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Central peaks, acoustic modes, and the dynamics of polar nanoregions in Pb[(Zn_{1/3}Nb_{2/3})_{x}Ti_{1-x}]O_{3} single crystals studied by Brillouin spectroscopy

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Temperature dependence of acoustic behaviors and quasielastic central peaks (CPs) of Pb[(Zn_{1/3}Nb_{2/3})_{x}Ti_{1-x}]O_{3} (PZN-xPT) single crystals with x=4.5% and 9% have been investigated in a temperature range of 300–900 K by using the Brillouin light scattering. The temperature dependence of the C_{11} elastic constant of both crystals showed a deviation from normal ferroelectric, indicating the onset of the dielectric susceptibility at the phase transition temperature (T_{d}) of about 730 K upon cooling, indicating the onset of the electrostriction coupling between the polar nanoregions (PNRs) and the longitudinal acoustic (LA) waves. Upon further cooling, depolarized CP began to appear at a certain temperature (T_{f}) located in 500–550 K, which was accompanied by substantial softening of the C_{11} elastic constant below this temperature suggesting anisotropic electrostrictive coupling between PNRs and the two acoustic waves. In addition, the onset of significant increase in the acoustic damping of both acoustic waves at T_{d} could be seen from the temperature dependence of the linewidth of Brillouin doublets. These results suggested that electrostriction coupling of the strain to the square of the local polarization of PNRs and the resultant order-parameter fluctuations are enhanced not at T_{d} but at a much lower temperature of T_{f}, which may be ascribed to a local structural transformation occurring in PNRs at T_{f}. This suggestion is consistent with recent studies on PZN-xPT single crystals reporting the appearance of strong acoustic emission signals [M. Roth et al., Phys. Rev. Lett. 98, 265701 (2007)] and substantial changes in the Raman spectrum [O. Svitelskiy, Phys. Rev. B 72, 172106 (2005)] at almost the same temperature. From the comparison of the present results to those of two typical relaxors, Pb(Mg_{1/3}Nb_{2/3})O_{3} and Pb(Mg_{1/3}Ta_{2/3})O_{3}, it was suggested that the existence of an intermediate characteristic temperature T_{d} below T_{f} may be considered as a more common characteristic in the temperature evolution of PNRs of relaxor ferroelectrics.

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I. INTRODUCTION

Lead-based perovskite A(B_{1/2}B'_{1/2})O_{3} and A(B_{1/3}B'_{2/3})O_{3}, relaxor ferroelectrics (RFEs) with A=Pb are a special group of ferroelectric materials that show complex structural and dynamical behaviors.\(^1\) Relaxors have attracted great attention from the viewpoints of both fundamental physics and applications, since they exhibit extraordinary electromechanical and dielectric properties having wide applications in the field of piezoelectric and pyroelectric devices, high-k capacitors, etc.\(^2\) A typical RFE, for example, Pb(Mg_{1/3}Nb_{2/3})O_{3} (PMN), shows a diffuse, frequency-dependent broad dielectric maximum in a temperature window,\(^4\) which is in contrast to the normal ferroelectrics which display a frequency-independent sharp, divergent dielectric susceptibility at the phase transition temperature. The temperature dependence of the dielectric maximum (T_{m}) is found to satisfy the phenomenological Vogel-Fulcher relationship, and the distribution of dielectric relaxation times becomes extremely polydisperse with divergent leading edge on cooling.\(^5\)

PMN exhibits no macroscopic symmetry change down to the lowest temperature of 5 K maintaining an average cubic structure although a local polar structure with rhombohedral distortion has been revealed by neutron diffraction study.\(^6\) This intrinsic local distortion constitutes the so-called polar nanoregions (PNRs) which begin to appear below a certain temperature. This temperature, which is called Burns temperature (T_{B}), is typically a few hundred degrees higher than T_{m}.\(^7\)

One of the key ingredients of relaxor behaviors is the lattice disorder introduced into the perovskite structure by chemical substitution or lattice defects.\(^8\) Chemically ordered nanosized regions (CORs) are formed by the two different cations with dissimilar valence states which occupy the perovskite B sites. Due to the different valence states, these short-range CORs induce charge disorder and thus become the source of quenched random fields in RFEs. Coupling between the random fields and ferroelectric degrees of freedom such as a soft lattice mode has been suggested to generate PNRs at high temperatures. Due to the random directions of polarizations of PNRs, there is no macroscopic polarization without electric bias. However, since the square of the local polarizations of PNRs is not zero, some physical properties coupled to PNRs via electrostriction may show abnormal behaviors when PNRs begin to appear.

