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Supplementary information

Enhanced pyroelectric and piezoelectric properties of PZT with aligned porosity for energy harvesting applications

Yan Zhang [a], Mengying Xie [a], James Roscow[a], Kechao Zhou[b], Yinxiang Bao [b], Dou Zhang[b,*], Chris R. Bowen [a,*]

[a] Department of Mechanical Engineering, University of Bath, BA2 7AY, United Kingdom

[b] State Key Laboratory of Powder Metallurgy, Central South University, 410083, China

a. Department of Mechanical Engineering, University of Bath, BA2 7AY, UK. E-mail: C.R.Bowen@bath.ac.uk
b. State Key Laboratory of Powder Metallurgy, Central South University, 410083, China. E-mail: dzhang@csu.edu.cn

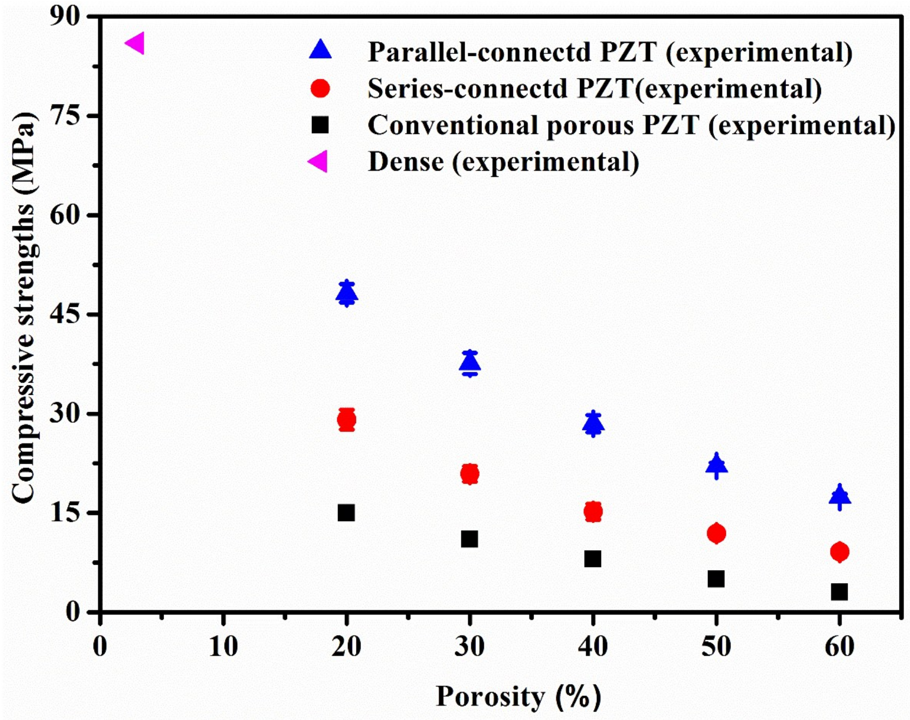


Figure S1 Compressive strengths of both parallel-connected and series-connected freeze-cast porous PZT. Data for conventional porous PZT with uniformly distributed porosity and dense PZT ceramics also shown.

a. Department of Mechanical Engineering, University of Bath, BA2 7AY, UK. E-mail: C.R.Bowen@bath.ac.uk
b. State Key Laboratory of Powder Metallurgy, Central South University, 410083, China. E-mail: dzhang@csu.edu.cn

