**Barium Titanate Stannate: A Promising Material for Future Generations**

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For more than 75 years, barium titanate (BaTiO3) has been of practical interest due to its alluring qualities. First of all, due to its high chemical and mechanical stability, secondly, due to its ferroelectric characteristics at and above room temperature, and finally, due to the ease with which ceramic polycrystalline samples can be manufactured and used [1]. Barium titanate has been employed in applications including multilayer capacitors (MLCs) and capacitors because of its high dielectric constant and low loss properties. One of the most significant ferroelectric ceramics is doped barium titanate, which is widely used in semiconductors, PTC thermistors, and piezoelectric devices.[2]

 

BaTiO3 exists in the perovskite structure. Perovskite structure can be described by the generic formula ABX3. A and B are two cations that are frequently extremely diverse in size, and X is an anion that frequently links to both cations through the oxide. Ba2+ atoms are located at the cube corners of BaTiO3, Ti4+ atoms are located at the body centre, and oxygen atoms are located at the face centre. Cation A has a coordination number of 12 and the co-ordination for cation B is 6.[3]

Impurity, porosity, particle size, phase, density, and grain size are the primary factors that affect the qualities of ceramic materials. To modify the variables and customise the properties, the A-site or B-site of the ABO3 perovskite crystal structure can be doped with an appropriate element. Doping of comparable size and ionic charge elements in the host matrix is a highly helpful approach for all of these aspects. It has been found that even a little quantity of doping in BaTiO3 can improve its electrical characteristics and microstructure. [4,5]

Due to its low Curie temperature (Tc) of 120o C and high temperature coefficient of resistance close to Tc, in its pure form, BaTiO3 cannot be employed in high-temperature applications. By properly doping foreign elements into BaTiO3, it is possible to shift the Curie temperature to a high temperature, which is also beneficial for prolonged ferroelectric behaviour. BaTiO3 has a flexible crystal structure that allows for various dopants. Part of the Ba2+ ions can be replaced with Pb2+, Sr2+, Ca2+, and Cd2+ while preserving the ferroelectric properties. Similar to how Sn4+, Hf4+, Zr4+, Ce4+, and Th4+ can partially replace the Ti4+ ion. Although pure BaTiO3 is a good insulator at ambient temperature, it can be doped at either the A or B-site depending on the dopant chosen to increase conductivity to semiconductor levels. It is well known that some dopants, such as La3+, Y3+, and Sb3+ doped at the A-site, and others, such as Mn4+, Nb5+, and Ta5+ doped at the B-site, increase the conductivity of BaTiO3[6,7].

Barium stannate titanate (abbreviated BTS, also known as BaSnxTi1-xO3) is synthesized by doping BaTiO3 with SnO2. Ferroelectric barium titanate and non-ferroelectric barium stannate make up the binary solid solution system known as BTS. They both have perovskite structures with the formula ABO3. Either titanium or tin ions occupy the B sites of BTS. Most research on BTS ceramics and films has recently focused on preparation, dielectric characteristics, diffuse phase transition, and tunability. Tin content can be changed to alter the BTS system's Curie temperature and dielectric maximum.[8]

For applications requiring high permittivity, BTS is an excellent candidate. The Sn composition and the microstructural parameters (grain size and grain boundary properties, secondary phases, porosity level, and core-shell structures) can be adjusted to change the properties of BTS. Since the dielectric constant of BTS solid solutions is significantly field-dependent, it can be changed by varying the strength of the applied field. Based on this characteristic, a wide range of devices can be created, including voltage-controlled oscillators, actuators, variable capacitors, phase shifters, microwave dielectric amplifiers, frequency multimeters, parametric devices, and actuators. These devices are especially useful in the development of circuits and devices required by the wireless communications industry as well as for scientific, aerospace, military, and commercial applications.[12]

