Review: **Future Prospects of Polymer Dielectric Nano-Composites & their Applications in Super-capacitors**

Mahesh M. Dhaigude [a], Rupali Nagarekar [a].

[a] Ramsheth Thakur College of Commerce and Science, Kharghar-410210, Mumbai, India

Abstract:

Recent breakthroughs in nanotechnology have significantly advanced Polymer Dielectric Nanocomposites (PDNCs) as promising materials for next-generation electronic applications. Incorporation of high-permittivity inorganic nanofillers such as barium titanate ($BaTiO_3$) and zinc oxide (ZnO) into flexible polymer matrices, including poly(vinylidene fluoride) (PVDF) and poly(methyl methacrylate) (PMMA), results in enhanced dielectric permittivity, energy density, thermal stability, and mechanical robustness compared to conventional polymer dielectrics. These synergistic improvements originate from controlled nanofiller dispersion and optimized polymer–nanoparticle interfacial interactions.

This review summarises recent progress in PDNC research, emphasising innovative synthesis strategies, surface functionalization, and structure–property correlations that enable precise tuning of dielectric behaviour, high breakdown strength, and low dielectric loss. Comprehensive characterisation techniques are highlighted as essential for performance optimisation, including X-ray diffraction (XRD) for phase identification and crystallinity analysis; scanning and transmission electron microscopy (SEM, TEM) and atomic force microscopy (AFM) for morphological and dispersion studies; and X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) for chemical bonding and interfacial analysis. Dielectric characterisation and dielectric breakdown strength testing provide critical insights into polarisation mechanisms, charge transport, and energy-storage performance. Owing to their multifunctional properties, $BaTiO_3$/ZnO-filled PVDF and PMMA nanocomposites are well suited for high-energy-density capacitors, flexible electronics, and advanced energy-storage systems.

Polymer dielectric nanocomposites (PDNCs) have emerged as promising materials for advanced electronic applications due to their enhanced dielectric, electrical, and thermal properties. Among various polymer matrices, polymethyl methacrylate (PMMA) and polyvinylidene fluoride (PVDF) have attracted significant attention owing to their good processability, mechanical flexibility, and dielectric performance. The incorporation of high-dielectric ceramic nanofillers such as zinc oxide (ZnO) and barium titanate ($BaTiO_3$) further improves the dielectric constant, energy density, and breakdown strength of these composites.

This review systematically discusses PMMA/PVDF-based dielectric nanocomposites filled with ZnO and $BaTiO_3$ nanoparticles, focusing on material selection, synthesis techniques, structural and dielectric behaviour, and electronic applications. Challenges and future research directions are also highlighted for next-generation polymer capacitors and embedded electronic devices.

Keywords: Polymer Dielectric Nanocomposites, Dielectric Properties, Nanoparticles, Polymer Matrix, Electronics Applications, dielectric constant, nanofillers, energy storage, PMMA, PVDF, ZnO, $BaTiO_3$, etc.

1. Introduction

Polymer Dielectric Nanocomposites (PDNCs) are materials that integrate dielectric nanoparticles into polymer matrices to enhance the material's dielectric properties. This combination allows for the development of materials with improved energy storage capabilities, mechanical strength, and thermal stability. Dielectric polymers such as PMMA and PVDF are widely used in capacitors and insulation due to high breakdown strength and processability. However, their low intrinsic permittivity limits energy density. Incorporation of dielectric nanoparticles (BaTiO3, ZnO) enhances permittivity via interfacial polarization (Maxwell–Wagner–Sillars effect) while maintaining low conductivity when well-dispersed and surface-modified.

Polymer dielectric [nanocomposites] based on poly(methyl methacrylate) (PMMA) and poly(vinylidene fluoride) (PVDF) matrices, reinforced with [zinc oxide (ZnO)] and [barium titanate] ($BaTiO_3$) nanofillers, represent a strategically engineered class of multifunctional materials at the forefront of next-generation electronics. Their development responds to convergent technological imperatives: miniaturization of energy storage components, enhancement of power density in pulsed systems, integration into flexible and wearable platforms, and mitigation of thermal and reliability bottlenecks in high-frequency circuits. A comprehensive review of the current research landscape reveals that the performance of these nanocomposites is not governed by simple additive rules but by a sophisticated interplay among polymer blend thermodynamics, nanofiller surface chemistry, [interfacial polarization] dynamics, and the intrinsic ferroelectric/semiconducting duality of the ceramic phases.

The foundational rationale for blending PMMA and PVDF lies in their complementary dielectric profiles. PVDF is a semi-crystalline ferroelectric polymer whose high intrinsic dielectric constant ($\varepsilon_r \approx 10–13$ in its α-phase, up to ~12–15 in the electroactive β-phase) stems from its strong molecular dipole moment and crystallinity-driven polarization. However, its ferroelectric hysteresis introduces significant energy loss and temperature-dependent instability (Sun et al., 2025). PMMA, an amorphous linear polymer, possesses a lower but highly stable dielectric constant ($\varepsilon_r \approx 3.5–4.5$), excellent optical transparency, and superior dielectric strength due to its lack of permanent dipoles and low conductivity. When blended—typically in ratios ranging from 70/30 to 80/20 (PVDF/PMMA wt%)—the resulting matrix exhibits a synergistic "hybrid" behaviour: the PVDF phase provides the primary polarization response, while the PMMA phase acts as a structural and electrical buffer. It suppresses the local polarization field in PVDF's amorphous regions, thereby weakening coherent coupling between ferroelectric domains and reducing hysteresis loss (Sun et al., 2025). This design principle directly addresses a core limitation of pure PVDF, transforming it from a high-loss ferroelectric into a more linear, high-performance dielectric suitable for capacitor applications[1-2].

Today, there is a rapidly growing demand for high-energy-density capacitors driven by the miniaturization of electronic devices, renewable energy systems, and advanced power

electronics. Conventional ceramic dielectrics, although exhibiting high dielectric permittivity, suffer from inherent limitations such as brittleness, poor mechanical flexibility, and processing difficulties, which restrict their use in flexible and lightweight electronic applications. In contrast, polymer dielectrics offer significant advantages including excellent mechanical flexibility, ease of processing, high breakdown strength, and low dielectric loss, making them attractive alternatives for modern electronic systems. However, their relatively low intrinsic dielectric permittivity limits energy-storage capability. The incorporation of nanoscale dielectric fillers into polymer matrices has therefore emerged as an effective strategy to enhance dielectric performance through interfacial polarization and nanoscale effects. In this context, the present review aims to systematically examine polymer dielectric nanocomposites based on **PMMA and PVDF** matrices reinforced with **ZnO and $BaTiO_3$ nanofillers**, focusing on material selection, processing strategies, structure–property relationships, and their potential for high-performance capacitor and electronic applications.

The incorporation of ZnO and $BaTiO_3$ nanoparticles serves distinct yet complementary functions. $BaTiO_3$ is a classic perovskite ferroelectric ceramic with an exceptionally high bulk dielectric constant ($\varepsilon_r \approx 1000–5000$ near its Curie temperature of ~120 °C). Its role is primarily to amplify the overall permittivity of the composite via the Maxwell-Garnett effective medium theory, where the large dielectric contrast between the filler and the polymer matrix drives charge accumulation at the interface—a phenomenon known as interfacial or Maxwell-Wagner-Sillars (MWS) polarisation. This effect is most pronounced when the filler is well-dispersed and forms a percolative network without direct physical contact, which would otherwise cause leakage current and catastrophic breakdown (Sengwa et al., 2023; Zhou et al., 2021). In contrast, ZnO is a wide-bandgap semiconductor ($E_g \approx 3.37$ eV) with a moderate dielectric constant ($\varepsilon_r \approx 8–12$) but exceptional electron mobility and piezoelectric properties. Its function is more nuanced: it can act as a secondary polarising agent, contribute to UV-shielding in optoelectronic devices, and, critically, serve as a structural modulator. When co-loaded with $BaTiO_3$, ZnO can disrupt the agglomeration tendency of the larger, higher-surface-energy $BaTiO_3$ particles, leading to a more homogeneous dispersion within the polymer blend. This improved morphology is a key determinant of performance, as evidenced by scanning electron microscopy (SEM) studies showing high homogeneity in PVDF/PMMA/$BaTiO_3$ films (Sengwa et al., 2023) and the successful fabrication of flexible, low-roughness cast films with enhanced breakdown strength [3-4].

