JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 9, No. 5, May 2007, p. 1511 - 1515

A PZT type piezoceramic material with high planar coupling factor used for a miniature bimorph ventilator

C. MICLEA[*], A. IUGA, C. TANASOIU, L. AMARANDE, M. CIOANGHER, C. T. MICLEA[a]
National Institute for Materials Physics, Bucharest-Magurele, Romania
[a]*Hyperon University, Faculty of Physics, Str. Calarasilor 169, Bucharest, Romania*

New PZT type ceramic materials, doped with Ni, were prepared by the usual solid state reaction. The best composition proved to be the one containing 6% atomic Ni and having the following chemical formula: $Pb_{0.95}Bi_{0.03}Nb_{0.02}Zr_{0.51}Ti_{0.43}Ni_{0.06}O_3$. Rectangular samples of this powder were pressed and sintered at 1200 °C for 4 hours and then it was cut in thin slices used to construct an efficient bimorph type ventilator to be used in miniaturized devices for cooling. Miniature ventilators made of PZT ceramics are preferred due to their smallness, high electromechanical efficiency and lack of rotating parts and last but not least of contiguous electrical contacts. We made such a device by using two thin ceramic PZT plates of the material with the best piezoelectric properties, assembled in a flexural oscillator through a proper bimorph association. The emerging doublet behaves itself very much like a bimetal system and possesses a good developed flexural mode. Attaching a metallic elastic plate to the bimorph produces a highly efficient miniature ventilator. A theoretical quantitative study of this flexural bimorph system with elastic plate attached was proposed.

(Received November 14, 2006; accepted April 12, 2007)

Keywords: PZT, Powder solid state reaction, Piezoelectric properties, Bimorph transducer

1. Introduction

Ceramics based on lead titanate-lead zirconate solid solution, known as PZT materials, find numerous application in all fields of activity [1-4]. Piezoelectric transducers made from such materials convert mechanical energy into electrical one and vice versa by means of their fundamental property to generate electric charge in the presence of mechanical stress (direct piezoelectric effect) and, conversly, to develop a dimensional deformation when subjected to an electrical field (converse piezoelectric effect). The choice of a particular piezoelectric material depends on the specific application to which the transducer is destined, but, in any case, its quality is directly dependent on the electromechanical coupling factor of the material in the way that a high k_p factor is nearly always desirable [5]. The properties of the ceramic material may be rather easily controlled by a proper replacement of the basic constituents with another izo or aliovalent ions in a manner in which the composition has to remain centered within the morphotropic phase boundary, where the piezoelectric properties show maximum values [6-8].

For the application we are presenting here, we have chosen a PZT type material, modified with Ni, since there were indication [9] that Ni can modify substantially the mechanical coupling factor k_p and the displacement constant d_{33}. Here we report on the material preparation and its main piezoelectric properties as well as the special transducer made from it, specifically a miniature bimorph ventilator.

2. Experimental

2.1. Preparation of the material

We investigated in the present work a soft type PZT material, doped with nickel having the general chemical formula: $Pb_{0.95}Bi_{0.03}Nb_{0.02}Zr_{0.51}Ti_{0.49-x}Ni_xO_3$, with $0.00 \leq x \leq 0.10$. The raw materials used for the experiment were oxides of p.a. purity. The materials were processed by the conventional ceramic technique with the following detailed data: six charges of oxide mixtures, with the stoichiometry corresponding to x=0.00; 0.02; 0.04; 0.06; 0.08 and 0.10 respectively were prepared. The stoichiometric amounts of oxides were wet mixed for 2 hours by means of a planetary ball mill, in agate vials of 400 ml capacity, using agate balls of about 10 mm diameter in a weight ratio: ball/oxides/acetone of 100/50/150. The mixed slurries were dried with continuous agitation on electrically heated plates, then manually crushed and sieved and then double calcined at 850 °C and 950 °C respectively for 2 hours with an intermediate milling of 3 hours and a final milling of 24 hours. BET measurements of the final milled powders gave an average specific surface area between 20-22 m^2/g corresponding to an average particle diameter of about 200 nm. In order to characterize the material we pressed from this powders standard disc shaped samples of 15 mm diameter and about 2 mm thick in a steel die at a pressure of about 50 MPa. The pressed samples were then sintered in dense alumina crucibles at temperatures between 1050 and 1300 °C for 4 hours. The density of each sintered sample was determined by Archimede’s method. Next, the sintered samples were mechanically processed by grinding up to a final dimension of 10 mm diameter and 1 mm thick. After ultrasonically cleaning and thermally recovery at 700 °C for 1 hour, the samples were silver electroded on both plan parallel faces and poled in a silicon oil bath at 220 °C under an electric field of 3 KV/mm. Piezoelectric properties were measured 24 h after poling by using the resonance spectroscopy and a HP 4194A Impedance gain/phase analyzer.

