

Sm 掺杂量对 $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ 弛豫铁电体场诱应变 温度稳定性的影响

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摘 要: $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ (PMN-PT)弛豫铁电材料因场诱应变大且滞后小而成为制备微位移致动器的优选材料, 然而场诱应变的温度依赖性阻碍了其进一步发展。针对这一问题, 以两步氧化物固相反应法制备了不同 Sm 掺杂量的 PMN-0.32PT 陶瓷, 研究了掺杂量对场诱应变温度稳定性的影响。结果表明, Sm^{3+} 的掺入打破了晶格的长程有序, 增大了微区化学成分的不均匀性, 宏观上表现出强烈的介电频率色散, 大量纳米畴及极性纳米区域的出现使样品展现出大场诱应变和高温度稳定性。受 PMN 弥散相变影响, 温度低于 -15°C 场诱应变很小, 高于 -15°C 场诱应变迅速增大。在 1 kV/mm 单向电场驱动下, $x=0.040$ 样品的径向场诱应变在 $-10\sim+50^\circ\text{C}$ 间高达 4.2×10^{-4} , 变化率小于 3.8%, 滞后小于 13.1%, 展现出良好的应用前景。

关键词: 弛豫铁电体; 铌镁酸铅-钛酸铅; 场诱应变; 温度稳定性; 钐掺杂

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微位移致动器在微机械加工、精密测量、航空航天、生物医学等领域具有广泛用途^[1-3]。微位移执行器性能的优劣可以从位移、迟滞、线性度和温度稳定性等方面来评价。如何提高微位移执行器的位移和定位精度一直是研究热点。相比于磁致伸缩^[4]、形状记忆合金^[5]等不同类型致动器材料, 以强压电性铁电材料为核心的微位移致动器因驱动力大、响应速度快、体积小、结构简单、抗电磁干扰等优势而极具吸引力^[6-8]。长久以来, 研究人员一直希望能获得一种场诱应变大、迟滞小、成本低且温度稳定性好的铁电材料, 以满足各种不同应用场合的需求。

$\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ (PMN)是一种典型的钙钛矿结构 B 位弛豫铁电体^[9], 与 PbTiO_3 (PT)反应生成的 PMN-PT 固溶体在 PT 摩尔分数为 0.27~0.35 之间存在一个准同型相界区(MPB)^[10]。PT 含量 ≤ 0.27 和 ≥ 0.35 时, 晶相结构分别为伪立方和四方; PT 含量介于 0.27 和 0.35 之间, 晶相结构复杂, 一般认为存在三方、单斜、正交、四方及其混合相。1980 年,

Cross 等报道 PMN-0.1PT 陶瓷在 2.5 kV/mm 下的应变可达 10^{-4} 量级^[11]。1995 年, Zhao 等研究发现 PMN-0.28PT 陶瓷在 1 kV/mm 下的应变达到 1.5×10^{-3} ^[12]。1997 年, Park 等报道 $\langle 001 \rangle$ 取向三方弛豫铁电单晶在 1.5 kV/mm 下场诱应变 $> 0.2\%$ ^[13]。显然, PMN-PT 是一种非常有力潜力的铁电材料, 从场诱应变和滞后角度进行分析, 其场诱应变特性可满足高性能微位移执行器的要求。然而, PMN-PT 在实际应用前仍需要解决一个关键问题: 场诱应变的温度稳定性。研究表明, 弛豫铁电体的场诱应变具有很强的温度依赖性, 场诱应变在退极化温度(T_d)处通常表现出最大值, 在 T_d 以上急剧下降^[12]。因此, 开发具有大场致应变且具有良好温度稳定性和低滞后的铁电陶瓷将是一项极具价值的工作。近年来, Li 等^[14]通过引入稀土元素 Sm^{3+} 增大化学组成的不均匀性, 获得了压电电荷系数(d_{33})高达 1500 pC/N 的改性 PMN-PT 陶瓷。更重要的是, 在 0.2 kV/mm 电场驱动下, 2.5%Sm 掺杂 PMN-0.31PT 陶瓷在 $0\sim+90^\circ\text{C}$ 间的场诱应变变化率为 11%, 使 Sm 掺杂

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PMN-PT 陶瓷有望成为一种不但场诱应变大、滞后小而且温度稳定性好的铁电陶瓷材料^[14]。本工作制备了一系列不同 Sm^{3+} 掺杂量的 PMN-0.32PT 陶瓷, 研究了 Sm^{3+} 掺杂量对场诱应变温度稳定性的影响。

