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Poling direction driven large enhancement in piezoelectric performance

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ABSTRACT

This study proposes enhancement in piezoelectric performance by tuning the poling direction in polycrystalline ceramics. Theoretically, it has been proven that transverse piezoelectric strain coefficient (d_{31}) and $\left(\frac{d_{31}^{eff}}{\varepsilon_{33}^{eff}}\right)$, governing factors for actuation and sensing respectively, get modified by altering poling direction. Finally, different polycrystalline materials have been employed to explore the effect of poling orientation on sensing and actuation capabilities. Optimised orientations were calculated for case of sensing and actuation. Among all materials under study, maximum increment in d_{31}^{eff} and $\left(\frac{d_{31}^{eff}}{\varepsilon_{33}^{eff}}\right)$ was observed for $0.3BaTiO_3 - 0.7NaNbO_3$ (BT-Nb). d_{31}^{eff} and $\left(\frac{d_{31}^{eff}}{\varepsilon_{33}^{eff}}\right)$ were as high as −356 pm/V and −0.152 pm/V respectively for BT-Nb at optimised orientation.

Piezoelectrics are a class of materials which have unique ability to produce electricity when subjected to mechanical strain and vice versa [1]. Therefore, piezoelectric materials play a vital role in electrical devices such as sensors, transducers, filters, accelerators etc. Out of different applications, piezoelectric materials have been widely used as sensors, actuators and for energy harvesting in particular [1–7]. For most of the practical sensing and actuation applications researchers have used cantilever with piezoelectric layers in bimorph configuration [8,9]. Typically, the piezoelectric energy harvester in cantilever beam configuration operates in transverse mode (d_{31} mode) [10–13]. Additionally, performance of piezoelectric materials operating in longitudinal (d_{33} mode) and shear (d_{15} mode) modes has also been explored [14–18]. However, due to complex fabrication and poling process the latter two modes are generally not common for practical applications.

Although, significant research has been carried out related to operation of piezoelectric materials in different modes still researchers focussed mainly on exploration of longitudinal piezoelectric strain coefficient (d_{33} mode). On contrary, numerical value of transverse piezoelectric strain constant (d_{31}) has not been reported for many materials in spite of being most commonly mode used for sensing, actuation and energy harvesting application. The maximum value of d_{31} according to our literature survey is −320 pm/V [19] while maximum value of d_{33} and d_{15} for polycrystalline ceramics reported so far are 697 pm/V [20] and 407 pm/V [21] respectively. Thus it is evident that the value of d_{31} in spite of being very commonly employed is less as compared to its counterparts. Therefore, there is need to enhance the performance of piezoelectric materials operating in d_{31} mode. Optimised piezoelectric properties can be achieved by altering the crystallographic orientation and/or composition and through domain engineering [22].

A detailed analysis has been carried out by researchers [23] between three operating modes namely d_{31}, d_{33} and d_{15}. It is clear that modes d_{31} and d_{33} are same in terms of poling direction while the strains developed are in two different directions. On other hand, for d_{15} mode the poling direction is along the length of the material. It is well established fact that different operating modes of piezoelectricity result in contrasting amount of harvested energy due to difference in piezoelectric coupling coefficients [24]. Davis et al. [25] have carried out study on a few material systems where they demonstrated how different domains in a domain engineered structure contribute towards d_{31}^{eff}. Along the same lines, we have explained theoretically how the actuation and sensing abilities of the piezoelectric materials can be enhanced by change in their poling direction. We have derived mathematical expressions for d_{31}^{eff} and $\left(\frac{d_{31}^{eff}}{\varepsilon_{33}^{eff}}\right)$ varying with poling orientation and optimised poling orientation as well. The motivation behind the study is to increase transverse piezoelectric strain coefficient by utilising the high numerical values of longitudinal and shear piezoelectric strain coefficients. The study focuses mainly on enhancement in sensing and actuation capabilities of the piezoelectric materials in cantilever configuration which primarily operates in d_{31} mode. We have considered here a class of materials including $0.3BaTiO_3$-$0.7NaNbO_3$ (BT-Nb), $Pb[Zr_xTi_{1-x}]O_3$ (PZT-5A and PZT-2), $K_{0.475}Na_{0.475}Li_{0.05}(Nb_{0.92}Ta_{0.05}Sb_{0.03})$ (KNLNTS) and $(Ba_{0.7}Ca_{0.3})TiO_3$-$0.48Ba(Zr_{0.2}Ti_{0.8})O_3$ (BCT-0.48BZT) (material properties presented in Table 1) for theoretical comparison of variation in sensing and actuation capabilities. We have

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Table 1
Physical properties of materials.