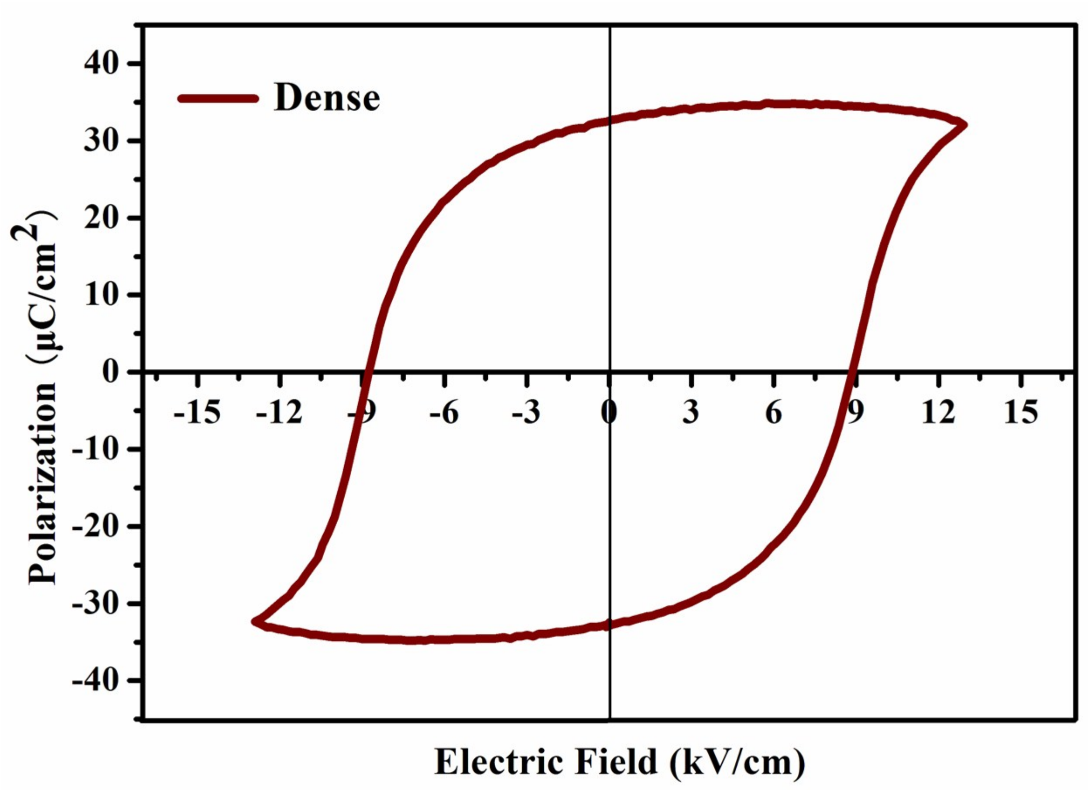


Figure S2 Polarisation (P) - electric field (E) hysteresis loops of the dense PZT.

a. Department of Mechanical Engineering, University of Bath, BA2 7AY, UK. E-mail: C.R.Bowen@bath.ac.uk
b. State Key Laboratory of Powder Metallurgy, Central South University, 410083, China. E-mail: dzhang@csu.edu.cn

3.3 Piezoelectric and dielectric properties

Piezoelectric coefficients for the series and parallel connection can be calculated by the following equations:

For series connection by Equations S1 and S2:

$$d_{33} = \frac{V^{PZT}\ d_{33}^{PZT}\ \varepsilon_{33}^{pc} + V^{pc}\ d_{33}^{pc}\ \varepsilon_{33}^{PZT}}{V^{PZT}\varepsilon_{33}^{pc} + V^{pc}\ \varepsilon_{33}^{PZT}}$$

(S1)

$$d_{31} = \frac{V^{PZT}\ d_{31}^{PZT}\ \varepsilon_{33}^{pc}\ s_{11}^{pc} + V^{pc}\ d_{31}^{pc}\ \varepsilon_{33}^{PZT}\ s_{11}^{PZT}}{\left(V^{PZT}\varepsilon_{33}^{pc} + V^{pc}\ \varepsilon_{33}^{PZT}\right)\left(V^{PZT}\ s_{11}^{pc} + V^{pc}\ s_{11}^{PZT}\right)}$$

(S2)

For parallel connection by Equations S3 and S4:

$$d_{33} = \frac{V^{PZT}\ d_{33}^{PZT}\ s_{33}^{pc} + V^{pc}\ d_{33}^{pc}\ s_{33}^{PZT}}{V^{PZT}\ s_{33}^{pc} + V^{pc}\ s_{33}^{PZT}}$$

(S3)

$$d_{31} = V^{PZT}\ d_{31}^{PZT} + V^{pc}\ d_{31}^{pc} \qquad \text{(S4)}$$

3.4 Pyroelectric properties

Theoretical pyroelectric formulations for the series and parallel connections are given by Equations (S5) and (S6) respectively.

For series connection:

$$p = \frac{V^{PZT}p^{PZT}\ \varepsilon_{33}^{pc} + V^{pc}\ p^{pc}\varepsilon_{33}^{PZT}}{V^{PZT}\ \varepsilon_{33}^{pc} + V^{pc}\ \varepsilon_{33}^{PZT}} + \frac{2\,V^{PZT}\,V^{pc}\left(\varepsilon_{33}^{pc}\ d_{33}^{PZT} - \varepsilon_{33}^{PZT}\ d_{33}^{pc}\right)(\alpha^{}}{\left(V^{PZT}\ \varepsilon_{33}^{pc} + V^{pc}\ \varepsilon_{33}^{PZT}\right)\left[V^{PZT}\left(s_{11}^{pc} + s_{12}^{pc}\right) + \right.}$$

(S5)