1 实验

1.1 样品制备

以氧化物粉体 Nb_2O_5 (分析纯)、 $(\text{MgCO}_3)_4\cdot\text{Mg}(\text{OH})_2\cdot 5\text{H}_2\text{O}$ [98% (质量分数)]、 Sm_2O_3 (99.99%)、 PbO (分析纯) 和 TiO_2 (分析纯) 为原料, 采用两步固相反应法制备 $\text{Pb}_{1-1.5x}\text{Sm}_x[(\text{Mg}_{1/3}\text{Nb}_{2/3})_{0.68}\text{Ti}_{0.32}]\text{O}_3$ ($x\text{Sm-PMN-0.32PT}$, $x=0$ 、0.020、0.030、0.035、0.040、0.045、0.050)。第一步, 按正化学计量比精确称量 Nb_2O_5 和 $(\text{MgCO}_3)_4\cdot\text{Mg}(\text{OH})_2\cdot 5\text{H}_2\text{O}$ 粉体, 行星球磨 2 h 后在 1200 °C 煅烧 6 h 合成 MgNb_2O_6 前驱体; 第二步, 将 MgNb_2O_6 前驱体与 Sm_2O_3 、 PbO 和 TiO_2 粉体按正化学计量比称量, 行星球磨 2 h 后在 900 °C 煅烧 4 h。为补偿 Pb 高温挥发损失, 额外添加 0.3% (质量分数) PbO 。随后, 将煅烧粉体与聚乙烯醇(PVA)黏合剂混合造粒, 压制成 $\phi 13\text{ mm}\times 1\text{ mm}$ 圆片生坯后排胶。最后, 将排胶后的生坯样品置于密封氧化铝坩埚中在 1250 °C 烧制 2 h。所获陶瓷圆片上下表面被上 Ag 浆后, 在 750 °C 煅烧 15 min。极化时, 将被 Ag 样品置于硅油槽中, 室温下施加 1 kV/mm 直流电场保持 10 min。电学性能测试待极化样品在室温下放置 24 h 后进行。

1.2 样品表征

用 PANalytical X'Pert3 型 X 射线粉末衍射仪 (XRD) 测定室温下未极化样品的晶体结构, 测试条件: Cu 靶, 步长 0.033°, 停留时间 0.5 s。用 ZJ-3 型准静态 d_{33} 测试仪获取室温下的压电电荷系数 d_{33} 。用 Precision Premier II 型铁电测试仪进行铁电性能测试, 激励信号为双向三角波电场, 电场强度为 1 kV/mm, 测试频率为 1 Hz。用 TH2816A 型 LCR 数字电桥测试样品的介电温谱, 测试频率为 1、5 kHz 和 50 kHz。用 ZX80A 型阻抗分析仪测试样品的径向谐振频率(f_r)和反谐振频率(f_a), 视 $(f_a-f_r)/f_r$ 趋于零时的温度为退极化温度 T_d ^[15]。用 MDS 微位移表驱动的 LVDT 线性可变差动变压器探头和 Keithley 2410 型源表进行单极性径向场诱应变测试, 驱动电场为 1 kV/mm, 测试频率为 0.01 Hz。用 GZ-ESPEC MC710P 型超低温环境试验箱提供实验过程中的温