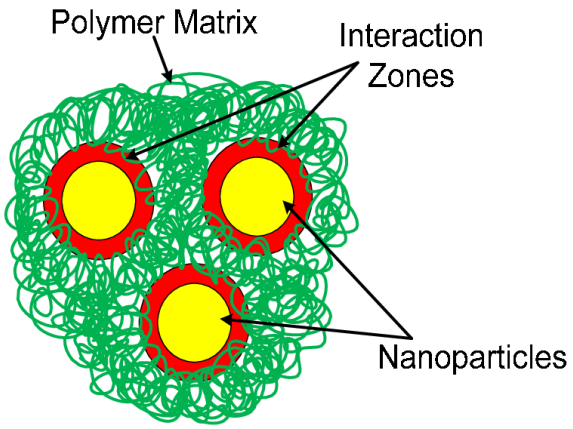


Fig. 1.1 Polymer Matrix & Nanoparticles

Despite these advances, several persistent challenges remain. The most significant is the inherent trade-off between dielectric constant and dielectric strength. While adding more $BaTiO_3$ increases ε_r, it also introduces more interfaces and potential defect sites, which can become preferential paths for electrical treeing and premature breakdown. This necessitates precise control over filler loading, typically optimized at 5–15 wt% for $BaTiO_3$, and underscores the value of hybrid fillers that improve dispersion without increasing total ceramic content. Another challenge is the frequency dependence of the dielectric response. As the applied field frequency increases, slower [polarization mechanisms]—including the orientational polarisation of PVDF chains and the interfacial polarisation at the polymer/ceramic boundary "freeze out," causing ε_r to decrease and loss to peak at characteristic relaxation frequencies. This dynamic behaviour must be carefully characterised across the broadband frequency range (from MHz to GHz) to ensure suitability for a given application, whether it be low-frequency energy storage or high-frequency signal filtering 3-4]

PVDF/PMMA-based nanocomposites reinforced with low loadings (3–5 vol%) of surface-modified $BaTiO_3$–ZnO hybrid fillers demonstrate excellent dielectric performance, including high relative permittivity (≈40–65 at 1 kHz), low dielectric loss ($\tan \delta < 0.05$), and high breakdown strength (>300 MV/m), leading to energy densities above 12 J/cm³. These properties rival commercial BOPP capacitors, making them suitable for high-demand applications such as electric vehicles, pulse-power systems, and electromagnetic launch technologies. Additionally, the system's compositional versatility allows multifunctionality: incorporation of organo-modified montmorillonite enables flexible all-solid-state devices, while adding carbon nanotubes with ZnO or $BaTiO_3$ enhances EMI shielding in lightweight, flexible films for advanced electronic packaging [3-5].

2. Polymer Dielectric Nanocomposites (PDNCs)

2.1 Definition of Polymer Dielectric Nanocomposites

Polymer Dielectric Nanocomposites (PDNCs) are advanced functional materials formed by dispersing dielectric inorganic fillers with nanoscale dimensions into insulating polymer matrices. The incorporation of nanofillers enables significant modification of the electrical, thermal, and mechanical properties of polymers by introducing large interfacial areas and additional polarization mechanisms. PDNCs aim to synergistically combine the high dielectric permittivity of ceramic materials with the flexibility, lightweight nature, ease of processing, and high breakdown strength of polymers, making them attractive for modern electronic and energy-storage applications.

2.2 Classification of Polymer Dielectric Nanocomposites

PDNCs can be systematically classified based on the **polymer matrix**, **filler type**, and **filler size**, which strongly influence dielectric behaviour and application suitability.

2.2.1 Based on Polymer Matrix

- **PMMA-based PDNCs:**
  Exhibit low dielectric loss, high transparency, and good electrical insulation.
- PMMA: amorphous polymer with low dielectric constant (~3.4–4), excellent transparency and dimensional stability.
- **PVDF-based PDNCs:**
  PVDF: semi-crystalline ferroelectric polymer (β-phase) with higher permittivity (~8–12 depending on phase) and intrinsic polarization.
- Show higher dielectric permittivity due to the polar nature and ferroelectric β-phase of PVDF. It also known for its excellent piezoelectric and ferroelectric properties.
- **PMMA/PVDF Blend-based PDNCs:**
  Combine the low loss and high breakdown strength of PMMA with the high permittivity and polarization capability of PVDF, resulting in balanced dielectric performance.

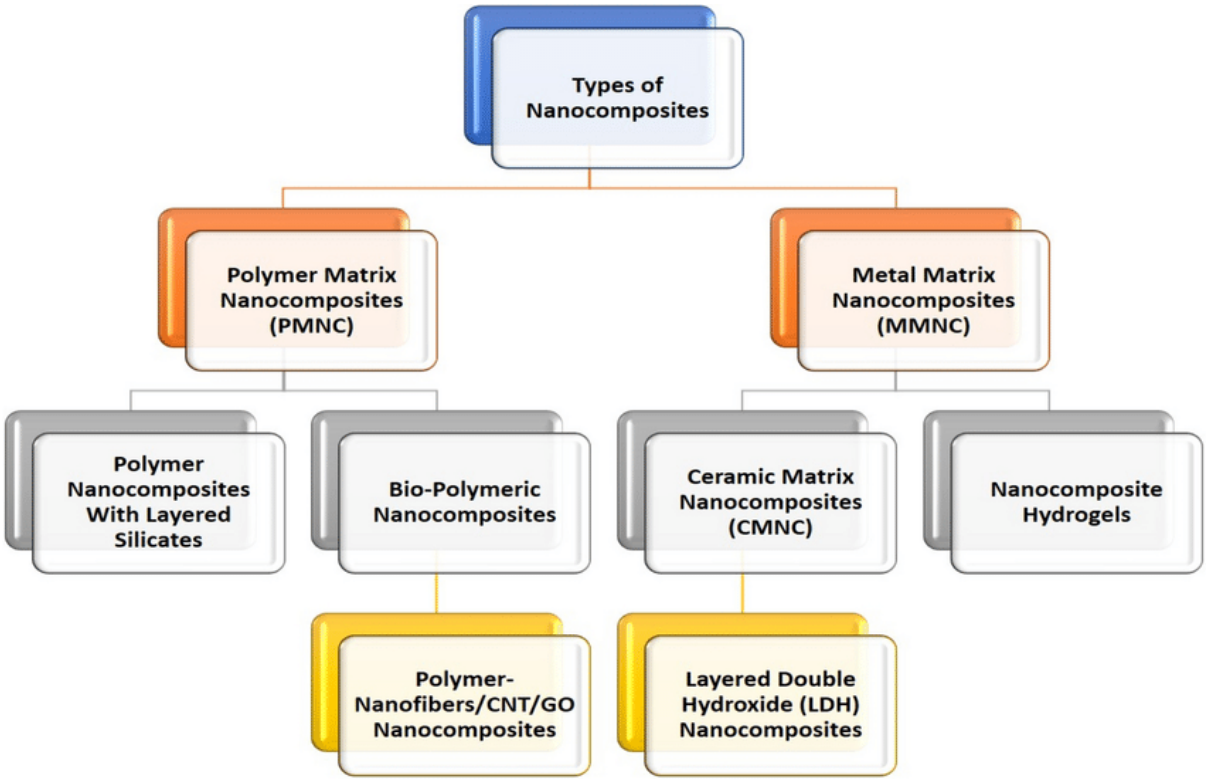


Fig. 2.1 Types of Nanocomposites

2.2.2 Based on Nanofiller Type

- **ZnO-filled PDNCs:**
  Utilize semiconducting nanofillers with moderate dielectric permittivity and enhanced interfacial polarization. ZnO: wide-bandgap metal oxide with moderate permittivity, useful for tunable dielectric behaviour and multifunctionality. **Zinc Oxide (ZnO):** Known for its varistor properties and dielectric performance.

- **$BaTiO_3$-filled PDNCs:** BaTiO3: high-permittivity ferroelectric ceramic widely used to raise ε' in polymer composites. **Barium Titanate ($BaTiO_3$):** Offers high dielectric constants and piezoelectric properties.

- **Other ceramic fillers:**

- **Epoxy Resins:** Used for their mechanical strength and thermal stability.

- **Polyurethane:** Offers flexibility and toughness.

- TiO_2, $SrTiO_3$, Al_2O_3, etc., used to tailor dielectric response. Employ ferroelectric ceramic fillers with very high dielectric constants for energy-density enhancement.

2.2.3 Based on Filler Size

- **Micro-filled composites:**
  Limited interfacial area and weaker polarization effects.
- **Nano-filled composites:**
  Large surface-to-volume ratio leading to strong interfacial (Maxwell–Wagner–Sillars) polarization and superior dielectric enhancement.

2.2.4 Fabrication Techniques

- **Solution Processing:** Involves dispersing nanoparticles in a polymer solution followed by casting and curing.
- **Melt Processing:** Involves blending nanoparticles with molten polymer followed by extrusion or molding.
- **In-Situ Polymerization:** Nanoparticles are incorporated during the polymerization process.

