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Electrocaloric effect enhanced thermal conduction of a multilayer ceramic structure*

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The electrocaloric effect of ferroelectric ceramics has been studied extensively for solid-state caloric cooling. Generally, most ferroelectric ceramics are poor thermal conductors. In this work, the possibility of enhancing the thermal conduction of ferroelectric ceramics through the electrocaloric effect is studied. A multilayer ceramic structure is proposed and the proper sequential electric field is applied to each ceramic layer. The result shows that the thermal conduction of the multilayer structure is significantly enhanced because of the electrocaloric effect of the ferroelectric ceramics. As a result, the work finds an alternatively way of applying the electrocaloric effect, prompting thermal conduction.

Keywords: electrocaloric effect, thermal conduction

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1. Introduction

Electrocaloric (EC) effect refers to the isothermal entropy change ΔS or adiabatic temperature change ΔT of a dielectric material when an electric field is applied or removed.[1–5] After a giant EC effect was found in $\mathrm{PbZr_{0.95}Ti_{0.05}O_3}$,[6] it gets a renaissance. Various strategies have been studied to enhance EC effect, *e.g.*, preparing ferroelectric thin film bilayers and novel layered ferroelectric, utilizing phase transitions and phase-boundary, and *etc*.[7–10] Antiferroelectric ceramic shows an interesting negative EC effect.[11,12] Some practical devices using EC effect for cooling.[13–17] and electrical energy generation[18] have been developed.

For ferroelectric ceramics, a high electric field has to be applied to induce a large EC effect.[5] Thus, ceramics have to be fabricated very thin to increase the electrical breakdown field.[19] The compromise is that the overall quantity of cooling is small due to reduced size. In the field of electronic ceramics, it is known that industrially manufactured multilayer ceramic capacitors (MLCC) are an innovative result of increasing the value of capacitance while reducing the size. These mature products find also novel properties like magnetoelectric effects[20–22] and EC effect[23]. The EC effect of MLCC has also studied extensively.[24–31] The dielectric materials used in MLCC commonly are $\mathrm{BaTiO_3}$-based ceramics, which have poor thermal conduction. It is then interesting to ask if the thermal conduction of these ceramics can be enhanced through the EC effect. Thus, in this work, a simple MLCC is designed and the proper sequential electric field is applied. The result indicates that the EC effect can enhance the thermal conduction of the structure significantly.

2. Theory

The one-dimensional (1D) heat flow equation can be expressed as

$$\dot{Q}_{\mathrm{cond}} = -kA\,\mathrm{d}T/\mathrm{d}X = -\mathrm{d}T/R, \tag{1}$$

in which $\dot{Q}$ is the rate of heat flow; k is the thermal conductivity; A is the cross-sectional area perpendicular to the path of heat flow; T is the temperature; X is the length of the material measured on a path parallel to the heat flow; R is the heat resistance. The total transferred heat Q during time t is $\dot{Q}\cdot t$. The temperature variation ΔT of a material because of the absorption of heat Q is

$$Q = mc\Delta T = \rho V c\Delta T = C\Delta T, \tag{2}$$

in which m is the mass of material; c is the specific thermal capacity; ρ is density; V is volume; C is the thermal capacitance.

A simple MLCC structure is designed as shown in Fig. 1, which consists of two layers dielectric ceramics in between three layers electrodes. Thus, there are two EC cooling units EC1 and EC2. During the calculation, EC1 connects with a cooling load while EC2 connects with a heat sink.

The thermal behavior of the electrode layer can be modeled as the series of one thermal resistance $R_{\mathrm{e}} = L_{\mathrm{e}}/k_{\mathrm{e}}A_{\mathrm{e}}$ and one thermal capacitance $C_{\mathrm{e}} = \rho_{\mathrm{e}}c_{\mathrm{e}}V_{\mathrm{e}}$.[24] Here L_{e} is the length of an electrode measured on a path parallel to the heat flow; k_{e} is the thermal conductivity of the electrode; A_{e} is the cross-sectional area perpendicular to the path of heat flow; ρ_{e} is the density; c_{e} is the specific thermal capacity; V_{e} is the volume. The thermal capacitance of the EC layer is $C_{\mathrm{EC}} = \rho_{\mathrm{EC}}c_{\mathrm{EC}}V_{\mathrm{EC}}$. Here ρ_{EC}, c_{EC}, and V_{EC} are the density, the specific thermal capacity, and the volume of the EC layer.

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By assuming that the cooling load temperature is $T_{\rm load}$ and the temperature of EC1 is $T_{\rm EC1}$, the 1D heat transfer Eq. (1) can be further expressed as

$$\dot{Q}(t) = (T_{\rm load} - T_{\rm EC1}/R)\,{\rm e}^{-t/Rc}, \tag{3}$$

where R is the overall thermal resistance and equal to $R_{\rm e}$; C is the overall thermal capacitance and equal to $(C_{\rm e}^{-1} + C_{\rm EC}^{-1})^{-1}$. Similar equations can also be built for describing the heat transfer between EC1 and EC2, EC2 and heat sink respectively. By combining Eqs. (1)–(3), the heat transfer problem of the proposed structure can be solved.

