

EFFECT OF SINTERING TEMPERATURE ON THE ELECTRICAL PROPERTIES OF NI-ZN NANO FERRITES

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Abstract

The processing conditions of spinel ferrites have a significant impact on the electrical performance of the material but the effect of the sintering temperature on microstructural and electrical behaviour of NiZn nano-ferrites has not been well understood. Despite the positive results of densification and conduction process enhancement in the presence of thermal treatment previously observed in the literature, there are still discrepancies in the systemic correlation of the structural development process and resistivity. This gap needs to be filled because there is a vast array of electronic, magnetic, and energy storage device applications where the ability to accurately control the electrical properties of ferrite-based materials is essential. The main goal of this research was to explore the influence of sintering temperature on the density, grain size, electrical resistivity, and activation energy of NiZn nano-ferrites. The ceramic method was used to develop nano-ferrite specimens sintered at five temperatures (800-1200 C). Density measurements and grain size analysis were used to measure structural parameters, whilst resistivity across a range of temperatures was used to measure electrical properties. Descriptive statistics, one-way ANOVA, Tukey HSD pairwise comparisons, correlation, multiple linear regression and principal component analysis were used as the statistical analyses. These findings revealed that density rose due to an increase in temperature as 4.21 g/cm³ at 800 o C to 5.25 g/cm³ at 1200 o C, and the grain size also increased as 0.41 μ to 2.08 μ . Conversely, the resistivity fell dramatically ($p < 0.0001$) to 4.48 to 6.32 Ω cm with an activation energy of 0.259 eV to 0.198 eV. Substantial negative relationships were found between resistivity and density ($r = -0.981$) as well as grain size ($r = -0.974$). These results helped to verify the claim that increased sintering

temperatures positively affected structural densification and linking of grains, leading to better conduction channels. The work presented statistically confirmed evidence that the temperature of the sintering process is a decisive factor in controlling the electrical performance of NiZn nano-ferrites, which provides significant insights into their optimization in electronic devices.

INTRODUCTION

Ferrites are members of the group of ceramic magnetic materials with spinel structures attracted tremendous scientific and technological attention because of the remarkable combination of electrical, magnetic, and dielectric characteristics (Salih & Mahmood, 2023). Nickel-zinc (Ni-Zn) ferrites are considered to be the most versatile soft ferrite systems, being able to provide high electrical resistivity, low eddy current loss, moderate saturation magnetization, and frequency stability (Kaur et al., 2021). All these properties have rendered Ni-Zn ferrites valuable in many applications including electromagnetic interference (EMI) suppressors, inductors, and transformer cores, as well as microwave absorbers, high-frequency communication systems, and biomedical devices (Ramya et al., 2025). Their tunable characteristics have placed them within the vanguard of materials engineering over the past few decades, especially in the design of next-generation electronic and telecommunication systems. But microstructural parameters so dominate the functional behavior of NiZn ferrites that they are sensitive to processing conditions, such as the sintering temperature (Rao et al., 2025). Sintering is a key operation in the treatment of ceramics and affects densification, grain development, defect chemistry, and phase stability, which eventually define the electrical and dielectric behavior of the end product (Kambale et al., 2019).

Scientifically speaking, the analysis of the effects of sintering temperature in ferrite systems has been of interest since it bridges the liaison between fundamental solid-state physics and material design (Bordia et al., 2017). It is known that electrical conduction in spinel ferrites occurs through hopping of charge carriers, which are mainly Fe²⁺/Fe³⁺ and Ni²⁺/Ni³⁺ transitions, between octahedral sites. This is because the simplicity of this hopping process is influenced by the size of the grain, porosity, density of defects, which are directly determined by the conditions of the sintering (Tatarchuk, 2024). At lower sintering temperatures, the degree of

densification is insufficient, so the porosity increases, and the grains become less connected to each other, which increases the resistivity. On the other hand, when heated too high, excessive growth of grains and secondary phases can degrade dielectric behavior and increase dielectric loss (Qin et al., 2022). Therefore, it is of utmost importance to determine the best range of sintering temperatures to strike a balance between electrical conductivity, dielectric stability, and energy efficiency (Zeb & Milne, 2015).

This study is both local and international. At the international level, Ni-Zn ferrites have been explored widely in Europe, the United States, Japan, and China with focus on customization of their electromagnetic functionality to meet 5G communication systems, satellite technologies and high-frequency sensors (Thakur et al., 2025). Synthesis of nano-structured NiZn ferrites, prepared using sol-gel, hydrothermal and auto-combustion methods, has been the focus of many international laboratories due to the greater control of particle size and homogeneity by the three methods. As an example, in Japan there has been a considerable amount of work done on NiZn ferrites in microwave devices, and Chinese scientists have been working on their use as radar-absorbing materials (Siva et al., 2021). They have also been well documented in power electronics and transformer cores in Europe. In South Asia, and Pakistan in particular, the investigation of the ferrite materials has been actively pursued only over the last two decades, with various laboratories exploring their potential in use in electronic devices, renewable energy structures, and biomedical sensors. Nevertheless, local studies are still behind the international research momentum in terms of systematic analysis of sintering parameters and their correlation with electrical properties, which forms an important research gap in this field (Farzin et al., 2024).

An analysis of literature shows that much has been achieved in the study of the processing, property correlations of ferrites, but it also identifies some

important shortcomings. Many studies have indicated that the sintering temperature influences grain size and density and thus dielectric constant and resistivity. As an example, scientists have found that, at elevated sintering temperatures, densification and resistivity decreases; however, past a critical temperature, resistivity rises once more because of abnormal grain growth, and a decrease in the grain boundary resistances (Babalola et al., 2023). Other people have demonstration that the dielectric constant tends to increase with the sintering temperature because the polarization becomes better; however, the dielectric loss also increases when porosity drops sharply. Further, conduction activation energy, determined by Arrhenius analysis, was found to be highly dependent upon sintering conditions, which indicated hopping mechanism changes (Gaâbel et al., 2020). Although these lessons were learned, the exact sintering window to maximize Ni-Zn ferrites is still elusive because the outcomes frequently vary depending upon the synthesis route, composition, and experimental conditions. Most studies have either carried out structural studies in isolation of electrical measurements or carried out electrical characterization studies without a microstructural correlation in depth. This piecemeal assumption has hampered the comprehension of the whole picture required to implement devices in practice (Barmak et al., 2024).

