



Electrostriction effects in space charge measurements with the pulsed electroacoustic method for ceramics

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Abstract

The pulsed electroacoustic (PEA) method is an established method for space charge measurements in polymeric dielectrics. In view of the poorly understood impact of space charge on the electrical resistivity and the dielectric breakdown behavior of ceramics, it is desirable to adapt the PEA technique to these materials. However, this adaption is non-trivial due to the constitutive properties of ceramics, which are, at least in part, very different from that of polymers. This contribution addresses a particular effect related to the electrostrictive properties of ceramics on the theoretical level. It is shown that these properties may cause an inversion of the sign of the sound wave generated by electrical voltage pulses when compared to typical polymers, which may in turn result in an incorrect interpretation of the measurement results. Using this finding, a reinterpretation of previous experimental results suggests that homo charge forms at the cathode in sheets of alumina ceramics subjected to high voltages.

Keywords Space charge · Ceramics · Pulsed electroacoustic method · Electrostriction

1 Introduction

Electroacoustic methods have been proposed as a space charge measurement technique for polymeric electric insulators in the 1980s [1, 2]. Since then, the pulsed electroacoustic (PEA) method has been developed into one of the reference methods for measuring space charge distributions in these materials [3, 4]. In the PEA method, a nanosecond electric pulse voltage (possibly superimposed on a DC bias voltage) is applied to a material sample, which causes the generation of a sound wave as a result of the interaction between the extra electric fields induced by the pulse and the electric charges accumulated in the sample and on the electrodes. This sound wave can be measured with a piezoelectric transducer attached to the ground electrode; and, after a calibration step, the space charge distribution in the sample can be inferred from the measured signal at the transducer by suitable postprocessing techniques.

As in the case of polymers, it is to be expected that space charge influences the electrical insulation properties

and the dielectric breakdown behavior of ceramics [5, 6]. Therefore, the ability to measure space charge becomes an important aspect with regard to the development of new ceramic materials as well as in the assessment and design of electrically insulating ceramic components. The state of the art in the determination of space charge in ceramics is to measure integral currents and use models to infer the space charge distribution, see, for example, Talbi et al. [7] and Neusel et al. [5]. Inherent to these models is the difficulty to validate them without a means of directly measuring space charge distributions; and in view of the incomplete knowledge of conduction mechanisms in ceramics, it is difficult to draw reliable conclusions from the data available. Often, the considerations are limited to particular mechanisms like Schottky, Poole-Frenkel and space charge limited current (SCLC) conduction, while other charge transport mechanisms like partial discharge effects at electrode edges, pores and other material defects [8, 9] are disregarded. In addition, the space charge accumulation behavior associated with the mentioned mechanisms is typically highly sensitive to defect chemistry and microstructure, and, as a consequence, quantitative assessments of space charge based on these models seem almost impossible. This situation motivates an investigation whether the PEA method or related methods like the pressure wave propagation method [3] can be adapted to

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ceramic materials for direct (or, at least, more direct) measurements of space charge. A first attempt towards implementing the PEA method for alumina ceramics has been made by Taira et al. [10]. However, while it has been shown that sound waves generated by electric pulses can be measured, the results remained inconclusive. In particular, it was found that the sign of the measured charges contradicted the polarity of the applied voltage; and the authors concluded that further experiments are necessary to understand the space charge behavior of alumina ceramics. Furthermore, the PEA method and the pressure wave propagation method have been applied to ferroelectric ceramics by Giacometti et al. [11] and De Reggi et al. [12], respectively. However, due to the complicating factors of remanent polarization and piezoelectric coupling, a discussion of these materials is beyond the scope of the present contribution.