The existence of T_{B} has been evidenced by many unusual properties of RFEs such as the deviation of the dielectric constant from the high-temperature Curie-Weiss law, appearance of diffuse elastic scattering, deviations of the index of refraction, the volume of the cubic cell from high-temperature linear behaviors, etc.\(^9\) In spite of all the experimental and theoretical efforts on relaxors including the random-field model,\(^10\) the dipolar glass model,\(^4\) and the recent spherical random-bond–random-field model,\(^11\) the exact
nature of PNRs and their relation with CORs have remained as one of the central problems of RFEs. Recent first-principles-based simulations on Pb(Sc\(_{1/2}\)Nb\(_{1/2}\))O\(_3\) showed that the characteristic lengthscale for PNRs is the same as for CORs and also that PNRs appear predominantly in these chemical nanoregions.\(^1\) However, it remains to be confirmed whether the compositional heterogeneity is prerequisite to the formation of PNRs since some phenomena typically related to the relaxation of dynamic PNRs, namely, the significant Brillouin quasielastic scattering, the softening of the longitudinal acoustic mode, and the deviation from the Curie-Weiss law above the Curie point were observed in PMN-55\%PT where CORs are known to be absent.\(^1\) More thorough experimental efforts are highly needed to find out the origin of PNRs, their growth mechanism, and their relation to CORs.

Recent systematic Raman studies on PMN, Pb(Zn\(_{1/3}\)Nb\(_{2/3}\))O\(_3\) (PZN), and Pb[(Zn\(_{1/3}\)Nb\(_{2/3}\))(1-x)Ti\(_x\)]O\(_3\) (PZN-xPT) with x=4.5\% indicated an existence of some intermediate characteristic temperature, denoted as \(T_g\) in this paper, located between \(T_R\) and \(T_m\).\(^1\)\(^4\)-\(^1\)\(^6\) This intermediate temperature is characterized by anomalies in the temperature dependences of frequency and/or intensity of Raman optic modes and low-frequency central peaks (CPs) observed in Raman spectra. \(T_g\) has been suggested as the onset temperature of long-lived correlations between off-center ions resulting in the formation of permanent PNRs.\(^1\)\(^5\) Neutron scattering studies suggested a local phase transition in PMN occurring at \(\sim 370\) K, below which the intensity of the elastic diffuse scattering increases substantially.\(^1\)\(^7\) This result was interpreted in terms of the random-field model and the cubic anisotropy.\(^1\)\(^8\) These results seem to be consistent with that obtained from recent acoustic emission measurement, which showed clear, strong signals near 510 K in PZN and PZN-9\%PT in addition to the acoustic emission activity near \(T_R\) \(\sim 730\) K in both components.\(^1\)\(^9\) More interestingly, succeeding studies on PZN-xPT with x=0.0-0.12 by the same group revealed that strong acoustic emission signals were observed in all the investigated crystals at very similar temperatures of 499-508 K, which were attributed to local martensitelike cubic-to-tetragonal ferroelectric transitions occurring in PNRs.\(^2\) It is also worth pointing out that these characteristic temperatures are close to the values at which the temperature-dependent component of the diffuse x-ray scattering intensity begins to grow in PZN-8\%PT\(^2\) and also some rhombohedral distortion begins to appear in PZN.\(^2\)\(^2\)