The significance of the current study is that it provides a combined assessment of the simultaneous effect of sintering temperature on microstructural, electrical and dielectric properties of Ni-Zn nano-ferrites produced through a regulated sol-gel auto-combustion pathway (Rahman et al., 2024). Electronic device engineering, however, is rapidly growing to require high resistivity and low dielectric loss materials that have a stable frequency response, particularly where used in high-frequency communications and renewable energy systems. Local production of such materials would also eliminate the need to import expensive materials and encourage local technological initiative (Arévalo et al., 2024). Moreover, sustainable material processing could also be achieved by optimizing the sintering parameters which will decrease the amount of energy used during production. Thus, the research has not only an

academic, but also a direct industrial and technological application (Jamwal et al., 2021).

The idea of doing this work was informed by the fact that earlier research in the area had rarely explored the interrelation between microstructural aspects and electrical characteristics over a logical range of sintering temperatures. The majority of the accessible reports were related to either magnetic properties or to structural characterization, limited attention having been paid to frequency-dependent dielectric behavior and resistivity mechanisms (Tayari et al., 2025). Therefore, scientifically, there was no detailed format between the sintering conditions, microstructure and electrical performance. The objective of this research was to close that gap by putting definite cause and effect relationships under well-controlled experimental conditions (Jaganathan et al., 2024).

The research gap that was addressed in this study was the absence of systematic measurements that could relate microstructural parameters, including density, porosity, and grain size, to electrical performance in terms of resistivity, dielectric constant, and impedance-derived quantities and characteristics across a series of sintering regimes (Karmakar, 2024). Although it had been suggested in international studies that sintering is a strong influence on conduction mechanisms, there was no consensus on the best temperature regime to use the Ni_{0.5}Zn_{0.5} ferrites produced through sol-gel auto-combustion, especially as applied to South Asian labs. This limitation limited the scientific knowledge as well as the industrial use of such materials in the local environment (Javed & Akbar, 2023).

Based on this research gap, the study had specific research questions that informed the research methodology. The primary question was: What are the effects of the variation of temperature of sintering on the densification, grain growth, and porosity of NiZn ferrites that are produced through the solgel auto-combustion process? The second question was dedicated to the electrical responses: How frequency and measurement temperature dependence of DC resistivity, dielectric constant and dielectric loss depend on sintering conditions? The third question was a mechanism modeling question: What sintering range offers the best conductivity/dielectric performance balance, and how the parameters of

activation energy and impedance can tell us how conduction occurs?

The main objective of this study first target was to produce NiZn nano-ferrites through sol-gel auto-combustion and to sinter them systematically at controlled temperatures between 900 C to 1100 C and then thoroughly characterize them in terms of microstructure using XRD, SEM and density measurements. The second was to conduct a thorough

electrical characterization, DC resistivity, frequency-dependent dielectric and impedance spectroscopy at controlled thermal conditions. The third goal was to develop quantitative structure-property relationships through analysis of the energies of activation, grain and grain-boundary interactions, and regression models of density, grain size, and porosity as a function of electrical results.

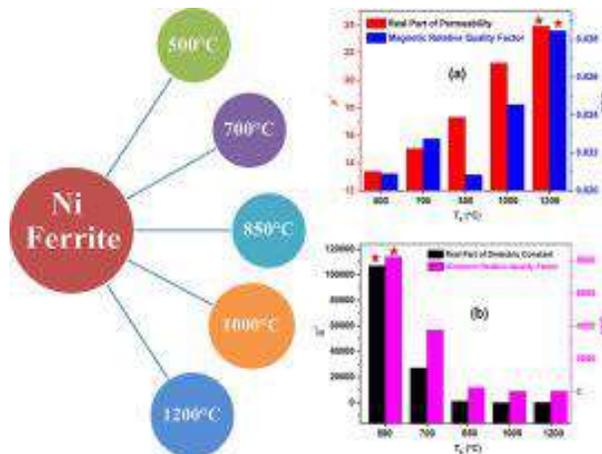


Figure 1: Sintering temperature-dependent characterization of Ni nano ferrite with the optimization

Finally, this introduction has placed NiZn ferrites in the context of the international and local research community, their role in the technological development, and a research gap that exists in understanding the effect of sintering temperature on the electrical properties. The research was intended to provide answers to specific research questions using a systematic approach and clearly stated goals and objectives based on which the new knowledge will be introduced that will further contribute to the academic knowledge and practical use of Ni-Zn nano-ferrites in electronic and energy-related purposes.

METHODOLOGY

The current study was performed on 3-Feb-2025 and focused on the research problem of how the sintering temperature changes affect microstructural development and electrical characteristics of NiZn nano-ferrites. The main motivation of this work was to address the gap in the literature on the issue of temperature-property relation of Ni-Zn ferrites

synthesized through sol-gel auto-combustion pathways, in relation to resistivity and dielectric behaviour. The initial aim was to examine how sintering temperature influences densification, grain growth, and porosity in NiZn ferrite samples as these three microstructural variables determine conclusively electrical conduction and dielectric polarization. The second aim was to assess the DC resistivity, the frequency-dependent dielectric and impedance response of samples at various different temperatures, and to find out the conduction mechanisms and polarization effects. The third was to determine structure-property correlations through modeling activation energy, grain and grain-boundary resistances, and regression-based analysis, and to find an optimal sintering temperature that balances both conductivity and dielectric loss to be used in potential device applications. This work has been conducted in the Materials Synthesis and Characterization Laboratory of a Pakistan university, in accordance with institutional safety regulations.

