Journal of Alloys and Compounds 509 (2011) 6920–6923

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Influence of magnetic fields on the mechanical loss of Terfenol-D/$PbZr_{0.52}Ti_{0.48}O_3$/Terfenol-D laminated composites

Yiping Yao[a], Ying Hou[a], Sining Dong[a], Xiaohua Huang[a], Qingxuan Yu[a], Xiaoguang Li[a,b,*]

[a] Hefei National Laboratory for Physical Sciences at Microscale, Department of Physics, University of Science and Technology of China, Hefei 230026, China
[b] International Center for Materials Physics, Academia Sinica, Shenyang 110015, China

ARTICLE INFO

Article history:
Received 16 February 2011
Received in revised form 31 March 2011
Accepted 31 March 2011
Available online 7 April 2011

Keywords:
Magnetoelectric composite
Mechanical energy dissipation
Domain wall motion

ABSTRACT

The influence of magnetic fields on the mechanical loss (Q^{-1}) of Terfenol-D/$PbZr_{0.52}Ti_{0.48}O_3$/Terfenol-D three-layer laminated composites is investigated systemically using the technique for measuring the resonance magnetoelectric (ME) effect. The results indicate that Q^{-1} varies non-monotonically with dc magnetic fields and shows a maximum near 500 Oe for all the samples with different layer thickness ratios (n) of Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$). Considering various kinds of mechanical energy dissipation, it is found that Q^{-1} is mainly dominated by the mechanical damping due to the domain wall motion in Terfenol-D under the actions of dc and ac magnetic fields as well as the stress at the interface. In addition, the effect of eddy current losses on the energy dissipation of the system is also discussed.

1. Introduction

The magnetoelectric (ME) effect induced by polarization/magnetization in magnetic/electric fields [1–3] is of fundamental and technological importance. Because the composite consisting of magnetostrictive and piezoelectric phases is expected to show a much stronger ME effect than that of single-phase ME materials, a number of possible applications based on this strain-mediated ME coupling have attracted a surge of interest, such as multifunctional sensors [4], filters [5] and power harvesting [6]. Extensive efforts for obtaining a strong ME effect were carried out in ME composites with ferrite, shape memory alloys or Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$) as magnetostrictive components and leadmagnesio-niobate single crystal or lead zirconate titanate $PbZr_{1-x}Ti_xO_3$ (PZT) ceramics as piezoelectric components [7–11]. A ME laminate composite composed of Terfenol-D and PZT is of particular interest due to the relative large piezoelectric/piezomagnetic coefficient as well as low cost. Many different configurations, including disk, rectangular and ring shapes, for this kind of composites were investigated [11–13], and the ME voltage coefficient can reach as high as several V Oe^{-1} cm^{-1} at a quasi-static frequency [13–15].

For the resonance situation, the ME coefficient is not only determined by the structures or operation modes but also related to the electromechanical coupling which closely depends on the energy dissipation, especially mechanical losses [16,17]. The mechanical losses in Terfenol-D and PZT have been widely investigated. It was reported that the magnetomechanical damping of Terfenol-D measured from the strain-stress hysteresis loop at low frequencies indicates that the energy dissipation is closely related to the non-180° ferromagnetic domain-wall movement induced by magnetic fields and prestress [18–22], and the mechanical loss in PZT is mainly attributed to the irreversible ferroelectric domain-wall movement [17]. However, little effort has been devoted to studying the variation of the mechanical energy dissipation Q^{-1} for Terfenol-D/PZT ME composite. Furthermore, several other crucial questions such as the influences of magnetic fields and frequencies on Q^{-1} in this ME composite are also unclear so far.

In this paper, we systemically investigate the mechanical energy dissipation in the laminate composite composed of Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$) and $PbZr_{0.52}Ti_{0.48}O_3$ (PZT). As the magnetic domain wall motion in Terfenol-D strongly depends on magnetic fields, the investigations of the ratio between Terfenol-D and PZT as well as magnetic field effects on Q^{-1} can effectively clarify mechanical losses of the system in nature. Our experimental results show that the mechanical energy dissipation of the composite is mainly dominated by the mechanical damping of Terfenol-D and can influence the resonance ME coefficient $\alpha_{ME,R}$.

