Proc. 3rd CanSmart Workshop on Smart Materials and Structures, 28-29 Sep. (2000) p.31

DEVELOPMENT OF HIGH-STRAIN LOW-HYSTERESIS ACTUATORS USING ELECTROSTRICTIVE LEAD MAGNESIUM NIOBATE (PMN)

D.F. Waechter, D. Liufu, M. Camirand, R. Blacow and S.E. Prasad
Sensor Technology Limited
P.O. Box 97
Collingwood, Ontario
Canada L9Y 3Z4

ABSTRACT

This paper describes the development of high-strain, low-hysteresis actuators using the lead magnesium niobate composition 0.9PMN-0.1PT. The material was fabricated using an economical direct synthesis technique, similar to that used for conventional PZT ceramics. In 0.9PMN-0.1PT a large electrostrictive effect occurs near the broad maxima of the dielectric permittivity. The samples reported here exhibited a strain of over 0.12% at a field of 3.5 MV/m and the maximum dielectric constant at 38 ºC and 100 Hz was over 30,000. The maximum field-dependent d_{33} occurred near 0.4 MV/m and had a value of 1776 pC/N.

The PMN material is suitable for smart structure applications that require precision actuation with low hysteresis. PMN samples have been fabricated in a variety of configurations including disks, plates, tubes and multi-layer stacks. This paper presents electrical, piezoelectric and mechanical data for single-layer samples and for a multi-layer stack.

INTRODUCTION

For the last several years, actuators for smart structure systems have been primarily based on piezoelectric ceramics using lead zirconate titanate (PZT). While this material is readily available in a variety of formulations that can be tailored to particular applications, there are certain gaps in the material property space that may be better filled by other materials. In particular, it is well known that hard PZTs have small hysteresis and small d_{33}, while the softer formulations have higher hysteresis and higher d_{33}. The choice between these formulations typically depends on whether high precision or high displacement is the primary concern, although other considerations such as Currie temperature and dissipation factor often come into play. There currently exists a need for an actuation material that simultaneously achieves both high strain and low hysteresis. Electrostrictive PMN is a leading candidate to fill this need.

PMN is a relaxor perovskite that achieves high strain and low hysteresis near a diffuse Currie transition (ferroelectric to paraelectric). In recent years PMN materials have been extensively studied for sonar applications where a tenfold increase in field-limited energy density compared to similar PZT-based transducers can be achieved (Lindberg, 1996). PMN ceramics are usually combined with a small quantity of ferroelectric lead titanate which determines the temperature, T_m, at which the real part of the dielectric permittivity is a maximum. Sensor Technology Limited recently introduced its BM600 material which consists of 0.9PMN + 0.1 PT and has a T_m value of 38 ºC. This material is the focus of the present work, although other formulations with lower and higher T_m are also being developed by the company. Dielectric and piezoelectric properties of the material as well as strain and hysteresis curves for a single layer disk and a multi-layer stack are presented.

EXPERIMENT

0.9PMN + 0.1 PT ceramic pieces were fabricated in a 25-kg batch using conventional ceramic fabrication techniques. The precursor oxides were combined in powder form and then underwent standard operations of milling and calcining. This was followed by further milling, pressing, bisquing and firing. Surface machining was then performed and silver metallization was applied by screen printing and firing. Unlike piezoelectric ceramics, the electrostrictive PMN does not require poling.

The direct synthesis approach described above is a considerable simplification over the commonly used "columbite process" developed by the Materials Research Laboratory of the Pennsylvania State University (Swartz, 1984). In the latter process MgO and Nb_2O_5 reagents are pre-reacted to form an intermediate $MgNb_2O_6$ phase having the columbite structure. This is then further reacted with PbO to form PMN. The resulting material should have very low concentrations of the undesired pyrochlore since the columbite structure is closer to that of a perovskite than a pyrochlore. However the process is considerably more complex and expensive than the direct synthesis approach used here.