Material	s^E_{11}	s^E_{12}	s^E_{13}	s^E_{33}	s^E_{44}	s^E_{66}	d_{31}	d_{15}	d_{33}	$\frac{\varepsilon^T_{11}}{\varepsilon_o}$	$\frac{\varepsilon^T_{33}}{\varepsilon_o}$	Ref.
$0.3BaTiO_3$–$0.7NaNb\ O_3$	14.9	−4.4	−4.4	14.9	38.8	38.8	10.5	937	5	2340	2342	[26]
BCT-0.48BZT	12.1	−4.2	−7.2	13.36	26.6	28.1	−188	335	542	5198	5778	[27]
KNLNTS	8.88	−5.2	−1.3	6.78	30.5	28.3	−75.5	256.8	121.7	501.7	878.8	[28]
PZT-5A	16.4	−5.7	−7.2	18.8	47.5	44.3	−171	584	374	1730	1700	[1]
PZT-2	11.6	−3.3	−4.9	14.8	45.0	29.9	−60	440	152	990	450	[29]

Note: (i) All s_{ij} and d_{ij} in Table 1 are reported as 10^{-12} m^2/N and pm/V respectively.

mathematically presented here the idea how the sensing and actuation depends on the poling orientation.

As a motivation and starting point, we first started exploring how the change in poling direction affects the induced electric field in different directions. It is shown in Fig. 1(a) that if the poling is along the thickness i.e. along 3rd direction and strains are developed in 1st direction then electric field is induced only in direction 3 due to activation of d_{31} mode. On the other hand, if poling direction is oriented at an angle θ and the strains are developed in 1st direction then electric field is induced due to activation of three different modes simultaneously. This phenomenon is depicted in Fig. 1(b) where electric field is induced due to d_{31}, d_{33} and d_{15} modes simultaneously. It is observed that the after changing the poling direction different piezoelectric strain constants contribute towards the transverse mode. It is also inferred that on changing the poling orientation along the length of the material and keeping the direction of force same the material will operate primarily in shear mode. Thus, it is clear that with change in poling orientation there will be a trade-off between d_{31} and d_{15} modes. Next step in

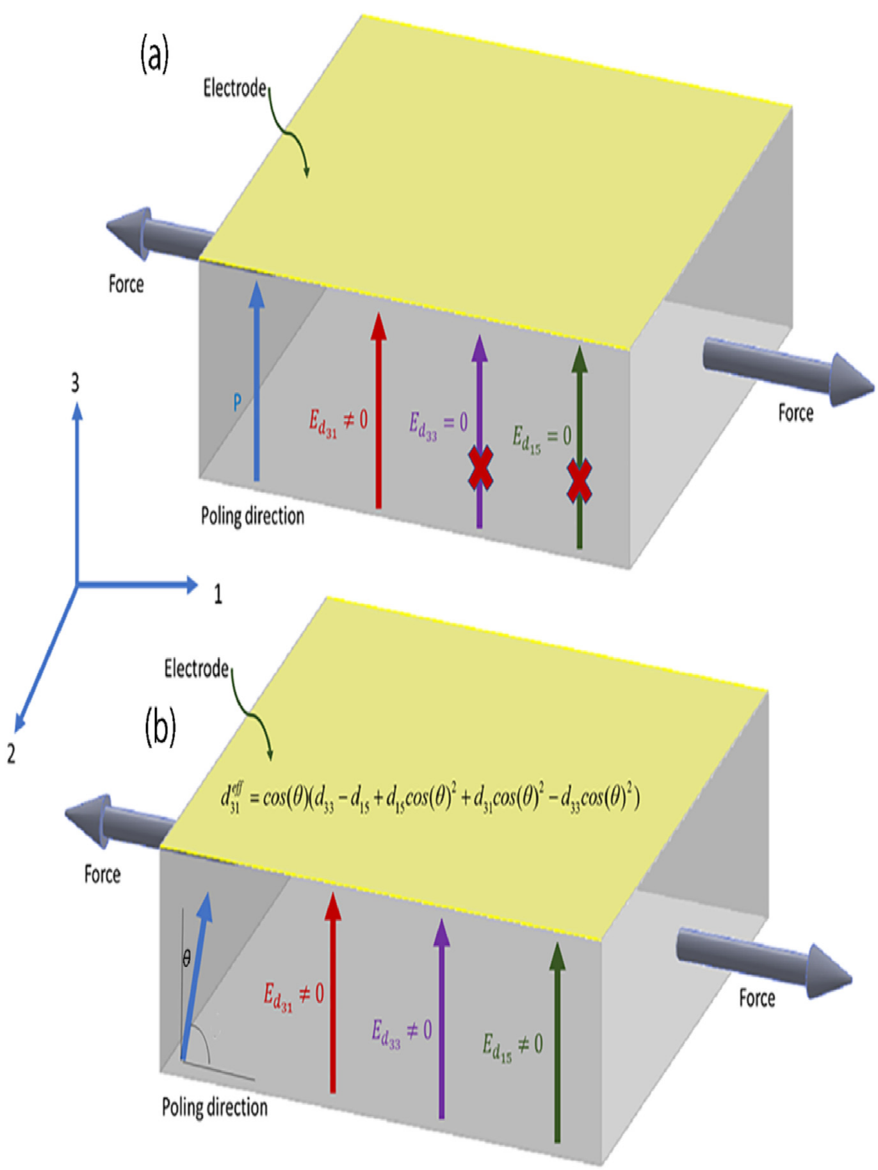

Fig. 1. Effect of poling direction on induced electric field due to different piezoelectric strain coefficients.