2. Experimental

Three-layer laminates of Terfenol-D/PZT/Terfenol-D with different thickness ratios (n) for Terfenol-D were fabricated, here n is defined as $2t_{TFD}/(2t_{TFD}+t_{PZT})$, t_{TFD} and t_{PZT} represent the thicknesses of Terfenol-D and PZT plates, respectively. The PZT component with a size of 12 × 4 × 1 mm^3 (t_{PZT} = 1 mm for all samples) was polarized under an electric field of 3 kV/mm at 120 °C in silicon oil in the thickness direction. The grain-oriented ⟨1 1 3⟩ polycrystalline Terfenol-D plates were magnetized along the longitudinal direction to form a longitudinal-transverse configuration and their

---

* Corresponding author at: Hefei National Laboratory for Physical Sciences at Microscale, Department of Physics, University of Science and Technology of China, Hefei 230026, China.

E-mail address: xglixg@gmail.com (X.G. Li).

0925-8388/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2011.03.184

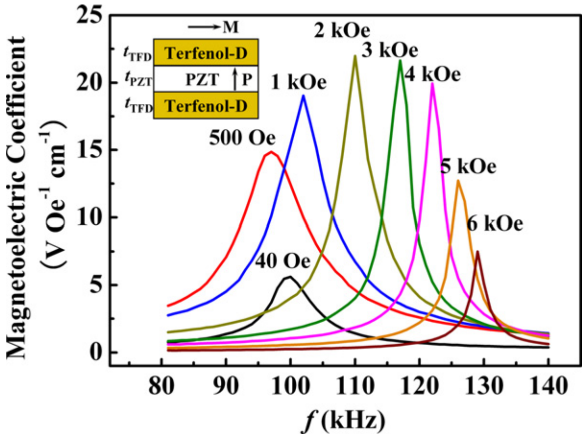

Fig. 1. Frequency dependence of the ME voltage coefficient at H_{ac} = 1 Oe, n = 0.67, and different H_{dc} from 0 to 6 kOe. The inset shows the schematic configuration of the samples.

dimensions were $12 \times 4 \times t_{TFD}$ mm^3. Here, the values of t_{TFD} are 1, 0.5 and 0.25 mm, and thus the values of n are equal to 0.67, 0.5 and 0.33, respectively. The PZT plate was laminated between two Terfenol-D plates using conductive silver epoxy bonder under pressure and the schematic diagram of the samples was shown in the inset of Fig. 1.

The ME voltage coefficient was determined by measuring the electric field generated across the sample with ac magnetic fields (H_{ac}, up to 2 Oe) and dc bias fields (H_{dc}, up to 6 kOe). A signal generator amplified by a power amplifier was used to drive a Helmholtz coil to generate the small H_{ac} superimposed on H_{dc}. The voltage generated across the piezoelectric layer was measured with an oscilloscope or a lock-in amplifier. The ME resonance behaviors were carried out by measuring the ME output around the resonance frequency range with a step of 0.5 kHz.

3. Results and discussion

Fig. 1 shows the frequency dependence of resonance ME properties of the Terfenol-D/PZT/Terfenol-D laminates for n = 0.67 under different H_{dc} with superimposed H_{ac} of 1 Oe. The resonance ME coefficient ($\alpha_{ME,R}$) increases with increasing magnetic bias and reaches up to ~23 V cm^{-1} Oe^{-1} at a resonance frequency f_r of 110 kHz under H_{dc} = 2 kOe. One of the most interesting results is that as H_{dc} increases, the resonance frequency f_r decreases at first, reaches its minimum near 400 Oe and then shifts up as shown in Fig. 2. This non-monotonic shift in f_r is due to the variation of Young's modulus caused by the domain wall motions of Terfenol-D under magnetic fields [16]. Furthermore, a decrease of f_r with increasing ac magnetic field H_{ac} is observed at a low H_{dc} range, see the inset of Fig. 2. Larger amplitude of H_{ac} forces the domain walls moving back and forth frequently more easily and thus leads to a decrease in f_r. The slow increase of f_r in the field range from 0.5 kOe to 6 kOe corresponds to the gradual saturation of the magnetization in Terfenol-D [23].

