

ZnO 掺杂对钛酸锶基陶瓷储能性能的影响

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摘 要: 采用传统固相合成工艺制备了 $(\text{Sr}_{0.42}\text{Na}_{0.15}\text{Bi}_{0.29}\text{Ca}_{0.07}\square_{0.07})\text{TiO}_3\text{-}x\%\text{ZnO}$ ($\square$ 表示空位, 化学式简写为 SNBCT- $x\%\text{ZnO}$, 质量分数)储能陶瓷, 并研究了 ZnO 掺杂对 SNBCT 陶瓷结构和储能性能的影响。结果表明: 所用组分样品均具有以立方相为主相的钙钛矿结构, 并表现出细长的电滞回线。ZnO 掺杂有效提高了 SNBCT 陶瓷的击穿强度, 并促进了其储能性能的提升。当 ZnO 掺杂量为 0.5% 时, 样品在 468 kV/cm 电场下的有效储能密度(W_{rec})达 5.16 J/cm³, 储能效率(η)为 88.2%。通过有限元分析建立了该组分陶瓷的晶粒/晶界模型, 模拟了电场作用下样品击穿裂纹的扩展, 分析了样品高耐击穿行为的内在机理。此外, 样品还具有良好的充放电性能, 放电能量密度(W_d)和放电速率($t_{0.9}$)在 280 kV/cm 电场下分别为 2.61 J/cm³ 和 227 ns, 同时样品表现出良好的温度稳定性, 在脉冲功率系统中展示出良好的应用潜力。

关键词: 电介质陶瓷; 钛酸锶; 储能性能; 脉冲充放电

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近年来, 随着化石燃料枯竭、空气污染、碳排放超标等问题的出现, 寻求发展可再生、无污染的清洁能源迫在眉睫^[1]。新型清洁能源的大力开发, 使寻找具有高效存储和运输的储能器件成为重中之重。在电能存储技术中, 电化学电容器、化学储能装置(电池)、固体氧化物燃料电池和介电电容器方面的研究和应用较为广泛。其中, 电介质电容器具有能量损失小、功率密度高、充/放电速率快、稳定性好以及循环寿命长等优势^[2-3], 在大功率/脉冲供电系统应用中备受关注。在主要的电介质材料中, 与具有击穿强度高的聚合物基介电材料相比, 陶瓷基介电材料具有更优异的温度稳定性和更长的使用寿命^[4]。SrTiO₃ 陶瓷具有立方相钙钛矿结构, 具有高击穿场强、低介电损耗、宽带隙和良好热稳定性等优点, 被认为是一种很有前途的储能候选材料^[1, 4]。但是, SrTiO₃ 陶瓷室温下的介电常数相对较低, 且缺乏自发极化, 导致其储能密度有限。因此, 通过对 SrTiO₃ 基陶瓷进行有效结构调控, 保持其高击穿场强的同时提高极化强度是提升其储能性能的重要途径。

离子掺杂、引入其它组元形成固溶体以及优化烧结工艺均能起到良好的储能提升效果^[5-11]。Zhu 等^[5]通过在 SrTiO₃ 引入 Bi³⁺ 形成 A 位缺陷, 提高了陶瓷的极化强度, 并有效细化了陶瓷晶粒尺寸, 进而大幅提高了材料的储能性能。所制备的 Sr_{0.7}Bi_{0.2}TiO₃ 陶瓷在 570 kV/cm 下实现了高的有效储能密度($W_{\text{rec}}=4.77\text{ J/cm}^3$)和良好的储能效率($\eta=85.7\%$)。Yang 等^[6]在 SrTiO₃ 中引入了具有高极化强度的 Ba_{0.85}Ca_{0.15}Zr_{0.1}Ti_{0.9}O₃ (BCZT) 和助烧剂 MnO₂, 辅以两步烧结工艺获得了高的击穿场强($E_b=436\text{ kV/cm}$)和大的极化强度($P_{\text{max}}=33.0\text{ }\mu\text{C/cm}^2$), 样品的 W_{rec} 和 η 分别达 5.36 J/cm³ 和 82.2%。Yan 等^[7]在通过 SrTiO₃ 基体中引入高极化的 BiFeO₃ 组元, 通过诱导 SrTiO₃ 陶瓷形成极性纳米微区进而提高其储能性能。通过流延成型技术和两步烧结工艺进一步优化陶瓷的显微结构, 在 0.35BiFeO₃-0.65SrTiO₃ 组分中获得了 $W_{\text{rec}}\sim 8.4\text{ J/cm}^3$ 和 $\eta\sim 90\%$ 的优异储能性能。Liu 等^[8]提出协同优化设计思路实现了 Sr_{0.7}Bi_{0.2}TiO₃-Bi(Ni_{2/3}Nb_{1/3})O₃ 体系的高储能性能, 通过两种组元的复合构筑了具