If there is some local structural changes in PNRs near \(T_g\), it should be accompanied by local strain fields around PNRs which may affect elastic properties of RFEs. In this respect, inelastic Brillouin light scattering can be a very useful tool because it can directly probe acoustic modes which can be coupled to the PNRs through electrostrictive coupling. In addition, characteristic time scales of the polarization fluctuations of PNRs, which manifest themselves as CPs in the low-frequency light scattering spectrum, are located in the Brillouin frequency window. The temperature dependence of the relaxation times of PNRs is an important information for the understanding of their dynamics. Previous Brillouin-scattering studies on PZN-x\%PT have mainly been focused on the diffuse phase transitions near the dielectric maxima and thus been carried out in limited temperature ranges of which the upper limits are much lower than \(T_R\).\(^2\)\(^3\)-\(^2\)\(^9\) In addition, detailed polarization analysis on CPs has not been carried out. Therefore, clear correlations between the relaxor dynamics, in particular, the temperature evolution of PNRs and the acoustic properties, could not be discussed. In our previous letter, changes in the acoustic waves and CP behaviors were pointed out at the intermediate temperature of \(\sim 550\) K in PZN-9\%PT.\(^3\)\(^0\) The present contribution reports on more detailed, systematic investigations of the temperature dependence of acoustic modes and CPs of PZN-xPT with x=0.045 and 0.9 as well as PMN and Pb(Mg\(_{1/3}\)Ta\(_{2/3}\))O\(_3\) (PMT) in a wide temperature range between 300 and 900 K. Special attention has been given to the correlation between the dynamics of PNRs and changes of acoustic properties of these RFEs in order to find out whether \(T_g\) has a real physical meaning in the temperature evolution of relaxor dynamics.

**II. EXPERIMENT**

PZN-4.5\%PT and PZN-9\%PT single crystals were grown by using the Bridgman method at the Shanghai Institute of Ceramics. Surfaces were polished to optical quality for light scattering experiments. Pseudocubic crystal orientation was determined using the Laue diffraction pattern. A 3+3 pass tandem Fabry-Pérot interferometer was used to measure the Brillouin spectra of PZN-xPT single crystals. A diode-pumped solid state laser (DPSS532) was used to excite the samples with a wavelength of 532 nm and a power of about 100 mW. Since the elastic scattering is very strong at a backward scattering geometry, a special right-angle scattering geometry was used for the measurement without any significant disturbance of the elastic scattering. Figure 1 shows a schematic diagram of the scattering geometry adopted in the present study. The laser light with a vertical polarization is incident on the (001) surface with an incidence angle of 45°. \(\vec{k}_i\) and \(\vec{k}_s\) denote the wave vectors of the incident and scattered light, respectively, propagating in the crystal. The photon propagation direction \(\vec{q}\) is thus along the [100] direction. Both the polarized (VV) and depolarized (VH) spectra were obtained during the cooling process by using an analyzer in front of the entrance pinhole of the interferometer. In order to

![FIG. 1. A right-angle scattering geometry adopted in the present study.](image-url)
cover a wide frequency range for probing CP, a free spectral range of 300 GHz was chosen and a scan range of ±450 GHz was used. A much narrower free spectral range of 20 GHz for scanning ±30 GHz was used for the investigation of acoustic modes. Two elastic stiffness coefficients $C_{44}$ and $C_{11}$ can be obtained in VH and VV scattering geometries, respectively, according to the Brillouin selection rule.$^{31}$

For comparisons of the acoustic properties of PZN-xPT with respect to typical relaxors, the Brillouin spectra of PMN and PMT were measured at the same scattering geometry in a wide temperature range. These crystals were grown by the flux method at the Ioffe Physico-Technical Institute in Russia and prepared in the same way as PZN-xPT single crystals. Both the LA and transverse acoustic (TA) modes were probed and analyzed for comparison. All the above Brillouin experiments were performed at the Institute of Materials Science, University of Tsukuba.

### III. RESULTS

#### A. Brillouin spectra and analysis

Figure 2(a) gives two Brillouin spectra of PZN-4.5%PT single crystals measured at 453 K in a narrow frequency window of ±15 GHz. As can be seen, the TA mode appears in the VH spectrum while the LA mode is shown in the VV spectrum. Similar spectra were also observed in PZN-9%PT. The sound velocities of the TA and LA modes are related to the elastic stiffness coefficients $C_{44}$ and $C_{11}$, respectively. The CP was investigated in a much wider frequency range of ±450 GHz, and one example of CP spectra at 453 K is plotted in Fig. 2(b). CP of PZN-4.5%PT develops with decreasing temperature and can be seen in both polarized and depolarized geometries at low temperatures below ∼550 K. The temperature evolution of CP in both VV and VH geometries can be seen from Fig. 3, which shows that the intensity of CP increases and its width decreases with decreasing temperature down to 453 K. The VH component disappears at high temperatures above 550 K, and the VV component of CP can also hardly be seen at high temperatures above 600 K although a slight slope in the spectrum persists even at much higher temperatures above $T_B$. This feature is similar to the case of PZN-9%PT which displays a persisting VV component of CP at high temperatures up to 900 K.$^{30}$

