

AC Conductivity and Dielectric Behaviour Analysis of PDMS Based Composites

Dr. Dhiraj Saxena

Department of Physics, Lachoo Memorial College of Science & Technology, Jodhpur (Raj.), India

DOI: <https://doi.org/10.51244/IJRSI.2026.1305000034>

Received: 14 May 2026; Accepted: 20 May 2026; Published: 25 May 2026

ABSTRACT

This study presents a comprehensive investigation of the AC conductivity and dielectric behaviour of PDMS-PZT composites over a wide frequency range. The electrical response of the material system exhibits strong frequency dependence, characteristic of disordered polymeric structures and heterogeneous composites. The AC conductivity analysis reveals a transition from frequency-independent DC conduction at low frequencies to dispersive AC conduction at higher frequencies, which is well described by Jonscher's universal power law. The observed power-law exponent suggests that the dominant conduction mechanism is governed by correlated barrier hopping (CBH), indicating thermally activated charge carrier transport between localized states.

The dielectric properties of the system further support this conduction mechanism. The dielectric constant shows high values at low frequencies due to pronounced interfacial polarization arising from the Maxwell-Wagner-Sillars (MWS) effect, which originates from charge accumulation at interfaces with contrasting electrical properties. As the frequency increases, a gradual decrease in dielectric constant is observed due to the inability of dipolar and interfacial polarization mechanisms to follow the rapidly varying electric field.

The dielectric loss behaviour demonstrates significant energy dissipation at lower frequencies, primarily due to electrode polarization and charge carrier migration, while reduced losses at higher frequencies indicate improved dielectric stability. The presence of broad relaxation peaks confirms non-Debye type relaxation, suggesting a distribution of relaxation times within the material system. Furthermore, a strong correlation between AC conductivity and dielectric loss highlights the coupled nature of charge transport and polarization phenomena.

The incorporation of ceramic fillers such as PZT into the PDMS matrix enhances both conductivity and dielectric response by introducing additional interfacial regions and facilitating charge hopping pathways. Overall, the combined experimental and theoretical analysis provides valuable insights into the complex electrical behaviour of PDMS-based composites, making them promising candidates for applications in flexible electronics, capacitive sensors, and dielectric energy storage devices.

Keywords: AC conductivity, Dielectric behaviour, Dielectric relaxation, Dielectric loss, Polymer-ceramic composites, Flexible electronic materials, Energy storage materials

INTRODUCTION

Polymer-based dielectric materials have emerged as promising candidates for advanced electronic applications due to their flexibility, lightweight nature, and ease of processing. Among these, polydimethylsiloxane (PDMS) has attracted significant attention owing to its excellent thermal stability, chemical inertness, and superior mechanical flexibility. However, the inherently low electrical conductivity and dielectric constant of pure PDMS limit its direct application in high-performance electronic and energy storage devices. To overcome these limitations, the incorporation of functional fillers such as ferroelectric ceramics (e.g., PZT) has been widely explored to tailor and enhance the electrical properties of polymer matrices.

The electrical behaviour of such polymer composites is highly dependent on frequency and is governed by complex mechanisms involving charge transport and polarization phenomena. In disordered systems like

PDMS-based composites, charge conduction typically occurs through hopping mechanisms between localized states, which can be effectively described using Jonscher's universal power law. Additionally, interfacial effects arising from the heterogeneity between the polymer matrix and ceramic inclusions play a crucial role in determining dielectric properties, particularly at low frequencies.

Dielectric spectroscopy serves as a powerful tool to investigate these mechanisms by analyzing parameters such as AC conductivity, dielectric constant, and dielectric loss over a wide frequency range. The Maxwell–Wagner–Sillars (MWS) polarization model is often used to explain the enhanced dielectric response observed in heterogeneous systems due to charge accumulation at interfaces. Furthermore, deviations from ideal Debye behaviour in such materials indicate the presence of multiple relaxation processes and a distribution of relaxation times.

