Original Article

Upside - down composites: Fabricating piezoceramics at room temperature

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\textbf{ABSTRACT}

Piezoelectric materials have a multi-billion dollar impact on the electromechanical transducers market. Their conventional synthesis includes a sintering step (at over 1000 °C) that often hampers direct integration into monolithic devices and confines their applications to heterostructures made using tedious multi-step assembly or to composites with poor electromechanical behavior. Here, we demonstrate a new and easy to scale method for the integration of piezoelectric ceramics at ultra-low temperatures without compromising their functionality. We show that all-ceramic “upside-down” composites with exceptionally high fractions of piezoelectric filler (75 vol. %) and low porosity can be achieved using aqueous dispersion of lithium molybdate as a binder. The method is based only on coating, mixing, moulding and drying sequences. The measured piezoelectric charge coefficient, \(d_{33} \approx 84 \text{ pC} \cdot \text{N}^{-1}\), outperforms any other known composite, whereas the voltage constant, \(g_{33} \approx 33 \text{ mV} \cdot \text{m}^{-1}\cdot\text{N}^{-1}\), competes with bulk materials, thus paving the way for versatile applications not previously considered.

\section{1. Introduction}

In recent decades a number of different piezoelectric materials have been explored including ceramics [1–5], polymers [6,7] and their composites [8–10]. Among these, owing to its outstanding electromechanical characteristics, lead zirconate titanate (PbZr\textsubscript{x}Ti\textsubscript{1-x}O\textsubscript{3} i.e. PZT) has been the most frequent choice of material for dynamic sensors (acceleration, force, stress and strain), actuators (motors, fluid injectors/dispensers, ultrasonic blenders and ultrasonic imaging systems and detection) and energy harvesters [11,12] and as such has had an enormous impact on daily life [1]. Piezoelectric ceramics are typically sintered at well above 1000 °C to reach their proper composition and structure, mechanical integrity and electromechanical functionality. Unfortunately, such high temperatures pose multiple practical challenges that seriously limit the direct integration of these materials. In the case of C-MOS and polymer based platforms, the low thermal budget and thermal coefficient mismatch are the major hurdles. On the other hand, unwanted inter-diffusion, solid-solid reactions, recrystallization and phase separation represent the problems when integration with metals or ceramics is required.

In an attempt to find alternative solutions to the problems associated with the high processing temperatures, additions of low temperature melting oxides [13–15] and glasses [16,17] were introduced to enable sintering at 600–800 °C [18]. The corresponding trade-off was that the typically large volume fraction of such additives seriously degraded the mechanical and/or piezoelectric properties [11,19]. Unfortunately, alternative materials such as piezoceramics based on polymers and polymer-ceramic composites, which could offer truly low temperature processing, have only a moderate functional performance and their mechanical properties differ greatly from those of ceramic materials [10,12,20,21].

Another approach for producing ceramic piezoelectrics at low temperatures is based on wet chemical reactions (also referred as soft solution processing), in which aqueous precursors are applied to form and deposit piezoelectric thin films on substrates by the means of electrochemical, sol-gel and hydrothermal reactions [22–27]. While a number of different thin film compositions have been demonstrated in the recent years, bulk materials with arbitrary shapes have not been synthesized.

Encouraged by the advantages of soft solution processing, the authors have recently developed a novel technology. In this technology, instead of synthesizing the functional inorganic materials, solution based processing is used to coat micro- and nanoparticles of ceramics with inorganic binders. The as-made nanocomposite is then wetted again by a saturated solution of the binder, applied to a mould, pressed (at 30–180 MPa) and dried (at 120 °C), thus facilitating the formation of a continuous two-phase ceramic filler and binder matrix at ultra-low temperature. Using lithium molybdenate (Li\textsubscript{2}MoO\textsubscript{4}) as the binder, functional all-ceramic composites have been produced with fillers such as TiO\textsubscript{2} and MnZn ferrite with very low pore volume fractions (10 vol.

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ti um titanate (BST) at room temperature, with an exceptionally high temperature manufacturing method for all-ceramic composites. Lithium molybdate (Li₂MoO₄) is applied as a binder to produce composites with an exceptionally high piezoelectricity. This enables an increased level of functional properties not previously shown for all-ceramic composites. This is due to the limited piezoelectric and mechanical coupling in traditional composites with low filler content (typically 10–40 vol.%). In this kind of “upside-down” composite, the amount of PZT is so high that it forms the matrix with only a small amount of LMO—hence the term “upside-down”. The novel ideas behind the fabrication method as well as the microstructure, dielectric and piezoelectric properties of the upside-down composite are presented.