For analyzing the Brillouin doublets corresponding to LA and TA modes, the response function of the damped harmonic oscillator was used, which was approximated by a Lorentzian function since the damping factor of acoustic modes was much smaller than the Brillouin frequency shift. In the fitting process, the Lorentzian function was convoluted by the Gaussian instrumental function of the Fabry-Pérot interferometer. In case of CP, a single Lorentzian function centered at zero was used for the fitting based on the assumption of a single Debye relaxational process for the relevant polarization fluctuations. The spectral response function $S(\nu)$ as a function of the frequency $\nu$ for CP is thus expressed as

$$S(\nu) \propto [n(\nu) + 1] \frac{2\pi \nu \tau}{1 + (2\pi \nu \tau)^2}, \quad (1)$$

where $n(\nu)$ is the Bose-Einstein thermal factor given by

$$n(\nu) = [\exp(h\nu/kT) - 1]^{-1}. \quad (2)$$

In this equation, $h$ and $k$ denote the Planck constant and the Boltzmann constant, respectively. The whole spectrum could be fitted by using a superposition of the above two response functions, and the Brillouin shift, the full width at half maximum (FWHM), and the intensity of the acoustic modes as well as the FWHM and the intensity of CP were derived
from the fitting results as a function of temperature.

The advantage of the present scattering geometry described in Fig. 1 is that the sound velocity can be obtained without the knowledge of the refractive index of the single crystals. The sound velocity $V$ is related to the Brillouin frequency shift $\nu_B$ as

$$V = \frac{\lambda_0 \nu_B}{\sqrt{2}},$$

where $\lambda_0$ is the laser wavelength in vacuum. The elastic stiffness coefficients $C_{44}$ and $C_{11}$ are related to the sound velocities according to the following equations:

$$C_{11} = \rho V_L^2,$$

$$C_{44} = \rho V_T^2.$$

In these equations, $\rho$ denotes the density of the crystals and $V_L$ and $V_T$ are longitudinal and transverse sound velocities, respectively. Densities of 8.31 and 8.71 g/cm$^3$ were used for PZN-4.5%PT and PZN-9%PT, respectively, in order to calculate the above elastic constants.

B. Longitudinal and transverse acoustic modes of PZN-xPT

The temperature dependences of $\nu_B$ and the FWHM of both LA and TA modes have been obtained and plotted in Figs. 4 and 5, respectively, for PZN-4.5%PT and PZN-9%PT single crystals. $T_B$ of PZN and PZN-9%PT are known to be located in the temperature range between 730 and 750 K, as has been confirmed by the acoustic emission measurements. These values are consistent the previously reported $T_B$ of PZN obtained by the refractive index measurement, which is about 750 K. The Brillouin frequency shift of the LA mode, denoted as $\nu_B^{LA}$, shows an almost linear behavior in the high-temperature range above $T_B$. The high-temperature slope of $\nu_B^{LA}$ of PZN-9%PT is steeper than the case of PZN-4.5%PT. Since no coupling is expected to exist between the acoustic modes and other degrees of freedom related to any phase transformation in this high-temperature range, the temperature dependence of the phonon frequency will be mainly dominated by the lattice anharmonicity. $\nu_B^{LA}$ deviates from its high-temperature linearity near $T_B$ in both crystals. Regarding the FWHM, PZN-9%PT shows a change in slope near $T_B$ and begins to increase at $\approx 570$ K upon cooling, below which $\nu_B^{LA}$ exhibits a significant softening. The FWHM of PZN-4.5%PT begins to increase at about 500 K and shows the onset of the most significant growth at $\approx 500$ K with lowering the temperature. It is worth paying attention to the fact that the FWHM of PZN-9%PT also shows a change in the slope at almost the same temperature around 500 K and a substantial increase below it, and these temperatures are very similar to the temperatures at which strong acoustic emission signals were observed in PZN-xPT single crystals. $\nu_B$ of TA mode ($\nu_B^{TA}$) in Fig. 5 exhibits a similar linear behavior in the high-temperature range, but seems to be less clear due to the more scattered data condition. Regarding the FWHM’s of both crystals given in Fig. 5, they show substantial increase below a certain temperature around 500 K similar to the case of the LA waves. At low temperatures, $\nu_B$ and the FWHM of both modes of PZN-9%PT display abrupt changes at the cubic-to-tetragonal phase transition temperature ($T_{C-R} \approx 430$ K). In case of PZN-4.5%PT, $\nu_B$ exhibits a broad minimum at 360–380 K, while the FWHM shows a broad maximum near the same temperature range, which is consistent with previous study. These results reflect broad phase transition behaviors of PZN-4.5%PT and are similar to the acoustic properties of typical RFEs such as PMN, PMT, and lanthanum modified lead zirconate titanate (PLZT).

