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BIASED PZT MATERIALS FOR ACOUSTIC TRANSDUCERS

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Abstract: Sensor Technology Limited is investigating the properties of new PZT compositions that use impurity doping to introduce an internal bias field. The internal field inhibits depoling and allows higher electric field amplitude to be applied in sonar transducers. In the case where the Young's modulus and piezoelectric d constants are not substantially reduced by the same impurity additions, it is possible to obtain increased output power density. In this paper the effects of two different impurity types on the properties of a Navy type I PZT ceramic are examined. The results show that both impurity types increase the internal bias field but that one impurity results in significantly less reduction of the piezoelectric d constants and less overall change of other material properties.

1. INTRODUCTION

The need to increase power densities in underwater acoustic projectors has led to interest in various alternatives to conventional lead zirconate titanate (PZT) ceramics. The new transduction materials include lead magnesium niobate [1] and single crystal materials such as PZN-PT [2]. However it is not entirely clear that current PZT-based materials have been fully optimized for maximum power density. It is desirable to determine whether significant increases in power density can be achieved with conventional PZT materials, before turning to turning to alternatives that either have less history in use or are more expensive to manufacture.

It has been recently shown that higher power densities can be achieved by operating conventional PZT under an externally applied DC bias so that larger AC fields can be used without depolarization [3]. But while this can improve the power density, it also requires more complicated and expensive drive electronics. An alternative approach is to use impurity doping to introduce an internal bias field that serves the same role as an externally applied field in inhibiting large amplitude-induced depolarization. In this way increased power density can be achieved without the need for external DC biasing. A variety of transition metals and other impurities, particularly those with acceptor-type properties in PZT, can achieve this effect. It is important however that such impurities not introduce a simultaneous degradation of other material properties, such as Young's modulus and d_{33}, that would negate the benefit of higher coercive field. Jones and Lindberg have noted that an important metric for high-power transducer materials is the field-limited energy density which is equal to one half the Young's modulus of the material times the square of the strain at the maximum field [4].

This paper reports on the properties of PZT materials that use two different impurities for the introduction of an internal bias field. One of the impurities is a transition metal and the other is a non-transition metal. These will be referred to hereafter as impurity #1 (transition metal) and impurity #2 (non-transition metal). Both impurities introduce acceptor states in PZT giving the materials low dissipation factors, large Q-factors and other properties typical of so-called “hard” PZT ceramics [5]. The experimental results show that both impurity types increase the coercive field to a similar extent, but that the degradation of d_{33} is less for impurity #2. The latter impurity also has less influence on other properties such as dielectric constant, and coupling coefficient.

2. SAMPLE PREPARATION

PZT ceramic samples were fabricated in a 4-kg batch using conventional ceramic fabrication techniques. The baseline composition for the experiment is the SensorTech BM400 PZT, a Navy type 1 equivalent. The precursor oxides along with chosen additives 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. The samples were poled at high voltage at elevated temperature. All samples regardless of impurity content were processed under identical conditions. A minimum of four different levels of each of the two impurities were used.

Samples for polarization and biased resonance measurements were disk-shaped with 14 mm diameter and 0.4 mm thickness. Samples for dielectric property measurements and low-field d_{33} measurement were bar-shaped with 4 mm square cross section and 12 mm length in the poling direction.

3. CHARACTERIZATION

Polarization vs. field measurements were performed using the Sensor Technology Limited SS05 polarization measurement system [6]. This is a commercially available measurement system that is based on a modified Sawyer-Tower circuit [7], as shown in Fig. 1. The system uses a large sampling capacitor in series with the device under test (DUT) and uses opto-couplers to protect major system components from high voltage spikes that might result from a dielectric breakdown event in a defective sample. The drive signal is generated digitally using a staircase sine wave approximation, which is passed through a 4th order low-pass filter and amplified. This approach allows easy customization of the drive waveform and test sequence under software control.

