Electroacoustic properties of 110-oriented Pb(Mg\(1/3\) Nb\(2/3\))O\(_3\) – PbTiO\(_3\) crystals under uniaxial stress

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Electroacoustic properties of \((110)\)-oriented \(\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-\text{PbTiO}_3\) crystals under uniaxial stress

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The electromechanical properties of \((110)\)-oriented \(0.7\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-0.3\text{PbTiO}_3\) crystals have been investigated under uniaxial stress \((\sigma)\). \((110)\)-oriented crystals have a longitudinal electromechanical coupling coefficient \((k_{33})\) of \(\approx 0.9\) and an acoustic power density of \(12\ \text{dB}\) which decreases to \(8\ \text{dB}\) with increasing \(\sigma\) between 0 and \(4 \times 10^7\ \text{N/m}^2\). The results demonstrate that the advantages in terms of power density and coupling coefficient of oriented piezocrystals are not constrained to the \((001)\)-orientation, but rather can also be obtained along the \((110)\).

\(\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-\text{PbTiO}_3\) \((\text{PMN-PT})\) crystals in transducer applications are twofold. First, the crystals have the potential for higher projected acoustical energy density due to their higher strain. Acoustic power densities of \(\approx 12\ \text{dB}\) have recently been obtained for \((001)\)-oriented specimens, under prestress. Recent investigations have shown high electromechanical coefficients for \((110)\)-oriented PMN–PT crystals. Values of \(d_{33}\) and \(k_{33}\) were found to be equally high as those along the \((001)\). An unusual electromechanical and elastic equivalence was found between the \((110)\) and \((001)\) directions. These investigations clearly demonstrated that the potential advantages of PMN–PT crystals for transducer applications are not constrained to a single crystallographic orientation, but rather to the \((110)\) plane.

The purpose of this investigation was to study the effects of uniaxial stress on \((110)\)-oriented single crystals of \(\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-30\%\text{PbTiO}_3\). In acoustic transducer applications, uniaxial prestress inherently needs to be used, in order to keep the transducer from going into tension and consequently to be able to harness the highest electromechanical response. Investigations have been performed using polarization versus field \((P-E)\), strain versus field \((\varepsilon-E)\), and strain versus stress \((\varepsilon-\sigma)\) methods.
larization rotation towards (001). In addition, the value of Young’s modulus $Y_1$ was measured calculated to be $1.8 \times 10^{10}$ N/m$^2$ from the standard resonance-antiresonance IEEE method.

Figures 2(a) and 2(b) show the unipolar $\Delta P-E$ and $\varepsilon-E$ responses for a bar-shaped (110)-oriented crystal under various uniaxial stresses. Decreases in $\Delta P$ and $\varepsilon$ are noticeable with increasing $\sigma$, in particular for $E>10$ kV/cm where the induced phase transition occurred. At $E=15$ kV/cm, $\Delta P$ decreased from $\sim 0.07$ C/m$^2$ under small loads to $\sim 0.058$ C/m$^2$ under $6 \times 10^7$ N/m$^2$. Correspondingly, $\varepsilon$ decreased from $\sim 1.9 \times 10^{-3}$ to $\sim 1.4 \times 10^{-3}$ with increasing $\sigma$. The data reveal essentially no change in the hysteretic losses with increasing $\sigma$. The dominant change with increasing $\sigma$ was to suppress the induced phase transformation, resulting in the $\Delta P-E$ and $\varepsilon-E$ responses becoming increasingly linear with increasing $\sigma$. For $\sigma=6 \times 10^7$ N/m$^2$, the electromechanical behavior is nearly ideally linear and anhysteretic, with an effective $d_{33}$ of $\sim 1000$ pC/N, as determined from the slope. These results are in contrast to the stress-dependent electromechanical properties of (001)-oriented crystals, which become increasingly nonlinear and hysteretic with increasing $\sigma$. It is also important to note that there was a difference in the field level at which the step in strain occurred between the plate-like specimen of Fig. 1(b) (10 kV/cm), and the long-rectangular one of Fig. 2(b) (12 kV/cm). The differences are attributed to small composition variations that shift the critical field of the induced transition.

