Piezoelectric materials are a unique class of materials in which the electrical and mechanical properties are coupled. The most popular piezoelectric material is lead-zirconate-titanate (PZT) due to its large electromechanical properties and the adaptability of its properties with dopants.

It is well known that the electrical boundary conditions and poling affect the elastic compliance of piezoelectric materials. The thermal properties, namely thermal conductivity, may also be expected to be affected by electrical boundary conditions and poling due to the fact that this property and elastic compliance both arise primarily from phonon mode phenomena.

The thermal properties of PZT ceramics have been studied at low temperature (20K-300K), and a transition temperature was found between 50K and 80K. It has also been studied at high temperature, between 300K-800K, which characterizes the affect of phase transition on the thermal properties. The relationship between these two thermal properties, the “electrothermal” coupling factor $k_{33}^D$, was found to be similar to the electromechanical coupling factor $k_{33}$ relating elastic compliance under short circuit and open circuit conditions. The thermal conductivity of the unpoled sample was found to have the lowest thermal conductivity. The significance of the thermal conductivity with regards to phonon mode scattering and elastic compliance was discussed.

The measured thermal diffusivity and thermal conductivity values for poled open circuit, poled short circuit, and depoled samples are described in Tab. 1 as an average of two measurements on three samples each. Samples were depoled by heating them and then checking their response on a $\delta_{33}$ meter. The short circuit thermal conductivity $\kappa_{33}^D$ is more than 1.5 times larger than the open circuit one $\kappa_{33}^O$. The unpoled thermal conductivity $\kappa_a$ showed the smallest value, 15% less than that of the open circuit case. The relationship between the open circuit $\kappa_{33}$ and short circuit thermal conductivity $\kappa_{33}^D$ can be described by a electrothermal coupling coefficient

$$\kappa = \alpha \kappa_p \rho. \quad (1)$$

The original report regarding the TC thermal diffusivity experiment presented a standard deviation of less than 5%. However, the results of this experiment had larger deviation (Tab. 1) due to the fact that the diameters of the samples were a few millimeters smaller than the sample holder. The error found is different for different boundary conditions and poling states, but this is believed to be random.

The electromechanical coupling factor of this ceramic found from electrical impedance spectroscopy is $k_{33} = 0.68$. Using Eq. 2 the “electrothermal” coupling factor can be calculated to be $k_{33}^D = 0.63$. The error between the two coupling factors may be due to

$$\kappa_{33}^E(1 - (k_{33}^E)^2) = \kappa_{33}^D, \quad (2)$$

$$s_{33}^E(1 - k_{33}^E) = s_{33}^D. \quad (3)$$
Table I. Thermal diffusivity and thermal conductivity depending on electrical boundary conditions

|                  | Thermal diff. +/− (mm²/s) | Thermal cond. +/− (W/m K) |
|------------------|---------------------------|---------------------------|
| Open circuit     | 0.50                      | 0.02                      | 1.4           | 0.06          |
| Short circuit    | 0.82                      | 0.08                      | 2.3           | 0.23          |
| Depoled          | 0.43                      | 0.03                      | 1.2           | 0.01          |

error in the thermal measurements and possibly other microscopic features which do not correlate between the \( k \) value determined from electrical and thermal measurements.

In summary, \( \kappa_{E33}^3 > \kappa_{D33}^3 > \kappa_* \). This may be understood from phonon mode scattering, orientation of domains, and elastic compliance. Because of the random orientation of domains in the depoled sample, it is expected that there will be the most phonon scattering in this material. Therefore, it will have the lowest thermal conductivity. Because the domains of the poled material are oriented, less scattering is expected and thermal conductivity will be larger for the poled material (\( \kappa_{E33}^3 \) and \( \kappa_{D33}^3 \)). The elastic compliance under short circuit conditions \( s_{E33}^3 \) is softer than the elastic compliance under open circuit conditions \( s_{D33}^3 \). This means that the lattice and domain wall motion are larger in the short circuit condition. The larger lattice vibration and domain motion in short circuit conditions will also correlate to a larger thermal conductivity in short circuit conditions \( \kappa_{33}^E \) due to increased phonon mode transport. This observation can also be used to understand the relation between \( k_{33} \) and \( \kappa_{33}^E \).

The clear result of the experiments is that thermal conductivity in ferroelectric ceramics depends on electrical boundary conditions. It is very possible that the electromechanical coupling factor in these materials is related to thermal properties as well, namely thermal conductivity and thermal diffusivity. A discussion was presented to explain the behavior using phonon scattering and domain orientation concepts. Future work includes studying the effect of microstructure on phonon mode transport in these materials and further clarifying the thermal-electrical coupling experimentally demonstrated in the experiments.

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