2. Materials and methods

2.1. The methods for the room-temperature fabrication of all-ceramic composites of PZT-Li₂MoO₄ (PZT-LMO)

The fabrication of the all-ceramic composite is based on two separate factors. The first is the bimodal particle size distribution of the filler (PZT), which is generally known to enhance the packing ratio. The second factor is the use of an LMO aqueous solution as a liquid phase including LMO particles, which facilitates the rearrangement of the particles during pressing and ultimately binds the particles together. PZT was selected for the active material as it is a well-known piezoceramic and most of the previously fabricated composites have utilized this material.

The use of LMO to aid the densification of the PZT was first studied by coating the PZT particles in a similar fashion to that described in [19]. The ability of LMO to coat the PZT particles is shown in Fig. 2, which presents a TEM image of PZT particles with an approximately 20 nm thick layer of LMO. As with all the binder systems, the ability of the LMO solution to coat the functional particles uniformly is of a great importance.

2.2. PZT ceramic preparation

Commercial lead zirconate titanate powder (type PZ29, Meggit Ferroperm-piezoceramics, Denmark) was used as the piezoelectric filler in the experiments. In the used PZT powder, 90 wt.% of particles were sieved to particle size of 180–400 μm and 10 wt.% of particles were fine powder with an average particle size of 6 μm. The particle size for the fine powder was determined using a LS 13320 laser diffraction analyzer (Beckmann Coulter Inc.).

Precipitation of LMO from a water solution was utilized in the coating of the PZT particles. On the basis of the SSA value it was calculated that 0.654 g of LMO was needed to coat 10 g of PZT particles with a 20 nm layer of lithium molybdate. The required quantity of lithium molybdate was dissolved in 10 ml of deionized water after which 10 ml of 1,2-butanediol (> 98%, Fluka) was added. Finally, the PZT particles were added and the water content from the LMO solution was evaporated while constantly mixing, resulting in a precipitate of the lithium molybdate on the PZT particles. The temperature was increased to remove most of the butanediol from the slurry, resulting in a thick paste. To produce PZT particles coated with a thin layer of LMO, the remaining 1,2-butanediol was evaporated by spreading the paste evenly in a Petri dish and heating in a laboratory oven at 150 °C for 18 h.

2.3. Processing of PZT-LMO samples

Lithium molybdate Li₂MoO₄ powder (> 99%; AlfaAesar) was prepared by milling the raw material in a ball mill followed by sieving through a 25 μm screen. The sieved powder was then manually mixed together with the previously prepared PZT powder in a 1:9 vol ratio. One gram of the mixed powder was then dispersed in 0.5 ml of saturated aqueous solution of LMO and poured into a cylindrical steel mould (of 10 mm diameter) and pressed at 250 MPa in room temperature to produce disc-shaped pellets. After pressing, the samples were weighed with a precision balance and then dried in a desiccator in room temperature for 48 h. Alternatively, to speed up the process, the drying was done in a laboratory oven at 120 °C for 18 h. After drying, the samples were weighed again to calculate the amount of vaporized water in order to estimate the quantity of additional LMO from the saturated solution. The dimensions of the disc were measured by a micrometer screw gauge for the density calculations. The sample preparation is schematically illustrated in Fig. 1.

2.4. Assessment of microstructure

Coated particles were examined using scanning transmission electron microscopy (STEM). The STEM images were obtained using a FEI Tecnai G2 F20 transmission electron microscope. The samples were prepared by dispersing the coated particles in water and drop-casting them onto a carbon-coated copper grid. The grid was then dried in a vacuum oven at 120 °C for 2 h. The resulting micrographs were analyzed using the ImageJ software to determine the size and shape of the particles. The micrographs also revealed the presence of nanocrystals within the particles, which is indicative of the high-quality material used in this study. The micrographs also showed the presence of a second phase, which is likely to be the lithium molybdate coating.