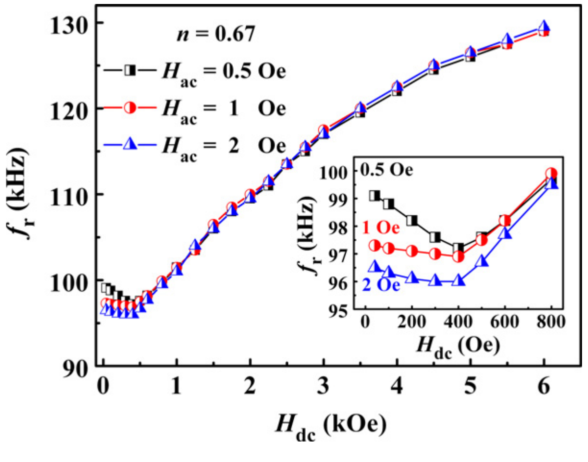

Fig. 2. Variation of the resonance frequency f_r of the Terfenol-D/PZT laminate as a function of H_{dc} for n = 0.67. The inset shows a close view of f_r at low H_{dc} with H_{ac} = 0.5 Oe, 1 Oe, and 2 Oe.

From the frequency dependencies of the ME coefficient, one can estimate the total mechanical energy dissipation (Q^{-1}) defined as $Q^{-1} = \Delta f_r/f_r$ [24], here Δf_r represents the 3 dB frequency bandwidth. Fig. 3(a) and (b) show the dc magnetic field dependencies of Q^{-1} under different H_{ac} and n, respectively. It is found that Q^{-1} has a peak near a dc magnetic field of 500 Oe for all n and H_{ac}, and increases with increasing n and H_{ac}. For a Terfenol-D/PZT ME laminate composite, one can regard that the total mechanical energy dissipation Q^{-1} is mainly composed of the mechanical damping of Terfenol-D ($Q^{-1}_{\text{mech,TFD}}$), mechanical damping of PZT ($Q^{-1}_{\text{mech,PZT}}$), the loss at the interface (Q^{-1}_{face}) between Terfenol-D and PZT. Suppose Q^{-1} can be expressed as:

$$Q^{-1} = nQ^{-1}_{\text{mech,TFD}} + (1-n)Q^{-1}_{\text{mech,PZT}} + Q^{-1}_{\text{face}} = n(Q^{-1}_{\text{mech,TFD}} + Q^{-1}_{\text{face}}) + (1-n)(Q^{-1}_{\text{mech,PZT}} + Q^{-1}_{\text{face}}) \qquad (1)$$