2.1.1. Material characteristics

Fig. 1 illustrates the behavior of the densities of sintered samples as a function of the sintering temperature for different composition doped with Ni. One can see that there is an optimum sintering temperature centered on 1200 °C where the densities reach maximum values. With increasing the dopant concentration *x* the densities increase, reaching the highest values for the composition with x=0.06 and then decreasing again. This behavior is well illustrated in the graph from Fig. 2 where a maximum density of 7.87 g/cm^3 (corresponding to about 98.5% of the theoretical density) was reached.

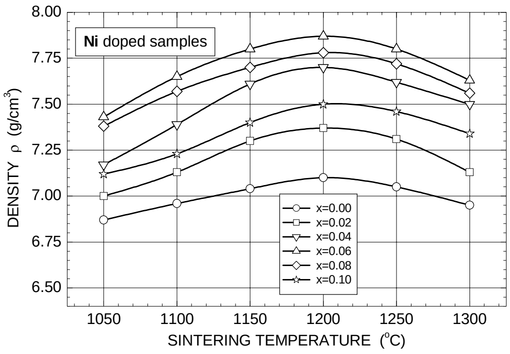

Fig. 1. The dependence of the density on the sintering temperature for Ni doped samples.

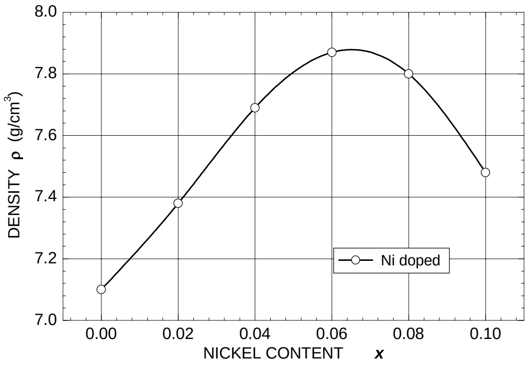

Fig. 2. The behavior of the maximum values of the density as a function on the Ni content.

Therefore the piezoelectric properties were determined only on samples with maximum densities, i.e. the samples sintered at 1200 °C.

Fig. 3 shows the dependence of the planar coupling coefficient k_p on the dopant concentration. As one can see k_p reaches a maximum value of 0.665 for the composition with x=0.06. The same trends and behaviors was recorded also for charge constant d_{33} which reached a value of 625 pm/V for the same composition as can be seen in Fig. 4.

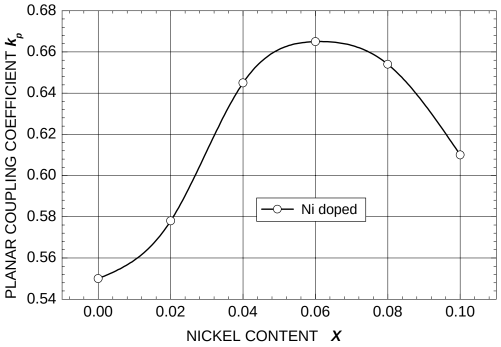

Fig. 3. The dependence of the planar coupling factor k_p on the Ni content.