度环境, 温度范围和升温速率分别为 -50~130 °C 和 1 °C/min。

2 结果与讨论

2.1 物相分析

图 1 为 $x\text{Sm-PMN-0.32PT}$ 未极化样品室温下的 XRD 谱。由图 1a 可见, 所有样品的主晶相均为钙钛矿相结构, $2\theta=30^\circ$ 附近微弱的衍射峰表明, $x=0.040$ 、0.045 和 0.050 样品含有少量烧绿石相, 衍射峰与卡片为 JCPDS #40-828 相对应, 化学式为 $\text{Pb}_2\text{Nb}_2\text{O}_7$, 含量(体积分数)分别为 2.95%、3.62% 和 3.96%。由参照文献[14]可知, Sm^{3+} 烧结后将取代 Pb^{2+} 进入 A 位, 随着 Sm^{3+} 掺入量 x 增大, 所有衍射峰均向低角度方向移动。若晶胞为立方结构, $2\theta=38.8^\circ$ 和 $2\theta=45.2^\circ$ 处的衍射峰应为左右对称的单峰; 若晶胞为菱方结构, 38.8° 峰将分裂为 (111) 和 (-111) 双峰, 45.2° 峰为左右不对称 (200) 单峰; 若晶胞为四方结构时, 38.8° 峰为 (111) 单峰, 45.2° 峰将裂解为 (002) 和 (200) 双峰^[16]。由局部放大衍射谱 (图 1b) 可见, (111) 和 (200) 衍射峰轮廓变化清晰。 $x=0.020$ 时, 38.8° 和 45.2° 处衍射峰均出现 1 个小肩。随着 x 增大, 38.8° 衍射峰裂解更加明显, 45.2° 处衍射峰裂解逐渐减弱。至 $x=0.050$, 38.8° 处的 (111) 和 (-111) 峰清晰可辨, 而 45.2° 处衍射峰 (200) 的小肩 (002) 峰已很弱。依照 PMN-PT 相图^[17], 所有样品的化学组成均处于 MPB 区域, 为菱方 R 、单斜 M_C 、单斜 M_B 、四方 T 混合相; x 增大, MPB 向富 PMN 方向移动。同时, 由图 1b 可见, 各衍射峰的强度随 Sm^{3+} 掺入量增大逐渐减弱, 表明化学组成的微区起伏增大, 晶格排列的有序化程度降低, 结果与 Li 等报道结果一致^[14]。

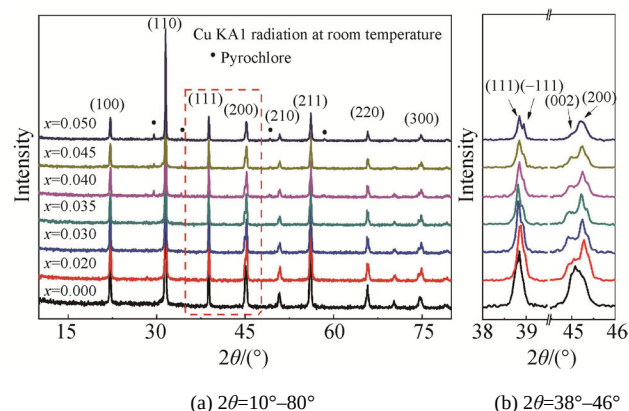


图 1 $x\text{Sm-PMN-0.32PT}$ 未极化样品室温下的 XRD 谱
Fig. 1 XRD patterns of $x\text{Sm-PMN-0.32PT}$ unpoled samples at room temperature