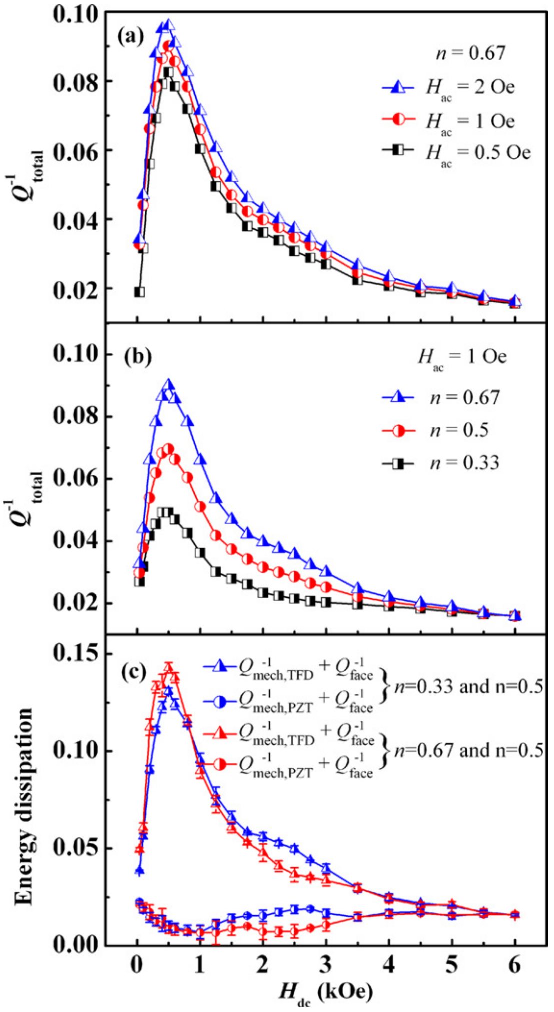

Fig. 3. (a) Total mechanical energy dissipation Q^{-1} of the Terfenol-D/PZT laminate as a function of H_{dc} with H_{ac} = 0.5 Oe, 1 Oe, and 2 Oe for n = 0.67. (b) Q^{-1} as a function of H_{dc} for n = 0.67, 0.5 and 0.33, and H_{ac} = 1 Oe. (c) $Q^{-1}_{\text{mech,TFD}}$ and $Q^{-1}_{\text{mech,PZT}}$ as a function of H_{dc}, the blue and red lines represent the calculated results with {n = 0.33 and 0.5} and {n = 0.5 and 0.67}, respectively(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

Considering Eq. (1) as a linear equation with two different variables as $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$ and $Q^{-1}_{\mathrm{mech,PZT}} + Q^{-1}_{\mathrm{face}}$, one can obtain the H_{dc} dependencies of $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$ and $Q^{-1}_{\mathrm{mech,PZT}} + Q^{-1}_{\mathrm{face}}$ for different n, as shown in Fig. 3(c). The blue and red lines represent the calculated results with $\{n = 0.33 \text{ and } 0.5\}$ and $\{n = 0.5 \text{ and } 0.67\}$, respectively. The overlapping of two group curves proves the self-consistency of our discussion based on Eq. (1). The contributions of all these losses to the total mechanical energy dissipation are discussed as follows:

It is known that the mechanical damping of PZT can be expressed as $Q^{-1}_{\mathrm{mech,PZT}} = 2\pi f_{\mathrm{r}} \left|Z_{\mathrm{m}}\right| C^{\mathrm{T}}(f_{\mathrm{a}}^2 - f_{\mathrm{r}}^2)/f_{\mathrm{a}}^2$ [25], where f_{a} represents the anti-resonance frequency. The capacitance C^{T} of a standalone PZT plate at a quasi-static frequency (1 kHz) and minimum resonance impendence $|Z_{\mathrm{m}}|$ measured by Agilent 4294A impendence analyzer are about 0.766 nF and 364 Ω, respectively. For $f_{\mathrm{r}} = 109.7$ kHz and $f_{\mathrm{a}} = 114.8$ kHz, one can get $Q^{-1}_{\mathrm{mech,PZT}} \sim 1.9 \times 10^{-2}$. The calculated $Q^{-1}_{\mathrm{mech,PZT}} + Q^{-1}_{\mathrm{face}}$ shown in Fig. 3(c) is in the same order of magnitude as $Q^{-1}_{\mathrm{mech,PZT}}$ but much smaller than $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$, indicating that Q^{-1}_{face} has little contribution to $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$.