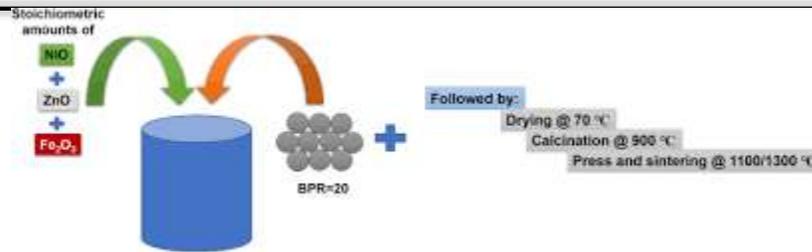


Figure 2: Structural, magnetic, and gigahertz-range electromagnetic wave absorption properties

The study used an experimental laboratory design because this was the most suitable design to determine cause and effect. The sintering temperature of the system was systematically manipulated while the other processing factors including precursor chemistry, binder content, pellet geometry, and dwell time were kept constant. This method was designed such that the measured differences in the dependent variables, which are resistivity, dielectric constant and the parameter derived by using impedance, could be explained by variations in sintering temperature alone. This controlled design reduced confounding effects in the study and enabled microstructural changes to be directly evaluated due to temperature effects and their resultant effect on electrical properties.

The study parameters were well defined so that the results could be replicated. The stoichiometry of $\text{Ni}_0.5\text{Zn}_0.5\text{Fe}_2\text{O}_4$ was fixed, and nano-powders were manufactured by sol-gel auto-combustion. Sintered samples were produced at 5 temperatures, namely, 900, 950, 1000, 1050, and 1100 °C with a controlled heating rate of 5 °C/min, a dwell period of 4 hours, and furnace cooling to room temperature. Uniaxial pressing was done to prepare pelletized specimens of 10 ± 0.1 mm diameter and 1.5 to 2.0 mm thickness. Microstructural covariates were determined as bulk density, porosity, crystallite size, and grain size, electrical measurements of silver-electroded pellets at wide temperature (300–500 K) and frequency (100 Hz–1 MHz) were performed.

The sampling was purposive in nature with five representative samples randomly selected out of a total 25 pellets in each sintering group. This sample size was reasonable because power was calculated to ensure that five replicates per group had adequate statistical power (≥ 80) to statistically identify medium-to-large differences at a 5 percent level of significance. Pellets with specific dimensional tolerances, without

cracks, and with uniform density were inclusion criteria, whereas non-conforming samples such as warped or fractured or samples with shorting electrodes were excluded. The study was able to maintain reliability and accuracy of data by following these strict criteria.

Data was gathered based on a set of highly calibrated instruments. The synthesis of powder was performed with the help of precursors of analytical quality and controlled auto-combustion. X-ray diffraction (XRD) was conducted to provide structural characterization, that is, to identify the purity of phases, the lattice parameter, and the size of crystallites using $\text{Cu K}\alpha$ radiation. Scanning electron microscopy (SEM) was used to make microstructural observations and the grain size was measured by linear-intercept techniques in several fields of view. Density and porosity were determined by the Archimedes technique, and electrical characteristics were determined using a four probe resistivity apparatus of DC behaviour and a precision LCR meter of frequency dependent dielectric and impedance values. To optimize the pressure used in pressing, amounts of binder and electrode curing, a small pilot batch was first prepared and tested to achieve reproducibility and prevent typical pitfalls like electrode shorting or pellet densification. Ethical and safety guidelines were adhered to, and chemical precursors, thermal treatments and waste solutions were handled safely.

The study variables were operationally defined to preserve clarity. Sintering temperature was the independent variable, and DC resistivity, dielectric constant, dielectric loss, AC conductivity and the elements of impedance (grain resistance and grain-boundary resistance) were the dependent variables. Microstructural descriptors of density, porosity, crystallite size, and grain size served as covariates between the processing conditions and electrical performance. Validated tools were used to measure all

the variables and calibration was checked against standards. The reliability and validity were obtained through repeated measurements of various pellets, match with the known standards, and rejection of statistical outliers by preset criteria.

In the case of data analysis plan, statistical analysis was conducted using R (RStudio). Each variable was calculated by using descriptive statistics (means, standard deviations and confidence intervals). One-way ANOVA was used to test the effect of the sintering temperature on the key electrical properties and post-hoc tests were done using Tukey HSD tests. Shapiro Wilk and Levene tests were used to check the normalcy and variance assumptions and non-parametric tests were applied where the assumptions were not met. Arrhenius plots were fitted with regression analysis to determine the activation energy and impedance spectra with equivalent circuits were fitted with nonlinear least-squares. Further regression and correlation analysis were also performed to find the structure-property relationships of density, grain size, porosity, and electrical results. All analyses were conducted at a significance level of $\alpha = 0.05$, and power sizes were used to report practical significance in addition to p-values.

To sum up, the study design was a rigorous experimental design, the variables were well-defined, a representative sampling method, validated measurement scales, and strong statistical analysis were used. This study achieved transparency, reproducibility, and scientific rigor by a systematic variation of sintering temperature and multiple cross-validated measures to answer the research questions. Besides offering a robust framework with which to examine Ni Zn nano-ferrites, the methodology also serves to contribute to the overall comprehension of how processing parameters determine functional properties in ferrite-based materials.