2.3 Interfacial Polarisation Concept

Interfacial polarisation, commonly known as Maxwell–Wagner–Sillars (MWS) polarisation, plays a dominant role in PDNCs. It arises due to charge accumulation at the interfaces between polymer matrices and nanofillers having different dielectric constants and electrical conductivities. At low frequencies, these trapped charges contribute significantly to enhanced dielectric permittivity. The extent of MWS polarisation strongly depends on nanofiller dispersion, surface functionalization, filler loading, and polymer–filler compatibility. Proper interfacial engineering is therefore essential to maximize dielectric constant while minimizing dielectric loss and leakage current. [7-8]

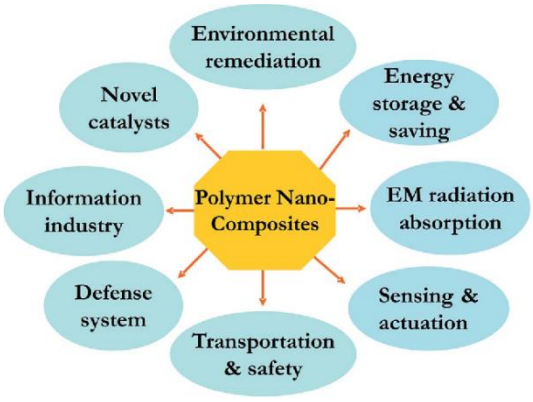


Fig. 2.2 Applications of Polymer Nano-composites

3. Materials Used

3.1 Polymer Dielectric Nanocomposites (PDNCs)

Its advanced materials are formed by incorporating dielectric inorganic nanoparticles into polymer matrices to achieve enhanced electrical, thermal, and mechanical properties. By combining the high breakdown strength, flexibility, and ease of processing of polymers with the superior dielectric permittivity of ceramic nanofillers, PDNCs overcome the limitations of conventional polymer and ceramic dielectrics. These materials are particularly attractive for modern electronic applications such as high-energy-density capacitors, flexible electronics, and embedded energy-storage systems, where both mechanical compliance and high dielectric performance are required [9-10].

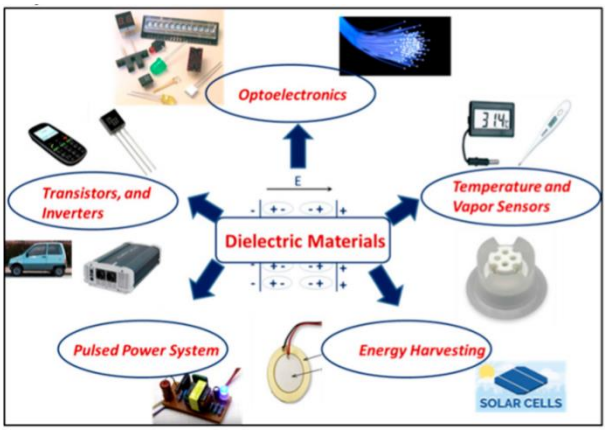


Fig.3.1 Applications of Dielectric Materials

3.2. Nanofillers

Nanofillers play a key role in enhancing the dielectric properties of PDNCs by introducing additional polarization mechanisms and increasing interfacial area. **Zinc oxide (ZnO) nanoparticles** are wide bandgap semiconductors with a moderate dielectric constant. Their incorporation into polymer matrices improves interfacial polarization and can enhance electrical conductivity control at low filler concentrations. ZnO is also cost-effective, chemically stable, and multifunctional, contributing to improved dielectric and polarization behavior in nanocomposites.

Barium titanate ($BaTiO_3$) nanoparticles are ferroelectric ceramics with a very high dielectric constant and are widely used in multilayer ceramic capacitors (MLCCs). When dispersed in polymer matrices at the nanoscale, $BaTiO_3$ significantly enhances dielectric permittivity and energy-storage capability through ferroelectric and interfacial polarization mechanisms. Its high dielectric response makes $BaTiO_3$ one of the most effective nanofillers for achieving high-energy-density polymer dielectric nanocomposites.

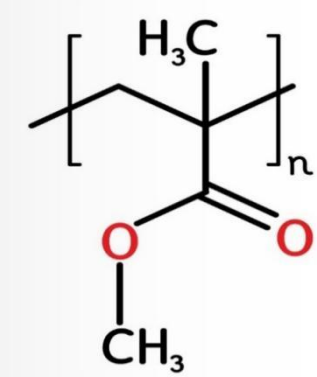


Fig. 3.2 Basic structure of PMMA

3.3 Polymer Matrices Used

The choice of polymer matrix plays a crucial role in determining the dielectric behavior and overall performance of PDNCs. Among various polymers, polymethyl methacrylate (PMMA) and polyvinylidene fluoride (PVDF) are widely investigated due to their complementary dielectric and mechanical characteristics.

3.3.1 Polymethyl Methacrylate (PMMA)

PMMA is an amorphous thermoplastic polymer widely used in dielectric applications due to its excellent optical transparency, low dielectric loss, good thermal stability, and high breakdown strength. It typically exhibits a moderate dielectric constant (~3–5), which remains stable over a wide frequency range. PMMA acts as an effective insulating matrix and helps suppress leakage current when used alone or blended with more polar polymers. Its excellent optical transparency. PMMA also provides high electrical insulation and breakdown strength, making it a suitable matrix for dielectric applications where low loss and reliability are critical.

Advantages of PMMA:

- Low dielectric loss
- High electrical insulation
- Good mechanical rigidity
- Excellent processability.

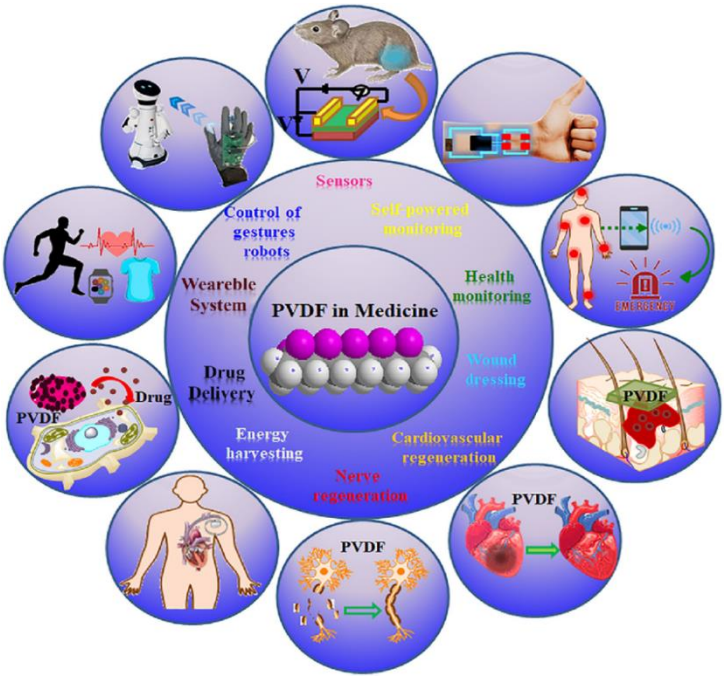
3.3.2 Polyvinylidene Fluoride (PVDF)

PVDF is a semi-crystalline polymer known for its strong dipolar nature and multiple crystalline phases (α, β, γ). The β-phase is highly polar and responsible for ferroelectric and piezoelectric behaviour, leading to a higher dielectric constant (~8–12). PVDF-based PDNCs are particularly attractive for energy-storage and sensor applications.

PVDF has primarily due to its strong molecular dipoles and ferroelectric β-phase. PVDF exhibits excellent chemical resistance, mechanical flexibility, and ferroelectric and piezoelectric properties, which make it particularly attractive for energy-storage, sensing, and actuator applications. However, its ferroelectric nature can introduce higher dielectric loss if not carefully controlled.

Advantages of PVDF:

- High dielectric permittivity
- Ferroelectric and piezoelectric properties
- Good chemical resistance
- Mechanical flexibility



- Fig.3.4 Applications of PVDF in Medicine

3.3.3 PMMA/PVDF Blends

PMMA/PVDF blends combine the advantages of both polymers by balancing dielectric permittivity and dielectric loss. In such blends, PMMA helps suppress dielectric loss and improve breakdown strength, while PVDF contributes higher polarisation and dielectric constant. Additionally, polymer blending improves interfacial compatibility with nanofillers,

leading to better dispersion and enhanced dielectric performance. Blending PMMA with PVDF is an effective strategy to balance dielectric performance. PMMA suppresses dielectric loss and improves breakdown strength, while PVDF contributes high permittivity and polarization. PMMA/PVDF blends often show improved interfacial compatibility with ceramic nanofillers and enhanced overall dielectric reliability [11-12].

