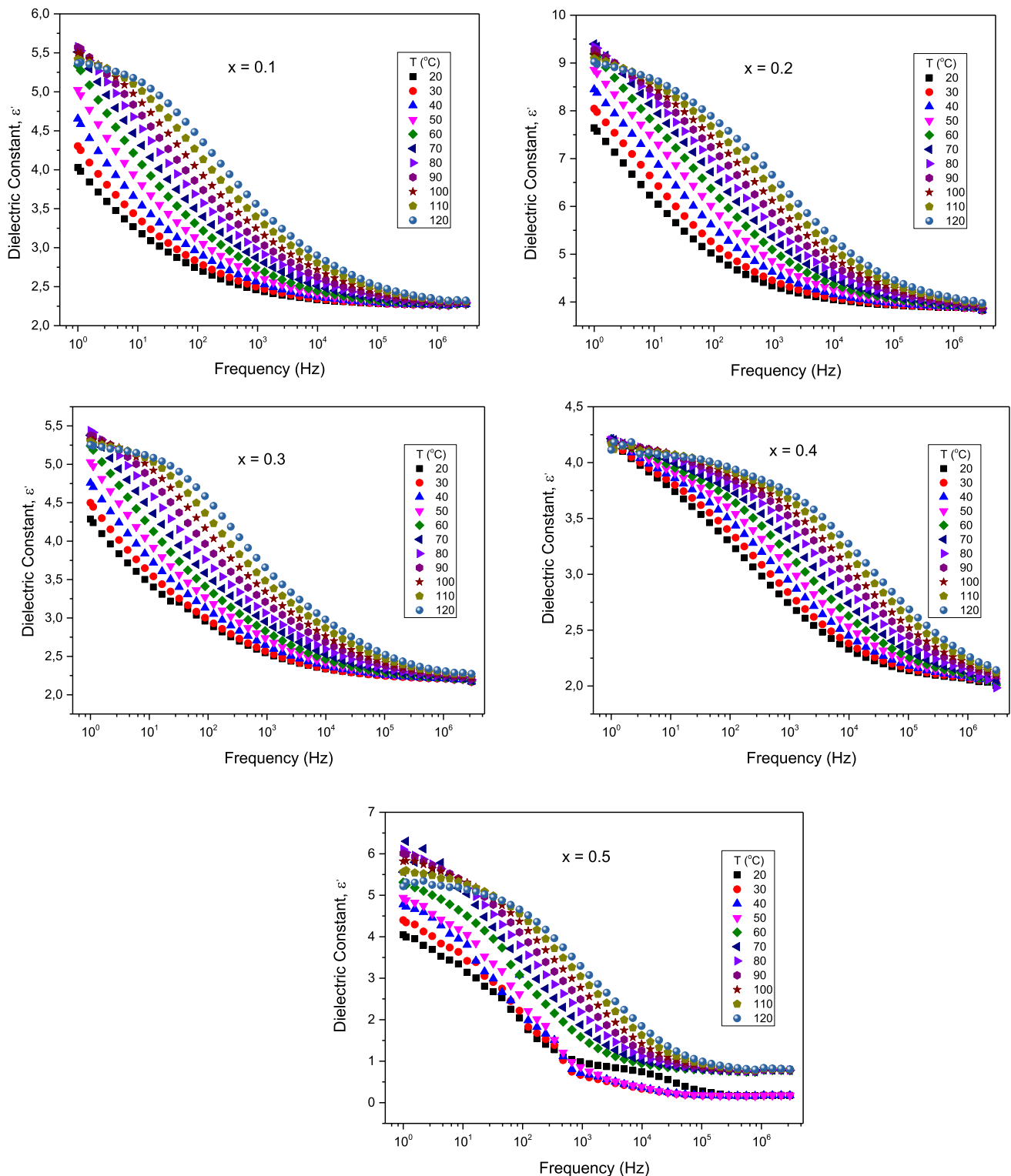


Fig. 7 Dielectric constants (ϵ') vs F (Hz) for H/S CFO/CuZnFO SFNFs

substitution of Co^{2+} , Ni^{2+} , Cu^{2+} and Zn^{2+} ions with Fe host ions in the SFs in both A and B sites. Therefore, the relaxation process in the SF's composites is

essentially related to numerous compositional defects such as charge polarization, cation distribution and