When the electric field in a piezoelectric sample is swept through a complete loop, starting from a given value, changing to another value and returning, the energy loss per unit volume during the cycle is equal to the area enclosed by the electrical displacement vs. electric field (D vs. E) loop [8]. For the case of typical piezoelectric ceramics the relative dielectric constant is large enough that the electrical displacement D is approximately equal to the polarization P, and P vs. E loops may be used for the same purpose. Disk samples were characterized by measuring P vs. E loops for small electric field amplitude and repeating the measurement for progressively higher electric field amplitude. At each amplitude the energy loss per unit volume was deduced from the area in the P-E hysteresis loop. In this manner it is possible to determine the electric field amplitude at which the loss per unit volume crosses a chosen threshold. The measurements were performed at a sweep frequency of 0.01 Hz.

The low-field d_{33} constant was measured on bar samples using a Sensor Technology Limited d_{33} meter, which is based on the Berlincourt method [9]. In order to examine the effect of DC bias fields the resonance characteristics of disk samples were measured under DC bias by an impedance analyzer as described by Mukherjee et. al. [10]. The resonance spectra of the fundamental radial mode were analyzed to obtain S^E_{11}, γ^T_{33}, d_{31} and k_p. In addition, the dynamic d_{33} coefficient was measured under bias using an optical interferometric technique as described in ref. [10].

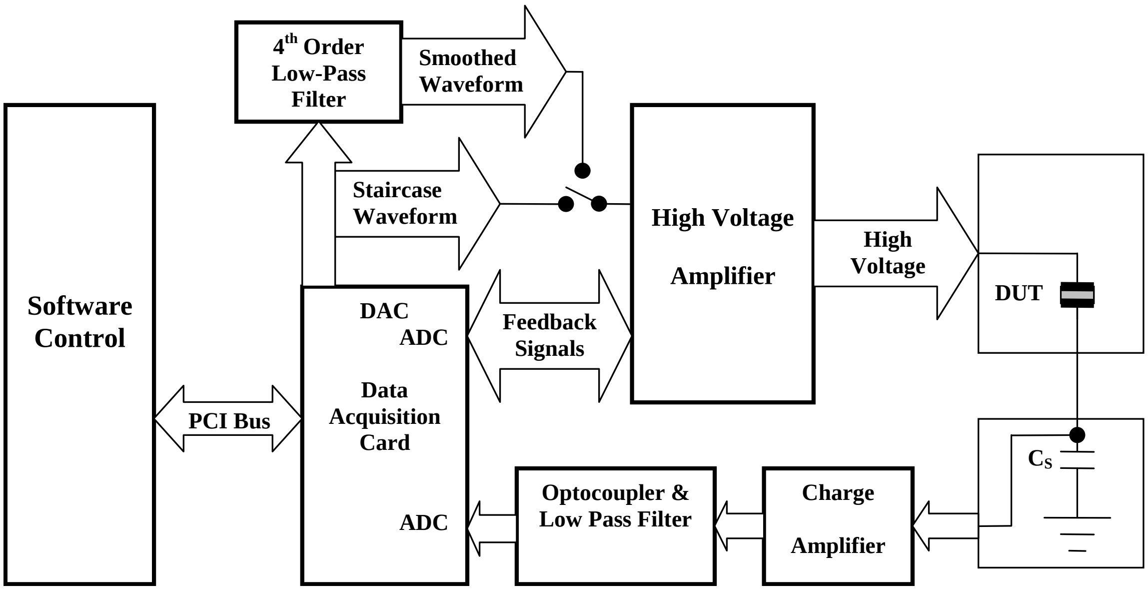

Fig. 1. Block diagram of SS05 polarization measurement system.

4. RESULTS

Figure 2 shows the energy loss per unit volume as a function of field amplitude for the BM400 baseline material. The inserts show the shape of the P vs. E loops at selected points in the characteristics. For low electric field amplitude the loops have a relatively simple and approximately symmetric shape. As the electric field increases beyond about 1.5 MV/m, the loops begin to bulge in the reverse polarity region due to the onset of depolarization. The energy loss then begins to increase more rapidly and very wide loops with high losses are observed in the high-field region.