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有高度动力学响应的极性纳米微区,在此基础上采用两步烧结工艺,进一步细化陶瓷晶粒,提高样品的耐击穿场强,实现了良好的储能性能。样品在 580 kV/cm 的电场下, W_{rec} 和 η 分别为 5.98 J/cm³ 和 98.6%。Yang 等^[9]采用冷烧结辅助两步烧结的方式在 $\text{Sr}_{0.7}\text{Bi}_{0.2}\text{TiO}_3$ 储能陶瓷中实现了晶粒细化和致密化的协同效应,有效提高了陶瓷的储能性能。样品在 550 kV/cm 电场下, W_{rec} 和 η 分别为 4.17 J/cm³ 和 92.84%。本课题组^[10–11]近期通过多尺度优化策略制备了高储能性能与优异稳定性兼备的 SrTiO_3 基陶瓷。在 SrTiO_3 基体 A 位掺杂 Na^+ 、 Bi^{3+} 后形成 $(\text{Sr}_{1-x-y}\text{Na}_y\text{Bi}_x\text{TiO}_3)$ 固溶体,依靠化学改性和缺陷化学的协同作用实现了陶瓷的良好储能性能。在 390 kV/cm 电场下, W_{rec} 和 η 分别为 3.94 J/cm³ 和 94.71%。在上述工作的基础上,在 A 位继续引入具有大极化率的 Ca^{2+} ,进一步提高了陶瓷的储能性能,在 440 kV/cm 电场下, W_{rec} 和 η 分别为 6 J/cm³ 和 92%。后续通过两步烧结、放电等离子烧结工艺调控陶瓷的显微结构,并详细研究了晶粒尺寸对陶瓷储能性能的影响。

在本工作中,选择前期研究的具有高极化强度的 $(\text{Sr}_{0.42}\text{Na}_{0.15}\text{Bi}_{0.29}\text{Ca}_{0.07}\text{TiO}_3)$ (SNBCT) 组分为基体^[11],通过引入 ZnO 作为助烧剂^[12]提高 SNBCT 陶瓷的烧结性能和致密化程度,进而提高陶瓷的击穿场强和储能性能。此外,研究了 ZnO 掺杂对 SNBCT 陶瓷结构和性能的影响。

1 实验

1.1 样品的制备

以 SrCO_3 (99%, Alfa Aesar)、 Na_2CO_3 (99.95–100.05%, Alfa Aesar)、 Bi_2O_3 (99.975%, Alfa Aesar)、 CaCO_3 (99.5%, Alfa Aesar)、 TiO_2 (99.6%, Alfa Aesar) 和 ZnO (99.9%, PrMat) 为原料,采取传统陶瓷制备工艺^[13]制备了 $\text{SNBCT-x}\%\text{ZnO}$ (质量分数, $x=0, 0.5, 1.0, 1.5$) 储能陶瓷。按化学计量比对原料进行称量后放入球磨罐中,以氧化锆球为球磨介质、无水乙醇为分散剂球磨 24 h。浆料干燥后在 950 °C 煅烧 4 h 合成粉体,随后 2 次球磨 24 h。将干燥好的粉料中加入浓度为 10% (质量分数) 的聚乙烯醇(PVA)粘结剂,经造粒后压制直径 10 mm、厚度 0.5 mm 的生坯片。550 °C 排除粘结剂后,样品在 1140 °C 保温 2 h 得到陶瓷体。用于介电性能测试的陶瓷样品经抛光后被覆银电极,用于储能和充放电性能测试的陶