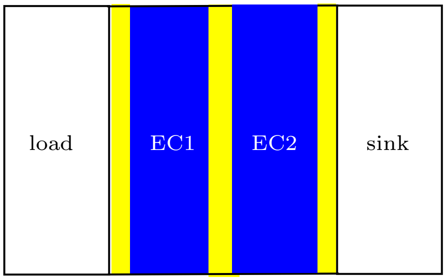

Fig. 1. The designed multi-layer structure. From left to right, there are cooling load, electrode, ferroelectric ceramic layer EC1, electrode, ferroelectric ceramic layer EC2, electrode, and heat sink.

3. Results and discussion

For commercialized MLCC, the terminal electrodes connect with the electrical circuit. Thus, each ceramic layer has the same applied electric field. The additional components have been included to transport heat. For the proposed MLCC as shown in Fig. 1, the different sequential electric field is applied for each EC unit as shown in Fig. 2. An EC cooling cycle is achieved by two adiabatic and two heat transfer processes. In one period, there are four steps for each EC unit. For instance, in step 1, there is a positive ΔT for EC2 unit because of the increase of the electric field; in step 2 it experiences heat transfer with constant electric field; in step 3 there is a negative ΔT for EC2 unit because the decreasing of the electric field; in step 4 it conducts heat transfer. The EC1 unit has the converse process in one cycle. In a period, EC1 unit absorbs heat from the cooling load while EC2 unit release heat to heat sink. In a stable state, the balance arrives when the absorbed, transferred, and released heats are equal. By solving this heat transfer problem, the EC effect on heat transfer of the proposed structure is revealed.

The geometrical and physical parameters of a commercial $\rm BaTiO_3$-based Y5V MLCC were applied during the calculation. Since $\rho_{\rm EC} = 5840$ kg·m^{-3}, $c_{\rm EC} = 434$ J·K^{-1}·kg^{-1}, $L =$ 3.3 mm, the effective width $W = 2.56$ mm, the thickness $d =$ 6.5 μm, the thermal capacitance $C_{\rm EC}$ is 1.391×10^{-4} J·K^{-1}. Since $\rho_{\rm e} = 8907$ kg·m^{-3}, $c_{\rm e} = 429$ J·K^{-1}·kg^{-1}, $k_{\rm e} =$ 94 W·K^{-1}·m^{-1}, the thickness $d = 2.0$ μm, the thermal capacitance $C_{\rm e}$ is 6.46×10^{-5} J·K^{-1}, and the thermal resistance $R_{\rm e}$ is 2.52×10^{-3} K·W^{-1}.

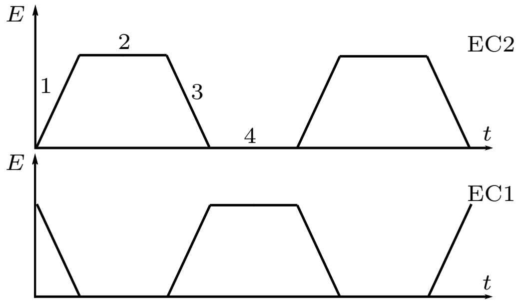

Fig. 2. The sequential electric fields applied to each EC units.

By assuming that the EC temperature change of the EC unit is 0.5 K.[23] The transferred heat during one cycle is calculated, which is the case 1 in Fig. 3. After calculating the overall thermal resistance of the proposed structure and the time constant, the heat transfer of the structure without the EC effect is gotten and plotted in Fig. 3 also, which is case 2. Finally, if the EC units are replaced by Ni metals, the heat transfer is plotted as the case III in Fig. 3. Obviously, although the heat transfer is less effective in comparison with the metal Ni, the EC effect prompts heat transfer significantly.

From the simulated result, the effective thermal conductivity of the proposed structure is 53.35 W·m^{-1}·K^{-1}, which is 20 times larger than that of the $\rm BaTiO_3$-based ceramics.[32]

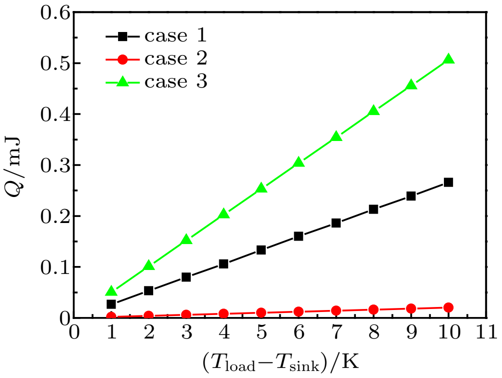

Fig. 3. The transferred heat Q as a function of the temperature difference between load and heat sink $(T_{\rm load} - T_{\rm sink})$. Here, case 1 is the transferred heat of the proposed MLCC with EC effect, case 2 is the transferred heat of the same structure without EC effect, and case 3 is the transferred heat of the same structure replacing EC layers with Ni metal.

