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Barium Titanate as a Sustainable Energy Harvester: A review on Materials, Mechanisms and Devices

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Abstract - The increasing demand for sustainable, miniaturized and eco-friendly power sources has spurred significant interest in nanogenerators for self-powered electronics. Among the materials explored, barium titanate (BT), a lead-free ferroelectric perovskite has emerged as a promising candidate owing to its high dielectric constant, strong piezoelectric response, and environmental compatibility. This review highlights the evolution of BT from its early discovery as a ferroelectric ceramic to its modern applications in energy harvesting systems. The fundamental aspects of BT, including its perovskite crystal structure, ferroelectric behavior, and piezoelectric mechanism, are discussed to establish its role as an effective energy transducer. Strategies for enhancing its modest intrinsic piezoelectric properties such as domain alignment, chemical doping, phase boundary engineering, grain texturing and composite or nanostructure design are thoroughly examined. Advances in device engineering have demonstrated the utility of BT nanostructures, including nanowires, nanotubes, and thin films, in piezoelectric nanogenerators (PENGs), triboelectric nanogenerators (TENGs) and hybrid nanogenerators (HNGs). Comparative insights into these systems reveal BT's dual role as both a primary energy harvester and a dielectric performance enhancer. Finally, the review underscores BT's technological relevance in wearable electronics, biomedical implants and Internet-of-Things (IoT) devices, positioning it as a sustainable alternative to lead-based ferroelectrics for next-generation self-powered systems. PACS Nos.: 77.84.-s, 77.65.-j, 84.60.-h, 84.60.Rb, 81.07.-b

Keywords - Barium titanate (BT), Lead-free ferroelectrics, Domain engineering, Nanostructures, Chemical doping, Energy harvesting Device.

I. INTRODUCTION

The global demand for sustainable and miniaturized energy sources has intensified the focus on nanogenerators for self-powered electronics. Among different nanomaterial used in energy harvesting devices, BT (BT), a lead-free ferroelectric ceramic, stands out due to its high dielectric constant, strong piezoelectric response and environmental compatibility [1, 2]. It offers a unique combination of physical and chemical characteristics that make it especially suitable for applications like piezoelectric nanogenerators (PENGs) [3, 4], triboelectric nanogenerators (TENGs) [5, 6], and hybrid systems [6, 7]. One of the main reasons for its popularity is its strong piezoelectric effect. When BT is subjected to mechanical stress, such as pressure, vibration, or motion it generates an electrical charge. This property allows it to convert mechanical energy from the environment into usable electrical energy. Although lead-based materials like PZT are known for stronger piezoelectricity, BT is preferred in many cases because it is lead-free and eco-friendly, making it suitable for biomedical and wearable applications [8]. Another important advantage of BT is its high dielectric constant, which allows it to store more electric charge. This property makes it valuable in triboelectric nanogenerators as well, where BT films can act as a dielectric filler to improve charge accumulation and output performance [5, 9]. Additionally, BT also has ferroelectric nature, meaning it can maintain a spontaneous polarization that can be reversed under an external electric field. This is essential for creating stable and responsive energy harvesting devices. The crystal structure of BT is also highly tunable. It has a

perovskite structure, which allows for chemical doping at different sites. Researchers can modify its properties by adding elements like zirconium or niobium to improve its piezoelectric response or thermal stability [10, 11]. This tunability is useful for designing devices for specific applications. Furthermore, BT can be synthesized in various nanoforms such as nanoparticles, nanowires, nano-cubes and thin films [13-15]. These nanostructures improve surface area, increase flexibility when combined with polymers, and enhance the efficiency of energy conversion [16]. As a result, BT is widely used in flexible and wearable energy harvesting systems.