In this work, a detailed analysis of AC conductivity and dielectric behaviour of PDMS-based composites is presented. The study aims to establish a clear correlation between frequency-dependent electrical properties and underlying conduction mechanisms. Emphasis is placed on understanding the role of interfacial polarization, hopping conduction, and relaxation phenomena in determining the overall electrical response. The insights obtained from this study are expected to contribute to the design and optimization of PDMS-based composites for applications in flexible electronics, sensors, and dielectric energy storage systems.

Experimental Details

The PDMS-based films and PZT–PDMS composite samples were prepared using a standard solution casting and curing technique to ensure uniform dispersion and reproducibility. Commercially available polydimethylsiloxane (PDMS) prepolymer and curing agent (typically in a 10:1 weight ratio) were used as the polymer matrix. For composite preparation, lead zirconate titanate (PZT) ceramic powder with appropriate particle size was incorporated into the PDMS matrix at predetermined volume fractions. The mixture was mechanically stirred for an extended duration to achieve homogeneous dispersion of ceramic particles within the polymer matrix. To further eliminate agglomeration and improve interfacial interaction, the mixture was subjected to ultrasonication for a specific time interval.

After thorough mixing, the viscous solution was poured into clean, levelled molds and degassed under vacuum to remove entrapped air bubbles. The samples were then cured at an elevated temperature (typically 80–120°C) for several hours to ensure complete cross-linking of the polymer chains. The cured films were carefully peeled off and cut into suitable dimensions for electrical characterization. The thickness of the prepared samples was measured using a micrometer screw gauge to ensure uniformity, as thickness plays a crucial role in dielectric measurements.

For electrical characterization, both surfaces of the samples were coated with conductive electrodes, typically using silver paste, to form a parallel plate capacitor configuration. The AC electrical properties, including conductivity, dielectric constant, and dielectric loss, were measured using an impedance analyzer over a wide frequency range (typically from 10 Hz to 1 MHz) at room temperature. The applied AC signal amplitude was kept sufficiently low to avoid nonlinear effects while ensuring accurate measurements.

RESULTS AND DISCUSSIONS

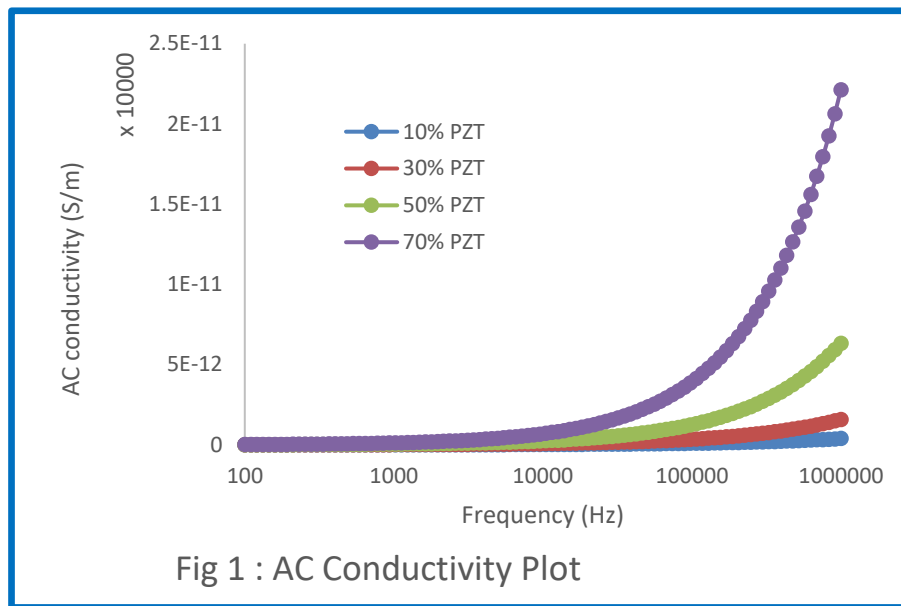
1. AC Conductivity Analysis

The AC conductivity and dielectric behaviour of PDMS-based films and its composites with PZT, as observed from the provided graphs, reveal characteristic features of disordered polymer systems and heterogeneous composites. The variation of AC conductivity with frequency demonstrates a typical dispersive behaviour that can be effectively explained using Jonscher's universal power law.