Several aspects require careful (re)consideration when adapting the PEA technique to ceramics. These include the fact that the acoustic impedance of ceramic materials is usually much higher than that of polymers. As a result, it may be beneficial to adjust the material selection in the experimental setup in order to achieve acceptable acoustic impedance matching between the sample, the electrodes, the piezoelectric transducer and the backing materials and, therefore, reduce the impact of reflections of acoustic waves. Another directly related issue is that the sound velocity is substantially higher in ceramics than in polymers, which implies that high spatial resolution can only be achieved by extremely short voltage pulses; and the latter, in turn, calls for usage of extremely thin piezoelectric transducers to cover the entire frequency band of the incoming sound wave. Yet another aspect resulting from the constitutive behavior of ceramics is discussed in detail in this contribution. In particular, it is shown that the dependency of the permittivity on mechanical strain (which is thermodynamically linked to what is commonly referred to as electrostriction) may cause a change of the sign of the sound wave when compared to that measured for a polymer with the same space charge distribution. It is argued that this may explain the seemingly contradictory results of Taira et al. [10]. A reinterpretation of the results from the latter work suggests that a region of negative space charge forms close to the cathode upon application of high DC voltages.

2 Theory

2.1 Generation of sound waves in PEA measurements

For simplicity, the discussion is limited to an idealization of the PEA setup typically used for the measurement of sheet specimens; and the actual piezoelectric measurement device

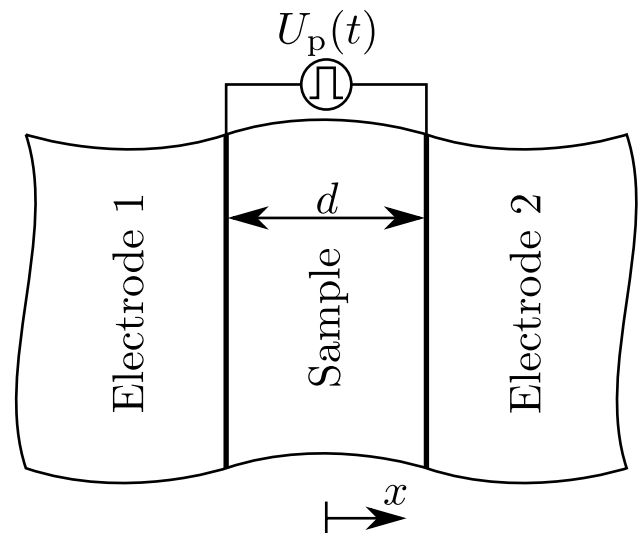


Fig. 1 Illustration of the domain under consideration

is not taken into account. As shown in Fig. 1, a solid sample of thickness d being sandwiched between two solid electrodes is considered. It is assumed that the lateral extent of the setup (perpendicular to the x -direction in the figure) is large compared to the thickness of the sample, such that it can be approximated as infinite. With regard to the material of the sample, it is assumed that the constitutive behavior is homogeneous, isotropic with regard to the unloaded state, linearly elastic in the absence of electric fields, and linearly dielectric in the absence of mechanical strain. Furthermore, the dependency of the permittivity on the mechanical strain is approximated as linear. The corresponding field problem, including electrostatic interactions, has been discussed in detail by Holé et al. [13] in a more general context. The main result relevant to the present contribution is that the generation of the longitudinal sound wave upon application of the voltage pulse $U_p(t)$ across the electrodes can be modeled in terms of the transient “electrostatic body force” $f_{es}(x, t)$ within the sample and the transient “electrostatic tractions” $t_{es,1}(t)$ and $t_{es,2}(t)$ on the electrodes 1 and 2, respectively. These are given by

$$f_{es}(x, t) = \left(1 - \frac{a_{11}}{\epsilon}\right) q(x) \frac{U_p(t)}{d} \quad (1)$$

$$t_{es,1}(t) = \left(1 - \frac{a_{11}}{\epsilon}\right) \omega_1 \frac{U_p(t)}{d} \quad (2)$$

$$t_{es,2}(t) = \left(1 - \frac{a_{11}}{\epsilon}\right) \omega_2 \frac{U_p(t)}{d}, \quad (3)$$

where t is the time, a_{11} the adiabatic¹ longitudinal electrostrictive coefficient of the material of the sample, ϵ the adiabatic permittivity of the material of the sample at zero strain, $q(x)$ the volume density of free charge present in the sample before application of the voltage pulse, and ω_1 and ω_2 are the densities of free surface charge present at the interfaces between the sample and the electrodes 1 and 2, respectively, before application of the voltage pulse. It is noted that terms being quadratic in $U_p(t)$ are neglected as it is assumed that the charges induced on the electrodes by the pulse itself are negligible compared to ω_1 and ω_2 . Moreover, it is assumed that the volume density of free charge, $q(x)$, is not substantially altered by the pulse.