Historical Context

The journey of BT in the field of energy harvesting is deeply rooted to its discovery and early use as a ferroelectric ceramic material. Its evolution into a modern energy harvesting component reflects the advancements in materials science, nanotechnology, and the global shift toward sustainable energy solutions. It was discovered independently in the US, Russia, Japan, and Germany around 1944 during World War II as a piezoelectric ceramic material [17, 18]. Its piezoelectric property was used to develop ceramic transducer for ultrasonic sonar systems during WWII and the US Navy played a key role in funding and applying this technology [19]. It was also among the first ceramic materials discovered to exhibit ferroelectricity; the ability to maintain a spontaneous electric polarization that can be reversed by an external electric field. This property led to its widespread use in capacitors, transducers, and electro-optic devices during the mid-20th century.

During initial period BT was not directly used for energy harvesting. At that time, lead based material such as PZT (lead zirconate titanate), was a dominant material in piezoelectric devices [20]. However, since humanity became aware about harmfulness of lead, research on lead free material starts to flourish. Thus, from around 1970s, attention began to shift towards BT for its piezoelectric capabilities [21]. It was mainly explored as a lead-free alternative of conventional piezoelectric materials. Researchers began to understand how grain size, doping, and sintering conditions could influence its performance [22].

The first systematic investigations of BT for energy harvesting began with the development of nanostructured forms, particularly nanowires and thin films, which exhibited enhanced electromechanical coupling due to their high surface area and dimensional confinement. A pioneering study by Wang et al. (Nano Letters, 2007) demonstrated that vertically aligned BT nanowire arrays grown on flexible substrates could convert mechanical energy into electrical output, thus validating the feasibility of BT as a nanoscale energy harvester [23].

The study reported open-circuit voltages of several hundred millivolts under cyclic mechanical deformation, establishing a foundation for subsequent research in this area. In parallel, researchers explored BT/polymer composite systems to achieve flexible and mechanically robust energy harvesting devices [24]. These composites leveraged the piezoelectric activity of BT with the flexibility of polymers like PVDF, enabling application in wearable and flexible electronics [24, 25].

Additionally, thin-film deposition techniques such as sol-gel and pulsed laser deposition were employed to fabricate integrated energy harvesting modules on silicon and polymer substrates [26, 27]. Despite its relatively modest piezoelectric constants compared to PZT, BT offers several advantages: it is lead-free, compatible with low-temperature processing, and exhibits good dielectric and ferroelectric behavior, particularly in nanostructured forms.

These attributes have positioned it as a promising candidate for the next generation of eco-friendly piezoelectric energy harvesting devices, especially in biomedical implants, Internet-of-Things (IoT) nodes, and wearable systems. Still, BT's application in actual energy harvesting devices remained limited due to its relatively lower piezoelectric constants compared to PZT.

Crystal structure, ferroelectric behavior and piezoelectric Effect of BT

The piezoelectric nature of a material is fundamentally determined by its crystal structure. Only materials that lack a center of symmetry in their crystal lattice exhibit piezoelectric properties [28]. Such materials are known as non-centrosymmetric crystals. When subjected to mechanical stress, the asymmetric structure of these crystals leads to the development of an electric polarization. Common examples of piezoelectric materials include quartz, ZnO, BT etc.

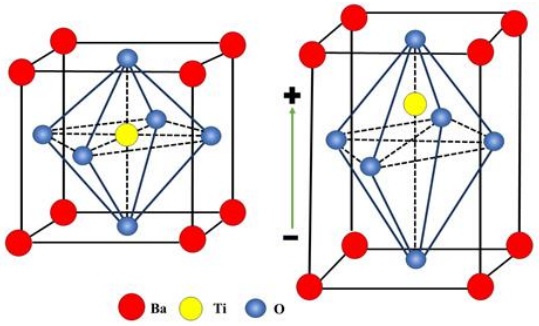

Figure1: (a) Cubic crystal structure of BT, (b) Tetragonal crystal structure of BT (The figure has been prepared by the authors based on well-established knowledge of the $BaTiO_3$ perovskite structure)

BT adopts the ABO_3 perovskite structure, where Ba^{2+} occupies the A-site, Ti^{4+} the B-site, and O^{2-} forms the oxygen octahedra. At room temperature, BT has a tetragonal structure characterized by the off-center displacement of the Ti^{4+} ion within the TiO_6 octahedron, resulting in a spontaneous electric dipole moment. This non-centrosymmetric crystal structure is the prerequisite for piezoelectricity [29]. However, above the Curie temperature (~120 °C), BT becomes cubic and centrosymmetric, losing its ferroelectric and piezoelectric properties. It is need to be remember that although BT has an internal piezoelectric structure but in unstressed condition, the electric dipoles inside the BT crystal either cancel out or are aligned in such a way that no resultant electric field is observed.