Now turn our attention to $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$. Because the trends of $Q^{-1}_{\mathrm{mech,TFD}} + Q^{-1}_{\mathrm{face}}$ in Fig. 3(c) are similar to those of the total mechanical energy dissipation Q^{-1} in Fig. 3(a) and (b) and Q^{-1}_{face} has little effect on Q^{-1} as discussed above, one can regard that $Q^{-1}_{\mathrm{mech,TFD}}$ plays a dominant role in the variation of Q^{-1}. It is known that the mechanical loss of Terfenol-D affected by magnetic fields is mainly attributed to the non-180° (that is 71° and 109° in Terfenol-D) domain wall motion [18,19]. Around a characteristic field, for example 500 Oe in our case, the non-180° domain wall motion and magnetostriction in Terfenol-D change very fast, accompanying with the highest strain rate under magnetic fields [26,27], and the mechanical energy losses induced by H_{ac} will reach the maximum. When H_{dc} goes to a higher value, the magnetic domains are almost aligned with each other in the same direction [28]. In this case, a small H_{ac} is hard to affect the magnetic moments as well as domain wall motion of Terfenol-D, and thus the energy loss reduces for further increasing H_{dc} as a result. In other words, a lower energy loss under magnetic fields corresponds to a higher stiffness, as indicated by the resonance frequency f_{r} dependences of Q^{-1} under different H_{ac} for $n = 0.67$, see Fig. 4. In addition, the peak values of $Q^{-1}_{\mathrm{mech,TFD}}$ at resonance frequency in our experiments are comparable to these of the magnetomechanical loss obtained from the strain-stress loop at low frequencies reported in Refs. [18,19]. Besides magnetic fields, the stress applied on Terfenol-D from PZT at the interface is another key factor affecting the magnetomechanical properties of Terfenol-D. The stress tends to rotate the domain walls away from the magnetization direction and prevents the saturation of magnetostriction [23,29]. Under the action of the stress, the corresponding magnetic field for the maximum domain wall motion in the ME composite is shifted away from that of a standalone Terfenol-D [30,31].

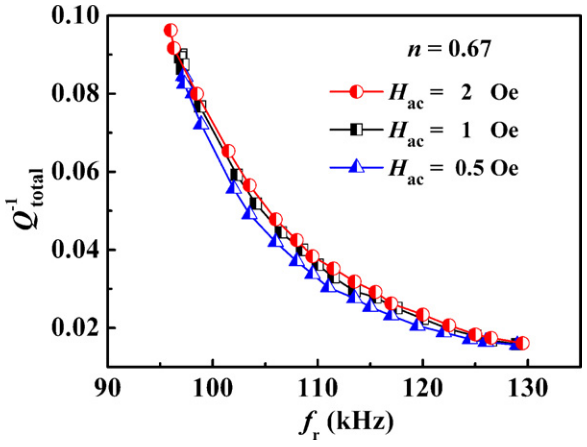

Fig. 4. f_{r} dependencies of Q^{-1} under $H_{\mathrm{ac}} = 0.5$ Oe, 1 Oe, and 2 Oe for $n = 0.67$.

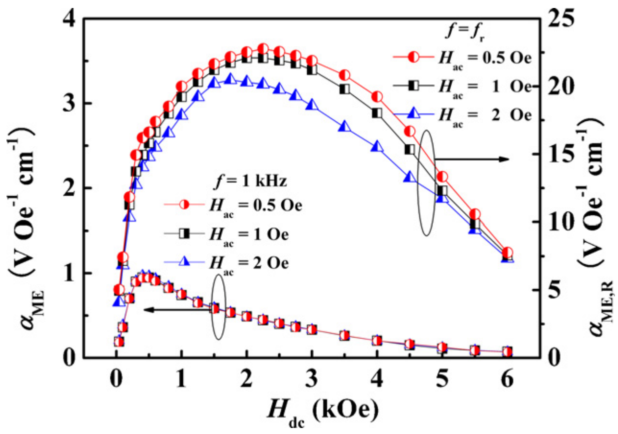

Fig. 5. H_{dc} dependencies of quasi-static ME voltage coefficient α_{ME} and resonance ME voltage coefficient $\alpha_{\mathrm{ME,R}}$ of the system with $n = 0.67$ under $H_{\mathrm{ac}} = 0.5$ Oe, 1 Oe, and 2 Oe. The study on the mechanical energy dissipation (Q^{-1}) of ME laminates composed of Terfenol-D and PZT utilizing the resonance ME effect was carried out, which has not been systemically reported so far. Three new results were obtained.