The prefactor

$$\gamma = 1 - \frac{a_{11}}{\epsilon} \quad (4)$$

in Eqs. (1)–(3) is of major importance for the qualitative outcome of PEA measurements. In particular, a change of the sign of γ causes a change of the sign of the generated longitudinal sound wave. It is noted in this context that γ describes the deviation from the “ideal” case that the force exerted on a charge is given through the product of charge and electric field (with no deviation corresponding to a value of 1). This deviation is caused by the dependency of the permittivity on the mechanical strain or, equivalently, by the electrostrictive effect. Often, the latter effect is neglected in theoretical treatments, see, for example, Eq. (1) in [15] and Eqs. (2.11)–(2.13) in [16], which amounts to assuming that $a_{11}/\epsilon \ll 1$. However, this does usually not pose a limitation in PEA measurements in planar geometry because a calibration step with a known charge distribution is involved, which implicitly accounts for the true value of γ . As pointed out by Holé et al. [13], the situation is different in non-planar geometries, where the assumption that $a_{11}/\epsilon \ll 1$ can cause substantial errors.

2.2 Determination of the constitutive property γ

There are several ways to determine the value of γ . These include measurements of strains in response to electric fields, measurements of the variation of the permittivity in

response to mechanical strains, and theoretical approximations. Below, four different methods are briefly described. In the subsequent section, the sign of γ is discussed for ceramics and polymers based on experimental data available from the literature.

Laterally constrained strain measurements in response to electric fields Probably the most direct way to determine γ for an isotropic material is to impose an electric field to a sample and measure the strain in the direction of the field while all other strains are constrained to zero. This can, for example, be achieved by attaching a thin film of the material to be studied to a sufficiently stiff electrode on one side, while the electrode on the other side is formed by a thin metallic film. Though being simple, this setup is usually not realized in experiments as the lateral constraint is deemed an unwanted effect. However, this setup is discussed here as it gives an intuitive interpretation of γ . In particular, it can be shown from the work of Holé et al. [13] that

$$\gamma = -\frac{2(\lambda + 2\mu)}{\epsilon} M. \quad (5)$$

In this equation,

$$M = \frac{S(E)}{E^2} \quad (6)$$

is a constant due to the quadratic relation between strain and electric field at small strain, λ and μ are the adiabatic Lamé constants of the material, and $S = S(E)$ is the engineering thickness strain in response to the applied electric field E . Since $\lambda + 2\mu > 0$ holds for the longitudinal modulus and $\epsilon > 0$ for the permittivity, it follows that $\text{sgn}(\gamma) = -\text{sgn}(M)$. That is, a material which contracts in this setup has a positive value of γ , while a material which expands has a negative value of γ ; and it is intuitively expected that a reversal of the sign of the deformation in this setup causes a change of the sign of the sound wave in PEA measurements (provided that the sound waves are longitudinal).

Measurement of the variation of the permittivity in response to strain The coefficient γ may also be determined based on the thermodynamic interrelation between electrostriction and the dependence of the permittivity on the mechanical strain. To illustrate this approach, a laterally constrained film is considered again. It is assumed that a strain S is applied in the thickness direction of the film, while the capacitance $C = C(S)$ of the film is monitored. It is straightforward to show that

$$\gamma = -\frac{1}{C(0)} \left. \frac{dC}{dS} \right|_{S=0} \quad (7)$$

¹ It is assumed that the entire process of sound wave generation and propagation is adiabatic. For sound wave propagation, this is valid for frequencies $f \ll \rho c_p c^2 / (2\pi\lambda)$, where ρ is the density of the material, c_p the specific heat capacity at constant pressure, c the adiabatic speed of sound, and λ the thermal conductivity [14]. Using typical material parameter ranges for ceramics, metals and polymers, it can be estimated that the assumption of adiabatic conditions is valid for frequencies up to several GHz at least; and since the pulse widths typically used with the PEA method are ≥ 1 ns, it appears reasonable to assume that the propagation of sound waves is adiabatic.

in this case. Evidently, an increase of capacitance upon compression results, under adiabatic conditions, in a positive value for γ , while a decrease of capacitance upon compression is associated with a negative value of γ (note that compression is associated with $S < 0$).