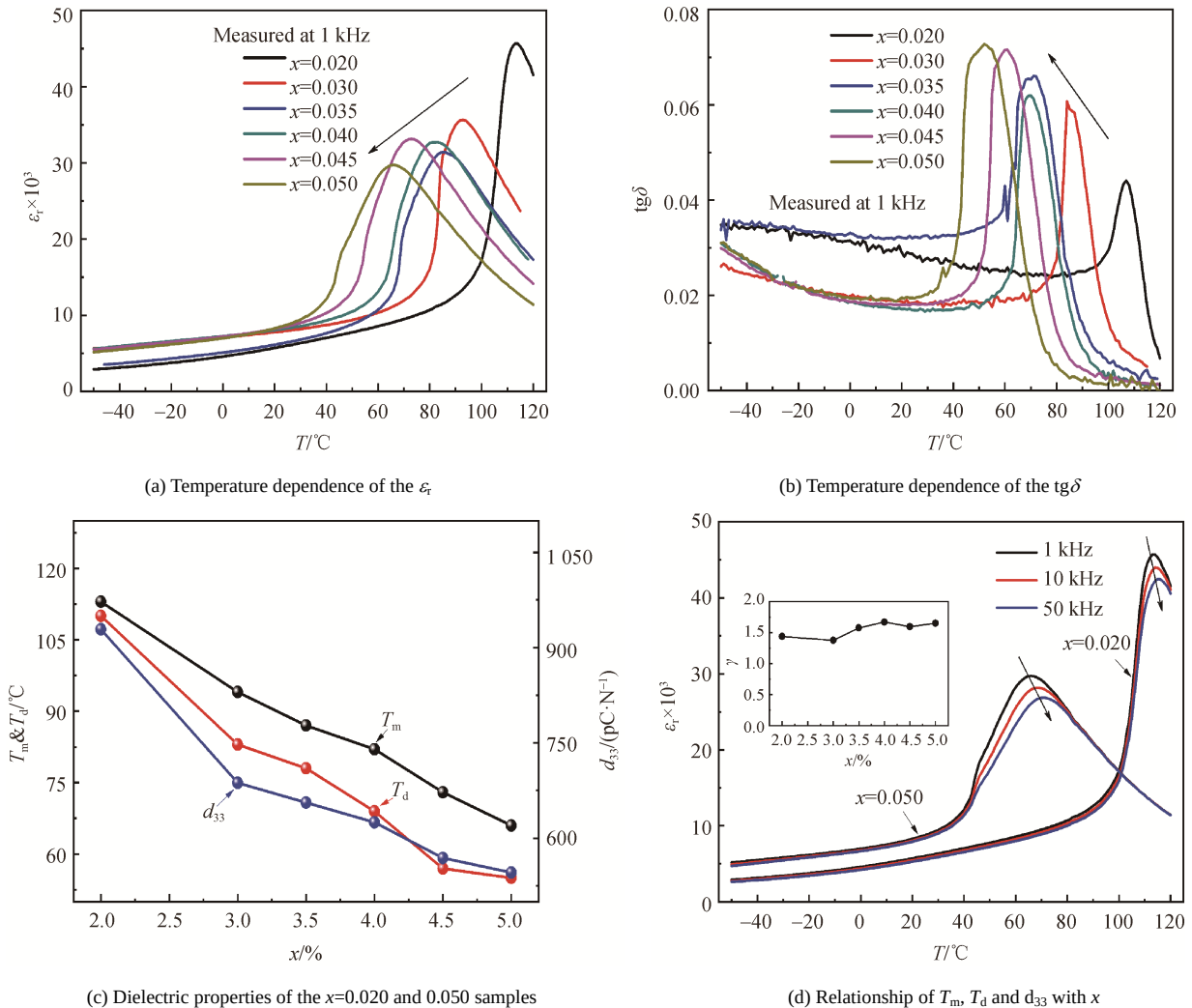
2.2 介电和压电性能分析

图2为 $x\text{Sm-PMN-0.32PT}$ 极化样品的介电和压电性能。由图2a和图2b可见,在1 kHz下,随着 Sm^{3+} 掺入量 x 增大,最大相对介电常数 ε_{r-m} 减小,最大介电损耗 $\text{tg}\delta_m$ 增大, ε_r 和 $\text{tg}\delta$ 峰展宽, ε_{r-m} 温度(T_m)移向低温。用修正后的 Curie-Weiss 关系式(1)对温度高于 T_m 的介电响应进行拟合。

$$1/\varepsilon_r - 1/\varepsilon_{r-m} = (T - T_m)^\gamma / C \quad (1)$$

其中: ε_r 为 T 对应的介电常数; ε_{r-m} 为 T_m 对应的介电常数; C 为 Curie-Weiss 常数; γ 为弥散系数, $1 \leq \gamma \leq 2$ 。随 x 增大弥散系数 γ 略微增大,在拟合误差 $R > 0.995$ 条件下 $1.374 \leq \gamma \leq 1.67$ (图2c插图);随着频率升高, ε_r 峰移向高温,频率色散随 x 增大明显增强(图2c)。对于 $x=0.020$ 和 0.050 样品,1 kHz和50 kHz条件下的 T_m 差值分别为 1°C 和 5°C 。比

较 T_m 和 T_d 并测试 d_{33} 随 x 的变化,可见随 x 增大, T_m 近似线性地减小, T_m 与 T_d 差值起始增大,其后相对稳定, d_{33} 由 $x=0.020$ 时的 929 pC/N 减小至 $x=0.050$ 时的 546 pC/N (图2d)。以上结果表明:所有样品均为弛豫铁电体, Sm^{3+} 的掺入增大了微区成分起伏,形成的铅空位等缺陷打破了晶格的长程有序,致使样品在 T_d 温度之下存在大量纳米畴及极性纳米区域(PNRs),自发极化强度矢量更易为外力场或外电场转向^[18–22]。此时,畴转产生的本征压电性占优,畴壁移产生的非本征压电性为辅, $x=0.02$ 样品的 d_{33} 远高于 PMN-PT 陶瓷最高值(720 pC/N)^[23]。随 x 增大 d_{33} 单调地减小。 d_{33} 减小的内在机制有2种可能性:一是 Sm^{3+} 掺入产生的无自发极化强度晶格畸变区域增大;二是受温度扰动自发极化强度重新紊乱取向的纳米畴或 PNRs 区域增大。



x —Mole fraction. ε_r —Dielectric constant. $\text{tg}\delta$ —Dielectric loss. T_m —Temperature corresponding to ε_{r-m} at 1 kHz. ε_{r-m} —Maximum value of the ε_r . T_d —Depolarization temperature. d_{33} —Piezoelectric coefficient.