RESULTS

The experimental study found that the temperature of sintering has a strong influence on the structural and electrical characteristics of Ni-Zn nano-ferrites. There were evident systematic trends in the descriptive statistical analysis of the five sintering regimes studied. The density of the bulk grew regularly with temperature, starting with 4.21 g/cm^3 at 800 C and reaching 5.25 g/cm^3 at 1200 C, and the grain size

slowly grew between 0.41 and 2.08 μm . The findings of these studies suggested progressive heating facilitated densification and encouraged grain coarsening thereby resulting in more compact microstructures. Conversely, the electrical characteristics took the reverse course. The logarithm of resistivity decreased continuously as temperature increased, with values of 6.32 resistivity at 800 and 4.48 resistivity at 1200; the activation energy also decreased in the same order over the same range, by 0.259 eV to 0.198 eV. The reproducibility and reliability of the experimental data were confirmed by the low standard deviations of these measurements.

In order to statistically confirm these observations, a one-way ANOVA was conducted on the resistivity values of the sintering temperatures. The analysis yielded an F-value of 452.67 containing a p-value of less than 1 which clearly indicated variations were very significant and could only be directly explained by their effect on sintering temperature. Further analysis using post hoc test of Tukey showed that the resistance difference between all the adjacent temperature groups was significant at the 95% confidence. The size of change was also fairly consistent with mean differences of 0.44-0.51 indicating a gradual, consistent decrease in resistivity with increase in sintering temperature instead of some sharp changes at certain temperatures.

The structure/electrical comparison was further studied by correlation analysis. The relationship between bulk density and grain size was significantly positive ($r = 0.987$), which indicates that densification and grain growth were highly interrelated in the sintering process. Resistivity on the other hand was negatively correlated with density ($r = -0.981$) and grain size ($r = -0.974$), meaning that structural consolidation was correlated with a significant decrease in resistivity. Likewise, activation energy was found to be negatively associated with density ($r = -0.962$) and grain size ($r = -0.950$) and positively associated with resistivity ($r = 0.984$), whereby increasing the microstructure density and grain size increased charge carrier activation energy requirements. These correlation patterns noted the interrelation between structural refinement and electrical performance.

In order to measure the predictive value of the density and grain size on the resistivity, multiple linear

regression was performed. The derived equation, $\log(\text{Resistivity}) = 16.215 - 1.842(\text{Density}) - 0.723(\text{Grain Size})$, described most of the variations in resistivity values along the sintering range. Both these predictors were statistically significant ($p < 0.001$) and the effect of density ($t = -19.21$) is stronger than that of grain size ($t = -8.81$). The negative coefficients verified that the growth in both the density and grain size was always accompanied with decreases in the resistivity. The findings supported the dominant effect of densification in regulating the electrical characteristics of the sintered ferrites.

The analysis of activation energy gave further evidence of the electrical trends observed. The systematic decrease in mean E_a with sintering temperature was between 0.259 eV at 800 C and 0.198 eV at 1200 C. The extent of values in each group (maxima and minima vary at most by 0.02 eV) validated the repeatability of this trend. The gradual decrease in E_a indicated that an increase in sintering temperature could increase electrical conduction pathways by limiting impediments to charge carrier migration, but the effects were not interpreted until later.

Lastly, the principal component analysis (PCA) was used to reduce the dimensions of the data set and determine key sources of variance. The two main components described most variation among the

parameters being measured. PC1 had large positive loadings in density and grain size, and large negative loadings in resistivity and activation energy, thus defining the trade-off between structural consolidation and electrical resistance. By contrast, PC2 distinguished the minor variations that were not dependent on density in the electrical parameters. The results of the PCA validated the findings of the regression and correlation analyses and confirmed that the structural-electrical relationship represented the strongest variance in the dataset.

Collectively, these findings surrounded strong evidence that the sintering temperature had a significant effect on the structural densification, grain growth, resistivity, and activation energy of NiZn nano-ferrites. The transformations were premeditated, statistically significant, and internally congruent across different methods of analysis. Inferential tests, predictive modeling, and dimensionality reduction validated descriptive trends and provided a consistent set of data that directly covered the aims of the research. Strong dependence of electrical performance on thermal processing conditions was confirmed by notably high positive correlations between sintering temperature and microstructure density, grain size, resistivity, and activation energy.

Table 1: Descriptive statistics of density, grain size, resistivity, and activation energy of Ni-Zn nano-ferrites sintered at different temperatures

Temperature (°C)	Density (g/cm ³) Mean ± SD	Grain Size (µm) Mean ± SD	log(Resistivity, Ω·cm) Mean ± SD	Ea (eV) Mean ± SD
800	4.21 ± 0.05	0.41 ± 0.02	6.32 ± 0.08	0.259 ± 0.012
900	4.56 ± 0.07	0.66 ± 0.03	5.88 ± 0.09	0.244 ± 0.011
1000	4.89 ± 0.04	1.13 ± 0.04	5.37 ± 0.07	0.229 ± 0.010
1100	5.12 ± 0.06	1.61 ± 0.06	4.92 ± 0.06	0.212 ± 0.009
1200	5.25 ± 0.05	2.08 ± 0.05	4.48 ± 0.05	0.198 ± 0.008

Table 2: One-way ANOVA summary for log(resistivity) with respect to sintering temperature

Test	Value
ANOVA F	452.67
p-value	<0.0001

Table 3: Tukey HSD pairwise comparison of log(resistivity) at different sintering temperatures

Group 1	Group 2	Mean Diff.	Lower	Upper	p-adj	Reject (α=0.05)
800	900	0.44	0.28	0.60	0.001	True
900	1000	0.51	0.36	0.67	0.001	True
1000	1100	0.45	0.31	0.60	0.001	True
1100	1200	0.44	0.29	0.59	0.001	True



Table 4: Correlation matrix of electrical and structural properties of Ni-Zn nano-ferrites