Laterally unconstrained strain measurements in response to electric fields Another possibility to determine γ by strain measurements is to use a similar setup as described above, but without constraining the lateral strain. For this situation, there is a strain $S^{\parallel}(E)$ in the direction of the electric field E and an isotropic strain $S^{\perp}(E)$ in the plane perpendicular to the electric field. In this case, the experimental difficulty is to avoid any lateral constraint, which would affect the results. If this is achieved to within sufficient accuracy, the coefficient γ follows from

$$\gamma = -\frac{1}{\epsilon} [(2\lambda + 4\mu)M_{11} + 4\lambda M_{12}], \quad (8)$$

where

$$M_{11} = \frac{S^{\parallel}(E)}{E^2} \quad (9)$$

$$M_{12} = \frac{S^{\perp}(E)}{E^2} \quad (10)$$

are constants.

Theoretical determination using the Clausius-Mossotti relation A theoretical possibility to obtain a value for γ is to use the Clausius-Mossotti relation. This relation predicts that the permittivity is only sensitive to changes in volume and, therefore, stays isotropic upon straining. In particular,

$$\frac{1}{1-S} \frac{\tilde{\epsilon}(S) - \epsilon_0}{\tilde{\epsilon}(S) + 2\epsilon_0} = \text{const.} \quad (11)$$

in the small strain limit, where ϵ_0 is the permittivity of free space, S is the volume strain and $\tilde{\epsilon} = \tilde{\epsilon}(S)$ represents the dependency of the permittivity on the volume strain. Differentiation of (11) at $S = 0$ yields

$$\left. \frac{d\tilde{\epsilon}}{dS} \right|_{S=0} = -\frac{(\epsilon - \epsilon_0)(\epsilon + 2\epsilon_0)}{3} = a_{11}, \quad (12)$$

where $\tilde{\epsilon}(0) = \epsilon$. Thus,

$$\gamma = 1 + \frac{(\epsilon - \epsilon_0)(\epsilon + 2\epsilon_0)}{3\epsilon} \quad (13)$$

is obtained from (4), which suggests that $\gamma \geq 1$ due to $\epsilon \geq \epsilon_0$.

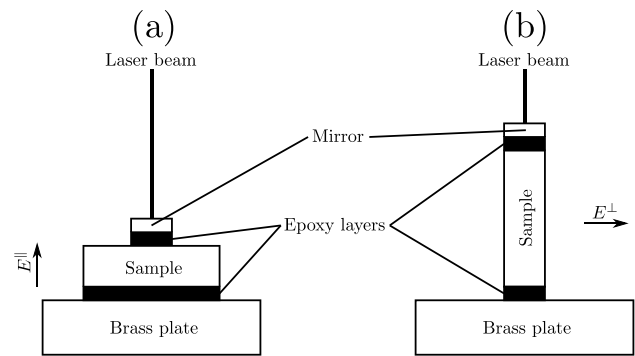


Fig. 2 Illustration of the experimental setup used by Yimnirun [17] and Yimnirun et al. [18] for measurements of strains in response to electric fields: (a) Setup for measurement of longitudinal coefficient \bar{M}_{11} , (b) Setup for measurement of transversal coefficient \bar{M}_{12}

3 Results and discussion

3.1 The sign of the constitutive property γ for ceramics and polymers

Due to the typically small magnitude of the effect and the resulting experimental complications, only few sources report electrostrictive characteristics of dielectrics; and it appears that the only systematic attempts to characterize the electrostrictive behavior of ceramics have been made by Yimnirun [17] and Yimnirun et al. [18] to date. The latter authors measured strain in response to electric fields under adiabatic conditions by means of laser interferometry in the experimental setups illustrated in Fig. 2(a) and (b). In particular, these setups have been used to determine the strains