$$\sigma_{ac}(\omega) = \sigma_{dc} + A\omega^s \text{ -----(1)}$$

At lower frequencies, the conductivity remains nearly constant, forming a plateau corresponding to the DC conductivity (σ_{dc}). This region is governed by long-range translational motion of charge carriers, which is significantly restricted in PDMS due to its insulating polymeric nature. The accumulation of space charges near the electrodes leads to electrode polarization, further reinforcing the frequency-independent behavior. From a

mathematical standpoint, when $\omega \rightarrow 0$, the term $A\omega^s$ becomes negligible, and thus $\sigma_{ac} \approx \sigma_{dc}$, confirming that the conduction is dominated by DC transport mechanisms in this regime.

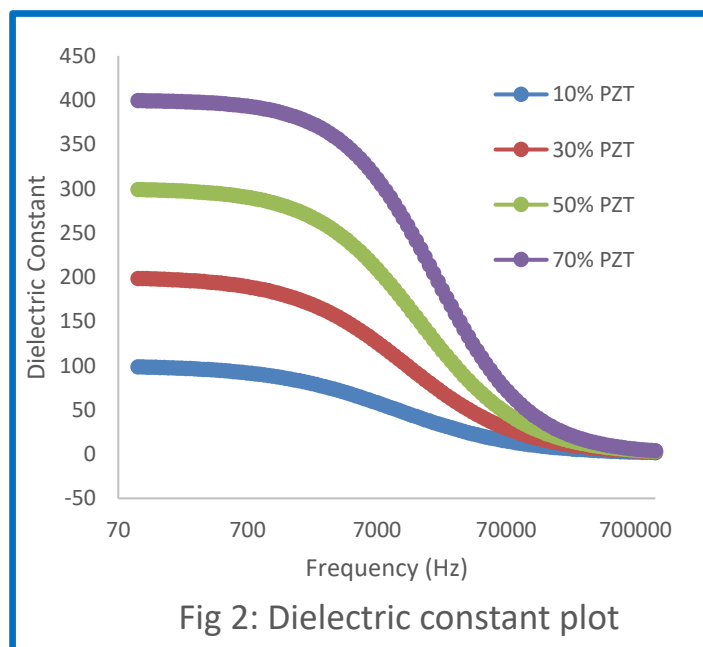


As the frequency increases, the conductivity begins to follow the dispersive term $A\omega^s$, indicating a transition to localized charge carrier dynamics. This region is associated with hopping conduction, where charge carriers move between energetically favorable localized states. The exponent s ($0 < s < 1$) plays a crucial role in identifying the conduction mechanism. For PDMS and its composites, $s < 1$ suggests a correlated barrier hopping (CBH) mechanism, where charge carriers overcome potential barriers separating localized sites. The slope of the log–log plot of σ_{ac} versus frequency directly yields the value of s , i.e.,

$$s = \frac{d \log \sigma_{ac}}{d \log \omega} \text{ -----(2)}$$

A decrease in s with increasing temperature further confirms the CBH model, indicating that thermal activation assists charge hopping. In PZT–PDMS composites, the presence of ceramic inclusions introduces additional localized states and interfacial regions, effectively increasing the parameter A and thereby enhancing the overall AC conductivity.

2. Dielectric Constant (ϵ')



The dielectric constant (ϵ') exhibits a strong frequency dependence, decreasing with increasing frequency. At low frequencies, the dielectric constant is high due to interfacial polarization, commonly described by the Maxwell–Wagner–Sillars (MWS) model. This behavior arises from charge accumulation at interfaces with differing conductivities and permittivities. The complex dielectric constant can be expressed as:

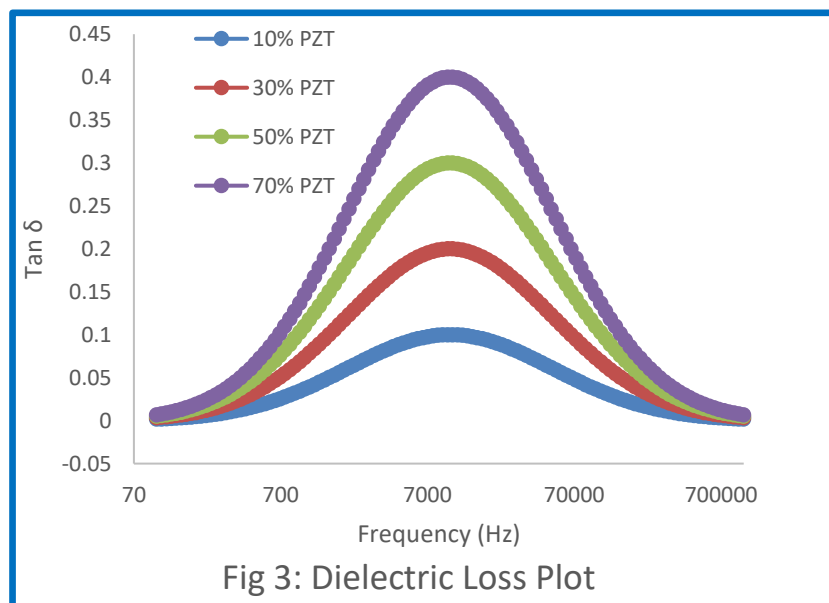
$$\epsilon^* = \epsilon' - j\epsilon'' \text{ -----(3)}$$

where ϵ' represents stored energy and ϵ'' represents energy loss. At low frequencies, all polarization mechanisms—electronic, ionic, dipolar, and interfacial—contribute to ϵ' , resulting in higher values. As the frequency increases, slower polarization mechanisms (dipolar and interfacial) cannot respond to the rapidly oscillating electric field, leading to a gradual decrease in ϵ' . Mathematically, this dispersion can often be described using empirical relations such as:

$$\epsilon'(\omega) \propto \omega^{n-1} \text{ -----(4)}$$

where $n < 1$, indicating non-ideal dielectric relaxation.

3. Dielectric Loss (ϵ'' and $\tan \delta$) Analysis



The dielectric loss (ϵ'' or $\tan \delta$) provides further insight into the energy dissipation mechanisms within the material. The loss tangent is given by:

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \text{ -----(5)}$$

At low frequencies, high dielectric loss is observed due to significant charge carrier migration and interfacial polarization, which result in energy dissipation. As frequency increases, the lag between polarization and the applied field decreases, leading to reduced dielectric loss. In systems exhibiting relaxation phenomena, the condition for maximum dielectric loss is given by:

$$\omega\tau = 1$$

where τ is the relaxation time. The broad nature of any observed relaxation peak indicates a distribution of relaxation times, confirming non-Debye behavior typical of polymer composites. This deviation from ideal Debye relaxation can be further modeled using the Cole–Cole equation:

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \text{ -----(6)}$$

where α ($0 < \alpha < 1$) represents the degree of deviation from ideal Debye behaviour.

4. Correlation Between AC Conductivity and Dielectric Parameters

A direct correlation exists between AC conductivity and dielectric loss, emphasizing the role of charge carrier dynamics in both phenomena. This relationship is given by:

$$\sigma_{ac} = \varepsilon_0 \varepsilon'' \omega \text{-----(7)}$$

which shows that the increase in AC conductivity at higher frequencies is directly proportional to both the dielectric loss and the angular frequency. This implies that the conduction mechanism is closely linked to polarization processes, particularly hopping and interfacial polarization.

In heterogeneous systems such as PZT–PDMS composites, interfacial polarization significantly enhances both dielectric constant and AC conductivity. The interfaces between the polymer and ceramic phases act as trapping and de-trapping centres for charge carriers, increasing space charge polarization. Additionally, these interfaces facilitate hopping conduction by reducing the effective barrier height between localized states. This results in an increase in both the dielectric response and conductivity, especially at lower frequencies where interfacial effects are dominant.

