Can you provide a brief summary of the main findings and conclusions of the research paper on spinel ferrite materials, focusing on their dielectric properties and their potential applications?
range were recorded through an Agilent 4294A impedance analyzer, whose frequency scale is of 40 Hz–110 MHz. For completely excluding the effects of sun shine and other sources of lights, the measurements were conducted under dark.

Results and discussion

From X-ray diffractométre, it is clear that the synthesized compound is single phase (Fig. 1). The Rietveld refinements of the XRD data performed using Fullprof program\textsuperscript{24} revealed that this compound crystallizes in the cubic structure with the \textit{Pm3m} space group in which \( \alpha = 8312 \, \text{Å} \) and \( V = 586.631 \, \text{Å}^3 \). Fig. 2 show the structure of Ni\textsubscript{0.5}Zn\textsubscript{0.5}Fe\textsubscript{2}O\textsubscript{4}. The average particle size \( D_{SC} \) was calculated using Scherrer’s formula:\textsuperscript{25}

\[
D_{SC} = \frac{(0.9 \times \lambda)}{(\beta \times \cos \theta)}
\]

where \( \lambda \) is the used wavelength (\( \lambda_{\text{CuK}} = 1.5406 \, \text{Å} \)), \( \theta \) and \( \beta \) are the Bragg angle and the full width at half maximum after subtracting the instrumental line broadening, respectively, for the most intense diffraction peak:

\[
\beta = (\beta^2_m - \beta^2_i)^{\frac{1}{2}}
\]

where \( \beta_m^2 \) is the experimental full width at half maximum (FWHM) and \( \beta_i^2 \) is the FWHM of a standard silicon sample. The \( D_{SC} \) value of our sample is about 72 nm.

Fig. 3 exhibits the variation of conductance as a function of frequency at different temperatures. This physical entity is expressed by the following relation:

\[
G = \frac{\sigma A}{l}
\]

where \( \sigma \) is the conductivity, \( A \) is the cross-sectional area of the material and \( l \) is its length. We can distinguish two regions. For low frequencies (50 Hz to \( 10^3 \) Hz) we notice poor conductance dependence on frequency, contrarily to the strong dependence behavior on temperature seen from the same spectra. Such behavior can be explained by the Maxwell–Wegner two-layer model suggesting that ferrites are made of well conducting grains surrounded by poorly conducting grain boundaries that are more active at lower frequencies. This leads to poor conductance resulting from weak electron hopping in the region.\textsuperscript{26} The second region that spreads from \( 10^3 \) Hz to \( 10^6 \) Hz presents a significant increase of conductance with rising frequency and can be described by the power law:\textsuperscript{27}

\[
G(\omega) = A(\omega)^s
\]

where \( A \) is a constant, \( \omega \) is the angular frequency and the exponent \( s \) is the slope of the frequency dependent region \( 0 \leq s \leq 1 \). Where \( s \) depends on the temperature and binding energy.\textsuperscript{27}

Fig. 4 exhibits the variation of conductance with temperature. Shown in green and the tetrahedral sites are in orange. It is well known that conduction in ferrites is led by the hopping of charge carriers between the sites.\textsuperscript{28}

The mechanism can be defined by the following equation:\textsuperscript{29}
where $B$ is a constant, $T$ is the absolute temperature, $E_a$ is the activation energy and $k_B$ is Boltzmann constant. We observe an increase of conductance with the rise of temperature at fixed frequency (83 Hz). This is due to an increase of hopping phenomenon with the increase of temperature. As clearly seen the rise is more pronounced at 700 K and the graph shows semiconducting behavior described by the increase of conduction with temperature. The linear relation between $\log(G.T)$ and $1000 \frac{T}{C_0}$ confirms the temperature dependence of conduction at 83 Hz. In fact, the remarkable change is attributed to the decrease of the potential barrier that creates free charge carriers. At high frequencies, we notice an acute decay of impedance that could be explained with the presence of a space-charge region resulting from the decline of charge barrier under the influence of temperature. It is known that grain boundaries are active interfaces for the creation of such region. Indeed, we can clearly observe constant values for $Z'$ at different temperatures for low frequencies suggesting an accumulation of charge carriers at the grain boundaries.