Figure 6 gives the temperature dependence of the two elastic stiffness coefficients in the pseudocubic coordinate system calculated by using Eqs. (3)–(5). It is found that PZN-4.5%PT is softer than PZN-9%PT single crystals in the whole temperature range. $C_{11}$ and $C_{44}$ of PZN-4.5%PT are 111 and 54 GPa, respectively, at room temperature. These results are similar to those values of [001]-poled PZN-4.5%PT single crystals obtained by the ultrasonic method. In case of PZN-9%PT, $C_{11} = 144$ GPa and $C_{44} = 62$ GPa at room temperature, somewhat higher than those of PZN-4.5%PT single crystals. This large difference might first be considered to be ascribed to the difference in the contribution

![Graph](https://via.placeholder.com/150)
from the domain motion and domain walls to the elastic properties of both crystals, because there has been no poling process during the measurement and the domain configuration at room temperature might be different for both crystals because of different PT content. However, the elastic constants of PZN-9%PT sustain higher values than those of PZN-4.5%PT single crystals in the cubic phase where there is no extrinsic contributions from the domain configurations. This indicates that large difference in $C_{11}$ and $C_{44}$ between the two PZN-$x$PT single crystals may be due to the different PT composition and resultant microstructure. Similar results have been observed in the PMN-42%PT and PMN-30%PT single crystals, where PMN-42%PT located in the tetragonal side of the phase diagram of PMN-$x$PT shows larger $C_{11}$ compared to that of PMN-33%PT. Another possibility is that there might be some large difference in the frequency dispersion between the two crystals due to different densities of PNRs and their correlation length depending on the PT content.

It is readily recognizable from Figs. 4 and 5 that $v_{BA}^{TA}$ begins to become softened at higher temperatures than $v_{BA}^{LA}$ does, implying that the electrostrictive interaction might be anisotropic for the two acoustic modes, i.e., the electrostrictive coupling constant for the LA waves is larger than that for the TA waves near $T_B$. Similar behaviors were found in PMN investigated by the ultrasonic method. This seems to indicate that the PNRs are more sensitive to LA waves due to higher coupling strength. In order to check whether this behavior is universal or not in RFEs, two archetypal RFEs have been investigated for comparison. The sound velocities of PMN and PMT single crystals have been obtained by using the scattering geometry described in Fig. 1. $C_{11}$ and $C_{44}$ of PMN and PMT have been plotted in Fig. 7. Both $C_{11}$ and $C_{44}$ show linear behaviors in the high-temperature range above $T_B$. $C_{11}$ deviates from the high-temperature linearity, reaches a maximum near the Burns temperature, and shows a softening below it. In contrast, $C_{44}$ exhibits softening at much lower temperatures. $C_{44}$ of PMN begins to decrease at about 430 K, but exhibits significant softening at and below $\sim 370$ K. It was also indicated that a strong dispersion begins to occur in both elastic constants at the same temperature with decreasing temperature, which was ascribed to the onset of the cubic anisotropy. It is also interesting to note that this characteristic temperature is almost the same to that at which Raman spectrum shows a substantial change. In the same way, $C_{44}$ of PMT reaches a maximum at about 380 K, and shows a softening below this temperature. It was also found that the acoustic damping of the LA waves of PMT begins to increase below this temperature upon cooling. These behaviors are very similar to those observed from PZN-4.5%PT and PZN-9%PT single crystals. Therefore, we may suggest that the electrostrictive coupling constant between the LA waves and PNRs is different from that between the TA waves and PNRs. The former is stronger at high temperatures near $T_B$ while the TA waves seem to couple to the PNRs at lower temperatures.
C. Central peak behaviors of PZN-xPT