Advantages of PMMA/PVDF Blends:

- Reduced dielectric loss
- Improved breakdown strength
- Tunable dielectric properties
- Enhanced mechanical stability

3.4 Nanofillers

3.4.1 Zinc Oxide (ZnO) Nanoparticles

ZnO is a wide bandgap semiconductor with moderate dielectric permittivity and good polarization capability. ZnO nanoparticles enhance interfacial polarization and can also improve electrical conductivity control at low filler concentrations. Additionally, ZnO can promote β-phase formation in PVDF, further enhancing dielectric and piezoelectric response.

Advantages of ZnO Nanofillers:

- Moderate dielectric enhancement
- Semiconducting behavior
- Cost-effective and chemically stable
- Multifunctional (dielectric, optical, piezoelectric)

3.4.2 Barium Titanate ($BaTiO_3$) Nanoparticles

$BaTiO_3$ is a ferroelectric ceramic with an extremely high dielectric constant, widely used in multilayer ceramic capacitors. When incorporated into polymer matrices at the nanoscale, $BaTiO_3$ significantly enhances dielectric permittivity and energy-storage density through interfacial and ferroelectric polarization mechanisms.

Advantages of $BaTiO_3$ Nanofillers:

- Very high dielectric permittivity
- Ferroelectric behavior
- Enhanced energy-storage capability
- Proven performance in capacitor technologies

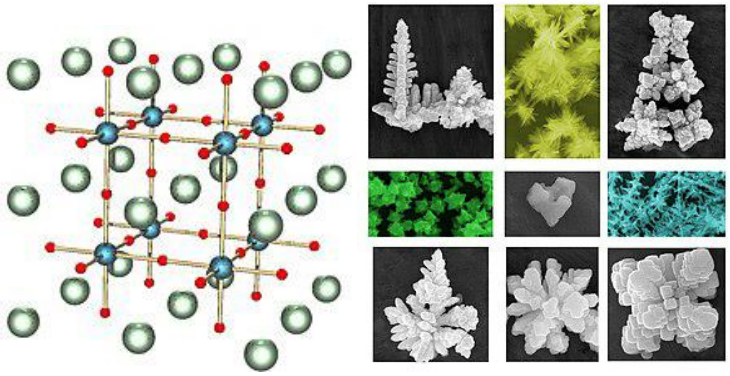


Fig. 3.5 Barium titanate structure

Category	**Material**	**Key Properties**	**Advantages**
Polymer matrix	PMMA	Low ε_r, low loss	High insulation, high breakdown
Polymer matrix	PVDF	High ε_r, ferroelectric	High polarization, flexibility
Polymer blend	PMMA/PVDF	Tunable ε_r & loss	Balanced dielectric performance
Nanofiller	ZnO	Moderate ε_r, semiconductor	Stable, multifunctional
Nanofiller	$BaTiO_3$	Very high ε_r, ferroelectric	High energy density

Table 3.1. Classification and properties of materials used in PDNCs

4. Synthesis and Fabrication Methods

The synthesis and fabrication techniques employed for Polymer Dielectric Nanocomposites (PDNCs) play a decisive role in determining nanofiller dispersion, interfacial interactions, and ultimately the dielectric performance of the composites. Uniform dispersion of nanofillers and strong polymer–filler interfacial bonding are essential to achieve high dielectric permittivity, low dielectric loss, and enhanced breakdown strength. The most commonly used fabrication methods for PMMA/PVDF-based PDNCs are described below.

Solution casting is one of the most widely adopted techniques for preparing polymer dielectric nanocomposites due to its simplicity and effectiveness in achieving homogeneous nanofiller dispersion at the laboratory scale. In this method, the polymer is dissolved in an appropriate solvent, and the nanofillers are dispersed into the solution using mechanical stirring and/or ultrasonication. The resulting mixture is cast onto a substrate, followed by controlled solvent evaporation to form thin composite films. Solution casting offers good control over film thickness and filler distribution; however, residual solvent removal and scalability remain key challenges [13-14].

Melt mixing is a solvent-free and industrially scalable fabrication technique in which polymer pellets are melted and mechanically mixed with nanofillers using an extruder or internal mixer. This method is particularly suitable for large-scale production and avoids solvent-related environmental issues. Melt mixing enables good dispersion when optimized shear forces are applied; however, high processing temperatures and shear stresses may induce nanofiller agglomeration or polymer degradation if not carefully controlled.

In-situ polymerization involves the formation of polymer chains in the presence of well-dispersed nanofillers, allowing intimate contact between the polymer matrix and filler surface. In this approach, nanofillers are first dispersed in monomer solutions, followed by polymerization through thermal, chemical, or radiation-induced initiation. In-situ polymerization often results in superior interfacial bonding and more uniform filler distribution, leading to improved dielectric and mechanical properties. Despite these advantages, the method can be complex and less suitable for large-scale processing.

Ultrasonication-assisted dispersion is commonly employed as a supplementary technique to improve nanofiller dispersion in both solution and melt-based processes. High-frequency ultrasonic waves generate cavitation effects that break nanoparticle agglomerates and promote uniform dispersion within the polymer matrix. While ultrasonication significantly enhances composite homogeneity, excessive sonication may damage polymer chains or alter nanofiller surface chemistry, necessitating careful optimization of processing parameters.

Together, these fabrication methods provide flexible routes for tailoring the microstructure and dielectric performance of PDNCs, enabling their adaptation for diverse electronic and energy-storage applications.

5. Structural and Morphological Characterization

Structural and morphological characterization is essential for understanding the dispersion of nanofillers, polymer–filler interactions, and the resulting structure–property relationships in Polymer Dielectric Nanocomposites (PDNCs). These techniques provide critical insights into crystallinity, phase composition, interfacial bonding, and surface morphology, which directly influence dielectric and electrical performance.

- Structural: XRD (particle phase/crystallinity), FTIR (PVDF β-phase quantification by characteristic peaks at ~840 cm^{-1}), Raman.
- Morphology: SEM/TEM (dispersion, agglomerates), AFM (surface topography), particle size distribution (DLS).
- Dielectric: broadband dielectric spectroscopy (ε′, ε″ vs frequency and temperature), dielectric breakdown strength (Weibull statistics), leakage current measurements, P–E loops (ferroelectric characterisation), energy storage density ($U = 1/2 \int E \cdot dP$ or simplified ½ε_0ε_rE_b^2 for linear dielectrics).
- Mechanical & thermal: TGA, DSC (Eg, crystallinity), tensile testing for flexible electronics.

5.1 X-ray Diffraction (XRD) is primarily used to investigate the crystalline structure and phase composition of both the polymer matrix and the incorporated nanofillers. In PDNCs, XRD helps identify the crystalline phases of nanofillers such as $BaTiO_3$ and ZnO and evaluate their structural integrity after incorporation into the polymer matrix. For PVDF-based systems, XRD is particularly useful in distinguishing different crystalline phases (α, β, and γ phases) and confirming the formation or enhancement of the electroactive β-phase induced by nanofillers. Changes in peak intensity and broadening also provide information about crystallite size and the degree of polymer–filler interaction.

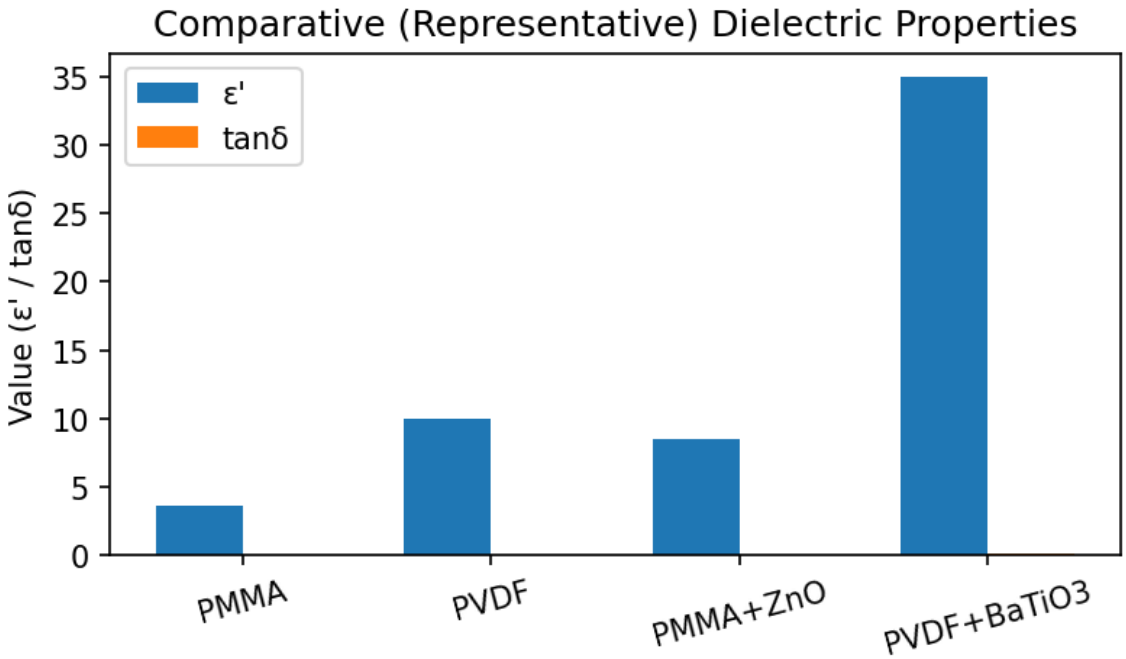
5.2 Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are widely employed to examine the morphology and dispersion state of nanofillers within the polymer matrix. SEM provides information on surface morphology, fracture surfaces, and the presence of agglomerates, while TEM offers high-resolution imaging of nanofiller distribution at the nanoscale. Uniform dispersion and strong interfacial adhesion observed through SEM and TEM are indicative of effective fabrication and are closely linked to improved dielectric properties and breakdown strength.