The effect of the impurity additions on energy loss characteristics are shown in Fig. 3. The results show that both impurity types are effective at increasing the threshold field for the onset of rapidly rising energy loss. The change of coercive field is evident from the shift of electric field amplitude for a given energy loss per unit volume (for example, 0.1 J/cc). The shift of coercive field is shown in the upper left graph of Fig. 4. The graph shows that both impurity types have a very similar effect on the coercive field and that approximately 12% higher electric field amplitude can be used for a given loss level, than is possible for the baseline material.

The remaining graphs of Fig. 4 show other material properties as a function of impurity content. The low-field d_{33} constant remains the highest for impurity #2 for all concentrations considered. The two impurities have similar effects on dielectric constant, frequency constant, dissipation factor and mechanical Q. Compared to impurity #1, impurity #2 gave slightly lower dissipation factor and frequency constant and higher dielectric constant.

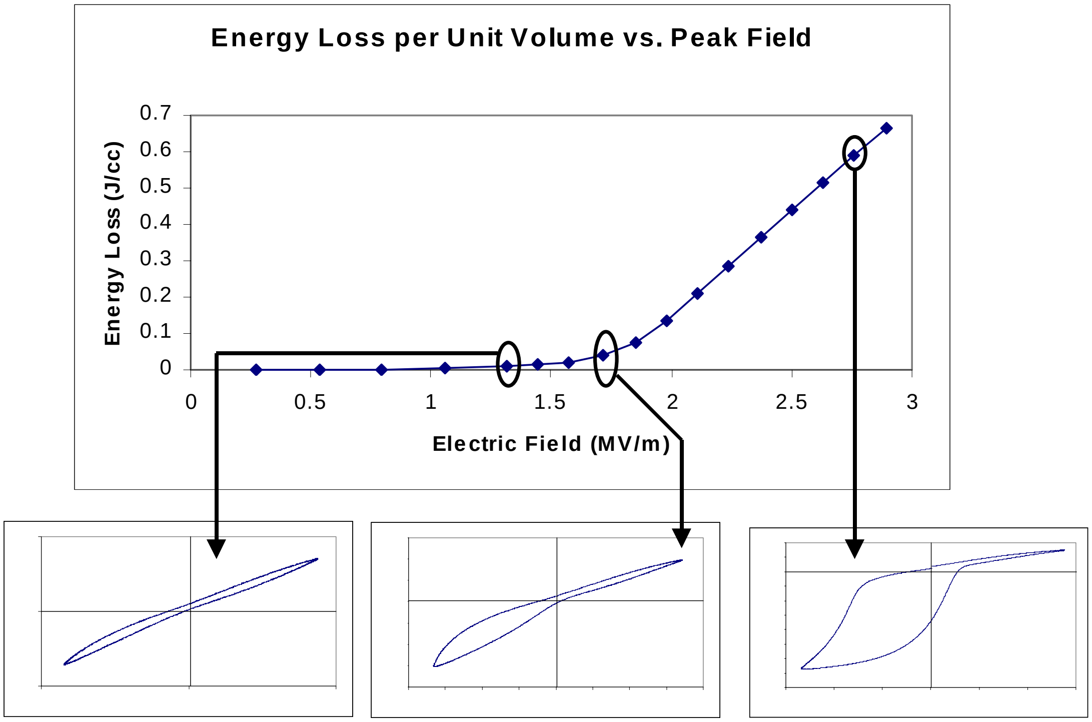

Fig. 2. Energy loss per unit volume as a function of electric field amplitude for BM400 PZT ceramic. The inserts show the shapes of the P vs. E hysteresis loops at different points of the characteristic.