$$\bar{M}_{11} = \frac{\bar{S}(E^{\parallel})}{E^{\parallel 2}} \quad (14)$$

$$\bar{M}_{12} = \frac{\bar{S}(E^{\perp})}{E^{\perp 2}}, \quad (15)$$

where \bar{M}_{11} is determined based on the setup shown in Fig. 2(a) from the strain along the direction of the laser beam, \bar{S} , and the applied electric field along the direction of the laser beam, E^{\parallel} , and \bar{M}_{12} is determined based on the setup shown in Fig. 2(b) from the strain along the direction of the laser beam, \bar{S} , and the applied electric field perpendicular to the direction of the laser beam, E^{\perp} . When attempting to calculate values for γ from \bar{M}_{11} and \bar{M}_{12} , a complication arises from the fact that the samples have been epoxied on one face to a 6–8 mm thick brass plate and a mirror has been attached to the other face with epoxy adhesive before interferometric measurement. With sample dimensions of 3–5 mm × 3–5 mm × 1–2 mm and mirror dimensions of 1.5 mm × 1.5 mm, these setups may induce substantial lateral

Table 1 Values for γ for ceramics and polymers computed from Eq. (8) setting $M_{11} = \bar{M}_{11}$, $M_{12} = \bar{M}_{12}$, and from Eq. (5) setting $M = \bar{M}_{11}$, respectively; ϵ_0 is the permittivity of free space; all quantities except the computed values for γ have been taken from [17, 18]

Material	$\frac{\epsilon}{\epsilon_0}$	$\frac{\lambda}{\text{GPa}}$	$\frac{\mu}{\text{GPa}}$	$\frac{\bar{M}_{11}}{\text{m}^2/\text{V}^2}$	$\frac{\bar{M}_{12}}{\text{m}^2/\text{V}^2}$	γ , Eq. (8)	γ , Eq. (5)
<i>Ceramics</i>							
Al ₂ O ₃	10.0	126	148	0.47·10 ⁻²¹	-0.13·10 ⁻²¹	-3.7	-4.5
MgO	8.1	73.9	131	0.55·10 ⁻²¹	-0.33·10 ⁻²¹	-3.8	-5.2
BeO	6.5	103	154	0.2·10 ⁻²¹	-0.23·10 ⁻²¹	-1.2	-2.9
Y-ZrO ₂	32.7	105	82	4.51·10 ⁻²¹	0.33·10 ⁻²¹	-8.9	-8.4
TiO ₂	92.7	127	108	21.9·10 ⁻²¹	2.77·10 ⁻²¹	-20.1	-18.3
Y-ZTA	13.3	146	135	1.05·10 ⁻²¹	-0.14·10 ⁻²¹	-6.7	-7.4
AlN	8.5	130	141	0.24·10 ⁻²¹	0.13·10 ⁻²¹	-3.5	-2.6
Si ₃ N ₄	7.9	159	125	0.17·10 ⁻²¹	-0.07·10 ⁻²¹	-1.4	-2.0
<i>Polymers</i>							
HDPE	2.4	1.29	0.28	-6.19·10 ⁻²¹	5.16·10 ⁻²¹	-0.2	1.1
PP	2.3	0.51	0.24	-6.71·10 ⁻²¹	2.98·10 ⁻²¹	0.4	0.6
PS	2.7	2.76	1.19	-4.27·10 ⁻²¹	2.82·10 ⁻²¹	0.5	1.8
PET	3.6	6.44	1.05	-4.65·10 ⁻²¹	5.12·10 ⁻²¹	-1.6	2.4

clamping. In order to address this aspect, values for γ have been computed from the measurement results of Yimnirun [17] and Yimnirun et al. [18] based on the assumptions (i) that no lateral clamping occurs, which amounts to setting $M_{11} = \bar{M}_{11}$ and $M_{12} = \bar{M}_{12}$ in Eq. (8), and (ii) that the samples are completely clamped laterally, which amounts to setting $M = \bar{M}_{11}$ in Eq. (5). Corresponding results are compiled in Table 1.

For ceramic materials, which are two orders of magnitude stiffer than typical epoxy adhesives, it is difficult to estimate the amount of clamping without knowing the exact thickness and properties of the adhesive layers. However, it can be seen from the results in Table 1, that the value of γ is negative for all ceramic materials for both extreme cases, no lateral clamping and full lateral clamping. Therefore, it seems likely that the actual value of γ is negative for all ceramic materials included in the table.