Fig. 5 Variation of $\log(G.T)$ with $1000 \frac{T}{C_0}$ for $x = 50\%$.

The variation of frequency dependent $Z''$ at varying temperature is shown in Fig. 7. We note that $Z''$ decrease when temperature increase. The plot indicates the presence of two peaks, called relaxation frequencies. The first peak, located between 50 Hz and $10^5$ Hz depending on the temperature, is attributed to the grain boundaries. Whereas the second one placed between $10^5$ Hz and $10^7$ Hz is attributed to the relaxation of the grain boundary. In fact, we can notice the shift towards higher frequencies as the temperature increases. This tendency indicates that charge carriers are thermally activated and are accumulated at the grain boundaries, and further confirms the semiconducting behavior of the nickel ferrites.

Fig. 6 Variation of real impedance $Z'$ with frequency at different temperatures.
On the other side, the resistance is very low and keeps decreasing with the rising heat. Furthermore, for the frequency range around $10^6$ we can clearly observe the merging of $Z^\prime$ regardless of temperature, which indicates the decrease of space charge polarization.

In order to determine the value of maximum frequency $f_{\text{max}}$ for which the imaginary impedance has maximum value, we superposed both $Z^\prime$ and $Z^\prime\prime$. We observe the presence of two pics which correspond respectively to the two inflexion points for $Z^\prime$ and two maximums for $Z^\prime\prime$. The frequency $f_{\text{max}}$ corresponds to the projection of the inflexion point on the frequency axis. For this case we have two inflexion points providing two maximums in agreement with the results discussed in the paragraph above.

Thus, from Fig. 8 we conclude the values of $f_{\text{max}} = 92.6 \text{ Hz}$ and $f_{\text{max}} = 782.4 \times 10^5 \text{ Hz}$.

The plot of normalized imaginary part of impedance $\frac{Z^\prime\prime}{Z^\prime\prime_{\text{max}}}$ as a function of normalized frequency $\frac{f}{f_{\text{max}}}$ is exhibited in Fig. 9.

The representation aims to enable the study of dielectric relaxation. We observe an overlap of spectra into a master curve which denotes that relaxation process is irrespective to temperature. In fact, the temperature independency indicates the existence of one relaxation mechanism for all spectra and the merging behavior could be explained by the emission of space charge. Moreover, the value of full width at half maximum is found to be > 1.14 decades indicating a poly-disperse non-exponential relaxation. This non-Debye (non-exponential) relaxation type may refer to a hopping mechanism of charge carriers along with time dependent mobility of the same type of charge carriers. To ground deeper explanation to this phenomenon we refer to the following relation defining the non-Debye relaxation:

$$\varphi(t) = \exp \left[-\left(\frac{t}{\tau}\right)^\beta\right] ; (0 < \beta < 1) \quad (6)$$

where $\varphi(t)$ is the time evaluation of electric field, $\tau$ is the relaxation time at peak and $\beta$ is the Kohlrausch exponent. The smaller value of $\beta$ indicates larger deviation of relaxation with respect to Debye type relaxation where $\beta = 1$. To calculate the relaxation time from $Z^\prime\prime$ vs. $\log f$ plot, we use the following relation:

$$\tau = \frac{1}{\omega} = \frac{1}{2\pi f_{\text{max}}} \quad (7)$$

where $f_{\text{max}}$ is the relaxation frequency. Logarithmic representation of relaxation frequency as a function of inverse temperature is shown in Fig. 10.