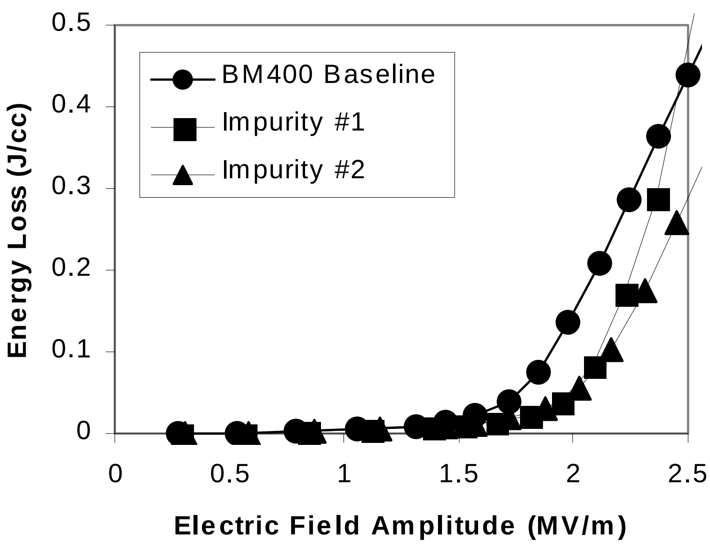

Fig. 3. Energy loss per unit volume as a function of electric field amplitude for BM400 PZT and BM400 with impurity additions.

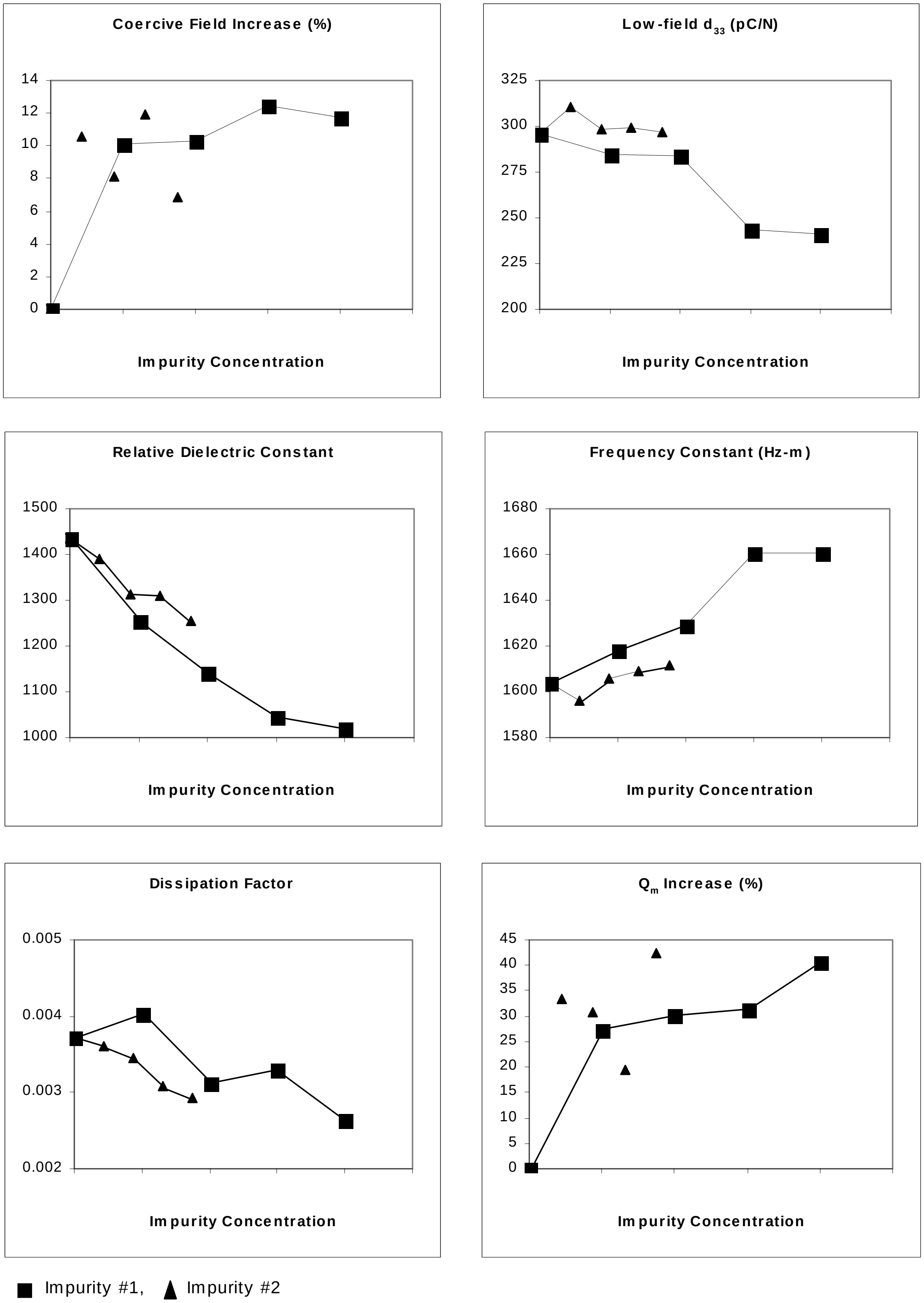

Fig. 4. Effect of impurity content on dielectric and piezoelectric properties.