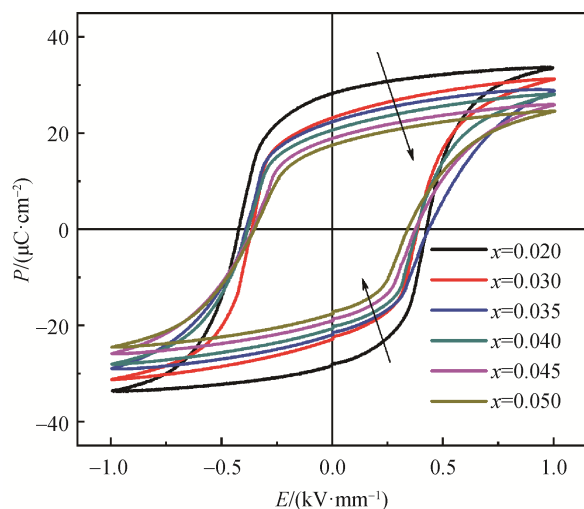
图2 $x\text{Sm-PMN-0.32PT}$ 极化样品的介电和压电性能

Fig. 2 Dielectric and piezoelectric properties of $x\text{Sm-PMN-0.32PT}$ poled samples

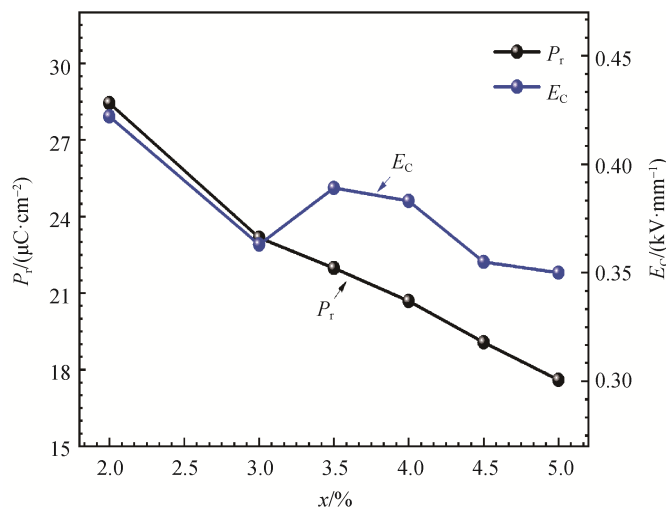
2.3 铁电性能分析

图 3 为 $x\text{Sm-PMN-0.32PT}$ 样品室温下的铁电性能。由图 3a 可见, 所有样品均展现出典型的铁电体电滞回线形状, 最大极化强度($P_{\max}$)随 x 增大单调减小, 证实了上述第 1 种可能性的存在。随着 x 的增

大, 剩余极化强度(P_r)单调减小, 由 $x=0.020$ 时 $28.4 \mu\text{C}/\text{cm}^2$ 大幅减小至 $x=0.050$ 时的 $17.6 \mu\text{C}/\text{cm}^2$, 矫顽电场(E_c)除 $x=0.030$ 外也呈现单调减小趋势(图 3b), 证实了第 2 种可能性的存在。至于 $x=0.030$ 奇异点出现的原因尚不明确, 推测与相组成相关。



(a) P - E curves



(b) Relationship of P_r and E_c with x

x —Mole fraction. P_r —Remanent polarization. E_c —coercive field.

图 3 $x\text{Sm-PMN-0.32PT}$ 样品室温下的铁电性能

Fig. 3 Ferroelectric properties of $x\text{Sm-PMN-0.32PT}$ samples at room temperature

2.4 场诱应变性能分析

图 4 为 $x\text{Sm-PMN-0.32PT}$ 未极化样品的场诱应变曲线。由于 LVDT 的限制, 测试温度设定在 $-55\sim+60\text{ }^\circ\text{C}$ 间。由图 4a 可见, 所有样品低温下的 S_m 均很小, 但随着温度升高至 $-10\text{ }^\circ\text{C}$ 附近迅速增大; $x=0.030\sim 0.045$ 样品在 $-10\sim+60\text{ }^\circ\text{C}$ 间的 S_m 温度稳定性明显好于 $x=0.020$ 和 0.050 样品; $x=0.030$ 和 0.040 样品在 $-10\sim+60\text{ }^\circ\text{C}$ 间 S_m 相对较大。比较 $x=0.030$ 和 0.040 样品的场诱应变曲线, 可见 $x=0.040$ 样品 $-10\sim+60\text{ }^\circ\text{C}$ 间的 S_m 温度稳定性明显好于 $x=0.030$ 样品(图 4b~图 4d)。用以下 2 个公式计算的 S_m 变化率(V)和场诱应变滞后(H),