The energy harvesting process using BT is a multi-step process. Here initially a force, vibration, or pressure is applied to the BT material. The applied stress changes the alignment of electric dipoles within the ferroelectric domains, generating a net polarization. The change in polarization leads to charge accumulation on the electrodes. This charge drives current through an external circuit, thereby converting mechanical energy into electrical energy [30]. If electrodes are placed on the surface, a measurable voltage or current can be observed (Figure 2). This phenomenon is the well-known direct piezoelectric effect. Conversely, when an electric field is applied across a piezoelectric material, it undergoes mechanical deformation. This is called the converse piezoelectric effect [31]. The relationship between the ability to generate an electric charge in response to mechanical stress in a piezoelectric material such as BT can be described tensorially as:

$D_{ij}=d_{jk}.\sigma_{jk}$.....(1)

Where, D_i: Electric displacement (C/m^2), σ_{jk}: Applied mechanical stress (N/m^2) andd_{jk}: Piezoelectric coefficient tensor (C/N). For practical device applications, this is often simplified using scalar constants for specific directions. For example, is the piezoelectric coefficient along the direction of polarization. Further the harvested energy can be calculated by integrating the power output over time

$E=\int \llbracket V(t).I(t)dt \rrbracket$ .....(2)

Where V(t): Voltage generated, and I(t): Current generated.

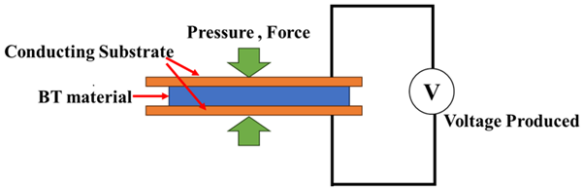

Figure 2: Simple schematic of piezoelectric energy harvester (Figure has been prepared by the authors based on well-established knowledge piezoelectric energy harvester)

4. Strategies to increase piezoelectric properties in BT Despite being one of the earliest and most studied lead-free ferroelectric materials,

Although BT offers several advantages such as non-toxicity, excellent chemical stability and compatibility with diverse fabrication techniques it inherently possesses not so excellent piezoelectric coefficient compared to lead-based ferroelectrics like PZT. interfacial stress and fatigue. Consequently, despite its environmental advantages and chemical stability, BT's performance remains constrained by intrinsic structural, thermal, and defect-related factors, motivating ongoing research into doped, composite, and nanostructured systems to enhance its Curie temperature, domain stability, and device reliability. This disparity in performance restricts its applicability in high-demand scenarios which requires strong electromechanical coupling and significant strain response. Consequently, researchers worldwide are actively exploring various strategies to enhance the piezoelectric properties of BT. Some of the methods used are domain alignment through poling, chemical doping, phase boundary engineering, texturing and grain orientation control, composite and nanostructure design, sintering and processing control etc [2, 30-36].

Domain alignment through Poling

In tetragonal BT, each grain consists of multiple ferroelectric domains separated by domain walls. The polarization vectors in these domains may differ by 180° (reversal of polarization without a change in strain) or 90° (reorientation involving both polarization and strain changes). In the unpoled state, these domains are randomly oriented, causing macroscopic polarization to cancel out [31]. Applying a sufficiently high electric field induces non 180° domain switching, increasing the fraction of domains aligned with the field direction. This results in a higher net polarization and improved electromechanical coupling. Additionally, the reversible motion of domain walls under small AC fields contributes to the intrinsic lattice response, thereby increasing d33 and the dielectric constant [31, 32]. Further, in doped BT, point defects such as oxygen vacancies can align with the spontaneous polarization, stabilizing the poled state. However, excessive defect pinning may restrict domain wall mobility and reduce piezoelectric efficiency [33]. For energy harvesting devices, higher d33 values directly enhance the generated charge (Q=d33F) and output voltage, making poling a crucial step for maximizing the performance of BT-based transducers, sensors, and generators [31].