To deeply understand the mechanical energy dissipation and resonance ME effect of the system, the relation between Q^{-1} and magnetoelectric effect should be considered. Fig. 5 shows the H_{dc} dependencies of $\alpha_{\mathrm{ME,R}}$ at f_{r} and α_{ME} at a quasi-static frequency of 1 kHz for $n = 0.67$ under different H_{ac}. One can regard that with increasing H_{ac} from 0.5 Oe to 2 Oe the apparent decreases of $\alpha_{\mathrm{ME,R}}$ are closely related to the increase of Q^{-1} (see Fig. 3(a)) although α_{ME} at 1 kHz changes little. As we know, α_{ME} is roughly proportional to the piezomagnetic coefficient of Terfenol-D ($d_{33,\mathrm{m}}$) which has a maximum around 500 Oe [15], and thus α_{ME} shows a maximum at this field. While for the resonance situation, under the influences of both $d_{33,\mathrm{m}}$ and Q^{-1}, $\alpha_{\mathrm{ME,R}}$ increases till $H_{\mathrm{dc}} = 2$ kOe, and then decreases with further increasing H_{dc}. This implies that the difference between α_{ME} and $\alpha_{\mathrm{ME,R}}$ with H_{dc} shown in Fig. 5 are closely related to the total mechanical energy dissipation of the system.

It should be pointed out that there is a magnetic loss besides the mechanical energy dissipation in this ME composite. In the frequency range of our experiments (~100 kHz), the magnetic loss (Q^{-1}_{eddy}) mainly caused by eddy current may reduce the magnetization and effective magnetostriction of Terfenol-D [32,33]. In this case, Q^{-1}_{eddy} can influence the magneto-mechanical energy conversion process of the composite via magnetoelectric coupling at the interface. However, it is difficult to obtain the contribution of Q^{-1}_{eddy} to Q^{-1} quantitatively through our experiments by analyzing the mechanical resonance of the ME composite because Q^{-1}_{eddy} characterizes the magnetic energy dissipation. The relationship between magnetic and mechanical energy dissipations and the questions about how to overcome Q^{-1}_{eddy} need further investigations.

4. Conclusions

The systemic study on the mechanical energy dissipation of ME laminates composed of Terfenol-D and PZT utilizing the resonance ME effect was carried out. The contribution of each loss is clarified via the analysis of resonance ME effect with different n and magnetic fields. The results indicate that Q^{-1} is mainly dominated by the mechanical energy dissipation of Terfenol-D due to the domain wall motion under the influence of magnetic fields and the stress at the interface.

Acknowledgments

This work is supported by the National Natural Science Foundation of China and the National Basic Research Program of China (2009CB929502 and 2011CBA00102).