To enhance the structural, electrical, dielectric, piezoelectric and ferroelectric properties several substitutions may be done in pure BT. Many interesting features in properties are exhibited in doping. A lot of work has been done but still, researchers are trying to enhance its properties under operating conditions. Some of the National and International studies are discussed below: -

* In **2007**, **F. Moura** *et al.* [9] conducted research on how the addition of Zr significantly changed the crystal structure and electrical characteristics of BT ceramics. According to reports, increasing the Zr content causes the average grain size to decrease, the dielectric permittivity (r) to decrease, and the leakage current to remain low and stable. With an increase in zirconium concentration, there is a decrease in the dielectric permittivity and residual polarisation, which is a sign of altered crystal structure and a predominance of relaxor behaviour.
* In ferroelectric BaTiO3 single crystals with (001) orientation, **R P Borges** *et al.* [10] implanted Fe in **2010** with an energy of 100 keV and a fluence of 11017 cm-2. Fe nanoparticles are created and exhibit typical superparamagnetic behaviour in the implanted crystals, according to an examination of their magnetic characteristics. With changes in the magnetization values and thermal hysteresis found at corresponding temperatures, the thermal dependency of the nanoparticle magnetization demonstrates the structural phase transitions of BaTiO3.
* Effects of dysprosium doping on the structural, dielectric, and electric properties of BTS ceramics were explored by **Shijie Wang** *et al*. [11] in **2010**. All of the Dy-doped BTS ceramics exhibit cubic perovskite structure, according to X-ray diffraction studies. Dy B site doping is favourable for compact and uniform grain distribution, as shown by SEM. As doping levels rise, the dielectric constant and loss tangent decrease. An examination using impedance spectroscopy shows that all samples are insulating at room temperature and that the doping contents have no impact on the electric structures.
* BaSnxTi1-xO3 ceramics were created in **2011** by **Nadejda Horchidan** *et al*. [12] with varying tin concentrations (x = 0; 0.05; 0.1; 0.15 and 0.2). When adding more Sn, the XRD study indicates a tendency for tetragonal to cubic transition. The dielectric results show that a ferroelectric-relaxor crossover and an increase in Sn content result in a decrease in the Curie temperature. The (E) dependency tends to become a non-hysteretic relaxor while losing some of its hysteresis as the Sn addition is increased.
* Nanocrystalline tin-substituted barium titanate ceramic’s structural, electrical, and piezoelectric capabilities were explored by **K. Chandramani Singh** *et al.* [13] in **2011**. The Curie temperature (Tc), which determines the phase transition, gradually decreases as the Sn content in the ceramic rises while the phase transition becomes more diffuse. Remnant polarisation (Pr) and the coercive field (Ec) both diminish as Sn concentration rises.
* In **2013,** **A.K. Nath** *et al.* [14] discovered that the ferroelectric property on BaTi0.975Sn0.025O3 declines with decreasing values of Pr and Ec. Additionally, the d33, electrostrictive strain, and electromechanical coupling coefficient (Kp) of piezoelectric characteristics drop. SEM micrographs show that following irradiation, grain size reduces and grain patterns changes.
* By injecting rare earth elements into BaTiO3**, Fatin Adila Ismail** *et al.* [15] demonstrated how to improve the dielectric behaviour and lower the transition temperature. At lower frequencies, they have a larger dielectric constant. Except Er-doped BaTiO3, the dielectric constant of La-doped BaTiO3, Er-doped BaTiO3, Sm-doped BaTiO3, Nd-doped BaTiO3, and Ce-doped BaTiO3 has increased and the transition temperature has decreased to ambient temperature. To enhance the electrical characteristics of BaTiO3, the dopant choice is crucial.
* Gamma radiation on Ba0.88Ca0.12Ti0.975Sn0.025O3 did not modify the perovskite structure, however, **Umaru Ahmadu** *et al.* [16] showed that the structure-sensitive 200 peaks shifted to higher 2 angles with increasing irradiation dose. As a result of radiation exposure, crystallite size reduces. According to XRD research, the perovskite BCST structure's decreased tetragonality caused the ferroelectric characteristics to degrade. Microstructural modifications and a modest reduction in grain size are also brought on by irradiation. As the amount of gamma radiation is increased, so does its chemical makeup.
* In **2017**, **W. X. DUN** *et al.* [17] doped Yb3+ with the BTS ceramic; when the doping level increases, the pattern's dielectric constant rises and the dielectric loss falls. The best dielectric characteristics are achieved at sintering temperatures of 1300o C and 0.5 mol% Yb3+ ion doping. Broadening the Curie peak by adding Yb3+ at low temperatures.