Fig. 1. Sample preparation. Left: FESEM image of traditional ceramic composite material with 25 vol-% of PZT (white spots) in LMO (gray material) Scale bar: 100 μm. Middle: (a) sintered, crushed and screened PZT particles, (b) native PZT particles (c) milled lithium molybdate powder filtered through 25 μm screen (d) schematic of pressure-assisted densification, excess lithium molybdate solution flows out from perimeters of piston densifying the pellet. (e) Dried and densified disc and (f) densified disc with screen-printed silver electrodes. Right: FESEM image of Upside-down ceramic composite material with 75 vol-% of PZT (white areas) in LMO (gray areas) Scale bar: 100 μm.
electron microscopy (JEOL JEM-2200FS 200 kV analytical STEM, JEOL USA Inc, USA). The microstructure of the composite was assessed using field emission scanning electron microscopy (FESEM, Zeiss Sigma, Carl Zeiss SMT AG) on cross-sectioned and polished specimens. Before FESEM analysis, a thin layer of carbon was sputtered on the polished surface to avoid charging effects.

2.5. Electrical characterization

Dielectric properties at room-temperature were measured with a LCR meter (Hewlett-Packard 4284 A, Agilent Technologies, USA). For dielectric and ferroelectric measurements thick film silver ink electrodes were screen printed (DuPont 5064H, DuPont Microcircuit Materials, Research Triangle Park, NC) on both sides of the discs and cured at 120 °C for 20 min. Ferroelectric measurements (up to 2 kV/mm electric fields) were performed at 24 °C using a ferroelectric tester (Precision 10 kV HVI-SC, Radiant Tech., USA). The waveform used in the measurements was a standard bipolar triangle at a frequency of 10 Hz. The maximum electric field that could be applied to the samples without breakdown at the edges was ~2.5 kV/mm. As a comparison, a commercial PZ29 disc shaped sample (Meggitt Ferroperm-piezo-ceramics, Denmark) was also analyzed with ferroelectric tester. The piezoelectric coefficient $d_{33}$ of each sample was measured after poling in a 2 kV/mm electric field for 1 h. The samples were shorted after poling and the measurement was performed after one week. Two measurement methods were used. In the first method, the direct piezoelectric effect was measured using a $d_{33}$ meter (Piezo $d_{33}$ Test System, APC International, Ltd.). The sample was clamped between cone shaped probes and an alternating force of 0.25 N at 110 Hz was applied. In the other measurement method, the converse piezoelectric effect was used. A sinusoidal AC signal was applied to the samples and the change of thickness was monitored using a laser-doppler vibrometer (OFV-552 measuring probe, Polytech GmbH, Germany).

3. Results and discussion

3.1. Electron microscopy analysis

Transmission electron microscope analysis was carried out to inspect the LMO-coated PZT particles. The particles were coated with a LMO layer with ~20 nm thickness (Fig. 2, top). LMO layer could be observed as a semi-transparent layer on the particles, confirmed with elemental mapping revealing molybdenum. This indicated good wetting ability of the PZT particles with LMO solution which was observed in further studies to enhance both the electrical and mechanical properties of produced samples.

The high packing density of the PZT particles was confirmed by scanning electron microscopy analysis of cross-sectioned composites (Fig. 2, bottom). The microstructure showed a uniform distribution of large PZT particles with a close proximity and surrounded by LMO phase. In the close-up image the small PZT particles and the LMO phase surrounding the large particles could also be detected. The bimodal size distribution of the PZT particles and their coating thus clearly enabled the minimization of the amount of dielectric binder maximizing the amount of piezoelectric material. The composition was measured to be 75.1 ± 0.7 vol.% PZT, 14.5 ± 0.4 vol.% LMO and 10.4 ± 0.8 vol.% voids.

3.2. Dielectric measurements

The relative permittivity ($\varepsilon_r$) and the dielectric loss tangent (tan $\delta$) measured between 100 Hz and 1 MHz on un-polled samples decreased...
with increasing frequency from ~250 to ~200 and 0.10 to 0.02, respectively with ± 5% tolerance between various samples (Fig. 3a). The measured frequency dependence of permittivity and loss is typical for ceramics showing the relaxation of different polarization mechanisms [36]. However, the nearly 50% of drop of permittivity was due to the high local dielectric variation in the composite. The relative permittivity of Li2MoO4 (at 1 MHz from a sample made in [29]) was 7.34, which is less than a percent of the value for bulk PZT29. When an electric field is applied, the interfaces can accumulate charges resulting in polarization in the composite [37] which cannot follow the AC field at higher frequencies, thus causing the permittivity to drop according to the Maxwell-Wagner-Sillars model [38]. Furthermore, the increased relative permittivity and loss tangent (Fig. 3b) with temperature indicated an increased conductivity with some anomalies detected at higher frequencies around at 250°C. This can be accounted for by the ferroelectric-to-paraelectric phase transition in PZT (Curie temperature, Tc, is 235 °C) [39].