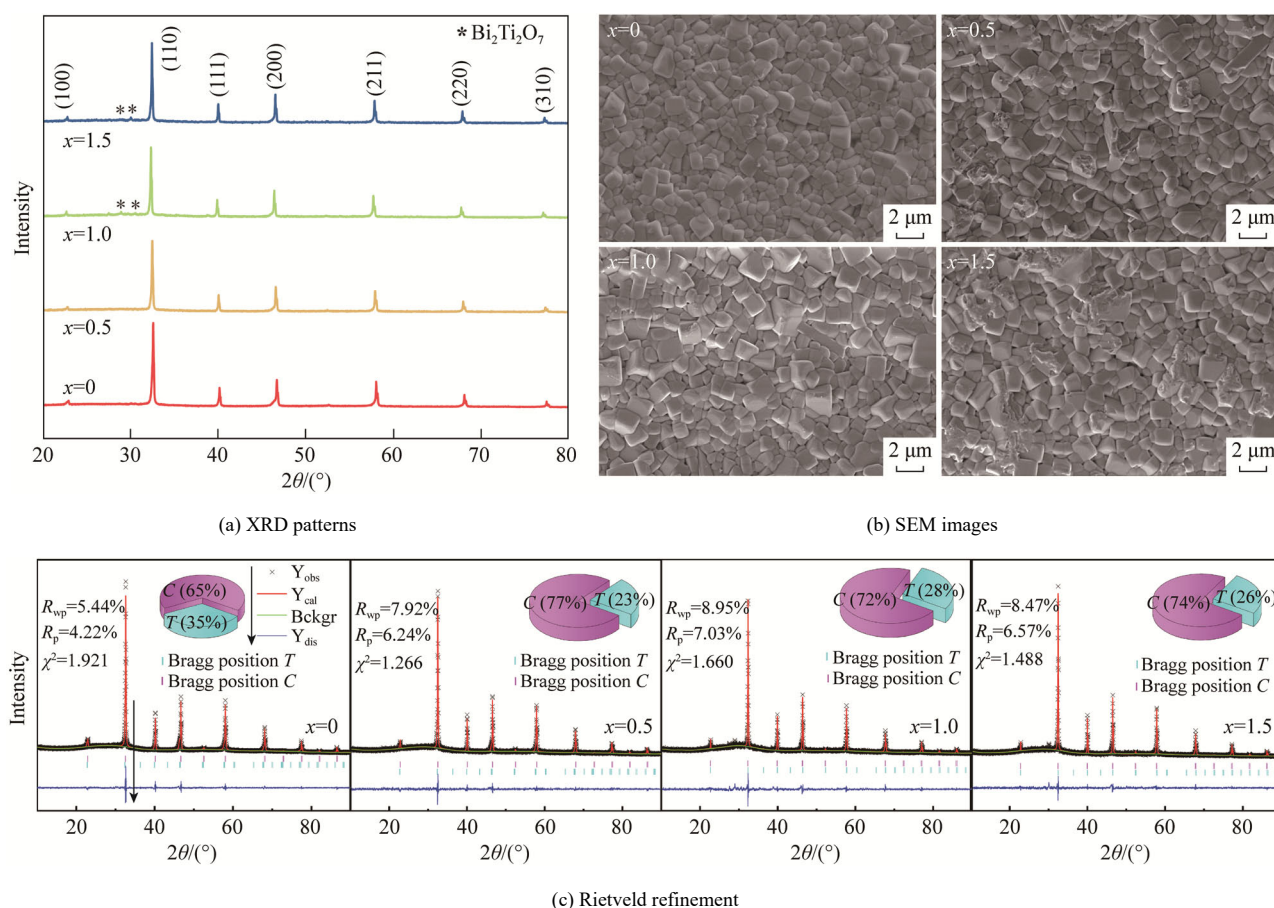
瓷样品打磨至 0.1 mm 左右,在其表面溅射直径 2 mm 的金电极。

1.2 样品的表征

采用 X 射线衍射仪(D8 advance, 德国 Bruker)分析陶瓷样品的物相结构,基于 XRD 测试结果,通过 GSAS 软件对样品进行 Rietveld 结构精修。采用场发射扫描电子显微镜(Merlin compact, 德国 Carl Zeiss)分析样品表面的微观形貌。采用铁电分析仪(TF Analyzer 3000, 德国 aixACCT)测试样品的铁电性能。采用阻抗分析仪(Wayne Kerr 6500B, 英国 WayneKerr)分析样品介电性能随温度的变化。采用充放电系统(CFD-003 plus, 上海同果科技)测试样品的充放电性能。

2 结果与讨论

图 1a 为 $\text{SNBCT-x}\%\text{ZnO}$ 陶瓷的 XRD 谱。由图 1 可见,所有样品均形成了以立方相为主相的钙钛矿结构,随着 ZnO 掺杂量的增加,衍射峰整体向左移动,说明 ZnO 掺杂引起了晶胞膨胀,这是由于较大离子半径的 Zn^{2+} ($r=0.740 \text{ \AA}$, CN=6) 进入了 SNBCT 晶格中取代了小离子半径的 Ti^{4+} ($r=0.605 \text{ \AA}$, CN=6) 造成的。另外,随着 ZnO 掺杂量提高至 1.0%,样品中出现了微弱的杂相成分($2\theta=30^\circ$ 附近的衍射峰),经对比 PDF 卡片确定其相组成为 $\text{Bi}_2\text{Ti}_2\text{O}_7$ (JCPDS 032–0118)。这可能是由于低价态的 Zn^{2+} 掺杂量过多时,引起材料组分的负电荷增多,为保持电中性,一些 Bi^{3+} 和 Ti^{4+} 将会从晶格中被排斥出来,进而相互结合形成 $\text{Bi}_2\text{Ti}_2\text{O}_7$ ^[14]。另外,为了进一步明确样品的相结构成分,采用 GSAS 软件基于 Rietveld 方法对样品的 XRD 谱进行了精修。根据我们之前的研究结果^[11],SNBCT 陶瓷组分的相结构是以立方相(C, $Pm\bar{3}m$)为主相,同时含有少量的四方相(T, $P4bm$)。在本工作中,ZnO 掺杂并未引起 SNBCT 的 XRD 图谱发生明显变化。因此,我们基于立方相(C, $Pm\bar{3}m$)和四方相(T, $P4bm$)两相共存结构对样品 XRD 谱进行精修(图 1b)。XRD 精修谱的加权剩余差方因子 R_{wp} 和剩余差方因子 R_p 值均小于 9%,且拟合优度 χ^2 小于 2.0,表明 Rietveld 精修结果可靠。可以发现,ZnO 掺杂后,样品的立方相(C, $Pm\bar{3}m$) / 四方相(T, $P4bm$) 的比例增多。图 1c 为 $\text{SNBCT-x}\%\text{ZnO}$ 陶瓷表面的 SEM 照片,可以看到 4 个组分陶瓷均具有良好的微观形貌,晶粒大小均匀,无明显的气孔。随着 ZnO 的掺杂,样品的晶粒尺寸变化不明显。



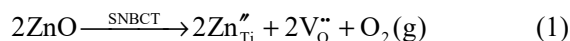
R_{wp} is the weighted profile factor. R_p is the profile factor. χ^2 is the goodness of fitting.

图 1 SNBCT- $x\%$ ZnO 陶瓷的 XRD 谱和表面 SEM 照片
Fig. 1 XRD patterns and SEM images of SNBCT- $x\%$ ZnO ceramics