As discussed above we conclude that the relaxation frequency is increasing with temperature. The two slopes, attributed to the two frequencies observed in the impedance spectra, are used to determine the values of activation energies. Following the Arrhenius law:

$$f_{\text{max}} = f_0 e^{\frac{E_a}{k_B T}} \quad (8)$$

where $f_{\text{max}}$ is the relaxation frequency, $f_0$ is the pre-exponential term and $k_B$ is the Boltzmann constant. We obtain activation energy values of 0.250 eV and 0.228 eV corresponding
respectively to the grain and the grain boundaries. Comparing the reported results from conduction and impedance spectra shows close values referring to the same hopping mechanism of charge carriers. *respectively to the grain and the grain boundaries. Comparing the reported results from conduction and impedance spectra shows close values referring to the same hopping mechanism of charge carriers.*

Fig. 11 exhibits the plots of imaginary part as a function of real part of complex impedance at various temperatures of Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$. This technique aims to investigate the contribution of grains and grain boundaries based on the frequency range. The plots present two semicircular arcs that are not centered on the axis of real impedance $Z'$ indicating a non-Debye type of relaxation as previously concluded, and the obedience to Cole–Cole formalism. *For complex impedance it is given by the following relation:*

$$Z'(\omega) = \frac{R}{1 + (\frac{\omega}{\omega_0})^{1-n}}$$  \hspace{1cm} (9)

For when $n \rightarrow 0$ it results in the classical Debye’s formalism.

The decentralization could also explain the presence of only one electrical conduction mechanism. *The decentralization could also explain the presence of only one electrical conduction mechanism.* In fact, we can attribute the low frequency semicircle to the grain contribution, whereas the second semicircle is attributed to the grain boundaries contribution.

The formation of two semicircular arcs suggests the existence of two types of relaxation phenomena with the relaxation time given by $\tau_0\omega_{\text{max}} = 1$, where $\tau$ is the relaxation time and $\omega_{\text{max}}$ is the relaxation pulsation. As a matter of fact, these results correspond to the findings reported in the previous paragraphs.

On the other hand, we note that the interception of the plots shifts toward lower values of $Z'$ as the temperatures increases. There is a gradual decrease of resistance while the temperature is rising. This behavior indicates the low grain resistance for high temperatures, and the appearance of semicircles is indicative of semiconducting behavior.

Using Z view software, we have simulated the plots of $Z''$ vs. $Z'$. Fig. 12 is showing the simulation accompanied with the equivalent circuit used for the Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ sample. The model contains a series of three $R$-CPE combination circuits where $R$ is the resistance, and CPE is the constant phase element referring to the complex element. The combinations are attributed to grains and grain boundaries. The constant phase element impedance is defined by the following equation:

$$Z_{\text{CPE}} = [A(\omega_0)^{\alpha}\omega]^{-1}$$  \hspace{1cm} (10)

where $A$ is a proportional factor, $\omega_0$ is the angular frequency and $\alpha$ is the exponent between 0 and 1. At $\alpha = 1$ the constant phase element is considered an ideal capacitive element, whereas for $\alpha = 0$ it is equivalent to resistance.

Using the relationship $R = Z'/2$ we calculated the resistance in order to further investigate the relaxation phenomena and the conduction distribution.

Table 1 presents the values of resistance $R$ and constant phase element CPE for each series at different temperature.

This data was used to draw the curve given in Fig. 13 showing the variation of resistance as a function of temperature. We can notice a sharp decrease of resistance between 300 K and 340 K more pronounced for $R_1$ than $R_2$ and $R_3$, thereafter it starts decaying gradually as the temperature increases.
decreasing slowly. The temperature dependent behavior of resistance is attributed to the increase of charge mobility and thus conduction process. As the rate of resistance decreases differently in each plot, the rate of conductance is also increasing differently which indicates different activation energies as previously seen. In fact, following the Arrhenius relation we have:

$$ R = R_0 \exp \left( \frac{E_{ac}}{k_B T} \right) $$

(11)

where $R_0$ is a pre-exponential term, $E_{ac}$ is the activation energy and $k_B$ is the Boltzmann constant. Based on the plots given in Fig. 13 this law enables us to conclude two different activation energies in agreement with the results reported in the previous paragraphs.