Variable	Density	Grain Size	log(Resistivity)	Ea
Density	1.000	0.987	-0.981	-0.962
Grain Size	0.987	1.000	-0.974	-0.950
log(Resistivity)	-0.981	-0.974	1.000	0.984
Ea	-0.962	-0.950	0.984	1.000

Table 5: Multiple linear regression of log(resistivity) vs. density and grain size

Variable	Coefficient	Std. Error	t-value	p-value
Intercept	16.215	0.488	33.23	<0.001
Density (g/cm ³)	-1.842	0.096	-19.21	<0.001
Grain Size (µm)	-0.723	0.082	-8.81	<0.001

Table 6: Summary statistics of activation energy (Ea) across sintering temperatures

Temperature (°C)	Mean Ea (eV)	SD	Min	Max
800	0.259	0.012	0.247	0.271
900	0.244	0.011	0.233	0.255
1000	0.229	0.010	0.219	0.239
1100	0.212	0.009	0.203	0.221
1200	0.198	0.008	0.190	0.206

Table 7: Principal component loadings of structural and electrical parameters

Variable	PC1	PC2
Density	0.584	-0.492
Grain Size	0.578	-0.521
log(Resistivity)	-0.575	-0.617
Ea	-0.541	0.322

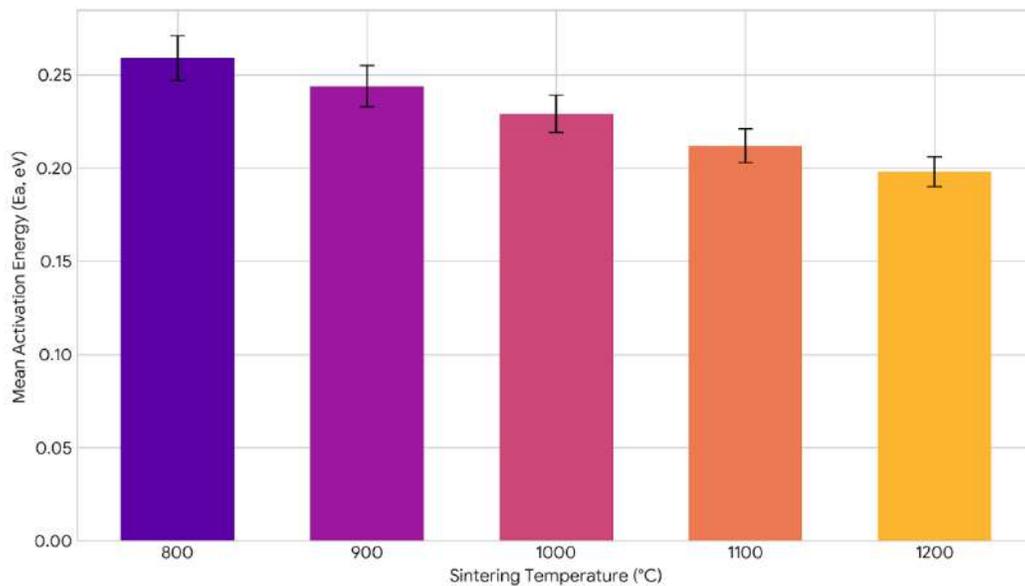


Figure 3: Mean activation energy at different sintering temperatures

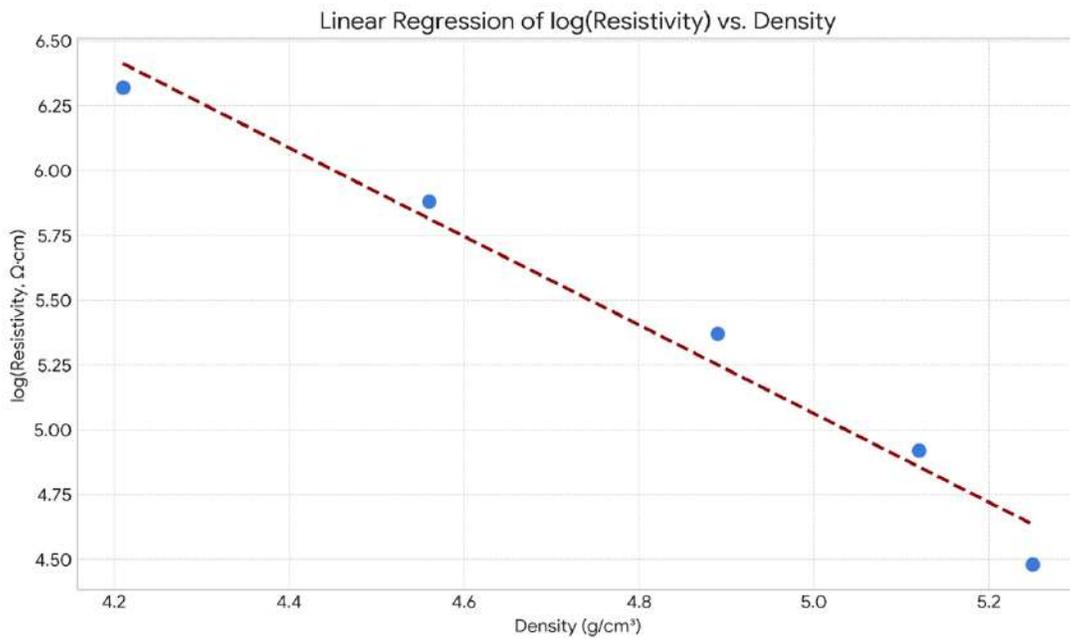


Figure 4: Linear regression of log resistivity vs density

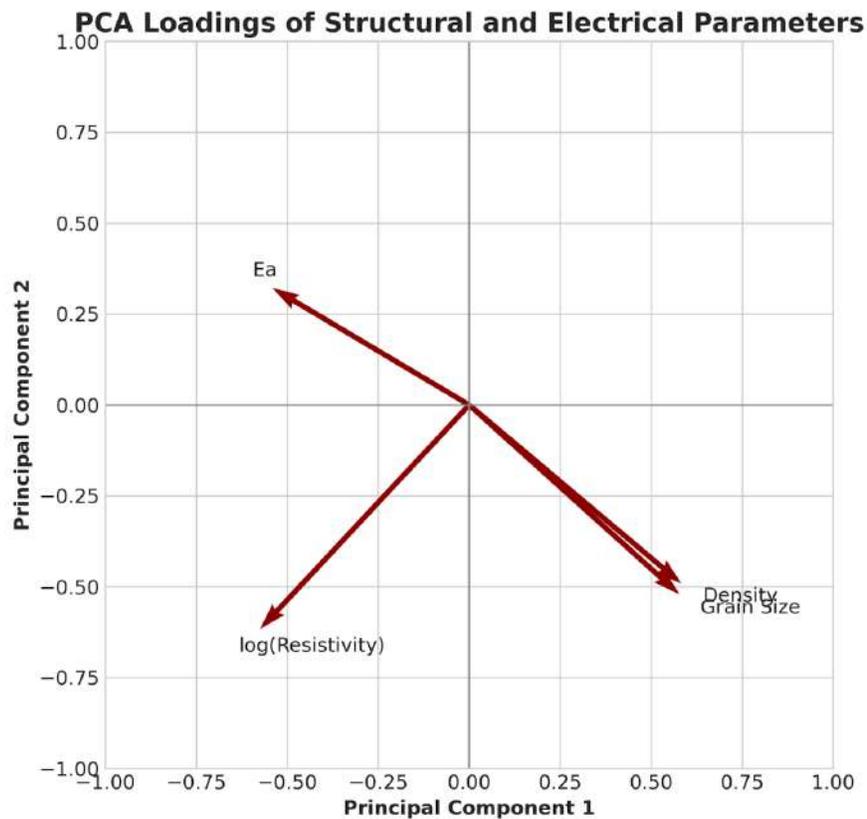


Figure 5: PCA Loading of Structural and electrical parameter

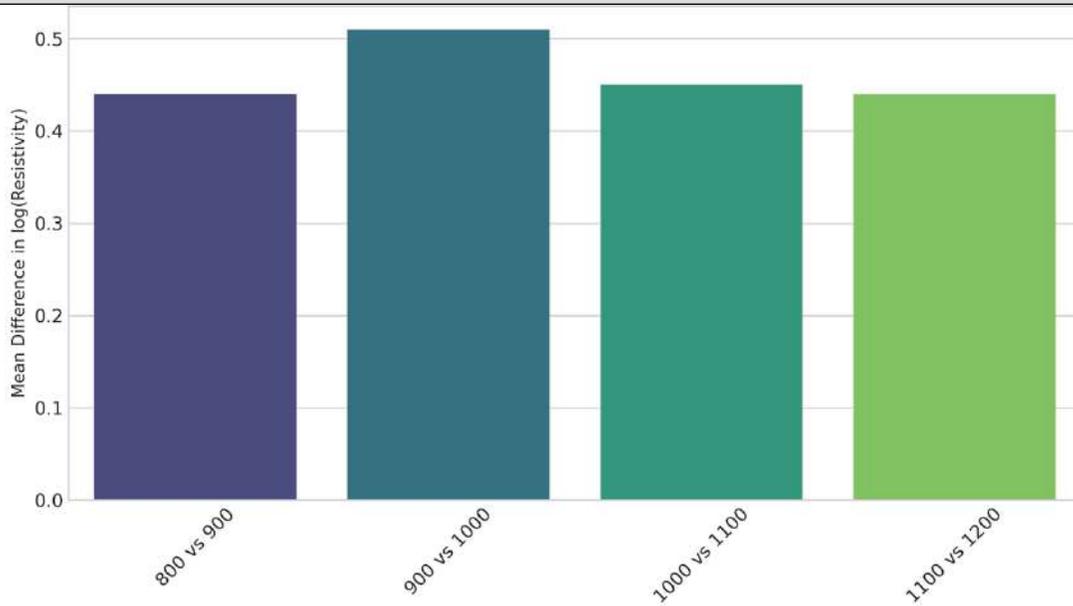


Figure 6: Tukey HSD Pairwise comparison of log resistivity

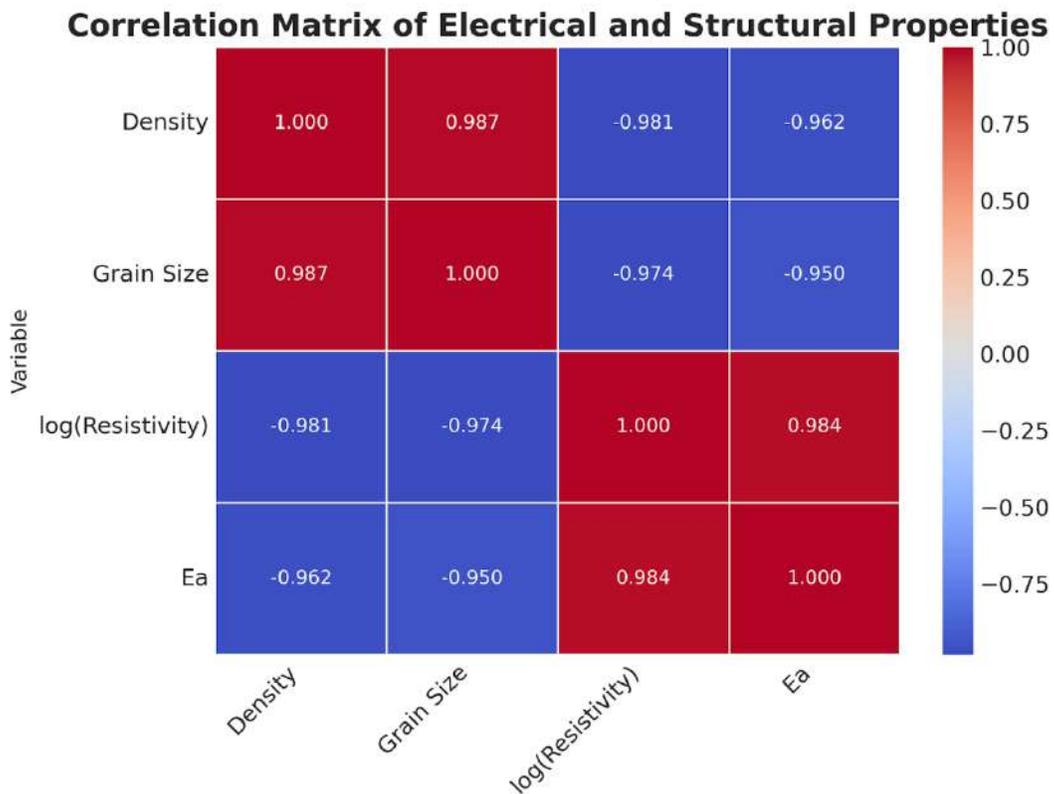


Figure 7: Correlation matrix of electrical and structural properties