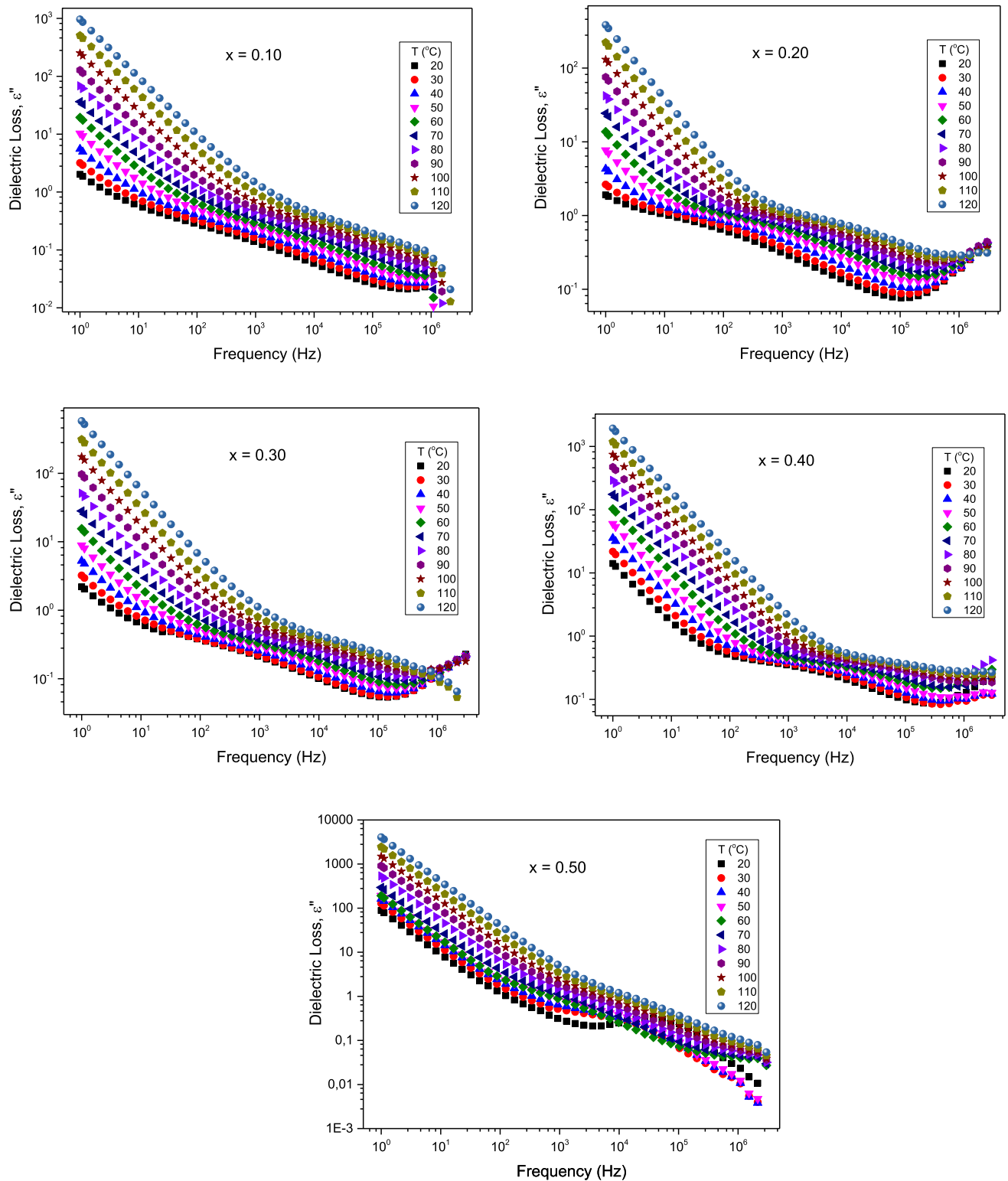


Fig. 8 Dielectric loss (ϵ'') vs F (Hz) for H/S CFO/CuZnFO SFNFs

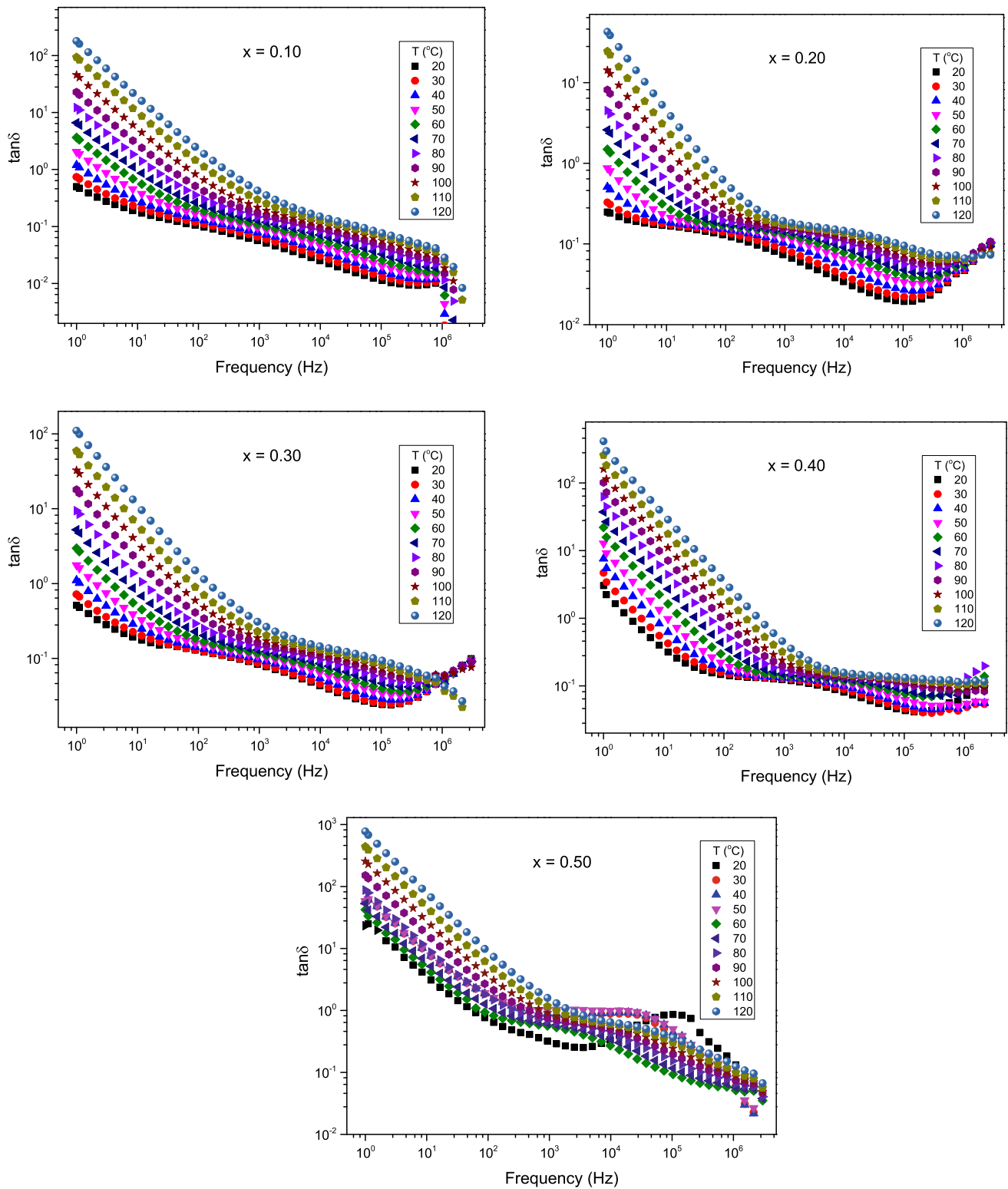


Fig. 9 Dielectric loss tangent ($\tan \delta$) vs F (Hz) for H/S CFO/CuZnFO SFNFs

T-induced ionic rearrangements because of substituted ions.

3.2.5 Dielectric loss tangent

The graphs of dielectric loss tangent vs F of H/S CFO/CuZnFO SFNFs are depicted in Fig. 9. It reveals similar dispersion curves as dielectric loss. The dielectric loss tangent has the maximum value in lower- F zone while it decreases noticeably with F and becomes almost F -independent at higher frequencies. As described above, the polarization reduces at higher value of external field. The variation of loss tangent with F can be assigned to the conduction mechanism in ferrites, which is generally clarified by Koop's model [34]. This model indicates that the effect of grain boundaries is more pronounced in the lower- F regions, and therefore, higher resistivity and higher loss tangent are realized. Consequently, substantial energy loss is occurred as significant amount of energy is required for electron exchange between Fe^{3+} and Fe^{2+} ions. For all composition ratios, quite expected trends were observed in the tangential loss along the changes of the F and T axis. However, the change in both T and F makes loss tangent to become more sensitive for any compositional ratio.