Samples for strain and dielectric property characterization were disk shaped with 10 mm diameter and 1 mm thickness. The samples for biased resonance tests were designed to isolate a particular resonance from competing modes. These included disks with 20 mm diameter and 1 mm thickness, 12x3x1 mm plates and 0.8x0.8x3 mm bars. A stack actuator was fabricated using square elements with 25 x 25 mm^2 surface area and 0.5 mm thickness. 40 such elements were assembled into a 20 mm tall stack using SensorTech's proprietary integrated actuator driver (IAD) technology (Jones et. al., 2000).

The dielectric constant and dissipation factor were measured as a function of temperature and frequency using a Stanford Research Systems Model SR715 LCR meter. The biased resonance technique (Sherrit et. al., 1999) was used to determine the dynamic coupling coefficients. Strain vs. field curves for a disk sample were measured using a linear variable differential transformer (LVDT) coupled to a computer and voltage supply as shown in fig. 1a. A similar arrangement was used to measure displacement vs. voltage curves for the stack actuator in both the direction parallel to the electric field, as shown in fig. 1b, and perpendicular to the field, as shown in fig 1c.

RESULTS

Dielectric Measurements

The dielectric constant and dissipation factor as a function of temperature are shown for three different frequencies in fig. 2. At 100 Hz the dielectric constant reaches a peak of over 30,000 at 38 ^{o}C. The dielectric constant decreases slightly with increasing frequency in the low temperature region but is frequency independent at higher temperatures. The dissipation factor shows considerable variation with temperature and decreases with decreasing frequency. The low frequency dissipation factor near T_m is similar to a soft PZT (~2%) but lower and higher values occur for higher and lower temperatures respectively.

Quasi-Static Strain Measurements

A quasi-static strain vs. field curve measured for a 1 mm thick disk sample is shown in fig. 3. The maximum strain at 3.5 MV/m was over 0.12% and the linear hysteresis at half the maximum field was only ~ 1%. By differentiating the strain curve it is possible to deduce a field-dependent d_{33}. The resulting curve is shown in fig. 4 and has a peak value of 1776 pC/N.

Displacement vs. voltage curves for the PMN stack actuator are shown in fig. 5. The upper curve shows the voltage induced expansion that occurs in the direction of the electric field as measured using the configuration of fig. 1b, while the lower curve shows the voltage induced contraction that occurs in the direction perpendicular to the electric field as measured using the configuration of fig. 1c. The maximum deflection in the parallel case is 10 µm at ±200 V. The ratio of the perpendicular contraction to the parallel expansion is 0.46 and the linear hysteresis of both curves is somewhat greater than that observed in fig. 3. It should be noted however that the maximum voltage for the stack corresponds to a field of only 0.4 MV/m and the results are consistent with a general observation in these materials that the linear hysteresis is larger for smaller peak fields. The maximum strain parallel to the field is 0.05% which is consistent with the fig. 3 results at 0.4MV/m. By comparison, a stack having the same geometry but using a soft PZT material with d_{33} = 580 pC/N would be expected to have a deflection at 200 V of 4.6 µm (deflection = $N \cdot d_{33} \cdot V$, where N = number of layers), which is less than half of the PMN result.

In an additional experiment, the stack was loaded with a 30 N restraining force. The resulting expansion curve was statistically indistinguishable from the unloaded curve of fig. 5. The upper limit of the force drive capability could not be tested with the present apparatus and is likely at least two orders of magnitude larger.

Dynamic Coupling Coefficients

The dynamic coupling coefficients measured at 38 ^{o}C using the biased resonance technique are summarized in table 1. The k_{33} values are over 0.5, although all of the results are a bit lower than those found in typical PZT formulations of both the hard and soft variety.

Table 1. Dynamic Coupling Coefficients @ 38 °C.

Maximum Values		Values @ Peak d_{33}	
k_{33} @ 6kV/cm	0.55	k_{33}	0.53
k_{31} @ 5kV/cm	0.25	k_{31}	0.25
k_p @ 5kV/cm	0.41	k_p	0.38
k_t @ 6 kV/cm	0.47	k_t	0.42

CONCLUSIONS

The 0.9PMN+0.1PT composition provides a range of properties that cannot be achieved with conventional PZT materials and may find applications in a variety of smart structure applications, particularly those requiring large displacement and low hysteresis. When fabricated by the non-columbite direct synthesis approach the material cost is similar to PZT.