The poling procedure in barium titanate (BT) is an essential post-sintering treatment used to align ferroelectric domains in a preferred orientation, thereby enhancing its piezoelectric performance. In this process, a strong DC electric field typically 1–3 kV/mm for bulk ceramics is applied across the sample at an elevated temperature, generally between 70 °C and 120 °C, just below the Curie temperature. The sample, with electrodes deposited on opposite faces, is immersed in an insulating oil bath such as silicone or transformer oil to prevent dielectric breakdown and ensure uniform thermal distribution. The electric field is gradually increased to the target value and held for 10–30 minutes, allowing sufficient time for domain reorientation. Cooling to room temperature is carried out under the applied field to "freeze" the aligned domain configuration. After cooling, the field is removed and the electrodes are short-circuited for several hours to neutralize surface charges, thereby stabilizing the piezoelectric properties [34].

The intrinsic piezoelectric effect of BT single crystals poled along their natural polar axis is relatively low. To overcome this limitation, researchers have adopted a domain wall engineering approach that takes advantage of the piezoelectric anisotropy of single crystals [37]. This technique involves applying the poling electric field at an angle to the crystallographic polar axis, rather than directly along it. For instance, in tetragonal ferroelectric crystals, when the field is applied along the [110] direction, two energetically equivalent ferroelectric domains are generated with spontaneous polarizations (P_s) oriented along [100] and [010], respectively [38]. Similarly, for a crystal poled along the [111] direction, three complementary domain orientations emerge with P_s aligned along [100], [010], and [001]. Such engineered, multi-domain configurations enhance the electromechanical coupling and lead to a significantly enlarged piezoelectric response compared to conventionally poled crystals [39].

Chemical Doping

In recent time chemical doping is emerging as a powerful approach to engineer the crystal structure, domain configuration, and defect chemistry of BT, thereby enhancing its piezoelectric performance [35]. Chemical doping is a well-established strategy to tailor the structural, dielectric, and piezoelectric properties of BT. Chemical doping can also be used for phase boundary engineering which involves tuning the composition, temperature, or external conditions of BT to stabilize multiple ferroelectric phases (e.g., tetragonal, orthorhombic, and rhombohedral) near room temperature [35]. The coexistence of these phases creates a morphotropic-like phase boundary (MPB) or a polymorphic phase boundary (PPB), which significantly enhances piezoelectric performance.

The chemical doping principle is based on substituting host ions in the A-site (Ba^{2+}) or B-site (Ti^{4+}) of the perovskite lattice with dopant ions of different sizes and valences, thereby modifying lattice strain, defect chemistry, and domain wall dynamics [40-50]. Depending on the site and nature of substitution, dopants can be broadly categorized as isovalent, acceptor and donor dopants. The isovalent doping is the doping process in which the dopant ion has the same valence as the host ion it replaces, ensuring no net charge imbalance. Here the primary effect is structural modification via lattice strain, which alters the ferroelectric domain configuration and Curie temperature. The isovalent doping can be both A-site or B-site doping. Some well-known A-site substitute of Ba^{2+} are Sr^{2+}, Ca^{2+} or Pb^{2+} [40-42].

These dopants can tune the phase transition behavior. For example, Sr^{2+} doping reduces the tetragonality (c/a ratio), broadening the temperature range of piezoelectric activity. On the other hand, some common example of B-site dopants are Zr^{4+} or Sn^{4+}. These type of substitution for Ti^{4+} modifies the polarizability of the TiO_6 octahedra and can shift the phase transition temperatures [41, 42].

In case of acceptor doping process, the acceptor dopants possess lower valence than the ion they replace, creating charge imbalance that is often compensated by oxygen vacancies ($V_O^{\bullet\bullet}$) [43].