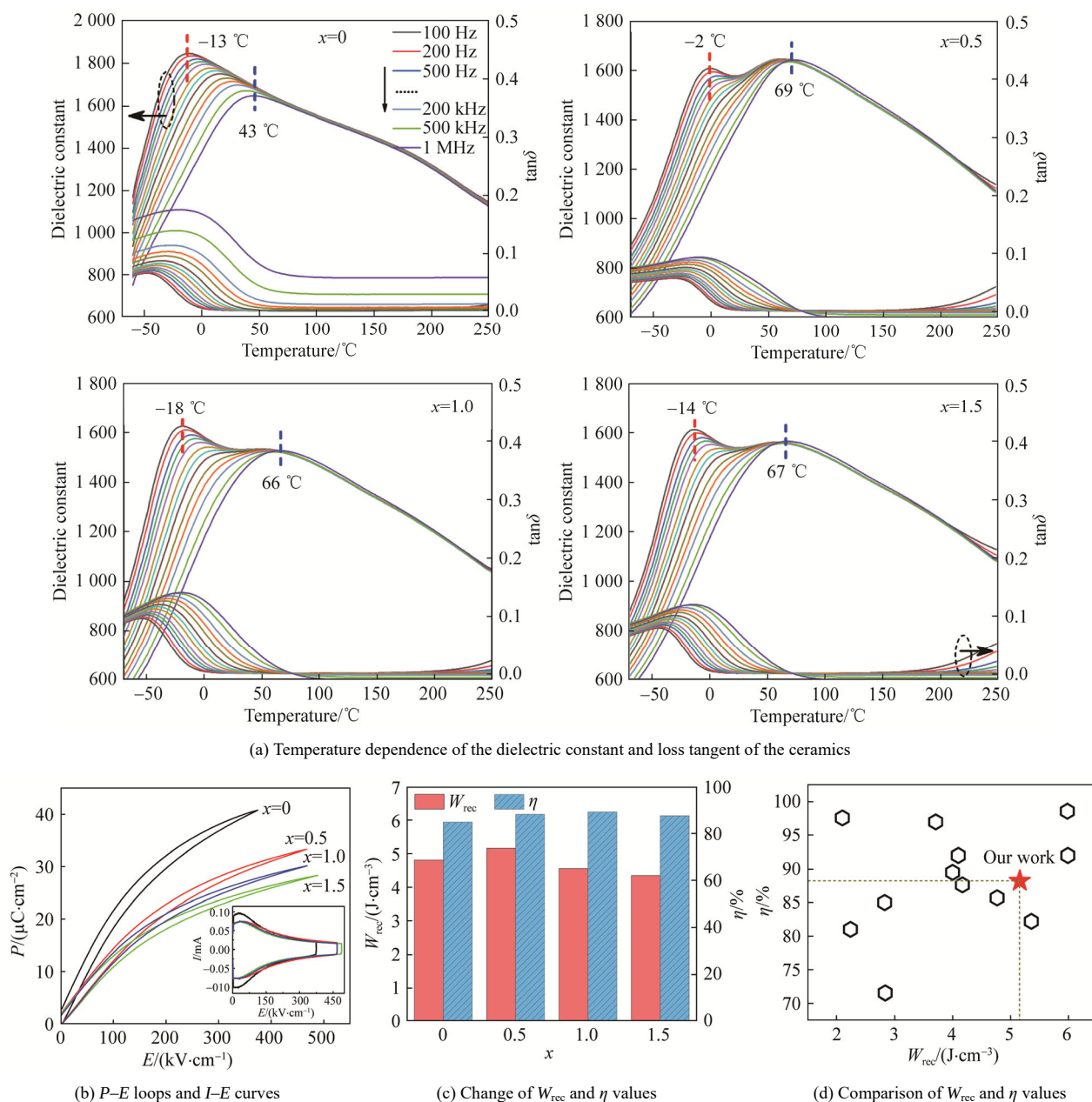
图 2a 为 SNBCT- $x\%$ ZnO 陶瓷在不同频率(0.1 kHz~1.0 MHz)下介电常数(ϵ_r)和介电损耗($\tan\delta$)随温度的变化曲线。本研究中, SNBCT 组分可以进一步书写为 $0.7(\text{Sr}_{0.6}\text{Bi}_{0.2}\text{Ca}_{0.1})\text{TiO}_3-0.3(\text{Na}_{0.5}\text{Bi}_{0.5})\text{TiO}_3$ 。由图 2a 可见, SNBCT 样品在室温附近呈现 1 个强介电峰 T_m , 对应样品弛豫铁电相到立方相的转变^[15], 样品在 175 °C 附近出现一个微弱且宽化的介电峰, 这是由于固溶体中的 $(\text{Na}_{0.5}\text{Bi}_{0.5})\text{TiO}_3$ 成分引起的。另外, 样品在室温附近的介电峰表现出明显的频率色散现象, 介电峰随着频率的增加向高温方向移动: 从 -13 °C (100 Hz) 移至 43 °C (1 MHz), 说明样品具有强弛豫特性。经过 ZnO 掺杂后, 样品的介电峰在低频条件下产生分裂, 形成台阶状, 随着频率的增大介电峰回归至单峰状态, 1 MHz 测试条件下对应的 T_m 温度分别为 69 °C ($x=0.5$)、66 °C ($x=1.0$) 和 67 °C ($x=1.5$)。

图 2b 为 SNBCT- $x\%$ ZnO 陶瓷的电滞(P - E)回线。由图 2b 可见, 4 个组分的样品均具有细长的 P - E 曲

线, 这与样品所具有的强弛豫特性相关。一方面, ZnO 的掺杂降低了 SNBCT 陶瓷的铁电性能, 表现为最大极化强度 $P_{\max}$ 呈现下降趋势; 另外一方面, ZnO 的掺杂较大幅度的提高了 SNBCT 陶瓷的击穿场强。因此, 综合效果来看, SNBCT 陶瓷的储能性能获得了一定程度的提升。由图 2c 可见, 当 ZnO 含量为 0.5% 时, 在最大电场 468 kV/cm 下, 样品有效储能密度(W_{rec})达 5.16 J/cm³, 储能效率(η)为 88.2%。由图 2d 可见, 与近期报道的 SrTiO_3 基储能陶瓷的性能(W_{rec} 和 η)相比^[5-6, 8-9, 11, 16-23], 该样品的储能性能处于较高水平。本研究中 ZnO 掺杂对样品耐击穿性能的提高, 是由于 Zn^{2+} 进入了 SNBCT 晶格中取代了 Ti^{4+} 后产生的氧空位 ($\text{V}_\text{O}^\bullet$) 降低陶瓷的漏导和介电损耗引起的^[24], 具体的缺陷化学反应式为:



另外, 陶瓷致密的显微结构和细小的晶粒尺寸也有助于获得高的击穿场强, 为了进一步验证上述



P is the polarization. E is the electric field. W_{rec} is recoverable energy storage density. η is energy storage efficiency.