ACKNOWLEDGMENTS

The authors thank Drs. B.K. Mukherjee and G. Yang of the Physics Department of the Royal Military College of Canada (Kingston, ON) for their assistance with the biased resonance measurements and Drs. T. Wheat and A. Ahmad of the Canada Centre for Mineral and Energy Technology (Ottawa, ON) for their assistance with the high field strain measurements. Partial funding of this research was provided by the U.S. Office of Naval Research and the Canadian Department of National Defense under the Dual Use of Science and Technology (DUST) program.

REFERENCES

Jones, D.F. and Prasad, S.E., “Integrated Actuator Drivers for Sonar Transducers”, Presented at the 2000 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, State College, Pa, 2000.

Lindberg, J.F., “Application of High Energy Density Transducer Materials to Smart Systems”, Materials for Smart Systems II: MRS Symp. Proc. vol. 459, p. 509, 1996.

Sherrit, S., Catoiu,G. and Mukherjee, B.K., “The Characterization and Modelling of Electrostrictive Ceramics for Transducers”, Ferroelectrics, vol. 228, p. 167, 1999.

Swartz, S.L., Shrout, T.R., Schulze, W.A. and Cross, L.E., J. Amer. Ceram. Soc., vol. 67, p. 311, 1984.

FIGURES

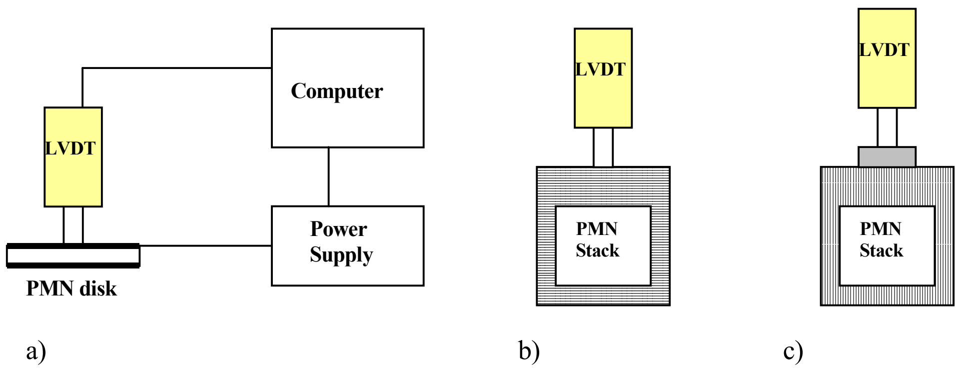

Figure 1. Strain measurement apparatus for a) disk sample, b) stack actuator with strain measured parallel to field, and c) stack actuator with strain measured perpendicular to field.

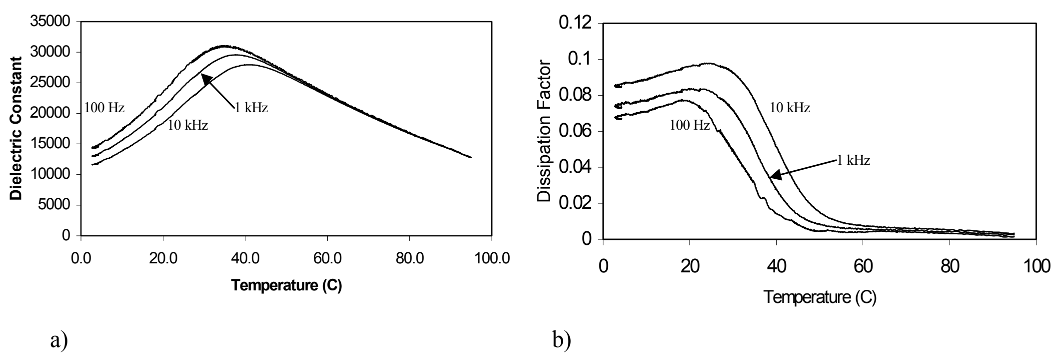

Figure 2. Dielectric properties as a function of temperature for PMN disk sample at three different frequencies; a) dielectric constant and b) dissipation factor.