References

[1] C.W. Nan, M.I. Bichurin, S.X. Dong, D. Viehland, G. Srinivasan, J. Appl. Phys. 103 (2008) 031101.
[2] S.M. Wu, S.A. Cybart, P. Yu, M.D. Rossell, J.X. Zhang, R. Ramesh, R.C. Dynes, Nat. Mater. 9 (2010) 756.
[3] K.F. Wang, J.M. Liu, Z.F. Ren, Adv. Phys. 58 (2009) 321.
[4] S.X. Dong, J.Y. Zhai, F. Bai, J.F. Li, D. Viehland, Appl. Phys. Lett. 87 (2005) 062502.
[5] L.N. Su, P. Liu, Y. He, J.P. Zhou, L. Cao, C. Liu, H.W. Zhang, J. Alloys Compd. 494 (2010) 330.
[6] P. Finkel, S.E. Lofland, E. Garrity, Appl. Phys. Lett. 94 (2009) 072502.
[7] J. Ma, Y.H. Lin, C.W. Nan, J. Phys. D: Appl. Phys. 43 (2010) 012001.
[8] S.Y. Chen, Q.Y. Ye, W. Miao, D.H. Wang, J.G. Wan, J.M. Liu, Y.W. Du, Z.G. Huang, S.Q. Zhou, J. Appl. Phys. 107 (2010) 09D901.
[9] S.X. Dong, J.F. Li, D. Viehland, Appl. Phys. Lett. 83 (2003) 2265.
[10] Y.D. Xu, G. Wu, H.L. Su, M. Shi, G.Y. Yu, L. Wang, J. Alloys Compd. 509 (2011) 3811.
[11] L. Li, X.M. Chen, Appl. Phys. A-Mater. 98 (2010) 761.
[12] Z. Shi, C.W. Nan, J. Zhang, N. Cai, J.F. Li, Appl. Phys. Lett. 87 (2005) 012503.
[13] S.X. Dong, J.F. Li, D. Viehlanda, J. Appl. Phys. 96 (2004) 15.
[14] J. Ryu, S. Priya, A.V. Carazo, K. Uchino, H.E. Kim, J. Am. Ceram. Soc. 84 (2001) 2905.
[15] S.X. Dong, J.F. Li, D. Viehland, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 50 (2003) 1253.
[16] G. Srinivasan, C.P. De Vreugd, V.M. Laletin, N. Paddubnaya, M.I. Bichurin, V.M. Petrov, D.A. FIlippov, Phys. Rev. B 71 (2005) 184423.
[17] K. Uchino, J.H. Zheng, Y.H. Chen, X.H. Du, J. Ryu, Y. Gao, S. Ural, S. Priya, J. Mater. Sci. 41 (2006) 217.
[18] M. Wun-Fogle, J.B. Restorff, A.E. Clark, J. Snodgrass, IEEE Trans. Magn. 39 (2003) 3408.
[19] T.Y. Ma, C.B. Jiang, F. Xiao, L.M. Yu, H.B. Xu, Y.M. Pei, D.N. Fang, J. Appl. Phys. 100 (2006) 023901.
[20] K.B. Hathaway, A.E. Clark, J.P. Teter, Metall. Mater. Trans. A 26 (1995) 2797.
[21] J.P. Teter, K.B. Hathaway, A.E. Clark, J. Appl. Phys. 79 (1996) 6213.
[22] Y.M. Pei, X. Feng, X. Gao, D.N. Fang, J. Alloys Compd. 476 (2009) 556.
[23] W.D. Armstrong, J. Appl. Phys. 81 (1997) 3548.
[24] F. Wang, Y.M. Wen, P. Li, M. Zheng, L.X. Bian, Sens. Actuators A-Phys. 141 (2008) 129.
[25] Y. Li, Z.K. Qian, Z.G. Zhou, Measurement of Piezoelectric and Ferroelectric Materials, Science Press, Beijing, 1984.
[26] A. Branwood, A.L. Janio, A.R. Piercy, J. Appl. Phys. 61 (1987) 3796.
[27] B.W. Wang, S.C. Busbridge, Y.X. Li, G.H. Wu, A.R. Piercy, J. Magn. Magn. Mater. 218 (2000) 198.
[28] G.W. Smith, J.R. Birchak, J. Appl. Phys. 40 (1969) 5174.
[29] A.E. Clark, J.P. Teter, O.D. McMasters, J. Appl. Phys. 63 (1988) 3910.
[30] W.J. Park, D.R. Son, Z.H. Lee, J. Magn. Magn. Mater. 248 (2002) 223.
[31] D. Kendall, A.R. Piercy, J. Appl. Phys. 76 (1994) 7148.
[32] R.D. Greenough, M. Schulze, IEEE Trans. Magn. 26 (1990) 2586.
[33] D. Kendall, A.R. Piercy, J. Appl. Phys. 73 (1993) 6174.