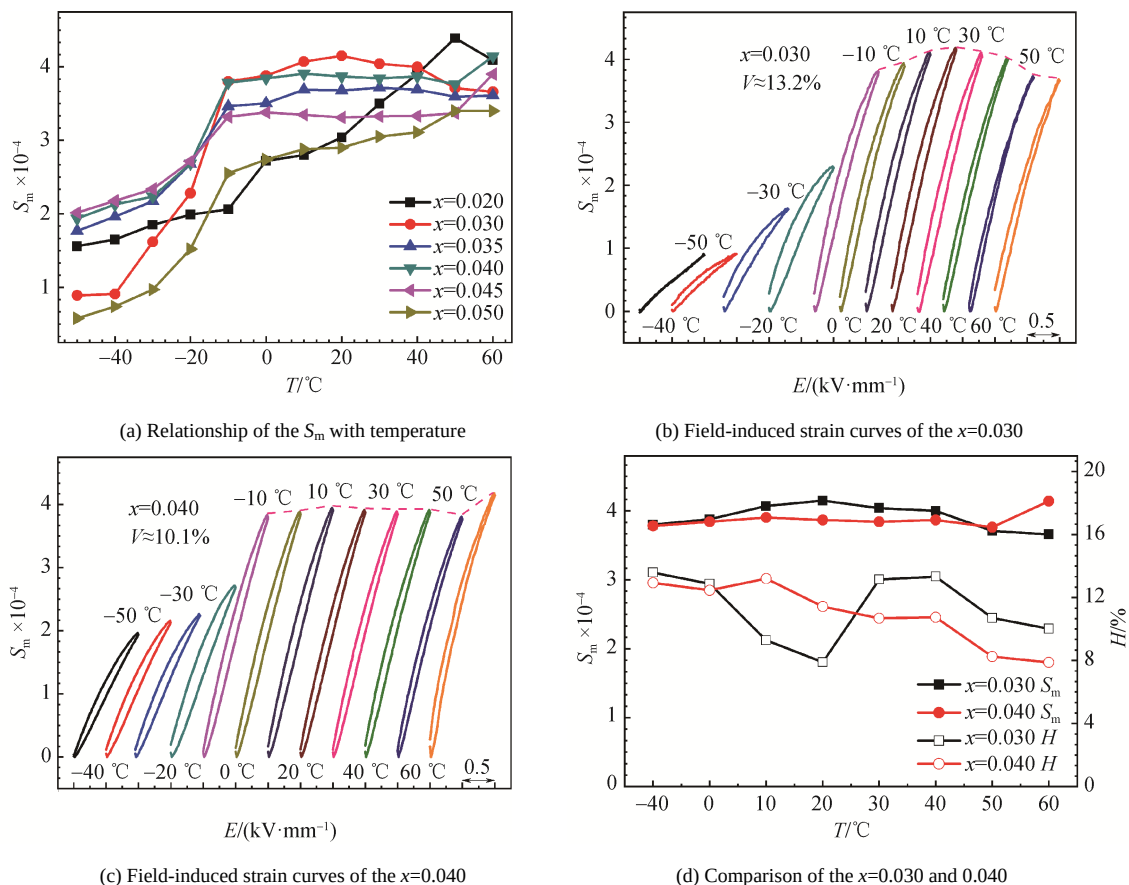
$$V = \frac{S_{m-\max} - S_{m-\min}}{S_{m-\min}} \times \% \quad (2)$$

$$H = \frac{\Delta S}{2S_m} \times \% \quad (3)$$

其中: $S_{m-\max}$ 和 $S_{m-\min}$ 分别为 S_m 的最大值和最小值; ΔS 为场诱应变 S 随电场增大和减小间的最大差值。 $-10\sim+60\text{ }^\circ\text{C}$ 间 $x=0.03$ 样品 $V\approx 13.2\%$, $H\leq 13.2\%$; $x=0.040$ 样品 V 约为 10.1% , $-10\sim+50\text{ }^\circ\text{C}$ 间减小至 V 约为 3.8% , $H\leq 13.1\%$ 。可见, $x=0.040$ 样品具有优