5.3 Fourier Transform Infrared Spectroscopy (FTIR) is used to analyze chemical bonding and interfacial interactions between polymer chains and nanofillers. FTIR spectra help identify functional groups, confirm surface modification of nanofillers, and detect changes in polymer chain conformation due to filler incorporation. In PVDF-based PDNCs, FTIR is especially important for identifying the β-phase through characteristic absorption bands, thereby correlating molecular structure with enhanced dielectric and ferroelectric behavior.

5.4 Atomic Force Microscopy (AFM)

It provides nanoscale information on surface topography, roughness, and phase distribution of PDNC films. AFM enables visualization of filler dispersion at the surface and assessment of interfacial uniformity, which are crucial for flexible and thin-film electronic applications. Surface roughness and phase-contrast imaging obtained from AFM can also be correlated with dielectric loss and breakdown performance.

Collectively, these structural and morphological characterization techniques form a comprehensive framework for evaluating PDNC microstructure, validating fabrication strategies, and optimizing material design for high-performance electronic and energy-storage applications.



- Fig. 5.1 Comparative (representative) dielectric properties (ε' and tanδ).

6. Dielectric Properties

The dielectric properties of Polymer Dielectric Nanocomposites (PDNCs) are the most critical parameters determining their suitability for electronic and energy-storage applications. These properties are strongly influenced by polymer matrix characteristics, nanofiller type and loading, dispersion quality, and interfacial interactions .

Dielectric Properties

- **Dielectric Constant:** Enhanced by the addition of high-dielectric nanoparticles.
- **Dielectric Loss:** Controlled by optimizing the dispersion and interface between nanoparticles and the polymer.

6.1 Dielectric Constant (ε_r)

The dielectric constant represents the ability of a material to store electrical energy under an applied electric field. In PDNCs, ε_r is significantly enhanced compared to neat polymers due to the incorporation of high-permittivity nanofillers such as ZnO and $BaTiO_3$. The enhancement arises from intrinsic filler permittivity, increased dipolar polarization in polar polymers (e.g., PVDF), and interfacial polarization at polymer–filler boundaries. PMMA/PVDF blend systems often show optimized ε_r values by balancing high polarization and electrical insulation.

The dielectric constant is typically calculated using the relation:

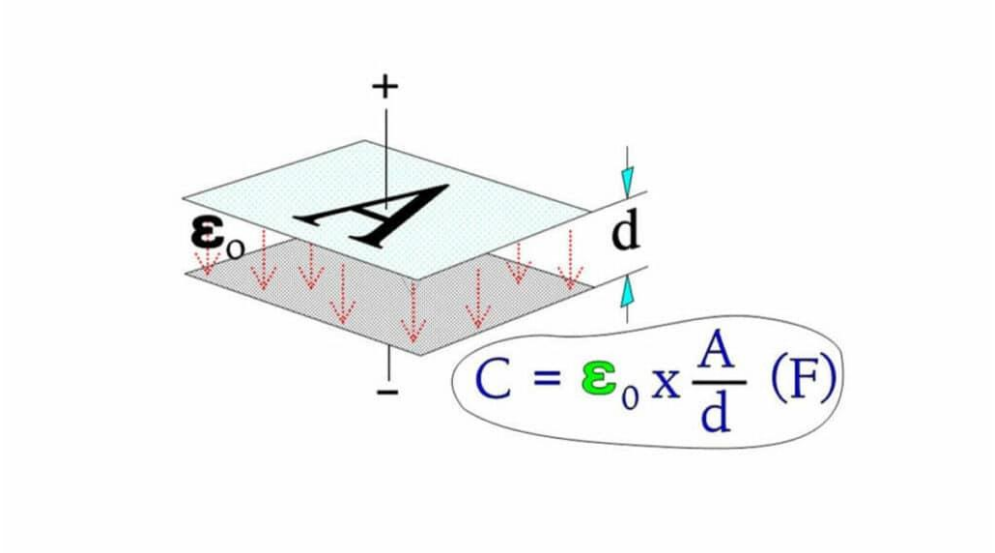


Fig. 6.1 Dielectric constant

where C is the capacitance, d is the sample thickness, A is the electrode area, and ε_0 is the permittivity of free space.

6.2 Dielectric Loss (tan δ)

Dielectric loss (tan δ) quantifies the energy dissipated as heat during polarization under an alternating electric field. In PDNCs, dielectric loss originates from dipolar relaxation, charge carrier conduction, and interfacial polarization losses. While nanofiller addition increases ε_r, excessive filler loading or agglomeration can lead to higher dielectric loss due to leakage pathways. PMMA-rich matrices and surface-functionalized nanofillers are effective in suppressing tan δ while maintaining enhanced permittivity.

6.3 Frequency and Temperature Dependence

Dielectric properties of PDNCs are strongly dependent on frequency and temperature. At low frequencies, dielectric constant is generally high due to contributions from dipolar and interfacial polarization mechanisms. As frequency increases, polarization mechanisms fail to follow the rapidly alternating electric field, leading to a decrease in ε_r and stabilization of tan δ.Temperature increase enhances polymer chain mobility, facilitating dipole orientation and charge transport, which may increase ε_r but also lead to higher dielectric loss. Understanding this behavior is crucial for applications operating over wide temperature and frequency ranges.

6.4 Interfacial Polarization (Maxwell–Wagner–Sillars Effect)

Interfacial polarization, also known as **Maxwell–Wagner–Sillars (MWS) polarization**, plays a dominant role in PDNCs. It arises due to charge accumulation at interfaces between materials with different dielectric constants and electrical conductivities, such as polymer matrices and ceramic nanofillers. The large surface-to-volume ratio of nanofillers intensifies this effect, leading to substantial enhancement in dielectric permittivity at low frequencies.

While MWS polarization is beneficial for increasing ε_r, excessive interfacial charge buildup can contribute to dielectric loss and reduced breakdown strength. Therefore, controlling nanofiller dispersion and interfacial chemistry is essential to maximize dielectric performance while minimizing losses.

Overall, the dielectric behavior of PDNCs results from a complex interplay between material composition, microstructure, and external conditions. Careful optimization of dielectric constant, dielectric loss, and stability across frequency and temperature ranges is essential for designing high-performance polymer dielectric nanocomposites for capacitors, flexible electronics, and energy-storage applications.

7. Electrical and Thermal Properties

The electrical and thermal properties of Polymer Dielectric Nanocomposites (PDNCs) are crucial for assessing their reliability, safety, and long-term performance in electronic and

energy-storage applications. These properties are strongly governed by polymer matrix characteristics, nanofiller type and loading, dispersion quality, and interfacial structure.

Thermal Properties

- **Thermal Conductivity:** Can be improved by certain nanoparticles, aiding in heat dissipation.
- **Thermal Stability:** Enhanced by the thermal resistance of nanoparticles and polymer matrix.

7.1 AC Conductivity

AC conductivity provides insight into charge transport mechanisms within PDNCs and is closely related to dielectric loss and leakage current behavior. In polymer nanocomposites, AC conductivity typically increases with frequency due to enhanced hopping of charge carriers between localized states. The incorporation of nanofillers such as ZnO and $BaTiO_3$ can modify conductivity behavior by introducing additional interfaces and trap sites. At low filler concentrations, well-dispersed nanofillers generally suppress charge mobility by trapping carriers at the polymer–filler interface, leading to low conductivity and improved insulating behavior. However, excessive filler loading or agglomeration may create conductive pathways, resulting in increased AC conductivity and dielectric loss. Therefore, optimized filler content and interfacial engineering are essential to maintain low conductivity while achieving high dielectric permittivity.