CP was fitted by a single Lorentzian centered at zero. Figures 8(a) and 8(b) show temperature dependences of the integrated intensity and the FWHM of CPs (∆CP), respectively, of PZN-9%PT measured at both polarized and depolarized scattering geometries below 600 K. It was previously shown that the polarized component of the CP persists at high temperatures even above TB (now shown in this figure). The intensity and the half-width of this VV contribution did not show any significant change with temperature. The situation is a little bit different in PZN-4.5%PT. Figures 9(a) and 9(b) give temperature dependences of the integrated intensity and the FWHM of CPs, respectively, of PZN-4.5%PT measured at the two scattering geometries. Similar to PZN-9%PT, the polarized component persisted in the high-temperature range above TB, but the intensity was much weaker compared to PZN-9%PT and reliable fitting procedure was not possible for this high-temperature range. The polarized component was clearly observed below 600 K and ∆CP decreased with lowering temperature. At about 525 K, the depolarized component of CP appears and grows upon cooling. The inset of Fig. 9(b) shows τp’s of the two CP components. Both relaxation processes exhibit slowing down with decreasing temperature, but τp of VH component is larger than that of VV component, which is different from the case of PZN-9%PT. The intensity of both components shows a broad maximum in a wide temperature range in contrast to the case of PZN-9%PT which exhibits significant...
The results described in the previous section indicated three characteristic temperatures, i.e., \( T_B, T_\text{R}, \) and \( T_m \) related to the dynamics of RFEs. At high temperatures above \( T_B, \) RFEs are in the nonpolar paraelectric phase, which is indistinguishable from the paraelectric phase of normal ferroelectrics. The real part of the complex dielectric constant follows the Curie-Weiss law, and other properties such as the refractive index, the strain, and the unit cell volume show linear behaviors as a function of temperature. The formation of PNRs at \( T_B \) has effects on these physical properties as well as acoustic properties via electrostrictive coupling. The correlation between \( T_B \) and the anomaly in \( \nu_B \) of LA mode has been observed in many RFEs, and was used to estimate the changes in the intensity at the phase transition temperature.

The above results suggest some common characteristics of CP behaviors in both PZN-xPT single crystals: (1) the VV component of CP persists at very high temperatures above \( T_B; \) (2) the VH component appears at temperatures around 520–550 K, lower than \( T_B \) by \( \sim 200 \) K, which is accompanied by the significant softening of \( C_{33}; \) and (3) the relaxation time of both components, related to the relaxation process of the relevant polarization fluctuations, displays dynamic slowing down with decreasing temperature from 550 K toward \( T_{C,T} \) or \( T_m. \)

IV. DISCUSSION

The results described in the previous section indicated three characteristic temperatures, i.e., \( T_B, T_\text{R}, \) and \( T_m \) related to the dynamics of RFEs. At high temperatures above \( T_B, \) RFEs are in the nonpolar paraelectric phase, which is indistinguishable from the paraelectric phase of normal ferroelectrics. The real part of the complex dielectric constant follows the Curie-Weiss law, and other properties such as the refractive index, the strain, and the unit cell volume show linear behaviors as a function of temperature. The formation of PNRs at \( T_B \) has effects on these physical properties as well as acoustic properties via electrostrictive coupling. The correlation between \( T_B \) and the anomaly in \( \nu_B \) of LA mode has been observed in many RFEs, and was used to estimate the changes in the intensity at the phase transition temperature.

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9%PT single crystals. That is, $T_d$ is characterized by (i) the appearance of the VH component of CP, (ii) significant decrease in $\Delta_{\text{CP}}$ of both VV and VH components of CP implying slowing down of the dynamics of PNRs, (iii) the onset of significant softening of $C_{44}$, and (iv) the increase of the acoustic damping in both LA and TA modes.