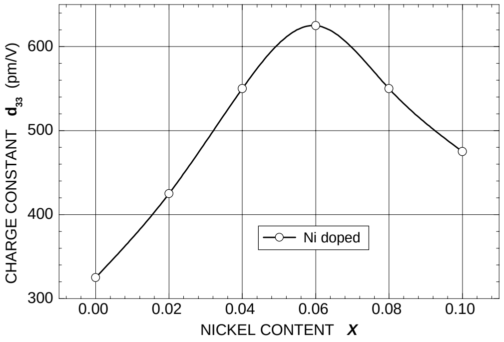

Fig. 4. The dependence of the charge constant d_{33} on the Ni content.

2.2. The bimorph transducer

The heart of any transducer is the piezoceramic active element. For the bimorph type ventilator we used thin plate like ceramics, and consequently we pressed a rectangular ceramic body of 60×15×20 mm^3 from the material with highest properties, that is with x=0.06 Ni, and sintered it at the optimum temperature of 1200 °C for 4 hours. After sintering we cut this block into thin slices and mechanically processed them to the final dimensions of 50×10×0.5 mm^3. Their main faces were electroded with

Ni by using an electroless procedure. After poling they were ready to construct the bimorph transducer.

The flexural ventilator uses the lateral mode of vibration of the two pieces of piezoceramic material clamped together with their electrical polarization parallel. An antiparallel electric field will drive them in opposite directions, so that a minimizing potential energy shape will be adopted, i.e. a flexural one. When the driving electrical force is oscillating, the system will execute flexural mechanical oscillations with the same frequency. In order to be more effective this oscillations can be amplified using a thin steel blade driven by the ceramics. This steel blade posseses a lower acoustic impedance and provides a better impedance matching of the transducer with the surrounding air, so that more acoustic power is emitted into the air and more air is moved.

The rectangular pieces of ceramic are fixed together with a metallic blade using a conductive resin as shown in Fig. 5. Electrical connections are made to both plates and to the central metallic blade so that the system is connected in derivation. The system is clamped at one end by an "infinite mass" and the other end is free.

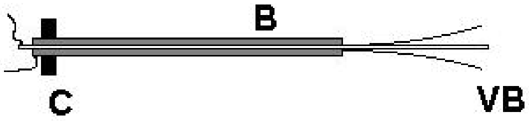

Fig. 5. A cross section view of the flexural ventilator: C - clamping masses, B – piezoceramic bimorph, VB – vibrating metallic blade.

2.2.1. The bimorph characteristics

Fig. 6 illustrates the frequency response of the ventilator, measured using a driving electrical oscillator with a peak to peak amplitude of the signal of 90 V. The amplitude of the free end of the metallic blade was measured using an optical method.

As one can see the maximum amplitude of about 9.5 mm is attained for a frequency of 49.8 Hz and the general behavior of the frequency response resemble fairly well the usual Lorentian curve (full line) characteristics for a medium damped oscillator.

As for the mechanical response of the transducer for the fixed maximum frequency of 49.8 Hz versus the driving *emf* it is illustrated in the plot of Fig. 7. One can observe the liniar increase of amplitude with increasing electrical signal.

The connection between the length of the ceramic bimorph and the resonance frequency and amplitude was measured in very similar conditions but varying the position of the clamping point and the results are shown in Fig. 8.

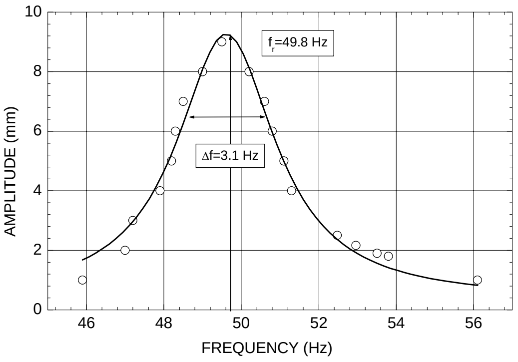

Fig. 6. The amplitude of the metallic blade at the free end as a function of the frequency of the bimorph construction for a driving emf of 90 V_{pp}.