7.2 Breakdown Strength

Dielectric breakdown strength is a critical parameter that determines the maximum electric field a material can withstand before electrical failure. Polymer dielectrics typically exhibit high breakdown strength, whereas the introduction of ceramic nanofillers may either enhance or reduce this property depending on dispersion quality and interface characteristics. In well-designed PDNCs, nanofillers introduce deep trap states at the polymer–filler interface, which hinder charge carrier acceleration and delay breakdown initiation. Conversely, filler agglomeration, voids, and defects can cause local electric field distortion, leading to premature breakdown. Breakdown strength is commonly analyzed using Weibull statistical analysis to evaluate reliability and uniformity of the dielectric performance. Achieving a balance between high dielectric constant and high breakdown strength is essential for maximizing energy-storage density.

7.3 Thermal Stability

Thermal stability is vital for PDNCs operating under elevated temperatures or high-power conditions. **Thermogravimetric Analysis (TGA)** is employed to evaluate thermal degradation behavior and decomposition temperatures, while **Differential Scanning Calorimetry (DSC)** provides information on glass transition temperature, melting behavior, and crystallinity changes. The incorporation of ceramic nanofillers such as ZnO and $BaTiO_3$ generally enhances thermal stability by acting as heat-resistant barriers and restricting polymer chain mobility. In

PVDF-based systems, DSC analysis also helps assess changes in crystalline phase content, particularly the β-phase, which influences dielectric and ferroelectric behavior. Improved thermal stability ensures dimensional integrity, consistent dielectric performance, and long-term reliability of PDNCs in practical electronic applications.

Overall, the combined evaluation of AC conductivity, breakdown strength, and thermal stability provides a comprehensive understanding of the electrical robustness and operational limits of polymer dielectric nanocomposites, guiding their optimization for high-performance capacitors, flexible electronics, and advanced energy-storage systems [17].

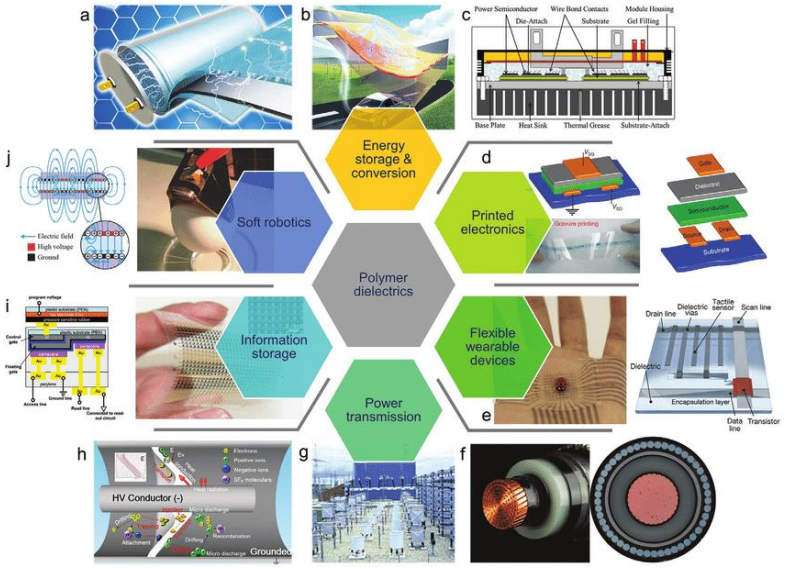


Fig.7.1 Applications of Dielectric polymers

8. Applications in Electronics

4.1 Applications in Electronics

Applications include high-energy-density capacitors, embedded capacitors in PCBs, flexible electronics, and improved cable insulation. Multilayer and gradient architectures allow spatial separation of high-ε and high-Eb layers to maximize energy density while maintaining reliability.

- **Capacitors:** High dielectric constants enable compact and high-performance capacitors.
- **Insulators:** Enhanced insulation properties for electronic devices.

Energy Storage

- **Dielectric Energy Storage:** Used in energy storage devices where high dielectric constants are critical.

Sensors and Actuators

- **Sensors:** Improved sensitivity and performance in various sensors.
- **Actuators:** Enhanced performance in piezoelectric actuators for precise control.

Telecommunications

- **RF Components:** Improved performance in RF and microwave components.

Automotive and Aerospace

- **Advanced Materials:** Utilized for lightweight, high-performance materials in these sectors.
- **Polymer capacitors** represent one of the most important applications of PDNCs. Compared to traditional polymer dielectrics, PDNC-based capacitors exhibit higher dielectric permittivity and improved energy-storage density while retaining excellent mechanical flexibility and reliability. The incorporation of $BaTiO_3$ significantly enhances permittivity, whereas PMMA/PVDF blending and ZnO addition help suppress dielectric loss and maintain high breakdown strength. These features enable the fabrication of compact, lightweight, and high-performance capacitors for power electronics and pulse-power systems.

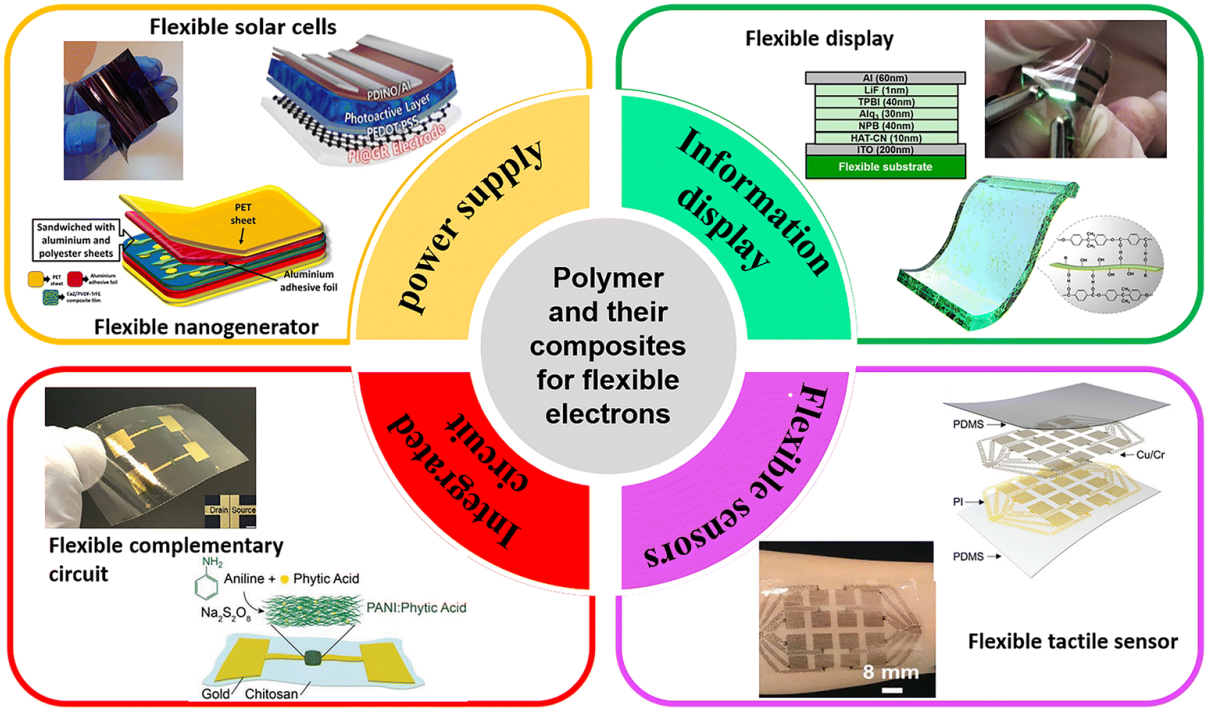


Fig. 8.1 Applications of PDNC in Electronics

Polymer Dielectric Nanocomposites (PDNCs) based on PMMA/PVDF matrices reinforced with ZnO and $BaTiO_3$ nanofillers have attracted significant interest for a wide range of electronic applications due to their unique combination of high dielectric performance, mechanical flexibility, thermal stability, and processability. The enhanced dielectric constant, low dielectric loss, and high breakdown strength achieved through nanocomposite design make these materials suitable for both conventional and emerging electronic technologies.

Applications of Polymer Dielectric Nanocomposites (PDNCs) in Electronics

Polymer Dielectric Nanocomposites (PDNCs) have attracted significant attention in electronic applications due to their unique combination of high dielectric permittivity, low dielectric loss, high breakdown strength, mechanical flexibility, and ease of processing. By integrating high-dielectric nanofillers such as ZnO and $BaTiO_3$ into polymer matrices like PMMA and PVDF, PDNCs offer enhanced electrical performance while overcoming the limitations of conventional ceramic dielectrics.

Polymer film capacitors are one of the most important applications of PDNCs. Compared to traditional polymer dielectrics, PDNC-based films exhibit higher dielectric constants and improved energy-storage density while retaining excellent mechanical flexibility and reliability. The enhanced breakdown strength of polymer matrices combined with the high permittivity of ceramic nanofillers enables the fabrication of compact, lightweight, and high-performance capacitors suitable for power electronics and pulsed power systems.