图2 SNBCT- $x\%$ ZnO 陶瓷的介电温谱、电滞回线、储能性能参数以及同 SrTiO_3 基储能陶瓷性能对比

Fig. 2 Dielectric spectra, P - E hysteresis loops and energy storage parameters of SNBCT- $x\%$ ZnO ceramics, comparison of energy storage parameters with SrTiO_3 -based energy storage ceramics

结论, 本研究通过有限元模拟分析了 SNBCT-0.5%ZnO 样品的电击穿行为。

图3为 SNBCT-0.5%ZnO 陶瓷在 300 kV/cm 和 468 kV/cm 电场下模拟的电势/局域电场/极化分布以及击穿路径(电树)图, 图4为样品在 468 kV/cm 电场下电树枝的演变过程。对于多晶陶瓷而言, 晶界的击穿能较高, 因此晶界可以承受更高的电场而不易击穿, 相比而言, 晶粒的击穿能相对较小, 晶粒在电场下作用容易被击穿。因此, 细晶陶瓷样品具有

更多的晶界, 能够阻碍电树枝在电场作用下的扩展, 使得陶瓷具有更高的击穿场强^[10–11]。对于本研究中的 SNBCT-0.5%ZnO 陶瓷, 样品细小的晶粒尺寸 ($\sim 0.99 \mu\text{m}$) 提供更多的晶界数目, 有助于获得更高的击穿电场。从图4中可以发现电树随着外加电场的增加而长大, 在 468 kV/cm 电场作用下, 电树生长曲线轨迹复杂, 电树枝较多, 说明电场下击裂纹的扩展受到了大量晶界的阻力。因此, 陶瓷获得了较大的击穿强度。

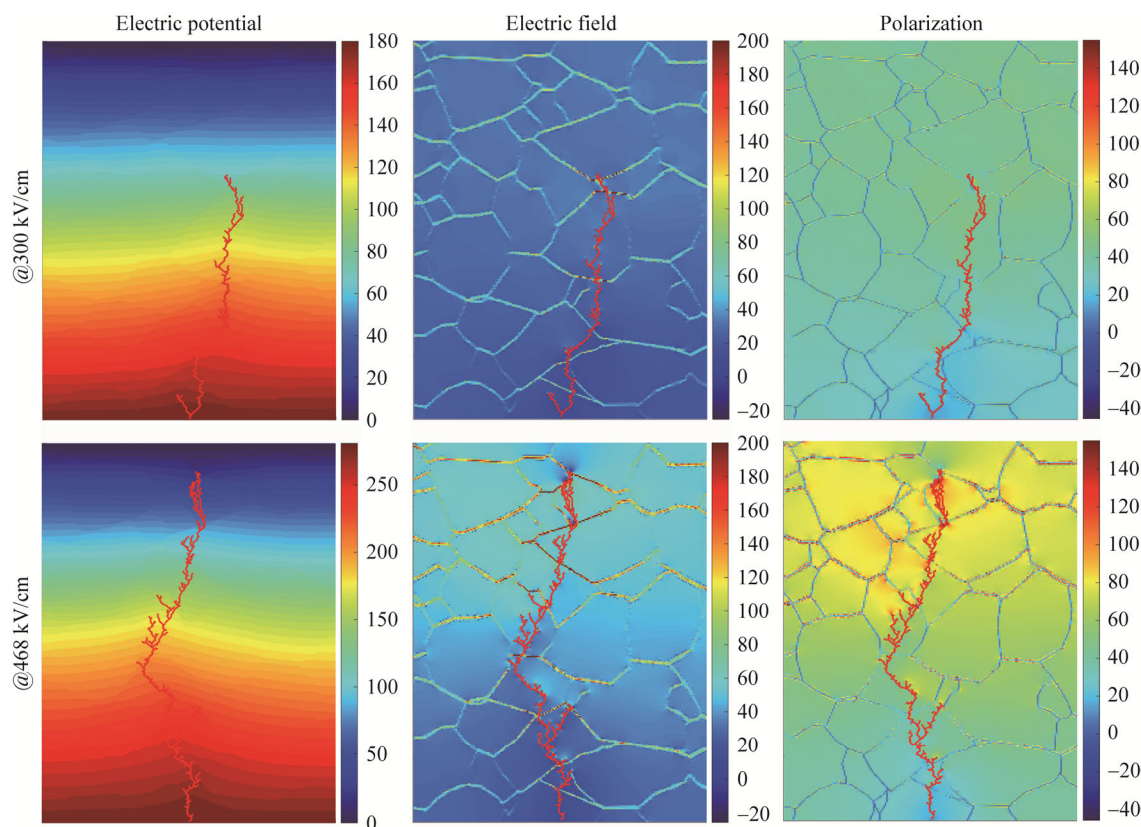


图 3 SNBCT-0.5%ZnO 陶瓷在不同电场下电势/局域电场/极化分布以及击穿路径

Fig. 3 Electric potential/field/polarization distribution with simulated breakdown path for SNBCT-0.5%ZnO ceramic under different electric field