Compared to the bulk PZT29, the relative permittivity of the poled PZT-LMO composite was an order of magnitude lower at 1 kHz [39]. Because the temperature in the synthesis was as low as room temperature, it is reasonable to compare the results with those of materials made under similar conditions, such as polymer or cement. Among these materials, the PZT-LMO has one of the highest values for permittivity (~290, at 1 kHz, poled samples) and one of the lowest dielectric losses (0.05, at 1 kHz, poled samples) (see Table 1) as a result of higher fill content and low loss value [29] of the binder material itself.

3.3. Ferroelectric and piezoelectric measurements

As expected, ferroelectric hysteresis loops (inset of Fig. 4a) measured at various applied voltages (at room temperature) showed a more pronounced hysteresis as well as higher remanent polarization and coercive fields with increasing applied voltage (and thus electric field). The remanent polarization of the composite after application of a 2.0 kV/mm electric field was 0.8 μC/cm² (with ± 7% variation between different samples), which is ~10% of the value measured for commercial PZT29 ceramics. These results are in excellent agreement with those obtained from dielectric measurements which also showed 10% of the bulk PZT29 values. Accordingly, it was concluded that the applied electric field coupled very well with the piezoelectric particles in the PZT-LMO composite, presumably because of the high packing density of the filler. Saturation of the remanent polarization could not be reached in the measurements because of an electrical flash-over observed at the edge of the samples with an applied field of ~2.5 kV/mm. It should be noted that such an electric field is already at the level utilized in the poling of typical bulk PZT compositions [40] and single crystals [41].

Piezoelectric measurements were carried out after poling the composite samples in a DC field of 2.0 kV/mm for 1 h at room temperature (7 days after the poling). The piezoelectric charge coefficient d can be calculated from the direct (1) and converse (2) piezoelectric effects as 

\[ d_{33} = \frac{\Delta P}{\Delta E} \approx \frac{\sigma}{E} \]

where D is electrical displacement, S is stress, E is electric field, g is the piezoelectric voltage coefficient and \( \varepsilon \) is the permittivity of the material. The index \( k \) denotes the direction component of \( D \) or \( E \), whereas \( m \) defines the direction of the mechanical stress or strain. The measured piezoelectric coefficient \( d_{33} \) (Fig. 4a) was at its highest at 10 Hz, exhibiting 105 pm/V (with ± 15% variation between samples) and decreased to 82 pm/V at 480 Hz (with ± 6% variation between samples). The frequency dependence of \( d_{33} \) was similar to that measured for the dielectric properties (Figs. 3 and 4a), i.e. the coupling of the field with the material was better at lower frequencies. It is worth noting that, due to the noise in the low frequency measurements, the standard deviation of \( d_{33} \) parameter for different samples was somewhat higher (± 15%).

The electromechanical displacement (Fig. 4b) showed a linear dependence on the applied voltage with a positive \( d_{33} \) coefficient indicating that the response was solely due to the piezoelectric effect and electrostriction did not play any significant role. Furthermore, when an alternating electrical field was applied, it was found that the displacement followed the field with almost exactly the same phase, thus providing additional evidence of piezoelectric actuation (inset of Fig. 4b) and ruling out artifacts such as interference or resonance.