* Ba(Ti0.96SnxZr0.04-x) O3 was synthesised in **2018** by **Muazu** *et al.* [18] with x=0.02, 0.03 and 0.04. With an increase in Sn content, the grain size tends to shrink. With the substitution of Sn and Zr, dielectric loss is reduced while the room-temperature dielectric constant rises. higher crystal tetragonality and higher polarisation and relative dielectric permittivity are caused by an increase in Sn content. When compared to BTSZ samples, which show no evidence of a phase transition and have a Curie temperature (Tc) of 90o C, BT's Tc is shown to be lower than that of room temperature with doping concentration. The composition BTSZ[x=0.03] was the ideal choice for MLCCs and energy storage applications due to its high real relative dielectric permittivity with dielectric loss.
* By adding lanthanum to the barium titanate structure, **M.V. Zdorovets** *et al.* [19] discovered that the phase composition changes, with the phase (Ba0.94La0.06) (TiO3) of the substitution solid solution and impurity inclusions of the anatase and BaTi2O5 phases predominating. The dielectric constant decreases the average particle size somewhat changes, and the absorption edge shifts as a result of the cubic phase's development. The formation of lanthanum-containing particles in doped structures and changes in the geometrical dimensions of those particles, which result in changes in the dislocation density and additional distortions and defects in the structure, are what causes the increase in resistance.
* In **2020**, **Manoj Kumar Mahata** *et al.* [20] investigated the photophysical characteristics of Ho3+-Yb3+doped BaTiO3 nanocrystals and suggested a simple technique to measure the matrix's temperature and crystal phase structure. The shift in Ho3+ locations in the final lattice causes a variation in the green-to-red emission intensity ratio during the crystallites' phase transition. It is discovered that the eccentricity present in the non-centrosymmetric BaTiO3 crystals is measured by the SHG signal intensity. As it transitions into a tetragonal phase, the Ho3+ occupancy rates that were 73% and 27% at the Ba2+ and Ti4+ sites, respectively, are modified to 64% and 36%. As a low-temperature probe, this material's temperature-dependent luminescence, with a sensitivity of as much as 0.0095 K−1 found at 12K.
* By using a traditional solid-state process, **A. K. Mahapatra** *et al*. [21] **2021** created a Bi substituted BaTiO3(BT) ceramic with the general formula Ba1-xBi2x/3TiO3. Single-phase symmetry can be shown in the structural behaviour revealed by XRD patterns, Rietveld refinement, and doping. With doping up to x=0.025, the dielectric behaviour exhibits an improvement in the dielectric constant and transition temperature, which decreases with an increase in doping concentration. According to the results, Bi doping the BaTiO3 matrix is an effective way to make the system a strong contender for MLCC and energy storage applications.
* Undoped, Cerium (Ce) doped, Manganese (Mn) doped, and Ce-Mn co-doped Barium Titanate (BaTiO3) with the general formula Ba1-xCexMnyTi1-yO3 were all synthesised by **Iqbal** *et al*. [22] in **2021**. The Ce-doped and Ce-Mn co-doped BaTiO3 have a cubic structure, according to X-ray Diffraction (XRD) research. However, the tetragonal-cubic mixed phases were confirmed by the undoped and Mn-doped BaTiO3. The locations of various peaks somewhat changed when the doping concentrations changed. Due to Mn's variable valency, the lattice parameter changed sporadically as the doping concentration increased. The J-V characteristic curves show that as the temperature rises, the doped and co-doped samples change from having a conducting to a semiconducting nature. The samples' dielectric constant rises with doping concentration, reaching a maximum of 4500. The co-doping of BaTiO3 with Ce and Mn is implied to be advantageous and cost-effective for its applications.
* In **2021**, **Manisha Kumari** *et al.* [23] synthesised Nd-doped BTS. Because the atomic radii of the atoms in the B site range in size, shrinkage in the lattice volume is seen as the Nd doping level is raised. While increased doping suppresses grain growth, doping of Nd initially accelerates it. The addition of Nd causes the typical ferroelectrics to change into relaxor-like ferroelectrics. After the doping of Nd, Ti's oxidation state did not change from +4 to +3, according to XPS. This demonstrates that the charge compensation in NBTS ceramics improves the dielectric properties by raising the dielectric constant and lowering the tangent loss. Consequently, it has the potential to be used as a dielectric material in devices such as capacitors for energy storage devices, UV detectors, photovoltaic applications, sensors, and actuators.
* By using applied strains to imitate those of PbTiO3, **Vaishali Shah** *et al.* [24] in **2023** show how the numerous properties of lead-free inorganic perovskite Ba0.5Sn0.5TiO3 are tuneable. BaTiO3 would be a promisingly powerful non-toxic alternative to lead zirconium titanates if its composition of Sn at the A-site and Zr as a B-site co-dopant were properly chosen. The optical and mechanical properties of Ba0.5Sn0.5TiO3 demonstrate a tuning possibility and a promising behaviour for energy applications in addition to the ferroelectric, structural, and electronic features.