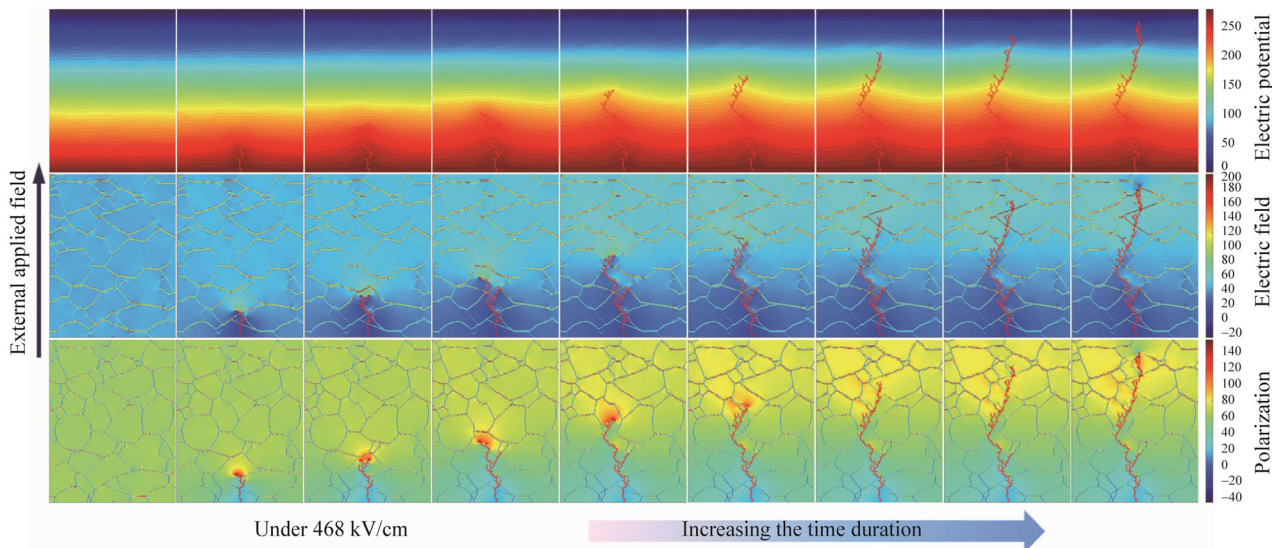


图 4 SNBCT-0.5%ZnO 陶瓷在 468 kV/cm 电场下的电势/局域电场/极化分布以及电树枝演变过程

Fig. 4 Simulated evolution of electric potential/field distribution, polarization distribution along with the growth of breakdown paths for SNBCT-0.5%ZnO ceramic under 468 kV/cm

充放电性能是储能材料实际应用中的重要指标,本实验采用充放电测试系统对样品进行了测试。图 5a 和图 5b 分别为 SNBCT-0.5%ZnO 样品在不同电场下的过阻尼放电电流-时间曲线和放电能量密

度-时间(W_d-t)曲线,负载电阻为 $200\ \Omega$ 。随着电场强度的增大,峰值电流不断增加,但放电波形基本保持不变。由图 5a~图 5c 可见,当电场强度为 $280\ \text{kV/cm}$ 时,该样品的放电电流达 $6.45\ \text{A}$,放电密度 W_d 为

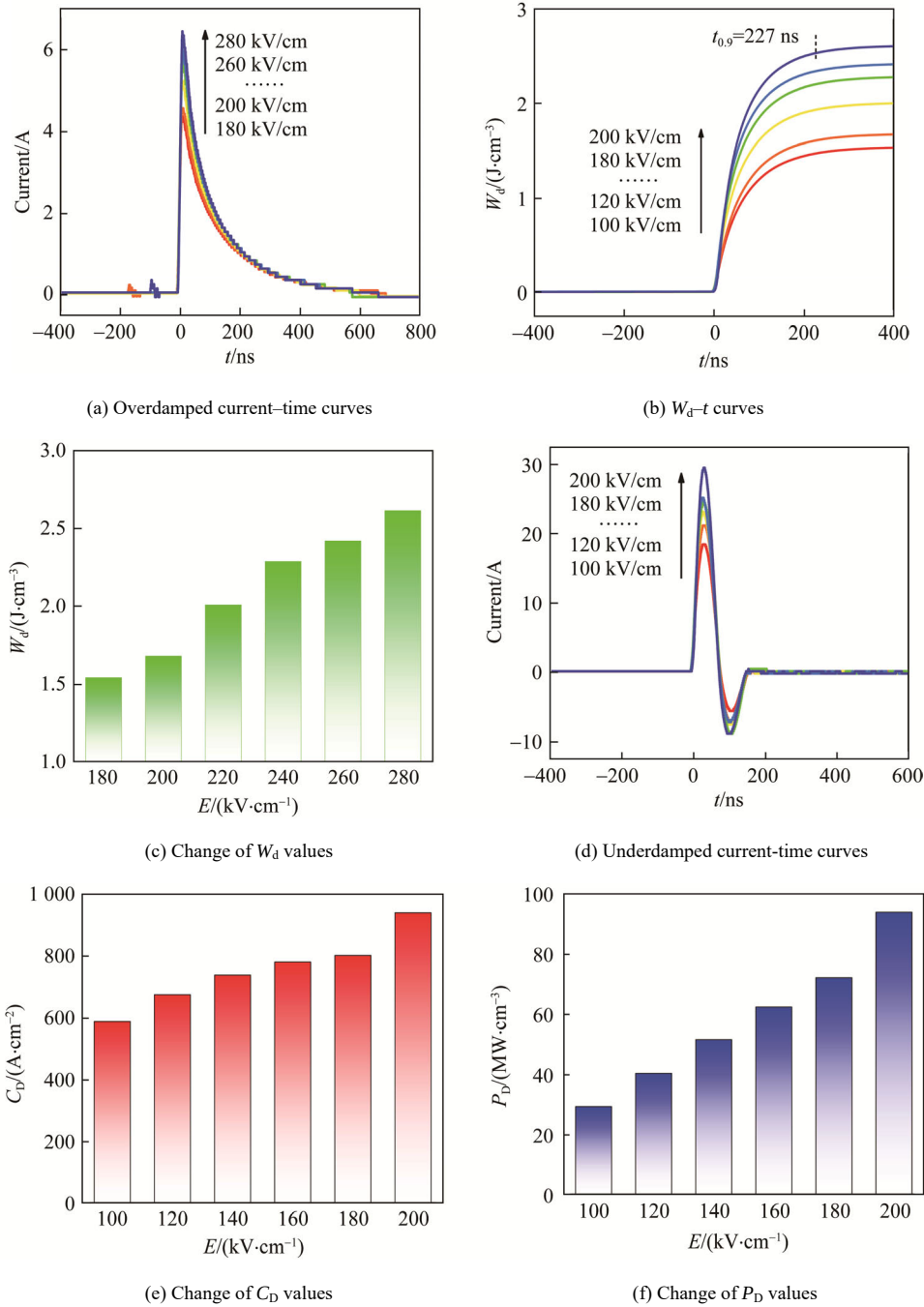
2.61 J/cm^3 。图中 $t_{0.9}$ 表示储能材料在放电过程中放出本身存储能量的 90% 时所用的时间, 其值越小, 表示放电速度越快。本实验样品的 $t_{0.9}$ 仅为 227 ns, 反应出样品具有较强的放电能力。图 5d 为 SNBCT-0.5%ZnO 样品陶瓷样品不同电场下的欠阻尼脉冲放电电流-时间曲线, 随着电场强度的增加, 电流的峰值不断增加, 从 100 kV/cm 电场下的 18.45 A 增加到 200 kV/cm 电场下的 29.5 A。电流密度 C_D 和功率密