To place the data in a broader context, it is worth to compare the measured electrical and electromechanical properties of the new composite with a variety of available piezoelectrics, including single and polycrystalline materials, organics and various composites (Table 1, Fig. 5). [12,14,15,17,20,21,34,39,42-51] Considering the piezoelectric

**Table 1**

<table>
<thead>
<tr>
<th>Compound</th>
<th>( \varepsilon_r ) (1 kHz)</th>
<th>( \tan \delta ) (1 kHz)</th>
<th>( d_{33} ) (pc/N)</th>
<th>( g_{33} ) (mV/m/N)</th>
<th>Fabric. T. (°C)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT29</td>
<td>2,900</td>
<td>0.019</td>
<td>575</td>
<td>22</td>
<td>1,280</td>
<td>[39]</td>
</tr>
<tr>
<td>PZT-LMO</td>
<td>290</td>
<td>0.051</td>
<td>84</td>
<td>33</td>
<td>22</td>
<td>this study</td>
</tr>
<tr>
<td>PC-PZT0.5-PVF0.5%</td>
<td>105</td>
<td>0.25</td>
<td>24</td>
<td>26</td>
<td>60</td>
<td>[48]</td>
</tr>
<tr>
<td>PC-PZT0.8 nano</td>
<td>131</td>
<td>-</td>
<td>54</td>
<td>46</td>
<td>60</td>
<td>[49]</td>
</tr>
<tr>
<td>PC-PZT0.5 620μm</td>
<td>176</td>
<td>0.79</td>
<td>26</td>
<td>17</td>
<td>60</td>
<td>[50]</td>
</tr>
<tr>
<td>PC-PZT0.5</td>
<td>300</td>
<td>-</td>
<td>55</td>
<td>21</td>
<td>65</td>
<td>[51]</td>
</tr>
<tr>
<td>PVDF-PZT0.7 cp</td>
<td>47</td>
<td>-</td>
<td>41</td>
<td>99</td>
<td>22</td>
<td>[46]</td>
</tr>
<tr>
<td>PVDF-PZT0.8 hp</td>
<td>70</td>
<td>-</td>
<td>50</td>
<td>150</td>
<td>46</td>
<td>[46]</td>
</tr>
<tr>
<td>PVDF-PZT + CNTO.8%</td>
<td>112</td>
<td>0.71</td>
<td>38</td>
<td>38</td>
<td>120</td>
<td>[21]</td>
</tr>
<tr>
<td>PDMS-PZT0.5</td>
<td>38</td>
<td>0.018</td>
<td>25</td>
<td>74</td>
<td>110</td>
<td>[47]</td>
</tr>
<tr>
<td>PVDF</td>
<td>12-15</td>
<td>0.018</td>
<td>-22</td>
<td>207</td>
<td>120</td>
<td>[12,20]</td>
</tr>
<tr>
<td>PNZ 001 sc</td>
<td>3,600</td>
<td>0.0008</td>
<td>1,100</td>
<td>35</td>
<td>1,200</td>
<td>[44]</td>
</tr>
<tr>
<td>PNZ 111 sc</td>
<td>900</td>
<td>0.012</td>
<td>83</td>
<td>10</td>
<td>1,200</td>
<td>[44]</td>
</tr>
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<td>KNN + ZnO</td>
<td>652</td>
<td>0.033</td>
<td>117</td>
<td>20</td>
<td>1,100</td>
<td>[14]</td>
</tr>
<tr>
<td>BNT + Mn0.1%</td>
<td>140</td>
<td>-</td>
<td>13</td>
<td>13</td>
<td>1,100</td>
<td>[43]</td>
</tr>
<tr>
<td>PZT + 4PbO3</td>
<td>1,050</td>
<td>0.018</td>
<td>340</td>
<td>37</td>
<td>1,000</td>
<td>[17]</td>
</tr>
<tr>
<td>PZT-SKN + LB + CuO</td>
<td>1,235</td>
<td>0.003</td>
<td>415</td>
<td>38</td>
<td>900</td>
<td>[15]</td>
</tr>
<tr>
<td>PSZT + PbTiO3-BZT-BF</td>
<td>760</td>
<td>0.007</td>
<td>241</td>
<td>36</td>
<td>1,050</td>
<td>[44]</td>
</tr>
<tr>
<td>PZT prw</td>
<td>1,600</td>
<td>0.003</td>
<td>420</td>
<td>30</td>
<td>1,100</td>
<td>[42]</td>
</tr>
<tr>
<td>PZT, cs + 700 °C (^2)</td>
<td>917</td>
<td>0.027</td>
<td>80</td>
<td>10</td>
<td>700</td>
<td>[34]</td>
</tr>
</tbody>
</table>