Considering the T effect, the dielectric tangential loss mostly rises rapidly in the F range of 1 Hz–1 kHz at all T_s . With the increase in T , the mobility of electrical charge carriers enhances generating greater dielectric polarization with electrical conductivity. The ions of the equivalent atoms exchange electrons or holes under the structural influence as a result of thermal excitation leading to individual dislocation of substituted ions. Accordingly, it can be supposed that electron/polaron hopping is the major process making a variation in the conduction mechanism. However, the variation in T remains quite limited above this F range, which evidently shows that the T effect is more pronounced at lower frequencies. Lastly, observed irregularity in the tangential loss with compositional ratios at higher frequencies can be referred to the readjustment of the polarization process in H/S $\text{CoFe}_2\text{O}_4/\text{Ni}_{0.3}\text{Cu}_{0.3}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$, as discussed in previous sections.

3.3 Cole–Cole plot

The Cole–Cole plot (Z'' and Z'), in general, reveals three consecutive semicircles displaying the

influences of grain, grain boundary and surface electrode, respectively [35]. The semicircle representing the resistance of the grain boundary appears in the low- F region while it appears in the high- F region for grain resistance. A real semicircle with its center on the Z' axis would appear for an ideal Debye relaxation [36]. The complex impedance is typically described as [37]:

$$Z^* = Z' - jZ'' = R_g - \frac{1}{j\omega_g C_g} + R_{gb} - \frac{1}{j\omega_{gb} C_{gb}} \quad (3)$$

where Z' and Z'' are the real and imaginary components of complex impedance, R_g and R_{gb} are the grain and grain boundary resistances, C_g and C_{gb} are the grain and grain boundary capacitances, and ultimately, ω_g and ω_{gb} are the frequencies of the semicircle for the grain and the grain boundary, respectively.

The Cole–Cole plot of H/S CFO/CuZnFO SFNFs recorded at various T_s in F range of 1 Hz–3 MHz and related graphs are shown in Fig. 10. Depending on the shape and number of semicircles, materials are defined by a suitable equivalent circuit. In accordance with current study, the proper equivalent circuit is given. In the present study, the shape of semicircles varies significantly with compositional ratios and T . Cole–Cole plots show only one semicircle whose diameter declines with increasing T . Such a decrease in diameters indicates an improvement in conductivity and a decrease in relaxation time. At low T_s , the curves, especially for the compositional ratio of $x = 0.1, 0.2$ and 0.3 , do not take the form of a semicircle, but instead represent a shape that shifts to a nearly straight line with decreasing T . This may be due to the grain boundary impedance being outside the measurement scale, and displays the insulating behavior of existing nanocomposites [38]. Additionally, the appearance of only one incomplete semicircle verifies the domination of grain boundary resistance and contribution of only grain boundary to conduction for all compositions in the low- F area. Higher quantities of defects are likely near the grain boundary region, which contributes greatly to grain boundary resistance and impedance [39]. With increasing compositional ratios x , the diameter of semicircle decreases indicating decline in impedance and advancement in conductivity which is consistent with AC and DC conductivities. When each sample is analyzed individually, it is seen that the radius of the semicircles is not on the Z' axis, which indicates