Although CPs can be related to several origins in condensed matters, CPs observed in ferroelectrics can arise from soft transverse-optic (TO) phonon, or from some relaxational entities, or from the coupling between them. Since previous studies reported that the TO phonons in PZN and PZN-8%PT are overdamped below $T_B$, the most probable origin of CPs in PZN-xPT would be the relaxational dynamics of PNRs. The CP dynamics is dominated by the reorientation of the PNRs and the CP width can be used to estimate the approximate relaxation time of the PNRs. It should be pointed out that the temperature at which the depolarized CP appears is lower than $T_B$ by approximately 200 K, consistent with the suggestion that local structural arrangements occur in PNRs at this temperature $\sim T_d$. The appearance of CP in the VH geometry at much lower temperatures than $T_B$ indicates that off-diagonal components of the polarizability tensor develop around this temperature. As temperature decreases, the correlation between off-centered ions in PNRs will become enhanced and thus their motion will become more restricted in fewer orientations, gradually losing the symmetric 180° reorientations. Since any local structural transformation in PNRs and the resulting local strain fields can couple to the propagating acoustic waves, the acoustic damping represented by the FWHM of acoustic modes will increase due to the enhancing order-parameter fluctuations. This has indeed been observed from the present study, as the FWHM of both LA and TA modes exhibit distinct changes in their slopes at $\sim 500$ K in both PZN-4.5%PT and PZN-9%PT single crystals (see Figs. 4 and 5). PMN and PMT show very similar characteristics. The FWHM of the LA mode of PMN and PMT begins to increase at approximately 350 and 400 K, respectively, which are much lower than their $T_B$'s. Similar results have also been observed in other RFEs such as PMN-xPT single crystals with $x = 33\% – 35\%$. Recent acoustic emission measurements on PZN-xPT with $x = 4.5\% – 12\%$ showed that strong acoustic activity was observed at almost the same temperature of about 500 K irrespective of the PT content, and this result was attributed to local microscopic phase transition in PNRs embedded in a nonpolar cubic matrix based on the fact that the acoustic emission signal is normally very sensitive to small structural changes. Considering that significant changes in the acoustic damping and the strong acoustic activity in addition to the substantial change in the Raman spectrum of PZN-4.5%PT occur at almost the same temperature, it can be safely concluded that both phenomena share the same microscopic origin related to some local structural changes in PNRs.

The exact nature of this local structural transformation in PNRs cannot be clearly revealed from the present Brillouin study, and more refined microscopic probe and analysis are necessary for resolving it. However, some possible candidate for the changes occurring in PNRs at $T_d$ might be suggested based on the symmetry considerations. In the cubic symmetry, there are three eigenvalues for the elastic constant matrix, that is, $C_{11} + 2C_{12}$, $C_{11} - C_{12}$, and $C_{44}$. The $C_{11} + 2C_{12}$ corresponds to hydrostatic deformation while $C_{11} - C_{12}$ and $C_{44}$ are related to the acoustic instabilities of the tetragonal and/or orthorhombic and rhombohedral (or trigonal) deformations, respectively. A phase transition associated with a uniform deformation should accompany vanishingly small elastic constant and sound velocity corresponding to that deformation. The most noteworthy result of this study is that, with decreasing temperature, $C_{44}/C_{11}$ of all the investigated RFEs exhibit the onset of softening at temperatures around $T_d$ much lower than $T_B$, the temperature for the formation of PNRs. Acoustic damping, desymmetrization of the polarization tensor represented by the appearance of the depolarized CP, and generation of strong acoustic emission signals accompany the onset of the softening of $C_{44}$. This might suggest that the nature of the local structural transformation occurring at $T_d$ and being enhanced upon further cooling is rhombohedral. The gradual softening of $C_{44}$ would then be correlated to the growth of the rhombohedral PNRs in the nonpolar cubic matrix. This onset of local transformation in PNRs may enhance the coupling between the TA waves and PNRs and thus be the origin of the anisotropic electrostrictive interaction between PNRs and the two acoustic waves. This suggestion is consistent with the results of previous neutron scattering studies on PZN, which showed that the rhombohedral phase appears at about 550 K, and that the local structure of PNRs at low temperatures is rhombohedral.