Multilayer ceramic capacitors (MLCCs) are widely used in modern electronics; however, their brittleness and limited flexibility restrict their application in flexible and wearable devices. PDNCs are being explored as potential alternatives or complementary materials to MLCCs by

offering polymer-based multilayer structures with enhanced dielectric properties. PMMA/PVDF-based nanocomposites filled with $BaTiO_3$ provide high dielectric constants comparable to ceramic layers, while maintaining improved mechanical compliance and resistance to mechanical failure. **MLCC substitutes** represent another promising application area. Conventional MLCCs provide high capacitance but suffer from brittleness and limited mechanical flexibility. PDNCs offer a viable alternative by enabling multilayer polymer-based capacitor structures with improved flexibility, shock resistance, and processability. PMMA/PVDF-based nanocomposites filled with $BaTiO_3$ can achieve dielectric properties comparable to ceramic layers while providing enhanced mechanical compliance, making them suitable for next-generation electronic packaging [18].

Energy storage devices benefit significantly from PDNCs due to their ability to store and release electrical energy efficiently under high electric fields. The synergistic combination of high dielectric constant and high breakdown strength in PDNCs leads to enhanced energy density and charge–discharge efficiency. These materials are therefore promising for applications in renewable energy systems, electric vehicles, and pulsed power devices where rapid energy storage and delivery are required.

Flexible and wearable electronics require dielectric materials that can maintain stable electrical performance under mechanical deformation such as bending, stretching, and twisting. PDNCs based on flexible polymer matrices like PVDF and PMMA/PVDF blends are well suited for such applications. The incorporation of nanofillers enhances dielectric response without compromising flexibility, enabling their use in wearable sensors, flexible displays, and energy-harvesting devices.

Embedded electronic components, including embedded capacitors in printed circuit boards (PCBs), demand thin, reliable, and thermally stable dielectric materials. PDNCs can be processed as thin films using solution-based or printing techniques, allowing seamless integration into multilayer electronic architectures. Their tunable dielectric properties enable precise control of capacitance and improved miniaturization of electronic systems.

Overall, PDNCs provide a versatile platform for advanced electronic applications, bridging the gap between rigid ceramic dielectrics and flexible polymer materials while meeting the performance demands of modern and emerging electronic technologies.

Embedded electronics, such as embedded capacitors in printed circuit boards (PCBs), demand dielectric materials with stable electrical performance, thin-film processability, and compatibility with standard fabrication techniques. PDNCs can be processed as thin films using solution casting, spin coating, or printing methods, enabling their integration into multilayer circuit architectures. Their tunable dielectric properties allow for precise control of capacitance within compact electronic systems.

Flexible electronics is an emerging field where mechanical flexibility, lightweight design, and durability under bending or stretching are critical. PMMA/PVDF-based PDNCs are particularly well suited for flexible and wearable electronic devices, including sensors, displays, and energy-harvesting systems. The flexibility of the polymer matrix combined with the enhanced dielectric response provided by ZnO and $BaTiO_3$ nanofillers enables reliable performance under mechanical deformation, making these materials ideal for next-generation flexible and wearable technologies.

Overall, the versatility of polymer dielectric nanocomposites enables their application across a broad spectrum of electronic technologies, bridging the gap between rigid ceramic dielectrics and flexible polymer systems while meeting the performance demands of advanced electronic and energy-storage devices [19-20].

9. Literature Review

A critical comparison with existing literature is essential to evaluate the relative performance of Polymer Dielectric Nanocomposites (PDNCs) and to highlight the advantages of

PMMA/PVDF-based systems incorporating ZnO and $BaTiO_3$ nanofillers. Numerous studies have reported that the dielectric properties of polymer nanocomposites are strongly influenced by the choice of polymer matrix, filler type, filler loading, and interfacial engineering strategies. Comparative analysis enables identification of performance trends and establishes benchmarks for practical electronic applications [21-22].

In general, **PMMA-based nanocomposites** exhibit low dielectric loss and high breakdown strength but show limited enhancement in dielectric constant due to the non-polar nature of the polymer. The addition of ZnO nanoparticles provides moderate increases in dielectric permittivity through interfacial polarization while maintaining low loss, making these systems suitable for insulation and embedded electronic applications. **PVDF-based nanocomposites**, on the other hand, demonstrate significantly higher dielectric constants owing to the polar β-phase of PVDF and strong dipolar polarization. Incorporation of $BaTiO_3$ nanoparticles further amplifies permittivity and energy-storage density; however, careful control of filler dispersion is required to prevent excessive dielectric loss and reduction in breakdown strength.

Polymer System	**Nanofiller**	**Dielectric Constant (ε_r)**	**Dielectric Loss (tan δ)**	**Application**
PMMA	ZnO	Moderate (6–9)	Low (≤0.05)	Embedded electronics
PVDF	$BaTiO_3$	High (20–50)	Moderate	Energy storage capacitors
PVDF	ZnO	Moderate–High	Low–Moderate	Sensors, actuators
PMMA/PVDF blend	ZnO + $BaTiO_3$	High with controlled loss	Low–Moderate	Flexible capacitors
PVDF	TiO_2	Moderate	Low	Dielectric insulation

Table 9.1 Representative Summary Table

Overall, the comparison with existing literature clearly indicates that PMMA/PVDF-based polymer dielectric nanocomposites reinforced with ZnO and $BaTiO_3$ nanofillers offer competitive dielectric performance when compared to other polymer systems. Their ability to achieve a favorable balance between dielectric constant, dielectric loss, and mechanical flexibility positions them as promising candidates for advanced electronic, energy-storage, and flexible device applications [19-20].

PMMA/PVDF blend-based nanocomposites reported in the literature offer a balanced dielectric response by combining the advantages of both polymers. These systems often exhibit improved dielectric–loss characteristics and enhanced reliability compared to single-polymer matrices. The inclusion of hybrid fillers such as ZnO and $BaTiO_3$ has been shown to synergistically enhance dielectric constant while suppressing loss, making them promising for high-energy-density capacitors and flexible electronic devices.

10. Challenges and Limitations

Despite significant progress in the development of Polymer Dielectric Nanocomposites (PDNCs), several challenges and limitations continue to restrict their widespread adoption in commercial electronic applications. One of the primary issues is the **agglomeration of nanoparticles**, which arises from the high surface energy and strong van der Waals interactions between nanofillers such as ZnO and $BaTiO_3$. Agglomeration leads to non-uniform dispersion, local electric field concentration, increased dielectric loss, and premature dielectric breakdown.

Another major challenge is **interfacial compatibility** between the inorganic nanofillers and the organic polymer matrices. Poor adhesion at the polymer–filler interface results in weak interfacial polarization control, higher leakage current, and reduced mechanical integrity. Surface chemistry mismatch often necessitates the use of coupling agents or surface modification strategies to improve compatibility.

Processing difficulties also pose significant limitations, particularly in achieving reproducible and scalable fabrication. Techniques such as solution casting may suffer from solvent residue and limited scalability, while melt mixing requires precise control of temperature and shear to prevent polymer degradation and filler agglomeration. Additionally, maintaining uniform filler dispersion during large-scale processing remains challenging.

Finally, **long-term stability** under electrical, thermal, and environmental stress is a critical concern. Prolonged exposure to high electric fields, elevated temperatures, or humidity can degrade dielectric performance, alter interfacial structure, and reduce breakdown strength, thereby affecting device reliability.

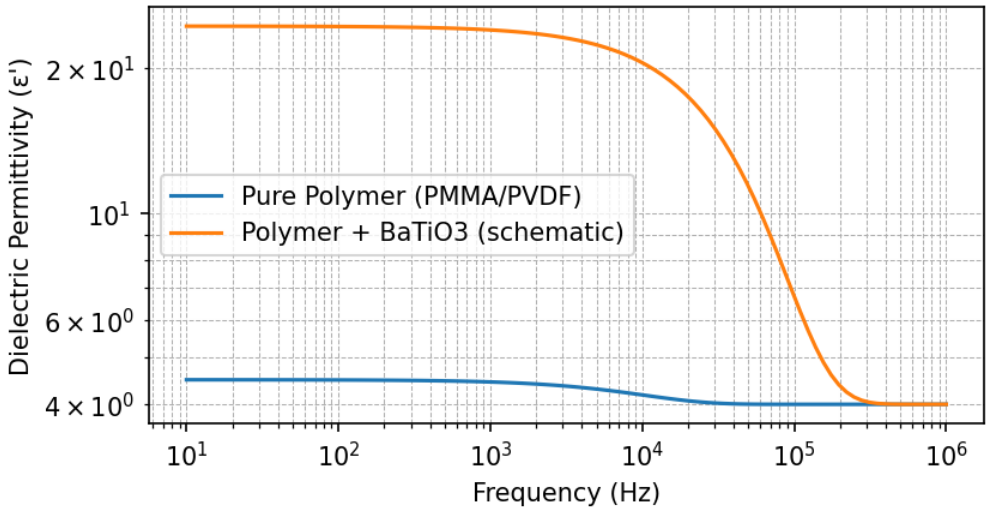


Fig. 10.1. Representative dielectric permittivity vs frequency (schematic).