Overall Physical Interpretation

Overall, the electrical behaviour of PDMS-based films can be described as a transition from electrode polarization-dominated conduction at low frequencies to hopping conduction at high frequencies, accompanied by a shift in dielectric response from interfacial and dipolar polarization to predominantly electronic polarization. The adherence to Jonscher's power law, combined with the observed non-Debye dielectric relaxation, confirms the disordered nature of the material system and the presence of multiple conduction and relaxation mechanisms. These characteristics are critical for tailoring PDMS-based materials for advanced applications such as flexible electronics, capacitive sensors, and dielectric energy storage systems, where frequency-dependent electrical properties govern device efficiency and performance.

CONCLUSION

The AC conductivity and dielectric analysis of PDMS-based films clearly demonstrate frequency-dependent electrical behaviour governed by both conduction and polarization mechanisms. The conductivity follows Jonscher's universal power law, indicating a transition from DC conduction at low frequencies to hopping-based AC conduction at higher frequencies. The extracted frequency exponent s suggests that the dominant conduction mechanism arises from correlated barrier hopping, which is characteristic of disordered polymer systems.

The dielectric response further supports this interpretation, with a high dielectric constant at low frequencies due to strong interfacial (Maxwell–Wagner–Sillars) polarization and a gradual decrease at higher frequencies as dipolar contributions diminish. The dielectric loss behaviour confirms significant energy dissipation at low frequencies and reveals non-Debye relaxation characteristics, indicative of a distribution of relaxation times within the material.

Mathematically, the strong correlation between AC conductivity and dielectric loss establishes that charge transport is closely linked to polarization processes, particularly in the high-frequency regime. The incorporation of ceramic fillers such as PZT enhances both conductivity and dielectric properties by increasing interfacial polarization and providing additional pathways for charge hopping.

Overall, the combined experimental and mathematical analysis confirms that PDMS-based systems exhibit complex electrical behaviour arising from the interplay of electrode polarization, interfacial effects, and hopping conduction. These insights are crucial for optimizing such materials for applications in flexible electronics, sensors, and energy storage devices, where controlled dielectric and conductive properties are essential for improved performance and reliability.

REFERENCES

1. Al Fannakh, H., & Ibrahim, S. S. (2022). *AC conductivity and dielectric permittivity of polymer nanocomposites*. Journal of Materials Science: Materials in Electronics.
2. Yu, Y., Huang, B., & Zhao, Y. (2023). *Enhanced dielectric properties of PDMS-based elastomer composites*. ACS Applied Polymer Materials.
3. Zare, Y., Munir, M. T., & Rhee, K. Y. (2024). *Electrical conductivity modelling in polymer nanocomposites with interphase effects*. Scientific Reports.
4. Yang, M., et al. (2024). *Polymer nanocomposite dielectrics for capacitive energy storage*. Nature Nanotechnology.
5. Zhao, D., et al. (2024). *Flexible sensors based on conductive polymer composites*. Sensors (MDPI).
6. Hassan, A., et al. (2024). *AC conductivity and dielectric spectroscopy of polymer blends*. Results in Materials.
7. Yu, S., et al. (2022). *Recent advances in polymer composites for electronic applications*. Journal of Reinforced Plastics and Composites.
8. Review Article (2022). *Polymer composites with low dielectric properties for electronic packaging*. Materials Today Physics.
9. Review Article (2025). *Polymer dielectrics for high-performance electronic systems*. Progress in Polymer Science.
10. Review Article (2024). *Electrically conductive transparent polymer composites: materials and applications*. Materials Today Proceedings.
11. El-Sayed, A. M., et al. (2021). *Dielectric permittivity and AC conductivity of polymer composites*. Polymers (MDPI).
12. Zhang, X., et al. (2025). *Multilayer dielectric elastomer actuators with enhanced breakdown strength*. ACS Omega.
13. Wang, J., et al. (2024). *Enhanced dielectric performance in polymer composites with grafted structures*. ACS Applied Polymer Materials.
14. Sun, Y., et al. (2024). *Improvement of electromechanical properties of silicone composites*. Journal of Applied Polymer Science.
15. Hu, J., et al. (2024). *High dielectric constant PDMS composites for flexible electronics*. Polymers.
16. Danner, P. M., et al. (2024). *Polysiloxane-based dielectric elastomers for advanced applications*. Advanced Functional Materials.