度 P_D 可由公式计算出:

$$C_D = I_{\max} / S \quad (2)$$

$$P_D = E \cdot I_{\max} / (2S) \quad (3)$$

其中: $I_{\max}$ 为最大放电电流 E 为电场, S 表示样品的有效面积。图 5e 和图 5f 分别为电流密度 C_D 和功率密度 P_D 值随电场强度的变化, 可以看到电流密度 C_D 和功率密度 P_D 都呈现出递增的趋势, 200 kV/cm 电场下的 C_D 和 P_D 分别为 939.49 A/cm^2 和 93.95 MW/cm^3 。



W_d is discharge energy density. E is the electric field. C_D is current density. P_D is power density.

图 5 SNBCT-0.5%ZnO 陶瓷的充放电性能

Fig. 5 Charge-discharge properties of SNBCT-0.5%ZnO ceramic

良好的稳定性是评估储能材料在高温环境下储能能力的重要指标。图 6a 为不同温度下的 SNBCT-0.5%ZnO 陶瓷样品 W_d - t 曲线, 测试电场为 200 kV/cm。图 6b 为 SNBCT-0.5%ZnO 陶瓷样品 W_d 随温度的变

化曲线。由图 6a~图 6b 可见, 样品在不同温度下的 W_d - t 曲线变化较小, 样品的放电能量密度 W_d 在 30~180 °C 测试温度范围内保持相对稳定($\Delta W_d < 15\%$), 表明该陶瓷具有良好的脉冲放电温度稳定性。

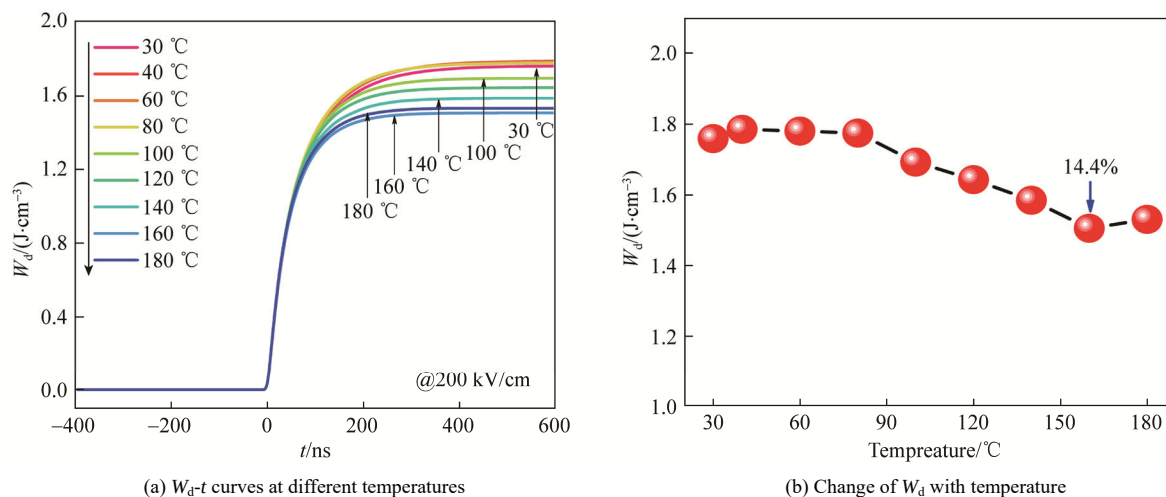


图 6 SNBCT-0.5%ZnO 陶瓷的高温充放电性能
Fig. 6 High-temperature charge-discharge properties of SNBCT-0.5%ZnO ceramic