These vacancies interact with ferroelectric domains and can either enhance or hinder domain wall mobility depending on the doping concentration. Trivalent ions such as Al^{3+}, Fe^{3+}, and Mn^{3+} substituting for Ti^{4+} on the B-site are classic examples of acceptor dopants. At low concentrations, acceptor doping can improve aging resistance and mechanical quality factor (Q_m) by partially pinning domain walls, which is beneficial for resonator and actuator applications. However, excessive pinning reduces d33 values and electromechanical coupling [2, 44-45]. On the other hand, in case of donor doping the charge imbalance is typically compensated by cation vacancies V_{Ba}'' or V_{Ti}'''' [43]. If the doping is A site doping, the substitution of Ba^{2+} with trivalent ions such as La^{3+} takes place while B site doping is achieved by substituting Ti^{4+} with pentavalent ions such as Nb^{5+}, Ta^{5+} or Sb^{5+}[46-50].

The donor doping is often associated with soft piezoelectric behavior, where increased domain wall mobility results in higher strain response and improved electromechanical coupling, which is ideal for sensor and low-power actuator applications [46]. Further, in many advanced applications, researchers often employ a co-doping strategy, where both donor and acceptor dopants are introduced into BT host to achieve a balance among mechanical quality factor (Q_m), dielectric loss, and piezoelectric coefficients. This approach enables a synergistic optimization of domain wall mobility and structural stability. For instance, co-doping of Mn with other element such as Zr, Nb etc has been shown to yield materials with simultaneously high Q_m and high d33, making them highly suitable for devices that demand both high-power performance and sensitive piezoelectric response [51, 52].

Other strategies

Texturing and grain orientation control has emerged as another key strategy to enhance the piezoelectric response of BT-based ceramics by aligning ferroelectric domains in favorable crystallographic directions. Texturing and grain orientation control in BT offers a powerful route to overcome the limitations of polycrystalline ceramics. Through

methods such as template grain growth and hot forging, preferential orientation along the [001] axis can be achieved, significantly improving piezoelectric coefficients and electromechanical coupling [53]. This strategy bridges the gap between polycrystalline ceramics and costly single crystals, enabling high-performance, lead-free piezoelectric devices for next-generation applications.

Similarly, composite and nanostructure design in barium titanate (BT) is another promising approach to enhance its piezoelectric response by exploiting interfacial effects, size control, and structural engineering. In composite systems, BT is combined with polymers (e.g., PVDF) to yield flexible polymer ceramic composites with improved dielectric constant, breakdown strength, and mechanical compliance [54], while ceramic-ceramic composites (such as BT-$BiFeO_3$) utilize phase synergy to boost electromechanical coupling [55], and metal ceramic hybrids with fillers like Ag or CNTs introduce interfacial field enhancement for higher polarization [56, 57].

At the nanoscale, BT nanoparticles and nanograins increase domain wall density and reduce internal stresses, nanowires and nanotubes provide one-dimensional anisotropy that facilitates polarization alignment, and thin films allow strain engineering through epitaxial growth, leading to enhanced electromechanical coefficients. Core–shell nanostructures and heterostructures with 2D materials (e.g., graphene) further stabilize polarization and enable interfacial charge transfer [58]. These strategies improve piezoelectricity through mechanisms such as interfacial polarization (Maxwell–Wagner effect), domain miniaturization, and strain-induced phase stabilization, with the effective piezoelectric coefficient describable by effective medium models incorporating both intrinsic and interfacial contributions. Such composite and nanostructured BT systems are increasingly applied in flexible energy harvesters, biomedical sensors, high-frequency MEMS transducers, and high-power piezoelectric devices, making them attractive lead-free alternatives to traditional PZT-based materials.

Device design for energy harvesting

The early 2000s saw a technological leap in nanomaterials and nanostructuring techniques, which significantly boosted interest in BT for energy harvesting. The development of first nanogenerators using ZnO nanowires, by researchers like Zhong Lin Wang, brought attention to materials that could convert mechanical energy into electricity on a small scale [59].