11. Future Perspectives

Future research on PDNCs is expected to focus on **surface functionalization** of nanofillers to improve dispersion and interfacial bonding. Functionalization using silane coupling agents, polymer grafting, or core–shell architectures can significantly reduce agglomeration, suppress dielectric loss, and enhance breakdown strength.

The development of **hybrid filler systems**, combining fillers such as ZnO and $BaTiO_3$, offers a promising route to synergistically balance dielectric permittivity, loss, and mechanical properties. Hybrid and hierarchical filler architectures can exploit multiple polarization mechanisms while preventing percolation-related losses.

PDNCs are anticipated to play a key role in **high-energy-density capacitors**, where achieving a balance between high dielectric constant and high breakdown strength is essential for maximizing energy storage density. Advanced interfacial engineering and multilayer architectures are expected to further improve energy efficiency and reliability.

Additionally, **flexible and wearable electronics** represent a rapidly growing application domain. The inherent flexibility of polymer matrices combined with enhanced dielectric performance positions PDNCs as ideal materials for next-generation flexible sensors, wearable energy-storage devices, and stretchable electronic systems.

12. Conclusion

This review has comprehensively examined Polymer Dielectric Nanocomposites based on PMMA and PVDF matrices reinforced with ZnO and $BaTiO_3$ nanofillers for electronic applications. The key outcome of this study is the identification of structure–property relationships linking polymer selection, nanofiller type, dispersion quality, and interfacial polarization to dielectric performance. Major trends in current research include the increasing use of polymer blends, surface-functionalized and hybrid nanofillers, and advanced fabrication techniques to achieve high dielectric permittivity with low loss and high breakdown strength.

PMMA and PVDF matrices loaded with ZnO and BaTiO3 nanoparticles present a versatile platform for next-generation dielectric materials in electronics. Performance hinges on dispersion, interfacial design, and achieving the right balance between permittivity and breakdown strength. Emerging strategies—core–shell particles, ternary blends, and scalable processing routes—are promising. Continued integration of characterisation, modelling, and scalable processing will accelerate practical devices (flexible capacitors, sensors, energy harvesters) based on these PDNCs.

Dielectric materials play a crucial role in modern electronic and electrical systems such as capacitors, sensors, actuators, and insulation components. Conventional polymers exhibit low dielectric constant but excellent mechanical flexibility and high breakdown strength. On the other hand, ceramic dielectrics possess high permittivity but suffer from brittleness and processing difficulties.

The application relevance of these materials is evident in their potential for high-energy-density capacitors, embedded electronic components, flexible electronics, and wearable devices. With continued advances in interface engineering, processing scalability, and long-term reliability, PMMA/PVDF-based polymer dielectric nanocomposites are expected to play a pivotal role in the development of next-generation electronic and energy-storage technologies.

13. References

1. Dang, Z.-M., Yuan, J.-K., Yao, S.-H., & Liao, R.-J. (2012). Flexible nanodielectric materials with high permittivity for power energy storage. *Progress in Materials Science, 57*(4), 660–723. https://doi.org/10.1016/j.pmatsci.2011.08.001

2. Lewis, T. J. (2004). Interfaces: Nanometric dielectrics. *IEEE Transactions on Dielectrics and Electrical Insulation, 11*(5), 739–753. https://doi.org/10.1109/TDEI.2004.1349789

3. Tanaka, T. (2005). Dielectric nanocomposites with insulating properties. *IEEE Transactions on Dielectrics and Electrical Insulation, 12*(5), 914–928. https://doi.org/10.1109/TDEI.2005.1522186

4. Li, Q., Chen, L., Gadinski, M. R., et al. (2015). Flexible high-temperature dielectric materials from polymer nanocomposites. *Nature, 523*, 576–579. https://doi.org/10.1038/nature14647

5. Wang, Y., Zhou, X., Chen, Q., et al. (2018). High-energy-density polymer dielectrics for electrical energy storage. *Advanced Materials, 30*(8), Article 1705931. https://doi.org/10.1002/adma.201705931

6. Sengwa, R. J., & Sankhla, S. (2017). Dielectric properties and energy storage behavior of PMMA–$BaTiO_3$ nanocomposites. *Ceramics International, 43*(16), 14268–14278. https://doi.org/10.1016/j.ceramint.2017.07.174

7. Patsidis, A. C., & Psarras, G. C. (2019). Dielectric behaviour of ZnO/PMMA nanocomposites. *Materials, 12*(19), Article 3216. https://doi.org/10.3390/ma12193216

8. Hedayati, M., et al. (2022). Energy storage performance of PVDF-based nanocomposites filled with $BaTiO_3$ nanoparticles. *Ceramics International, 48*(8), 11234–11245. https://doi.org/10.1016/j.ceramint.2022.01.067

9. Rajeh, A. (2023). Structural, dielectric and electrical properties of ZnO-filled polymer nanocomposites. *Journal of Materials Science: Materials in Electronics, 34*, Article 215. https://doi.org/10.1007/s10854-022-09542-4

10. Zhang, T., Liu, L., & Liu, Y. (2015). Multilayer polymer nanocomposites for high energy density capacitors. *Journal of Polymer Science Part B: Polymer Physics, 53*(5), 627–637. https://doi.org/10.1002/polb.23671

11. Li, H., Zhou, Y., & Wang, Q. (2022). Interface engineering in polymer nanocomposites for dielectric energy storage. *Materials Today Energy, 27*, Article 101033. https://doi.org/10.1016/j.mtener.2022.101033

12. You, L., et al. (2023). Structure–property relationships of polymer dielectric nanocomposites. *Nanomaterials, 13*(12), Article 1896. https://doi.org/10.3390/nano13121896

13. Bouharras, F. E., et al. (2023). Dielectric characterization of $BaTiO_3$/PVDF core–shell nanocomposites. *Polymers, 15*(10), Article 2461. https://doi.org/10.3390/polym15102461

14. Mohammed, M. I. (2021). Frequency-dependent dielectric behavior of ZnO-based polymer nanocomposites. *Journal of Applied Polymer Science, 138*(30), Article 50412. https://doi.org/10.1002/app.50412

15. Kaur, D. (2021). Dielectric properties of ZnO-based polymer nanocomposites: A review. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 13*(4), Article e1693. https://doi.org/10.1002/wnan.1693

16. Liu, S., et al. (2024). Gradient dielectric polymer nanocomposites for enhanced energy density. *Advanced Functional Materials, 34*, Article 2309812. https://doi.org/10.1002/adfm.202309812

17. Zhou, X., et al. (2023). Sandwich-structured polymer nanocomposites with high breakdown strength. *Energy Storage Materials, 58*, 102–112. https://doi.org/10.1016/j.ensm.2023.01.015

18. Gao, L., et al. (2024). Interfacial effects on breakdown strength of polymer nanodielectrics. *IEEE Transactions on Dielectrics and Electrical Insulation, 31*(1), 145–154. https://doi.org/10.1109/TDEI.2023.3321004

19. Joshi, G. M., et al. (2024). PVDF-based nanocomposites for flexible electronics and EMI shielding. *Composites Science and Technology, 245*, Article 110346. https://doi.org/10.1016/j.compscitech.2024.110346

20. Wang, Q., & Zhu, L. (2020). Polymer nanocomposites for electrical energy storage. *Journal of Polymer Science, 58*(3), 355–377. https://doi.org/10.1002/pol.20190394

Books & Book Chapters

21. Deshmukh, K., Ahamed, M. B., Deshmukh, R. R., Pasha, S. K. K., Bhagat, P. R., & Chidambaram, K. (2019). Biopolymer composites with high dielectric performance. In *Interface engineering* (Chap. 3, p. 51). Elsevier.

22. Behara, A. (2022). *Advanced materials*. Springer.

23. *Carbon-based nanomaterials and their properties*. (2022). Springer.

24. Sabir, S. (2018). *Polymer-based nanocomposites for enhanced dielectric properties and energy storage capacity*. Elsevier.

25. Mohammad, S. (2018). *Dielectric polymers*. Springer.

26. Rane, A. V., Kenny, K., Abitha, V. K., & Thomas, S. (2018). *Methods for synthesis of nanoparticles and fabrication of nanocomposites*. Elsevier.

27. *Nanomaterials and nanocomposites*. (2016). Wiley.