3 结论

ZnO 掺杂有效提高了 SNBCT 基体陶瓷的耐击穿强度, 促进了陶瓷储能性能的提升。当 ZnO 添加量为 0.5% 时, 样品在最大电场 468 kV/cm 下的有效储能密度(W_{rec})和储能效率(η)分别为 5.16 J/cm³ 和 88.2%。通过有限元分析建立了陶瓷的晶粒/晶界模型, 模拟了电场作用下样品击穿裂纹的扩展, 解释了样品所具有的高耐击穿行为。此外, 样品还具有良好的充放电性能和温度稳定性, 在脉冲功率系统中展示出良好的应用潜力。

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Effect of ZnO Doping on Energy Storage Properties of Strontium Titanate-Based Ceramics

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Extended Abstract

Introduction Dielectric capacitors are used in pulse power systems due to their advantages of high energy storage efficiency, long storage lifetime, and fast charge/discharge speed. Among the major dielectric materials, ceramic-based dielectrics have a superior temperature stability and a longer lifetime rather than polymer-based dielectrics. Dielectric energy storage ceramics have attracted recent attention. Among various dielectric energy storage ceramics, SrTiO₃ ceramic with a linear dielectric behavior at room temperature is a promising dielectric energy storage material with a high breakdown strength and a low dielectric loss. However, SrTiO₃ ceramic has a relatively low dielectric constant and lacks a spontaneous polarization, resulting in a limited energy storage density. Therefore, SrTiO₃ ceramic cannot meet requirements for specific energy storage application. Improving the polarization strength while maintaining the high breakdown strength through effective structural adjustment can be an effective method to enhance its energy storage performance. In this paper, we fabricated high-performance (Sr_{0.42}Na_{0.15}Bi_{0.29}Ca_{0.07}□_{0.07})TiO₃ (SNBCT) energy storage ceramics with a small amount of ZnO as doping species. In addition, the effect of ZnO doping on the structure and energy storage properties of the ceramics were also investigated.

Methods SNBCT-x%ZnO energy storage ceramics were prepared by a conventional ceramic preparation process. The raw materials were weighed and then mixed in alcohol by grinding in a ball mill for 24 h. The slurry was dried and calcined at 950 °C for 4 h to obtain the powders. After further grinding for 24 h, the powders were mixed with polyvinyl alcohol (PVA) binder solution and then pressed into pellets with 10 mm in diameter and 0.5 mm in thickness. After burning off the PVA, the disk samples were sintered at 1 140 °C for 2 h. The samples used for dielectric performance tests were polished and coated with silver electrodes, and the samples used for energy storage and charge/discharge performance testing were thinned to a thickness of 0.1 mm, and gold electrodes with a diameter of 2 mm were sputtered on their surfaces.

The structure of the ceramic was analyzed by a model D8 advance X-ray diffractometer (Bruker Co., Germany). The microstructure of the ceramics was determined by a model Merlin compact field emission scanning electron microscope (Carl Zeiss Co., Germany). The ferroelectric properties of the ceramics were analyzed by a model TF Analyzer 3000 ferroelectric analyzer (aixACCT Co., Germany). The temperature-dependent dielectric properties were characterized by a model Wayne Kerr 6500B impedance analyzer (WayneKerr Co., UK). The charge–discharge characteristics were analyzed by a model CFD-003 plus pulsed charge–discharge system (Tongguo Technology Co., China).

Results and discussion ZnO-modified SNBCT samples show a perovskite structure with a cubic phase. A trace of impurity peak appears in the XRD pattern as ZnO doping amount increases to 1.0%, corresponding to a small amount of the secondary Bi₂Ti₂O₇

phase (JCPDS 032–0118). All the ceramics show a uniform and dense microstructure.

The ZnO doping has little influence on the microstructure of the ceramics as the average grain size in these compositions changes slightly.

For the electrical properties, the doping of ZnO weakens the ferroelectric properties of SBNCT ceramics, which is manifested by a decreased maximum polarization strength $P_{\max}$. In addition, the doping of ZnO improves the breakdown strength, thus enhancing the energy storage performance of SBNCT ceramics. For the sample doped with 0.5% ZnO, a high recoverable energy-storage density (W_{rec}) of 5.16 J/cm^3 and a high energy-storage efficiency (η) of 88.2% in a large breakdown electric field of 468 kV/cm are obtained. Compared with the SrTiO_3 -based energy storage ceramics, a great energy storage performance of the studied sample is obtained. A simulation model containing grains and grain boundaries is proposed to explain the enhanced breakdown strength, and the results show that fine grains with many grain boundaries hinder the propagation of breakdown cracks. For the charge-discharge performance, the sample doped with 0.5% ZnO shows a discharge energy density (W_d) of 2.61 J/cm^3 and a discharge rate ($t_{0.9}$) of 227 ns in an electric field of 280 kV/cm.

Conclusions All the samples exhibited a perovskite structure dominated by a cubic phase, and provided a slim P – E loops. ZnO doping effectively improved the breakdown strength of the SBNCT matrix, thus enhancing the energy storage performance. The effective energy storage density (W_{rec}) of the sample reached 5.16 J/cm^3 and the energy storage efficiency (η) was 88.2% in the electric field of 468 kV/cm for the sample doped with 0.5% ZnO. A simulation model containing grains and grain boundaries was established and the extension of breakdown cracks in an external electric field was simulated, which explained the enhanced breakdown strength. In addition, the sample doped with 0.5% ZnO had a good charge-discharge performance, showing a discharge energy density (W_d) of 2.61 J/cm^3 and a discharge rate ($t_{0.9}$) of 227 ns in an electric field of 280 kV/cm. Meanwhile, the sample exhibited a good temperature stability. These results indicated that the SBNCT- $x\%$ ZnO ceramics could be promising materials for pulse power capacitor applications.

Keywords dielectric ceramics; strontium titanate; energy storage performance; pulsed charge-discharge