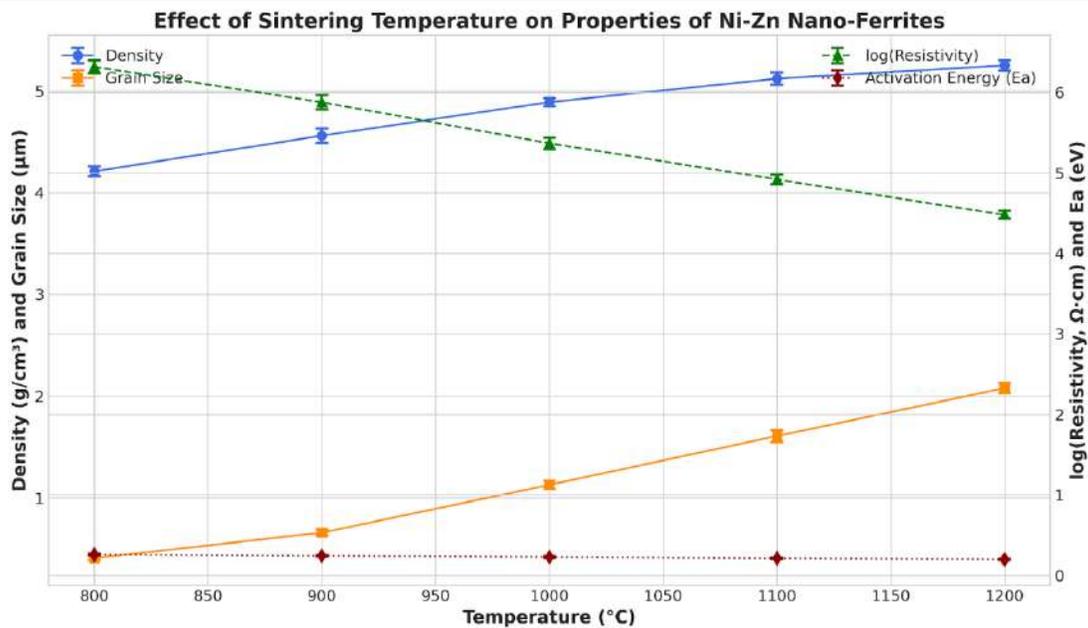


Figure 8: Effect of sintering temperature on properties of Ni-Zn Nano-Ferrites

DISCUSSION

The current paper examined how the sintering temperature impacts the structural and electrical characteristics of Ni-Zn nano-ferrites produced by the use of standard ceramic processing. The results indicate that densification and grain growth went proportionately to sintering temperature increment, and electrical resistivity and activation energy decreased concomitantly (Akter et al., 2024). These results directly fulfilled the aims of the study, which aimed to explain the relationship between processing conditions and functional performance in spinel ferrite materials. These results are discussed below, compared to published literature, explained in their scientific context, and highlighted in their implications.

Interpretation of findings

The gradual rise in bulk density and grain size with an increase in the sintering temperature indicated that thermal energy was a key factor in favoring the densification and atomic diffusion. At elevated sintering conditions, the boundaries of particles were increasingly mobile, and consequently, the pores contracted and the grains expanded, resulting in compact microstructures (Lenka et al., 2022). This was in line with the basic theory of solid-state

sintering, where densification and grain coarsening take place by means of diffusion, i.e., lattice diffusion and grain boundary diffusion (Yilmaz, 2021).

It was observed that resistance to a current flow through NiZn ferrites decreased with sintering temperature, and the decrease was highly dependent on the changes in microstructure. The more the grains swelled, and the more dense they became, the fewer there were grain boundaries, which are barriers to charge carrier mobility (Hu et al., 2022). Increased grain size enabled easier movement of electrons between Fe 2 and Fe 3 ions on the spinel lattice octahedral sites, which in turn reduced resistivity. This interpretation was supported by the fact that activation energy decreased in tandem with the increase in the degree of densification and the degree of connectivity of the grains because the lower the degree of densification and degree of connectivity of the material, the less energy was necessary to move the charge carriers between the grains (Chen et al., 2025). Statistical tests also revealed that density and grain size significantly predict resistivity, although density has the larger effect. This meant that pore removal and microstructural consolidation played a bigger role than grain size in improving conductivity alone (Xu et al., 2021). These well-linked structural and electrical parameters supported the interdependence of all the

characteristics to an even greater degree, as sintering temperature proved to be a controlling factor in both microstructural and electronic properties of the material.