The electromechanical coupling coefficient ($k_{33}$) at various uniaxial loads can be calculated as given in Eq. (1):

$$k_{33} = d_{33}^2 Y_1 / (\chi_0 K),$$

where $Y_1$ is Young’s modulus, $\chi_0$ is the permittivity of free space ($8.85 \times 10^{-12}$ F/m), $K$ is the relative dielectric constant, and $d_{33}$ is the longitudinal piezoelectric coefficient. $K$ can be approximated from the $P-E$ response over a quasi-linear range as $\delta P_3/\delta E_3$, and $d_{33}$ can be approximated over a quasi-linear range as $\delta e_3/\delta E_3$, both of which have limitations. Quasilinear approximations were performed for an $E_{dc}$ of 8 kV/cm and an $E_{ac}$ of 4 kV/cm. The value of $Y_1$ can be

![FIG. 1. Unipolar $P-E$ and $\varepsilon-E$ characteristics of (110)-oriented PMN–PT plate-like crystals. (a) $P-E$ response, and (b) $\varepsilon-E$ response. Data are shown for various maximum ac drives of 10, 20, and 40 kV/cm. The data for the various maximum ac drives are distinguished by the size of the points in the figure.](image)

![FIG. 2. $P-E$ and $\varepsilon-E$ responses for (110)-oriented long-rectangular shaped crystals, taken at various uniaxial stresses between 0 and 6 $\times 10^7$ N/m$^2$. (a) $P-E$ response, and (b) $\varepsilon-E$ response.](image)
determined from measurements of the $e$–$\sigma$ response. Accordingly, $Y_1$ was determined at various dc bias levels ($E_{dc}$) by stress-strain ($e$–$\sigma$) measurements. The $e$–$\sigma$ curves were linear and $Y_1$ was calculated from the slopes. The value of $k_{33}$ is shown in Fig. 3(a) as a function of $\sigma$. In this figure, $k_{33}$ can be seen to be somewhat independent of $\sigma$. For example, $k_{33}$ varied between 0.95 at $\sigma=0$ N/m$^2$ to $\sim$0.86 at $\sigma=6 \times 10^7$ N/m$^2$. The value of $k_{33}$ under zero uniaxial stress is close to that determined by the resonance-antiresonance method earlier. These results clearly demonstrate (110)-oriented crystals maintain a high electromechanical coupling coefficient under realistic operational conditions for use in acoustic transducers. In fact, $k_{33}$ is equally as high along the $\langle110\rangle$, as along the $\langle001\rangle$.1–4 This is essential to their use in high performance applications that require enhanced bandwidth.

By convention, the acoustical energy density can be defined relative to that of a standard PZT-8 material, as given in Eq. (2a),7,8 where

$$E_{\text{acoustic}} = 10 \log (E_{\text{elastic}}/E_{\text{PZT-8}}),$$

$$E_{\text{elastic}} = 1/2 Y_1 e_{\text{rms}}^2,$$

$E_{\text{PZT-8}}$ is the acoustical energy density of the standard PZT-8. $E_{\text{PZT-8}}$ is calculated by assuming a linear piezoelectric response over the operational field range, i.e., $e_{ij} = d_{ijk}E_k$. The accepted values of $d_{ijk}$ and $Y_1$ for PZT-8 are equal to 2.25 $\times 10^{-10}$ C/N and 7.4 $\times 10^{10}$ N/m$^2$. Thus, the value of $E_{\text{PZT-8}}$ can be estimated as 936.6 J/m$^3$ under an applied electric field of 10 kV/cm. Using the values for $E_{\text{elastic}}$, the corresponding acoustical energy density can be calculated using Eq. (2a). Figure 3(b) shows the acoustical power density (dB) as a function of $\sigma$. In this figure, the acoustical power density can be seen to decrease with some with increasing $\sigma$. For example, the acoustical power density varied between 11.75 dB at $\sigma=0$ to $\sim$9.5 dB at $\sigma=6 \times 10^7$ N/m$^2$.

The results demonstrate that $\langle110\rangle$-oriented PMN–PT crystals are near linear electromechanical materials with high acoustic energy densities, high coupling, and essentially no loss. For $\sigma<2 \times 10^7$ N/m$^2$, they offer a $k_{33}>0.95$ and an acoustic power density of $\sim10$ dB. We believe that (110)-oriented crystals have a unique character, which offers promise for transducer applications, even potentially over that of $\langle001\rangle$ crystals. This is that twinning occurs along the $\langle110\rangle$. A stress applied along the $\langle110\rangle$ will not favor one twin state over another. Thus, the electromechanical response has increased linearity and lower losses due to a lack of domain contributions, and better accommodation to applied stress.

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