Ferroelectric materials are a possible choice for energy storage and other applications due to their high dielectric constant, low dissipation factor, and high power density. BaTiO3-based ceramic materials, such as BaZrxTi1-xO3, BaSnxTi1-xO3, CaxBa1-xTiO3, etc., are mentioned as an attractive candidate among different ferroelectric materials because they now exhibit relatively high dielectric constant and low loss properties. BTS is a lead-free material that possesses high permittivity, a high dielectric constant that is depending on the field, and low loss characteristics, making it a possible candidate for use in a variety of applications such as capacitors in energy storage devices, dielectric resonator oscillators, actuators, phase shifters, etc.

Although there is a wealth of information about bulk BT capacitors, there haven't been many attempts to change the compositional engineering of BTS ceramics. It is fundamentally technologically interesting to synthesise barium titanate stannate nanoparticles with the right dopant, regulated size, and composition.

Due to their excellent use in microelectronic devices, ceramic materials have advanced recently. These materials have large dielectric constants for storage applications like capacitors and nanosized memory, while much lower dielectric constants can be used at high frequencies as a microwave absorber. The thermodynamics of the environment, such as temperature, pressure, and the quality of the materials used to build device components, affect how well microelectronic devices work.

It is vital to synthesize a material with properties that are stable throughout a broad temperature and frequency range to improve the overall performance of devices. Ceramics made from barium titanate (BaTiO3) have gained popularity in recent years due to their exceptional dielectric characteristics and diverse range of uses. BaTi1-xSnxO3 (BTSx) has recently gained a lot of attention, thanks to its use in capacitors, relaxors, and sensors, as well as its benefits of low internal stresses, affordable production, and the ability to design systems using materials without lead. The Curie temperature or dielectric maximum can be significantly changed by varying the tin content.

The permittivity is extremely high and temperature and bias field sensitivity are also present. As a result, it can be applied in many different ways, including as a capacitor, bolometer, actuator, microwave phase shifter, etc., variety of other applications, such as electrical transformers, liquid crystal displays, dielectric resonator oscillators, capacitors for energy storage devices, etc.

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