Fig. 14 shows the variation of dielectric constant with frequency at various temperature ranging from 300 K to 400 K. As a matter of fact, we notice a giant permittivity of the order $10^6$. In fact, the behavior of the permittivity could be divided according to the frequency. For low frequencies ($<10^3$ Hz) the real part of dielectric constant increases with temperature which indicates the thermal activation of the charge carriers and thus affects the polarization. In order to explain this trend, we resort to Maxwell–Wagner double layer model designed for inhomogeneous structures.$^7,41$

We assume that the material is composed of two layers where the grains possess high conductance and grain boundaries have poor conductance. At lower frequencies the grain boundaries possess high resistance, so the electrons gather and generate polarization at the boundaries which explains the dielectric behavior of the material in the low frequency area. Thereafter we notice a rapid decrease of the dielectric constant independent of temperature. This could be attributed to the reverse electron motion as the frequency increase,$^7$ resulting in

| Temperature (K) | $R_1$ (Ω) | CPE1T (F) | CPE1P (F) | $R_2$ (Ω) | CPE2T (F) | CPE2P (F) | $R_3$ (Ω) | CPE3T (F) | CPE3P (F) |
|----------------|------------|-----------|-----------|------------|-----------|-----------|------------|-----------|-----------|
| 300            | 16 161     | 312 × 10^{-6} | 0.59627   | 4382       | 11 332 × 10^{-8} | 0.76477   | 6377       | 1320 × 10^{-10} | 0.95868   |
| 320            | 7412       | 1726 × 10^{-6} | 0.69692   | 2956       | 27 092 × 10^{-8} | 0.70014   | 3695       | 1390 × 10^{-10} | 0.962     |
| 340            | 4088       | 14 846 × 10^{-6} | 0.74431   | 1626       | 13 597 × 10^{-7} | 0.61015   | 2406       | 1912 × 10^{-10} | 0.943     |
| 360            | 2259       | 10 538 × 10^{-6} | 0.8178    | 778.7      | 32 877 × 10^{-6} | 0.46832   | 1912       | 5821 × 10^{-10} | 0.86629   |
| 380            | 1189       | 76 433 × 10^{-7} | 0.89876   | 529        | 11 626 × 10^{-5} | 0.50459   | 1428       | 1607 × 10^{-9} | 0.79896   |
| 400            | 685.2      | 6138 × 10^{-7} | 0.95869   | 429.2      | 47 528 × 10^{-6} | 0.646     | 1034       | 5586 × 10^{-9} | 0.72454   |
| 420            | 463.3      | 56 788 × 10^{-7} | 0.98073   | 326.4      | 33 432 × 10^{-6} | 0.696     | 738.6       | 10 148 × 10^{-8} | 0.68974   |

![Fig. 13](image1.png)  
Fig. 13 Temperature dependence of resistance.

![Fig. 15](image2.png)  
Fig. 15 Variation of imaginary part of dielectric constant with frequency at different temperatures.

![Fig. 14](image3.png)  
Fig. 14 Evolution of real part of dielectric permittivity ($\varepsilon'$) as a function of frequency.
The evolution of ac conductance as a function of temperature and frequency is found to follow Maxwell–Wagner two-layer model. Complex impedance plots have revealed the presence of two semicircular arcs (grain and boundary grain). This behavior was modeled by an electrical equivalent circuit composed of three series sets of resistance and capacitance in parallel. Nyquist plots show two semicircles, revealing the presence of two relaxations processes in our material associated with grains and grain boundaries. Moreover, the real and imaginary part of dielectric constant were studied as a function both of temperature and frequency. The decrease of giant permittivity values with the increase in frequency proves the dispersion in low frequency range and is showing the Maxwell–Wagner interfacial polarization.

We note a light increase of dielectric loss. This behavior could be explained by the piling up of the electrons at the grain boundaries after reaching the area through hopping mechanism.

**Conclusions**

$\text{Zn}_{0.5}\text{Ni}_{0.5}\text{Fe}_2\text{O}_4$ spinel ferrite is synthesized using the solid-state reaction technique. X-ray diffractogramme reveals that our sample is pure and crystallizes in the orthorhombic system with $Pbnm$ space group. The dielectric study is performed by complex impedance spectroscopy in a wide range of temperature [300–420 K] and frequency [40–10$^7$ Hz]. The relaxation frequency values are determined from impedance spectroscopy, which are thermally activated.

**Conflicts of interest**

There are no conflicts to declare.

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