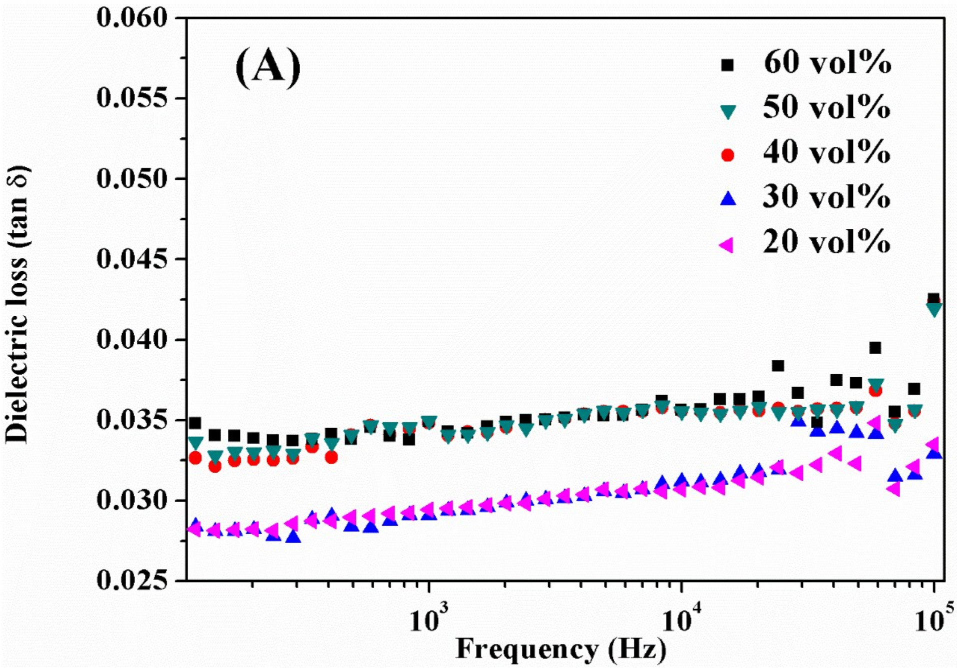
For parallel connection:

a. Department of Mechanical Engineering, University of Bath, BA2 7AY, UK. E-mail: C.R.Bowen@bath.ac.uk
b. State Key Laboratory of Powder Metallurgy, Central South University, 410083, China. E-mail: dzhang@csu.edu.cn

$$p = V^{PZT}p^{PZT} + V^{pc}p^{pc} + \frac{V^{PZT}\ V^{pc}\ p^{PZT}(\alpha^{pc} - \alpha^{PZT})\,(d_{33}^{PZT} - d_{33}^{pc})}{V^{PZT}\ s_{33}^{pc} + V^{pc}\ s_{33}^{PZT}}$$

(S6)

where α is thermal expansion coefficient.



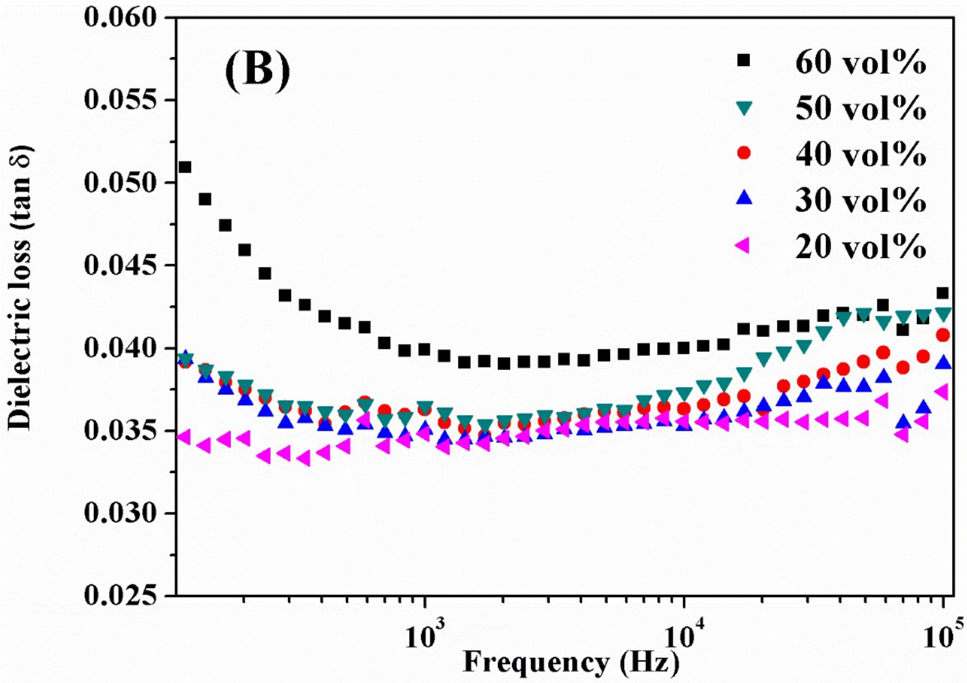


Figure S3 Dielectric loss of the aligned porous PZT with (A) Parallel-connected and (

a. Department of Mechanical Engineering, University of Bath, BA2 7AY, UK. E-mail: C.R.Bowen@bath.ac.uk
b. State Key Laboratory of Powder Metallurgy, Central South University, 410083, China. E-mail: dzhang@csu.edu.cn

B) Series-connected modes.

Table S1 Model fitting parameters of the piezoelectric coefficients of the freeze-cast porous PZT with both series and parallel connectivities.

Porosity (%)	d_{33}		d_{31}	
	Series-connected	Parallel-connected	Series-modelled	Parallel-connected
	m	n	m, n	N/A
20	6.012	0.781	m=6.012, n=0.781	-
30	6.019	0.762	m=6.019, n=0.762	-
40	6.021	0.759	m=6.021, n=0.759	-
50	6.032	0.757	m=6.032, n= 0.757	-
60	6.089	0.755	m=6.089, n= 0.755	-

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