1 \( d_{33} \) measured with vibrometer at 110 Hz, PC = Portland cement, PZT = PbZr\(_{0.5}\)Ti\(_{1-x}\)O\(_{3}\), PVDF = poly(vinylidene fluoride), nano = nanoparticles, cp = cold-pressed, hp = hot-pressed, CNT = carbon nanotube, PDMS = poly(dimethyl siloxane), PNZ = Pb(Zn, Nb)O\(_3\), sc = single crystal, KNN = (K,Na)NbO\(_3\), BNT = (Bi,Na)TiO\(_3\), SKN = Sr(K,Na)O\(_3\), LB = LiBiO\(_2\), BZT-BF = Bi(Zn, Ti)O\(_3\) - BiFeO\(_3\), PSZT = PbSrZr\(_{0.5}\)Ti\(_{1-x}\)O\(_3\), μ\(\nu\) = microwave sintered.

2 \( d_{33} \) cold sintered (cs) and annealed.
charge coefficient, which describes the ability of a material to convert mechanical force or displacement into electrical charge or voltage and vice versa, the new composite outperformed any other composites with its \( d_{33} \) value 84 pC/N\(^{-1}\). Only bulk ceramics and single crystals have a higher \( d_{33} \) coefficient.

However, in order to estimate the potential of any piezoelectric material for sensor applications it is necessary to evaluate the piezoelectric voltage coefficient (\( g_{33} \)) which indicates the ability of the material to generate an electric field upon a mechanical input (stress). It is defined as \( g = \frac{d}{\varepsilon} \), where \( d \) is the piezoelectric charge coefficient and \( \varepsilon \) is the permittivity of the material. The \( g_{33} \) of the low-temperature all-ceramic composite was \(33\) mV mN\(^{-1}\), which is higher or similar level to that of most of the bulk materials, but lower than that of some of the polymer based composites or pure PVDF. This is due to the very high PZT loading causing a high effective permittivity. It should be noted that only polymers or composites based on polymers or cements are processed at similarly low temperatures, while almost all the other materials are prepared above 1000 °C. [42] Also it should be kept in mind that the depolarization temperatures and melting temperatures of PVDF based materials (\( T_c \) from \(65\) to \(140\) °C, melting around \(150\) °C) restrict their usage [12,20]. Taking these into account, the fabricated novel upside-down composite is competitive in many cases.

Piezoelectric \( d_{33} \) is divided with the fabrication temperature (in Kelvin) of the compound thus showing piezoelectric activity with perspective about the energy used in process. Although some single crystals (green) and bulk ceramics (red) show high \( d_{33} \) per temperature ratios, the novel upside-down composite is competitive in many cases. Furthermore, it easily outperforms all other composites (blue) and PVDF (purple), since it is having the highest \( d_{33} \) and lowest fabrication temperature among these materials.

4. Conclusions

This paper has introduced the first all-ceramic piezoelectric composite material realized at room temperature and exhibiting clear piezoelectric response. Simple and industrially benign low-temperature process suitable for the production of all-ceramic composites was demonstrated using lead zirconate titanate particles with bimodal size distribution as a filler and aqueous lithium molybdate as a binder. The approach enables extremely high filler loading (75 vol.%) and relatively low porosity (10 vol.% of the composite, which results in high piezoelectric charge and voltage coefficients (\( d_{33} = 84\) pC/N\(^{-1}\) and \( g_{33} = 33\) mV mN\(^{-1}\), respectively). The results reported here are expected to pave the way for new types of integrated piezoelectric devices, and to prompt further studies towards other filler-ceramic systems with ultra-high volume fractions of the functional material.

Data availability

The data supporting the results reported in the article are available from the corresponding author on request.

Competing financial interests

The authors declare no competing financial interests.

Acknowledgements and author Contributions

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H.J., H.K. and M.N. conceived the idea for the fabrication method. J.J. conceived the hypothesis and fundamental perspectives of
piezoelectrics and the required measurements. M.N. fabricated the samples. Electrical properties were measured by M.N. and T.S. Electromechanical properties were measured and analyzed by T.S. Crystal structure and microstructure were measured and studied by H.K., M.N. and T.S. K.K. made overall assessment of the work and results and their revisions. All the authors took part in analyzing the data and writing the manuscript. H.J. K.K. and J.J. supervised the work and the validity of the data and its interpretation.

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