The material properties determined from biased resonance measurements are summarized in Fig. 5. The results shown are hysteresis loops that were generated as the bias electric field was swept over a range of ±2 MV/m. The results shown are for impurity concentrations that were near the higher end of the ranges considered. For all of the loops measured, the width of the hysteresis loop was widest for the BM400 baseline material and was smaller for the samples with addition of either impurity type. The magnitude of all of the material properties in the positive bias region was smaller for both impurities but the magnitude of the drop was less with impurity #2. The lowering of the compliance (equivalent to an increase of Young’s modulus) is beneficial in terms of the field-limited energy density, which as noted previously, is proportional to Young’s modulus multiplied by the square of the maximum strain. The magnitude of, d_{31} was degraded by the impurity additions, but the effect is less for impurity #2.

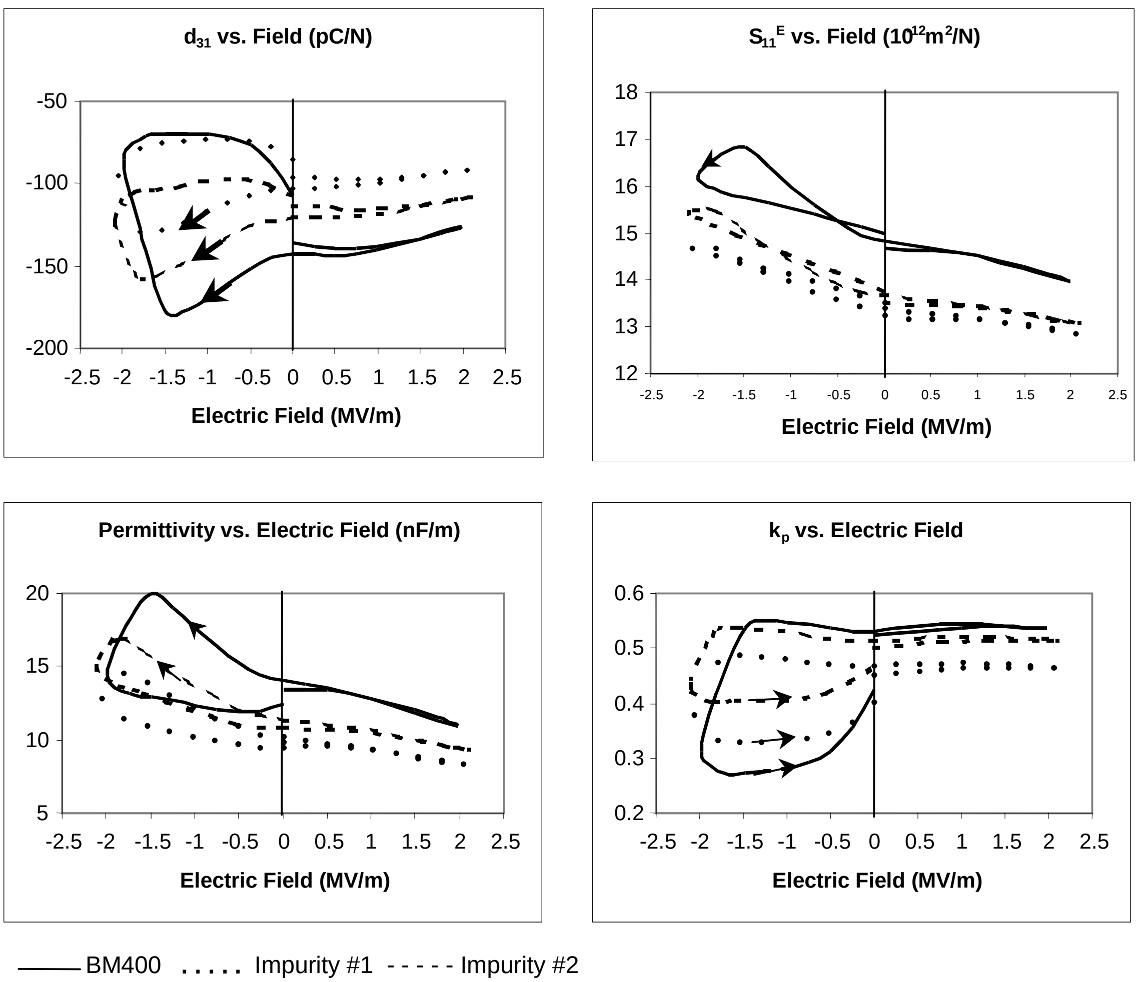