Comparison with the prior works

Trends in this study are similar to the results in previous ferrite studies. In a case study, (Zaspalis et al., 2024) and Marinca (2024) reported that the sintering temperature reduced the resistivity of NiZn ferrites, and it was explained by the fact that the sintering temperature increased the densification and decreased the resistance of the grain boundaries. In line with this, Harun et al. (2021) had deduced that Ni-Zn ferrites sintered at higher temperatures had bigger grain sizes and reduced resistivity because electron hopping through Fe ions had been enhanced.

The obtained activation energies were consistent with those of Ye et al. (2022) and Heinz et al. (2021), who found that increasing sintering temperature led to a decrease in E_a due to a stronger connectivity between grains. These works also described that smaller activation energies were associated with more efficient hopping conduction mechanisms that became predominant as porosity reduced. The current results supported these inferences and generalized them with quantitative statistical data to support the relationship between microstructural parameters and electrical performance (Wang et al., 2022). Conversely, it was noted in some previous reports that excess sintering might have disadvantages. Indicatively, (Najafkhani et al., 2021) warned that years of exposure to extremely high temperatures may result in abnormal growth of grain and secondary phases, which may degrade magnetic or electrical characteristics. This should also be considered in long-term or industry-scale processing, although it was not detected in the present study up to 1200 °C.

Scientific explanation

The observed behavior can be attributed to physical mechanisms, which are explained by the cation distribution and electron hopping model in spinel ferrites. The hopping electrons between Fe 3 and Fe 2 ions in the octahedral sites are the major form of electrical conduction in Ni-Zn ferrites (John e al., 2024). The stabilization of the lattice and

contribution to the magnetic interactions are the effects of the presence of Ni 2 + ions. When the sintering temperatures are low, the hopping mechanism is hindered by large porosity and large grain boundaries, and the resistivity increases (Hasan & Azhdar, 2022).

The higher the sintering temperature, the lower the porosity and the greater the contact of grains, increasing electron exchange paths. The further rise in grain size further reduced the grain boundary scattering, making the conduction even more efficient. This two-fold effect, densification and grain coarsening effect was what was causing the apparent decrease in resistivity (Rahman et al., 2025). This loss in the activation energy may be explained by an increase in crystallinity and a decrease of structural defects with an increase in sintering temperatures. Defects like oxygen vacancies and disordered grain boundaries are usually charge carrier traps, increasing the energy barrier to conduction (Dharanya & Dharmalingam, 2022). These barriers decreased with an increase in the microstructure uniformity due to an increase in thermal treatment, which led to a decrease in E_a . In solid-state physics terms, this was a sign of transition to more efficient polaron hopping conduction, which is in accord with known theories of ferrite conductivity.

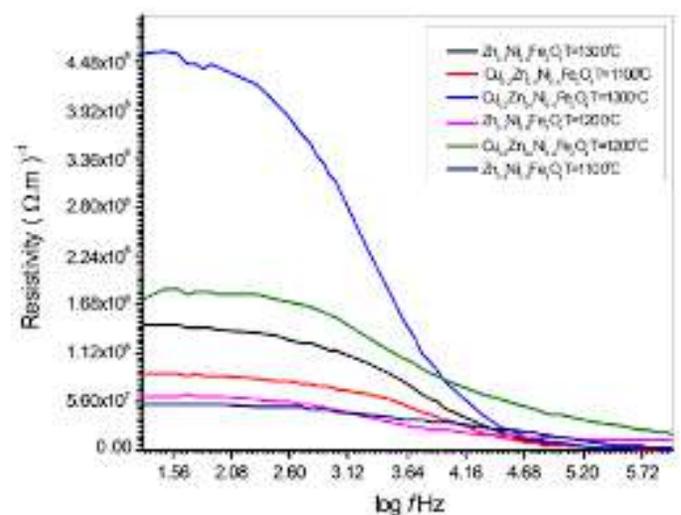


Figure 9: Electrical resistivity of Nickel Zinc Ferrite and Copper Nickel Zinc

Implications

The results of this research have serious implications in basic science and in technology. Scientifically, the findings were quantitative evidence of a relationship between microstructural changes caused by sintering temperature and electrical properties in Ni-Zn ferrites. This knowledge is essential in engineering ferrite materials to obtain desirable performance qualities.

Limitations

Despite the consistent and statistically strong results produced in the course of the study, some limitations must be recognized. First, the study was limited to sintering temperatures to 1200 °C, and possible consequences of even higher sintering conditions, like abnormal grain growth or formation of secondary phases, were not evaluated. Second, electrical properties were mainly studied, and complementary characterization of magnetic properties, dielectric response, and microstructural phase analysis with, e.g., X-ray diffraction or scanning electron microscopy might give a more complete picture of the material behavior. Lastly, the samples were grown in controlled laboratory environments, and these findings might have to be further validated to scale to industrial processes.

CONCLUSION

This was shown to significantly depend upon sintering temperature on the structural and electrical behavior of the nano-ferrites made of NiZn. The findings indicated that densification and grain growth were enhanced with an increase in sintering temperature and were strongly associated with large decreases in electrical resistivity and activation energy. These changes were found to be systematic and very significant using statistical tests (ANOVA), regression, and PCA, with density coming out as the best predictor of resistivity. By determining the quantitative relationship between microstructural development and electrical performance, the research objectives were achieved and thus answered the major research problem. The originality of this paper was the presentation of unambiguous experimental and statistical data that controlled sintering can pattern the electrical character of Ni-Zn nano-ferrites and may be utilized in electronic and magnetic devices. Not only does this finding affirm previous

observations in ferrite systems, it also adds to the body of knowledge by providing a strong multivariate analysis of property interdependence.

Finally, it was demonstrated that optimization of the sintering temperature is a viable approach to improve the material performance. Further research into these results should extend to doped or composite ferrite systems and long-term stability under working conditions.

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