异的场诱应变量和温度稳定性。

基于以上结果, 可知 Sm^{3+} 取代 Pb^{2+} 进入钙钛矿相结构占据 A 位打破晶格的长程有序, 微区的化学组成不均匀性增大, 大量纳米畴及 PNRs 的出现是样品是否具有大场诱应变和高温度稳定性的关键^[24-25]。由以往研究可知^[12,18], 弛豫铁电体随温度升高铁电畴将逐渐裂解, 小的畴尺寸易于为外电场取向, 当温度接近 T_d 时场诱应变最大, 温度高于 T_d 后场诱应变急剧减小。对于 $x\text{Sm-PMN-0.32PT}$ 陶瓷, Sm^{3+} 的掺入使 T_d 向低温方向移动, 同时, T_d 也因微区化学组成不均匀性增大呈现宽的分布, 当温度接近某些微区的 T_d 时, 微区中的铁电畴就会逐渐裂解, 因此场诱应变也将在较宽温区中展现出良好的稳定性。至于为何不同 Sm^{3+} 掺入量样品的场诱应变均在 $-10\text{ }^\circ\text{C}$ 以下大幅衰减, 认为这应与 PMN 的相变温度相关。PMN 的弥散相变温度约为 $-15\text{ }^\circ\text{C}$ ^[26], 考虑纳米畴或 PNRs 分布于 PMN 基体中, 当温度低于 $-15\text{ }^\circ\text{C}$ 时, 受 PMN 弥散相变的影响纳米畴或 PNRs 逐渐融合, 生成更大尺寸的微畴, 此时极化强度难于为外电场取向, 致使场诱应变大幅衰减。



x —Mole fraction; S_m —Maximum value of field-induced strain; H —Hysteresis of field-induced strain loops.

图4 $x\text{Sm-PMN-0.32PT}$ 样品在 1 kV/mm 双向电场下的场诱应变温度稳定性

Fig. 4 Temperature dependence of the field-induced strains of $x\text{Sm-PMN-0.32PT}$ samples under 1 kV/mm unipolar electric field

3 结论

采用两步固相反应法制备 $\text{Pb}_{1-1.5x}\text{Sm}_x[(\text{Mg}_{1/3}\text{Nb}_{2/3})_{0.68}\text{Ti}_{0.32}\text{O}_3(x\text{Sm-PMN-0.32PT}, x=0.000、0.020、0.030、0.035、0.040、0.045、0.050)$ 陶瓷, 研究了 Sm^{3+} 掺杂量对 $x\text{Sm-PMN-0.32PT}$ 陶瓷场诱应变温度稳定性的影响。结果表明, 所有样品均为弛豫铁电体, 随着 Sm^{3+} 掺入量增大, MPB 区向富 PMN 方向移动, 极化样品的 T_m 、 T_d 和 d_{33} 减小, 微区成分起伏增大, 介电频率色散增强, 最大 $d_{33}=929$ pC/N 出现在 $x=0.020$ 处。场诱应变与温度关系密切, 当温度低于 -15°C 时, 受 PMN 弥散相变的影响纳米畴或 PNRs 逐渐融合, 生成更大尺寸的微畴, 此时极化强度难于为外电场取向, 致使场诱应变大幅衰减。1 kV/mm 单向电场驱动下 $x=0.040$ 样品的场诱应变在 $-10\sim+50^\circ\text{C}$ 间高达 4.2×10^{-4} , 变化率小于 3.8%, 滞后小于 13.1%, 展现出良好的应用前景。

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Effect of Sm Doping on Temperature Stability of Field-Induced Strain in $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{--PbTiO}_3$ Ceramics

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Introduction Micro-displacement actuators are widely used in micromachining, precision measurement, aerospace and biomedical. The performance of micro-displacement actuators can be evaluated in terms of displacement, hysteresis, linearity and temperature stability. For a long time, researchers have been hoping to obtain a ferroelectric material with high field-induced strain, low hysteresis and good temperature stability for a variety of different applications. $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ (PMN) is a typical perovskite type relaxor ferroelectric, and PMN– PbTiO_3 (PT) solid solution possesses a morphotropic phase boundary (MPB) region from PT mole fractions of 0.27 to 0.35. The field-induced strain and hysteresis of PMN–PT could meet the requirements of high-performance micro-displacement actuators. However, the temperature stability of field-induced strain still needs to be improved before practical application. In this work, effect of Sm^{3+} doping on the temperature stability of field-induced strain in PMN–0.32PT ceramics was investigated.