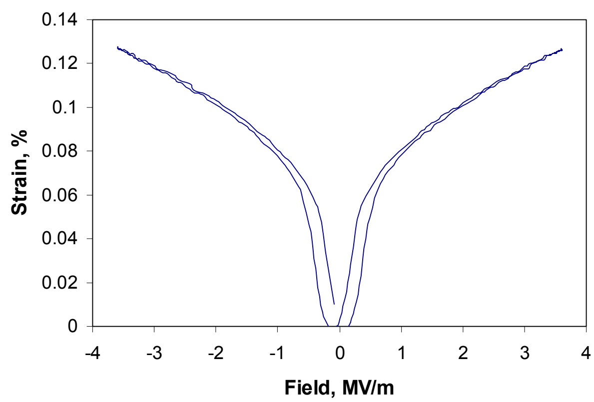

Figure 3. Strain vs. field for PMN disk sample at 25°C.

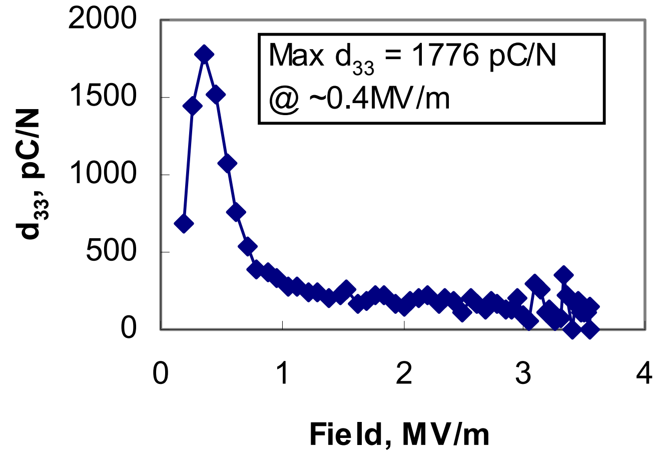

Figure 4. Field dependent d_{33} obtained by differentiation of the fig. 3 curve.

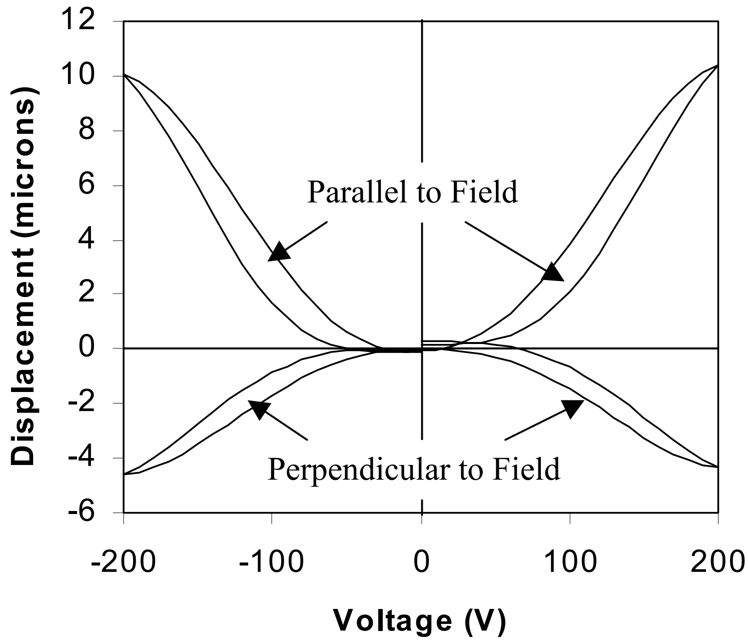

Figure 5. Displacement vs. voltage parallel and perpendicular to the electric field for PMN stack actuator.