From the above results and discussions, it becomes obvious that the coupling between the dynamics of PNRs and acoustic modes, in particular, TA waves, become substantial at $T_d$. In addition, the increase of the intensity of CP and their narrowing in width signify that the density of PNRs and interactions between them begin to grow at this temperature. Therefore, it may be indicated that $T_d$ is a characteristic temperature at which long-lived PNRs begins to form via local phase transformation into, probably, rhombohedral symmetry, inducing local strain fields. According to recent neutron scattering studies on PMN, a local phase transformation at $T_d (\sim 370$ K) has been suggested and interpreted in terms of the role of the cubic anisotropy and the random-field-driven phase transition. These strain fields around PNRs will be coupled to the acoustic modes resulting in the changes of acoustic properties, in particular, substantial acoustic damping observed in this study. Upon further cooling, PZN-9%PT shows a clear structural phase transition at $T_d$ exhibiting discontinuous changes in acoustic properties and thus long-range ferroelectric order is realized due to the high PT content, while PZN-4.5% displays broad acoustic behaviors typical in RFEs during the diffuse phase transition. The PT content would affect the strength of the random fields as well as the percolation condition of PNRs in PZN-xPT.

Finally, it is worth comparing the present results with acoustic properties of seemingly very different relaxor systems, KT$_{1-x}$/Nb$_2$O$_5$ (KTN). From this previous ultrasonic study on KTN single crystals with four different Nb concentrations, it was found that a significant softening of $C_{11}$ and $C_{44}$ and a substantial increase in their corresponding attenuations occur in the temperature range above the phase tran-
sition temperature where PNRs appear. Moreover, $C_{44}$ was observed to soften closer to the transition temperature than $C_{11}$. All these results are very similar to those of PZN-xPT obtained in the present study. It should thus be pointed out that more systematic and thorough investigations into the polarization-strain coupling and associated phenomena in different relaxor systems are highly desirable in order to identify general features of relaxor dynamics.\textsuperscript{35}

V. SUMMARY AND CONCLUSION

The temperature dependence of acoustic properties of PZN-xPT with $x=0.045$ and 0.09 single crystals has been investigated in a wide temperature range by Brillouin light scattering. Temperature dependences of the acoustic modes and CP of these relaxor-based complex perovskites revealed three characteristic temperature regions divided by two characteristic temperatures, $T_B$ and $T_d$, which can be correlated to the temperature evolution of the dynamics of PNRs.

(1) Above $T_B$, the acoustic phonons showed a linearly decreasing behavior with increasing temperature reflecting normal lattice anharmonicity. The quasielastic CP is polarized with a weak intensity without any depolarized component. The Brillouin frequency shift of the LA waves shows a decreasing behavior with increasing temperature reflecting the slowing down of the dynamics related to the reorientation of PNRs.

(2) At a certain temperature of $T_d$ located below $T_B$ by more than 200 K, depolarized CP began to appear concomitant with the drastic softening of $C_{44}$ upon cooling from this temperature. In addition, the onset of substantial increase of the acoustic damping of both acoustic waves at $T_d$ could be seen from the temperature dependence of FWHM of Brillouin doublets suggesting enhanced electrostrictive coupling of the strain to the square of the local polarization of PNRs due to local structural changes occurring in PNRs. Based on the symmetry considerations, it is suggested that the local transformation occurring in PNRs might be rhombohedral. With further cooling from $T_d$, the CP width decreased and the relaxation time of the relevant polarization fluctuations increased reflecting the slowing down of the dynamics related to the reorientation of PNRs.

The present Brillouin-scattering study suggests a clear experimental evidence of the existence of the intermediate characteristic temperature $T_d$ located in 500–550 K in PZN-xPT at which significant changes in acoustic properties are brought about, and this temperature might indicate that long-lived PNRs and associated local strain fields are formed not at $T_B$ but at a much lower temperature $T_d=500–550$ K. This suggestion is further supported by the fact that strong acoustic emission signals, diffuse neutron scattering, and substantial changes in the Raman spectrum appear at almost the same temperature. Considering almost the same temperature characteristics of $C_{11}$ and $C_{44}$ and related acoustic damping factors observed from two representative RFEs, PMN and PMT, this conclusion might be considered as being more common properties of RFEs and the dynamics of PNRs rather than being restricted to only PZN-xPT single crystals.

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