4. Conclusion and perspectives

In conclusion, after designing a simple MLCC structure and applying the proper sequential electric field, the result shows that the EC effect can fast heat transfer significantly. The effective thermal conductivity is 20 times larger than that of $\rm BaTiO_3$-based Y5V ceramic. Our result demonstrates a novel strategy of applying the EC effect, prompting heat transfer.

References

[1] Valant M 2012 *Prog. Mater. Sci.* **57** 980
[2] Moya X, Kar-Narayan S and Mathur N D 2014 *Nat. Mater.* **13** 439
[3] Liu H and Yang X 2015 *AIP Adv.* **5** 117134

[4] Liu H 2017 *Chin. Phys. B* **26** 117701

[5] Liu H 2018 *Chin. Phys. B* **27** 127701

[6] Mischenko A, Zhang Q, Scott J, Whatmore R and Mathur N 2006 *Science* **311** 1270

[7] Shirsath S E, Cazorla C, Lu T, Zhang L, Tay Y Y, Lou X, Liu Y, Li S and Wang D 2020 *Nano Lett.* **20** 1262

[8] Si M, Saha A K, Liao P Y, Gao S, Neumayer S M, Jian J, Qin J, Wisinger N, Wang H, Maksymovych P, Wu W, Gupta S K and Ye P D 2019 *ACS Nano* **13** 8760

[9] Zhao C, Yang J, Huang Y, Hao X and Wu J 2019 *J. Mater. Chem. A* **7** 25526

[10] Li G, Li J, Li F, Li Y, Liu X, Jiang T, Yan F, He X, Shen B and Zhai J 2020 *J. Alloys Compd.* **817** 152794

[11] Pirc R, Rožič B, Koruza J, Malič B and Kutnjak Z 2014 *Europhys. Lett.* **107** 17002

[12] Geng W, Liu Y, Meng X, Bellaiche L, Scott J F, Dkhil B and Jiang A 2015 *Adv. Mater.* **27** 3165

[13] Jia Y and Sungtaek Ju Y 2012 *Appl. Phys. Lett.* **100** 242901

[14] Gu H, Qian X, Li X, Craven B, Zhu W, Cheng A, Yao S C and Zhang Q M 2013 *Appl. Phys. Lett.* **102** 122904

[15] Plaznik U, Kitanovski A, Rožič B, Malič B, Uršič H, Drnovšek S, Cilenšek J, Vrabelj M, Poredoš A and Kutnjak Z 2015 *Appl. Phys. Lett.* **106** 043903

[16] Defay E, Faye R, Despesse G, Strozyk H, Sette D, Crossley S, Moya X and Mathur N D 2018 *Nat. Commun.* **9** 1827

[17] Plaznik U, Vrabelj M, Kutnjak Z, Malič B, Rožič B, Poredoš A and Kitanovski A 2019 *Int. J Refrig.* **98** 139

[18] Epstein R I and Malloy K J 2009 *J. Appl. Phys.* **106** 064509

[19] Neusel C and Schneider G A 2014 *J. Mech. Phys. Solids* **63** 201

[20] Israel C, Mathur N D and Scott J F 2008 *Nat. Mater.* **7** 93

[21] Israel C, Kar-Narayan S and Mathur N D 2008 *Appl. Phys. Lett.* **93** 173501

[22] Israel C, Petrov V M, Srinivasan G and Mathur N D 2009 *Appl. Phys. Lett.* **95** 072505

[23] Kar-Narayan S and Mathur N 2010 *J. Phys. D: Appl. Phys.* **43** 032002

[24] Kar-Narayan S and Mathur N D 2009 *Appl. Phys. Lett.* **95** 242903

[25] Crossley S, McGinnigle J R, Kar-Narayan S and Mathur N D 2014 *Appl. Phys. Lett.* **104** 082909

[26] Smith N A S, Rokosz M K and Correia T M 2014 *J. Appl. Phys.* **116** 044511

[27] Sette D, Asseman A, Gérard M, Strozyk H, Faye R and Defay E 2016 *APL Mater.* **4** 091101

[28] Lu B, Wen X, Tang Z, Liang B, Tao T, Xie Z, Zhang T, Tang X, Xiang Y, Liao J and Lu S 2016 *Sci. China-Technol. Sci.* **59** 1054

[29] Faye R, Strozyk H, Dkhil B and Defay E 2017 *J. Phys. D: Appl. Phys.* **50** 464002

[30] Moya X, Defay E, Mathur N D and Hirose S 2018 *MRS Bull.* **43** 291

[31] Nair B, Usui T, Crossley S, Kurdi S, Guzmán-Verri G G, Moya X, Hirose S and Mathur N D 2019 *Nature* **575** 468

[32] He Y 2004 *Thermochim. Acta* **419** 135