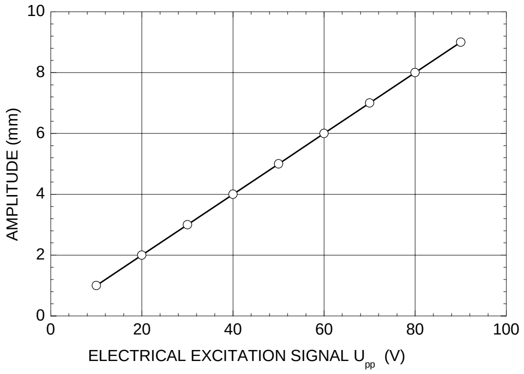

Fig. 7. The mechanical response of the ventilators as a function of the emf signal for a given frequency.

One observes that while the frequency remains practically constant for any ceramic blade length, the amplitude vary and show a rather steady increase with increasing length.

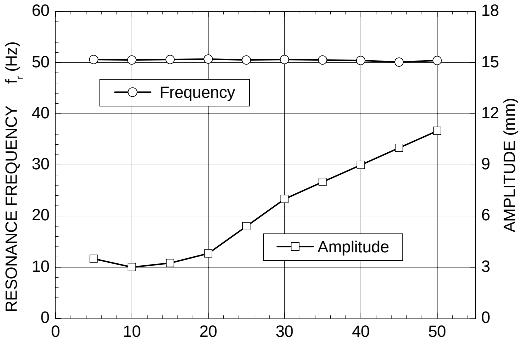

Fig. 8. The resonance and amplitude dependence of the length of the free and of the ventilator.

One can see from Fig. 6 that the frequency response of the transducer resembles fairly well the usual *lorenzian* curve characteristic for medium damped oscillators. The width of the spectrum is *3.1 Hz* at *3 dB* under the peak which corresponds to a mechanical *Q number* of about *16*.

The *emf* response shown in Fig. 7 is completly linear, which is an indication that the transducer works in the linear regime. Fig. 8, suggests that, at least in the measured frequency range, there is no significant dependence between the resonance frequency and the linear dimensions of the ceramic bimorph. This allows a great simplification in the modeling of the ventilator: the metallic blade can be considered as an oscillator *per se*, driven by some external driver (the bimorph) and it establishes the resonance of the whole resonator. In order to verify this assumption we considered the free part of the metallic blade as being a particular case of a lateral oscillating bar one end clamped and the other end free. The equation of motion of such a bar [10, 11] can be approximated as:

$$\frac{\partial^2 u}{\partial \tau^2} + k^2 b^2 \frac{\partial^4 u}{\partial x^4} = 0 \qquad (1)$$

with the boundary conditions for the clamped end:

$$u(0) = 0 \text{ and } \left|\frac{\partial u}{\partial x}\right|_{x=0} = 0 \qquad (2, 3)$$

and for the free end are as follows:

$$\left|\frac{\partial^2 u}{\partial x^2}\right|_{x=l} = 0 \qquad \text{and}$$

$$\left|\frac{\partial^3 u}{\partial x^3}\right|_{x=l} = 0\,. \qquad (4, 5)$$

In equation 1 b represents the velocity of the compressional waves through the particular material from which the bar is made of, and k^2, the moment of inertia of a transversal section through the bar relative to its central equilibrium line, versus its cross sectional area. In these conditions the frequency of the bar with rectangular cross section is given by:

$$f = \frac{k \cdot b}{2\pi \cdot l^2} m^2 \text{ where } k^2 = \frac{1}{12} t^2\,. \qquad (6, 7)$$

Here t is the blade thickness and l its length and for the first clamped-free mode, m is a constant equal to 1.875.

The shape of the blade will be described by a linear combination of trigonometric and hyperbolic sines and cosines:

$$\begin{aligned} u = (\sin m + \sinh m)\{\cos\frac{m \cdot x}{l} - \cosh\frac{m \cdot x}{l}\} - \\ -(\cos m + \cosh m)\{\sin\frac{m \cdot x}{l} - \sinh\frac{m \cdot x}{l}\} \end{aligned} \qquad (8)$$