The development of BT-based piezoelectric nanogenerators (PENGs) stems from the long-standing interest in BT as one of the first discovered ferroelectric perovskite oxides in the mid-20th century, widely recognized for its strong dielectric, ferroelectric, and piezoelectric properties [3]. Early research primarily focused on its bulk ceramics and single crystals for capacitor, actuator and transducer applications. With the advancement of nanotechnology, attention shifted towards BT nanostructures, such as nanoparticles, nanowires, and thin films, which exhibit enhanced polarization switching and domain wall mobility compared to their bulk counterparts [4].

The first demonstrations of BT nanostructures in PENGs highlighted their ability to generate output voltages and currents from low-level mechanical vibrations, offering a lead-free and environmentally benign alternative to PZT-based systems. In 2016, Tsege et al. reported a flexible PENG constructed from vertically aligned BT nanotube arrays grown via in situ hydrothermal conversion of anodized TiO_2 on a Ti-mesh substrate; encapsulating the oriented BT nanotube film within PDMS and sandwiching it between ITO/PET electrodes yielded output voltages of up to ~10.6 V and currents around 1.1 μA, sufficient to drive an LCD screen—demonstrating both the feasibility and functionality of BT nanostructured PENGs [60]. Around the same period, albeit slightly later, another research group developed a high-performance PENG based on a nanoimprinted sol–gel BT nanopillar array, which, following polarization with a strong electric field and ultraviolet treatment, achieved enhanced outputs of approximately 10 V and a current density of ~1.2 $\mu A/cm^2$ in comparison to flat films [61]. These early works laid the groundwork for the field by illustrating

how tailored BT nanostructures such as nanotubes and nanopillars etc could significantly enhance piezoelectric coupling and mechanical-to-electrical energy conversion efficiency. Current research is directed toward optimizing the electromechanical coupling of BT through domain engineering, interface modification, and hybrid composite strategies with polymers or carbon-based materials to improve flexibility, power density, and device durability. Furthermore, integration of BT-based PENGs into self-powered wearable sensors, biomedical implants, and Internet-of-Things (IoT) devices underscores their growing technological relevance [62-64].

Triboelectric nanogenerators (TENGs) have rapidly emerged as a versatile energy-harvesting technology, leveraging contact electrification and electrostatic induction to convert mechanical stimuli into electrical power. TENGs use triboelectricity, commonly called static electricity, to convert common mechanical energy sources into electric power [5]. Here, the electric charges are separated on the contact surfaces, and an electrical potential is generated between the surfaces. The alternating potential resulting from the dynamic mechanical motions can be used to charge a battery or for powering electric devices such as a wireless sensor. In addition, the potential profile, or the current profile, of a TENG can be used as a sensor to monitor motion or various chemicals. BT (BT), a lead-free perovskite ferroelectric, has been widely adopted in TENGs due to its high spontaneous polarization and dielectric constant. Notably, Dien et al. (2025) reported a high-performance nylon-11/BT–PVDF composite TENG fabricated via electrospinning. This hybrid device exhibited remarkable output characteristics of 280 V open-circuit voltage, 12 μA short-circuit current, and a peak power density of 1.45 W/m^2; which was successfully demonstrated by powering a calculator, timer, and multiple LEDs. [65] This work exemplifies the significant enhancement BT nanowires (BTNWs) impart on triboelectric performance. Other approaches include screen-printed TENGs using BT-enhanced copy paper, yielding 103 V and 3.6 μA with excellent durability (over 57,600 cycles) and a power density of 32.4 μW/cm^2 [66] .Collectively, these studies underscore how strategically engineered BT nanostructures paired with polymer matrices can dramatically improve triboelectric charge generation, device robustness, and energy-harvesting efficiency, positioning BT-based TENGs as strong candidates for sustainable, flexible power sources in wearable, biomedical, and IoT applications.