For polymers, the sign of γ is mixed depending on the type of polymer if lateral clamping is assumed to be absent, while γ is generally positive if full lateral clamping is assumed. Considering that (i) the orders of magnitude of the Young's moduli of epoxy adhesive and polymers are expected to be similar, (ii) the adhesive layer is thin compared to the dimensions of the sample, and (iii) the brass disc and the mirror are stiff compared to the adhesive, it appears likely that a high amount of lateral clamping is involved in the longitudinal strain measurements for polymers. This applies in particular to the center portion of the sample, where the measurements are taken. As a result, the values computed for γ based on the assumption of full lateral clamping are expected to be a better approximation to the actual behavior than those computed based on the assumption of no clamping. As the values measured by Yimnirun [17] for \bar{M}_{11} were negative in all cases, this leads to the

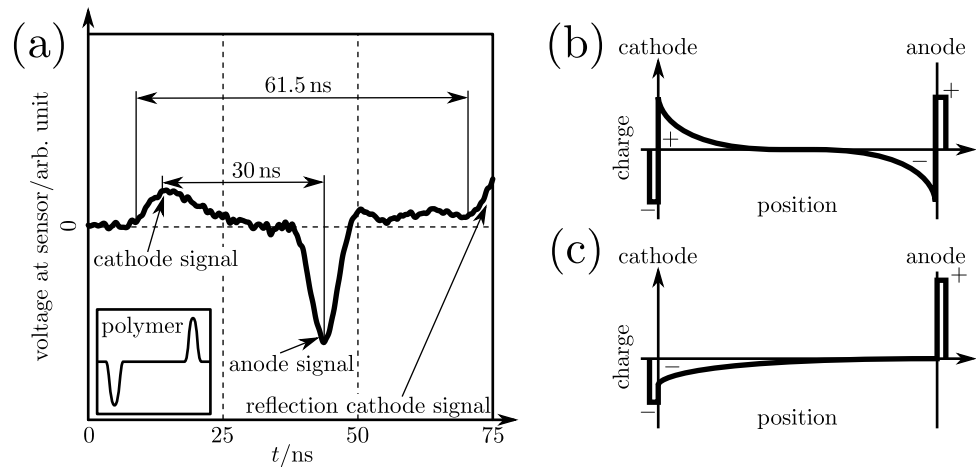
conclusion that the actual values of γ are likely to be positive for the polymers listed in Table 1. However, the magnitude of γ is still subject to a large degree of uncertainty since it is proportional to the elastic constants; and the latter have been taken from the literature and datasheets by Yimnirun [17], while the elastic behavior can vary by a large degree for the same type of polymer. A further result supporting the conclusion that γ is positive for polymers has been obtained by Nakamura and Wada [19]. These authors concluded that the behavior of most non-polar polymers is predicted well by the Clausius-Mossotti relation; and $\gamma \approx 1.5 \dots 3$ is computed from Eq. (13) given that the relative permittivity ϵ/ϵ_0 of polymers is usually in the range of 2 ... 5. It is additionally noted in this context that the above results suggest that the Clausius-Mossotti relation cannot be applied to ceramics since it does predict γ to be positive, which is in contradiction to the values given in Table 1.

3.2 Implications for the application of the PEA method to ceramics

The results presented above indicate that non-polar polymers are usually associated with a positive value of γ , while γ takes negative values for ceramics. This also suggests the existence of materials, which cannot be measured with the PEA method because γ is close to zero. A general trend visible from Table 1 is that ceramics with larger permittivity tend to be associated with larger absolute values of γ , which does also apply for materials obeying the Clausius-Mossotti relation.

Due to the different sign of γ , it is to be expected that the sign of the sound wave obtained with the PEA method is reversed when comparing ceramics and polymers with similar space charge distributions; and this aspect may explain