Method Experimental samples of nominal composition $\text{Pb}_{1-1.5x}\text{Sm}_x[(\text{Mg}_{1/3}\text{Nb}_{2/3})_{0.68}\text{Ti}_{0.32}]\text{O}_3$ (xSm–PMN–0.32PT, x=0, 0.020, 0.030, 0.035, 0.040, 0.045, 0.050) were prepared via a two-step columbite precursor method. The sintered disks were sintered at 750 °C for 15 min, poled in silicone oil bath under 1 kV/mm for 10 min at room temperature. The electrochemical properties of sintered samples were measured 24 h late after poling. The crystal structure of sintered samples was determined by PANalytical X'Pert3 X-ray diffractometer (XRD) at room temperature. The dielectric, piezoelectric, ferroelectric and resonant properties of sintered samples were measured by TH2816A LCR meter, ZJ–3 quasi-static d_{33} meter, Radiant Precision Multiferroic Materials Analyzer and ZX80A impedance analyzer, respectively. The field-induced strain of sintered samples was measured using LVDT linear variable differential transformer probe controlled by MDS micro-displacement meter and Keithley 2410 source meter. The temperature environment was provided by GZ–ESPEC MC710P environmental test chamber.

Results and discussion All samples exhibited typical perovskite phase, and the chemical compositions of them were similar as that of MPB, a mixture of rhombohedral R, monoclinic M_C , monoclinic M_B and tetragonal T phases. The MPB shifted towards to the

PMN-rich direction with the increase of x value. The dielectric temperature spectra showed that the dispersion coefficient (γ) increased slightly with the increase of x , $1.374 \leq \gamma \leq 1.67$. As the frequency increased, values of ϵ_{r-m} shifted to a higher temperature and the frequency dispersion increased significantly with the increased x value. d_{33} values decreased from 929 pC/N at $x=0.020$ to 546 pC/N at $x = 0.050$. These results indicate that all samples are relaxor ferroelectrics. The substitution of Sm^{3+} for Pb^{2+} broke the long-range ordering of lattice, resulted in the existence of numerous nanodomains below depolarization temperature (T_d), and the spontaneous polarization vector was more easily switchable with external electric field. The ferroelectric properties showed that both the remanent polarization (P_r) and coercive field (E_C) decreased monotonically with increased x value. In addition, the maximum value of field-induced strain (S_m) was very small at low temperature, but increased rapidly near -10°C . The temperature stability of S_m for $x=0.040$ sample was much better than other samples when temperature ranged between -10°C to $+60^\circ\text{C}$. It is known that the ferroelectric domains in relaxor ferroelectric would be gradually into the small domains with increased temperature, which were easily oriented for external electric field. The field-induced strain was the largest near T_d , but decreased sharply when the temperature was higher than T_d . For $x\text{Sm-PMN-0.32PT}$ ceramics, value of T_d shifted to lower temperature due to substitution of Sm^{3+} for Pb^{2+} , and T_d also showed a broad distribution due to the increased inhomogeneity of chemical composition in the microregion. As the temperature approached the T_d of certain microregions, the ferroelectric domains will be gradually cleaved into the small domains, and thus the field-induced strain will show good stability over a wide temperature range. As the field-induced strain decayed remarkably below -10°C , it may be related to the diffuse phase transition of PMN.

Conclusions PMN-PT was the preferred material for micro-displacement actuators due to its high field-induced strain and low hysteresis. The substitution of Sm^{3+} for Pb^{2+} broke the long-range ordering of lattice, increased the inhomogeneity of chemical composition in the microregion, resulted in a strong dielectric frequency dispersion, and the appearance of numerous nanodomains and polar nanoregions made samples exhibit large field-induced strains and high temperature stability. The field-induced strain was much smaller below -15°C and increased rapidly near -10°C under the influence of diffuse phase transition of PMN. A field-induced strain of 4.2×10^{-4} and hysteresis of less than 13.1% in $x=0.040$ sample were achieved with excellent temperature stability that the strain fluctuation was smaller than 3.8% in the temperature between -10°C and $+60^\circ\text{C}$.

Keywords relaxor ferroelectric; lead magnesium niobate-lead titanate; field-induced strain; temperature stability; samarium doping