Although BT has been extensively employed in both PENGs and TENGs, however the structural configuration, and energy-conversion mechanisms differs in both the two systems. In PENGs, BT nanostructures such as nanowires, nanoparticles, thin films, or nanocomposites are typically sandwiched between conductive electrodes. When subjected to external mechanical stimuli (e.g., stress, vibration, or bending), the induced strain reorients ferroelectric domains and modifies dipole alignment, thereby generating a change in spontaneous polarization. This polarization difference drives charge accumulation at the electrodes, producing an output voltage and current through an external circuit. In contrast, in TENGs, BT is most often incorporated as a nanofiller within a polymeric triboelectric matrix (e.g., PDMS, PVDF, nylon), or as a coating on contact layers. Here, mechanical contact and separation between two dissimilar triboelectric materials lead to charge transfer at the interface [67]. The presence of BT enhances the dielectric constant and contributes additional polarization via its ferroelectric properties, increasing surface charge density and boosting output. Structurally, while PENGs rely on the direct piezoelectric response of aligned BT domains, TENGs harness contact electrification assisted by BT-induced dielectric polarization. Functionally, PENGs are highly effective for harvesting continuous vibrations and mechanical strain, whereas BT-based TENGs are particularly advantageous for intermittent or low-frequency motion due to their higher charge output. Thus, BT serves as the primary energy transduction medium in PENGs, but in TENGs it acts as a performance enhancer by amplifying triboelectric charge generation through its ferroelectric and dielectric contributions.

Hybrid nanogenerators (HNGs), which integrate piezoelectric and triboelectric mechanisms within a

single device, have emerged as an effective approach to overcome the intrinsic limitations of individual energy harvesting technologies and to maximize energy conversion efficiency [68, 69]. In such systems, mechanical excitations such as bending, vibration, or contact separation simultaneously activate piezoelectric polarization and triboelectric charge transfer, thereby enabling dual-mode energy harvesting and synergistic enhancement of output performance [70]. The incorporation of functional nanomaterials, particularly BT nanoparticles or nanorods embedded in polymeric matrices such as PDMS or chitosan, significantly improves device efficiency by increasing dielectric permittivity, polarization strength, and surface charge density through enhanced interfacial coupling [71, 72].

Further optimization strategies, including surface microstructuring (e.g., micro-pyramids or microneedles) and dopant engineering (e.g., Al-doped BT), have been shown to enhance the effective contact area and stabilize ferroelectric domain orientation, leading to substantial improvements in energy output [73, 74]. As a result, BT-based HNGs have demonstrated open-circuit voltages exceeding several hundred volts and power densities reaching tens of watts per square meter, sufficient to power portable electronics or serve as sustainable self-powered sensors [74, 75]. Moreover, the synergistic interaction between piezoelectric and triboelectric effects enables self-charge pumping and pre-alignment of ferroelectric domains, which not only boosts performance but also enhances device durability and charge retention. Collectively, these advancements establish BT-based HNGs as a rapidly developing platform at the intersection of materials science, surface engineering, and device physics, offering significant potential for next-generation wearable electronics, biomedical monitoring, and large-scale self-powered systems.

II. CONCLUSION

Barium titanate has transitioned from one of the earliest discovered ferroelectric ceramics to a central material in the design of modern nanogenerators. Its lead-free composition, strong dielectric and ferroelectric properties, and tunable perovskite structure position it as a viable alternative to traditional lead-based piezoelectrics such as PZT. Although BT exhibits relatively moderate intrinsic piezoelectric coefficients, advancements in doping strategies, domain engineering, texturing, and nanostructure design have significantly improved its energy harvesting performance. In PENGs, BT functions as the primary energy transducer, while in TENGs, it enhances dielectric polarization and charge density, and in HNGs, it enables synergistic coupling of both mechanisms.

These developments underscore BT's versatility across multiple energy harvesting platforms. Current progress has already demonstrated the capability of BT-based devices to power low-power electronics and serve as reliable self-powered sensors. Looking ahead, further optimization of interfacial engineering, large-scale fabrication methods, and hybrid material systems will be crucial to achieve higher power densities, long-term stability, and integration into real-world applications. With its eco-friendly nature and wide adaptability, BT is poised to play a pivotal role in the advancement of self-sustaining electronics and the broader transition toward green energy technologies.

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