Fig. 3 Transient PEA measurement signal at the piezoelectric transducer and interpretation for alumina ceramics: **(a)** Typical measurement signal obtained by Taira et al. [10] together with wave form typically observed for polymers (inset); **(b)** Qualitative charge distribution proposed by Taira et al. [10]; **(c)** Qualitative charge distribution following a reinterpretation of the measurement results



the seemingly contradictory results obtained by Taira et al. [10] for a 330 μm thick alumina ceramic plate loaded with a DC voltage of $\approx 10\text{ kV/mm}$. Indeed, the latter authors found that the wave form observed for alumina ceramics (see Fig. 3(a)) is reversed when compared to that of polymers (see the inset in the figure). Based on the implicit assumption that the sign of γ is the same for polymers and ceramics, Taira et al. [10] speculated that the result may be caused by hetero charge at both, the cathode and the anode, as shown in Fig. 3(b). In particular, it has been proposed that parts of the respective electrode charges and the adjacent space charge annihilate each other in the signal due to the limited spatial resolution of the PEA method. However, from the measurement principle of the PEA method one would expect that, despite the limited spatial resolution, the total amount of the charges close to the cathode and the anode is still reflected in the signal (in an integral sense); and, if this holds, the result shown in Fig. 3(a) contradicts the sign of the DC voltage.

Taking into account that $\gamma < 0$, the result shown in Fig. 3(a) may be interpreted differently. In particular, the positive cathode signal corresponds in this case to a negative charge, and the negative anode signal to a positive charge. Taking additionally into account that the cathode peak is much lower in magnitude than the anode peak and at the same time more spread out into the sample, the following interpretation appears plausible: There is a region of negative space charge near the negatively charged cathode, while little space charge is present at the positively charged anode, see Fig. 3(c) for an illustration of this situation. It is noted in this context that it appears that Taira et al. [10] assumed that the two peaks in the signal correspond to positions inside the sample, while it is assumed in this work that the peaks roughly correspond to the two interfaces between the sample and the electrodes. The latter assumption is supported by the time difference between the two peaks of $\approx 30\text{ ns}$, which is consistent with the velocity of longitudinal waves in dense alumina ceramics of $\approx 11000\text{ m/s}$ [20–22] and the thickness

of the sample of 330 μm . In contrast, the discussion of Taira et al. [10] suggests a time difference between cathode and anode signal of $\approx 38\text{ ns}$. The latter would correspond to a longitudinal wave velocity of $\approx 8700\text{ m/s}$, a value which is considerably too low for alumina ceramics unless the porosity is $\approx 20\%$ [20, 21]. A complicating factor in the interpretation of the results of Taira et al. [10] may be reflections caused by an acoustic impedance mismatch at the anode interface. The presence of such a mismatch is suggested by the repeated increase in the signal about 61.5 ns after the arrival of the first cathode signal at the piezoelectric transducer, which is clearly visible towards the right in Fig. 3(a). The fact that the reflected cathode signal reaches the magnitude of the first cathode signal appears only explainable in terms of a huge acoustic impedance mismatch between the sample and both electrodes. Furthermore, the sign of the reflection indicates that the acoustic impedance of the anode side electrode is less than that of the sample. It is emphasized, however, that a substantial amount of speculation is involved in this discussion since Taira et al. [10] did neither report the details of the setup nor the exact type of alumina ceramic used for the experiment. Therefore, future experimental investigations are required to confirm or dismiss the reinterpretation given above. If the presence of negative space charge at the cathode is confirmed, this would be consistent with single carrier injection from the cathode upon application of high DC voltages, as has been proposed by Taira et al. [7], Schneider [23] and Neusel et al. [5] based on measurements of the integral electrical current.

4 Conclusions

In the present contribution, the impact of electrostriction on the sound waves to be expected for space charge measurements with the PEA method has been discussed for polymers and ceramics. It has been shown that it is likely that the sign

of the sound wave generated for ceramics is reversed when compared to polymers with a similar charge distribution. The relevance of this aspect has been demonstrated by discussing a measurement result obtained by Taira et al. [10] for alumina ceramics. In particular, it is concluded from a reinterpretation of this measurement result that homo charge forms at the cathode upon application of high electric voltages. This, in turn, suggests single carrier injection from the cathode as a conduction mechanism. However, further measurements with the PEA method or similar methods are required to back this result and to answer the question whether it can be generalized to different electrode materials and ceramics as well as to study the transient nature of this mechanism. Another interesting aspect of the above discussion is that PEA measurements may be useful as an indirect means of determining electrostrictive material characteristics.

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Declarations

Ethical approval Not applicable.

Statement regarding research involving human participants and/or animals Not applicable.

Informed consent Not applicable.

Conflict of interest The authors declare that there are no competing interests.

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