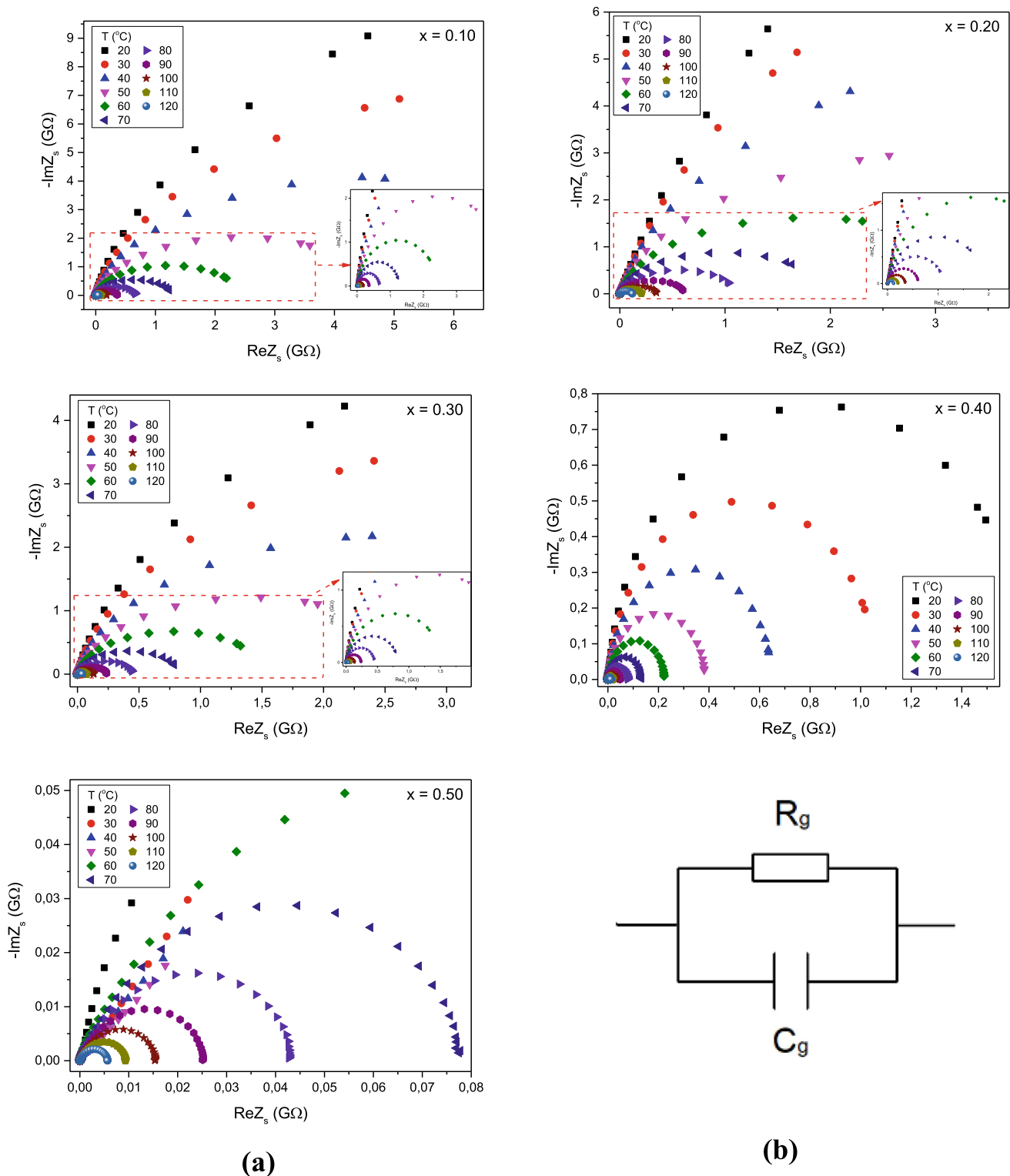


Fig. 10 **a** Cole–Cole plot for H/S CFO/CuZnFO SFNFs and **b** RC equivalent circuit for the samples with single semicircles

deviation of dielectric behavior from the Debye relaxation model [40]. The appearance of a single semicircle in all samples suggests a single relaxation

mechanism that can be explained by the jump relaxation model. In this model, the conduction is essentially due to the jumping of Fe^{3+} and Fe^{2+} ions

between the A and B regions in the low-F zone, while the jumping is significantly constrained at high frequencies [41].

4 Conclusion

The H/S CFO/CuZnFO SFNFs were produced by electro-spin. The SF structures were approved by XRD and HR-TEM. The SEM and TEM exhibited the nanofiber morphology. The electrical and dielectric properties of H/S CFO/CuZnFO SFNFs were extensively investigated as a function of F and T. The AC conductivity of NCs exhibits F-independent behavior in the low-F region ($< \sim 1$ kHz) while it turns into F-independent as the F increases. The DC conductivity displayed Arrhenius behavior in two separated regions. The AC and DC conductivities enhanced with T indicating thermally induced conduction mechanism. The maximum AC and DC conductivity was observed for $x = 0.5$ as 3.73×10^{-8} S/cm and 2.25×10^{-9} S/cm at 120 °C. The highest E_a values both before and after the transition T were observed for the $x = 0.1$ (172 and 297 meV), and the lowest values were computed for the $x = 0.5$ (78 and 233 meV). The dielectric constant, dielectric loss and dielectric loss tangent are considerably dependent on F, T and compositional ratios, and accordingly, in general, all parameters exhibited a decline with increasing F while they improved with T. The Cole–Cole plots showed mainly single incomplete semi-circle emphasizing deviation from Debye behavior and dominant contribution of grain boundaries to conduction mechanism. It also indicated a single relaxation mechanism ascribed to grain-to-grain boundaries which is explained by Koop's model. The functional electrical and dielectric properties of prepared nanocomposites can offer them to be potential candidates for various electronic devices such as medical devices, multilayer chip inductors, gas and biosensors.

Author contributions

MAA and HE conceived and designed the work. HE took part in investigation, writing and explaining. YS and AS carried out the formal analysis. AB was

responsible for project administration, editing and writing—reviewing and editing.

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The authors have not disclosed any funding.

Data availability

All data generated or analyzed during this study are available within this article.

Declarations

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

Ethical approval This article does not contain any studies involving animals performed by any authors. Also, this article does not contain any studies involving human participants performed by any of the authors.

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