Fig. 5. Material properties as a function for DC bias determined using biased resonance measurements.

Fig. 6 shows the dynamic d_{33} constant as a function of DC bias for BM400 and BM400 with impurity #2. Once again reduced hysteresis for a given electric field amplitude is observed with the impurity doping. The positive bias d_{33} is little affected by the doping with impurity #2.

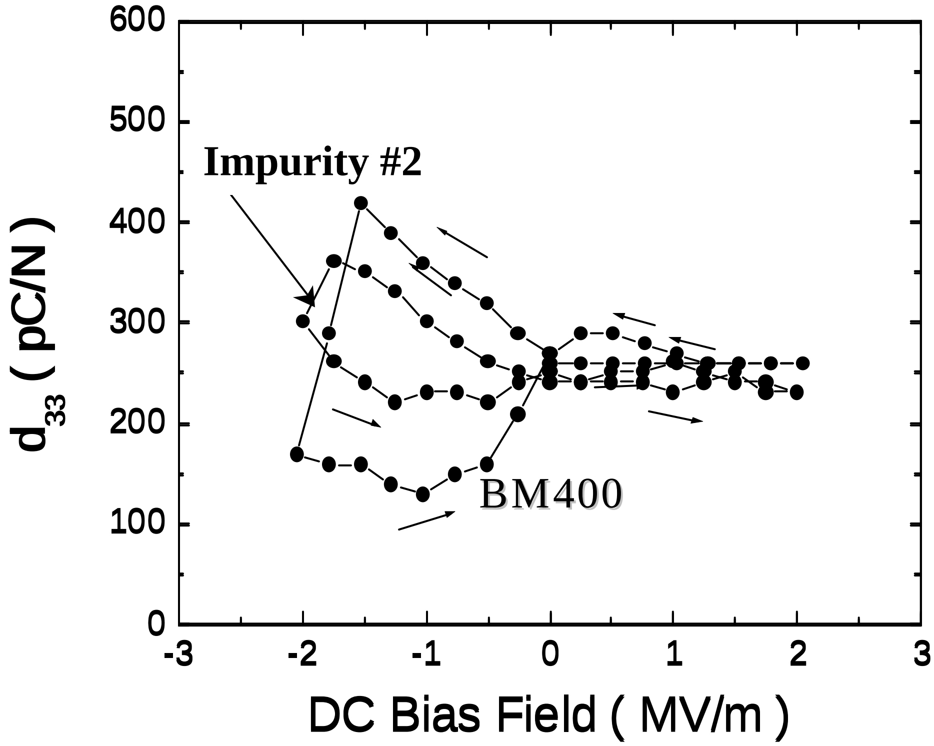

Fig. 6. d_{33} as a function of DC bias for BM400 and BM400 with impurity #2.

5. CONCLUSIONS

The results show that both impurity types considered increase the coercive field of the PZT baseline material and increase the Young's modulus. Both of these effects benefit the field-limited energy density of the material. Both impurities caused some degradation of d_{31} but little or no degradation of d_{33} was observed for impurity #2. Biased PZT materials with non-transition metal doping appear to be a promising candidate for higher-power transducer applications.

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