From all these a natural and legitimate process of reasoning ensues: why not design the ceramic bimorph itself (which plays the role of the driver), at resonance. This is expected to increase proportionally (in the limits imposed by the losses) the global response of the ventilator. For a driving frequency of *50 Hz* and the given thickness t of the ceramic bimorph, relations *(6)* and *(7)* grant the necessary length for full resonance as being proportioned to the characteristics of the vibrating blade as follows:

$$\frac{l_2}{l_1} = \sqrt{\frac{b_2}{b_1}\frac{t_2}{t_1}} \qquad (9)$$

where indices *1* refer to the metallic blade and *2* to the ceramic bimorph. Thus knowing the resonant length of the first clamped-free mode of the blade, the value obtained for the ceramic is l_2=12.5 cm. This value for the resonant length of the bimorph explains the uniformity of the frequency response in the squares drawn plot from Fig. 8. The length of the bimorph in those measurements is less than a half from 12.5 cm so that from (6) its resonant frequency should be more than four times greater. When compared with the typical frequency response of the blade from Fig. 6 where a shift of frequency of about 5% suffices to reaching the “far from resonance plateau” this passive behaviour is fully justified.

5. Conclusions

A PZT type piezoceramic material doped with Ni was prepared and characterized. The composition containing 6% at Ni showed maximum values for the piezoelectric properties that is an electromechanical coupling factor $\boldsymbol{k_p}$ of 0.665 and a charge constant $\boldsymbol{d_{33}}$ of 625 pm/V. Using this material in the shape of thin plates a bimorph type ventilator was constructed and analysed.

The strong lateral mode of a piezoceramic plate was converted into flexural vibrations through a parallel rectangular bimorph. The vibrations were communicated to an interstitial metallic blade which, driven at resonance, exhibited large displacements of its free end. The movements of the free part of the blade were successfully assimilated with the lateral vibrations of a bar, subjected to one end clamped and one end free boundary conditions, and driven by the ceramic bimorph. *Thus the resonance properties of the system are dictated mainly by the free part of the metallic blade.* The experiments have proved that in the studied frequency range, the ceramic bimorph plays an insignificant role in the establishment of the value of the resonance frequency. The only important factors in this are the geometrical (thickness and length) and acoustical (velocity of the compressional sonic wave in the material) properties of the free part of the vibrating blade. The shape assumed by the blade in its vibration is given by the specific solution of the equation of movement for the lateral vibrating bar. The whole response of the ventilator could be further increased through a corresponding design of the bimorph itself to the resonance length of a lateral vibrating bar, one end clamped and one free. It follows that the reciprocal influence of the ceramic bimorph and the metallic blade is fairly weak allowing the components of the ventilator to be treated separately.

References

[1] J. Randeraat, R. Setterington, Piezoelectric Ceramics, Phillips Appl. Book, Acad. Press, Mullard, London (1974).

[2] D. Handen, Application of piezoelectric materials, NATO Sci. Ser. High Techn., **76**, 335-346 (2000).

[3] W. Wolny, Application of piezoceramics, Proc. Int. Conf. for End Users (2002).

[4] W. Wolny, Application driven industrial development of piezoceramics, J. Eur. Cer. Soc., **25**, 1971-1976 (2005).

[5] J. Gallego-Suarez, Piezoelectric ceramics and ultrasonic transducers, J. Phys. E Sci. Instr., **22**, 804-806 (1989).

[6] G. Haertling, Ferroelectric Ceramics: History and Technology, J. Am. Cer. Soc., **82**, 797-818 (1999).

[7] B. Jaffe, W. Cook, H. Jaffe, Piezoelectric Ceramics, Acad Press London, New York (1971).

[8] T. Yamamoto. Piezoelectric properties of PZT system, Jpn. J. Appl. Phys., **35**, 5104-5108 (1996).

[9] C. Miclea, C. Tanasoiu, C. F. Miclea, L. Amarande, A. Gheorghiu, F. Sima, Efect of iron and nickel substitution on the piezoelectric properties of a PZT type ceramics, J. Eur. Cer. Soc. **25**, 2397-2400 (2005).

[10] J. Rayleigh, "The Theory of Sound", Dover Publications, New York, 1976.

[11] D. Berlincourt, D. Curran, H. Jaffe, “Piezoelectric and Piezomagnetic Materials and Their Function in “Transducers”, Physical Acoustics, Academic Press 1964.

---

*Corresponding author: cmic@infim.ro