Deformation Anisotropy of Y + 128°-Cut Single Crystalline Bidomain Wafers of Lithium Niobate

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Abstract—Bidomain single crystals of lithium niobate (LiNbO3) and lithium tantalate (LiTaO3) are promising materials for use as actuators, mechanoelectrical transducers, and sensors capable of working in a wide temperature range. One need to take into account the anisotropy of the properties of the crystalline material when such devices are designed. In this study we investigated deformations of bidomain round shaped Y + 128°-cut wafers of lithium niobate in an external electric field. The dependences of the piezoelectric coefficients on the rotation angles were calculated for lithium niobate and lithium tantalate and plotted for the crystal cuts which are used for the formation of a bidomain ferroelectric structure. In the experiment, we utilized an external heating method and long-time annealing with the lithium out-diffusion method in order to create round bidomain lithium niobate wafers. Optical microscopy was used to obtain the dependences of the bidomain crystals’ movements on the rotation angle with central fastening and the application of an external electric field. We also modelled the shape of the deformed bidomain wafer with the suggestion that the edge movement depends on the radial distance to the fastening point quadratically. In conclusion, we revealed that the bidomain Y + 128°-cut lithium niobate wafer exhibits a saddle-like deformation when a DC electric field is applied.

Keywords: lithium niobate, lithium tantalate, bidomain crystal, anisotropy of deformation, actuator, piezoelectric properties

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INTRODUCTION

Lithium niobite is a ferroelectric material, which is widely employed in optical, acoustic, and electronic instrument engineering [1–6]. Its diverse application is mainly determined by the opportunity to control the domain structure of ferroelectric crystal, as well as its temporal stability. A large number of earlier studies were devoted to various technological approaches to designing the predetermined configuration of the domains in lithium niobate, as well as structurally identical lithium tantalate [7–19].

Among numerous possible variants of implementation of the ordered domain structure, bidomain single crystals of lithium niobate and tantalate are of interest due to their possible application as precise piezoelectric bimorph actuators for the position control systems of probe microscopes [20] and X-ray diffractometers [21], in mechanoelectrical radioisotopic power generators [16], high-temperature vibration sensors [22], and highly sensitive magnetic field sensors based on composite multiferroics [23]. The broad range of possible applications is due to the unique combination of the following advantages of lithium niobate over the conventional ceramics of lead zirconate-titanate (PbTi1−xZrxO3, PZT):

—high Curie point;
—thermal stability of piezoelectric units;
—relatively low values of dielectric permittivity;
—absence of nonlinearity, hysteresis, and creep during the deformation under the action of an electric field [24].

In addition, there are no adhesive layers and grain boundaries in bidomain crystals. Several approaches for forming a bidomain ferroelectric structure in a 180°-cut ferroelectric crystal with a pseudoilmenite structure have been suggested, which provide the head-to-head and tail-to-tail configuration of the domains in lithium niobate (LiNbO3) [8, 17–19, 25, 26] and the head-to-head configuration of domains in lithium tantalate (LiTaO3) [18].

During the development and fabrication of actuators and mechanoelectrical transducers, it is important to consider the anisotropy of the mechanical and electric properties of the material of which these devices are produced. Some authors previously investigated the anisotropic character of the deformation of...
PZT-based actuators [27–29]. At the moment, there are no such works on single-crystal bidomain structures. At the same time, single-crystal piezoelectrics possess a more significant anisotropy of the mechanical and electric properties compared to piezoceramics, which require greater attention during the development of a particular device. The results of the studies of the deformation of round \( Y + 128° \)-cut single crystalline wafers of lithium niobate with head-to-head and tail-to-tail bidomain ferroelectric structures are considered below.

**THEORETICAL ANALYSIS**

During the application of an electric field, a crystalline bidomain wafer is deformed in analogy with a bimorph; one of the domains expands, while the other one contracts. This leads to a bend of the entire structure. The driving force of this deformation is a transverse piezoelectric effect. Let us locate the Cartesian coordinate system in such a way that the \( Y'' \) axis is perpendicular to the wafer plane, while the \( X'' \) and \( Z'' \) axes lie on the wafer plane. In the general case, any cut of a crystal can be obtained by two sequential turns of the crystallographic coordinate system at Euler angles \( \alpha \) and \( \varphi \) from the standard orientation, for which there are usually reference data on various properties of the material (Fig. 1).

The piezoelectric modules constitute tensor \( d_{ijk} \) of the third-rank, which contains 27 components. When the coordinate axes turn, the tensor is transformed as follows:

\[
d_{\bar{i}mn} = a_{\bar{i}} a_{\bar{m}} a_{\bar{n}} d_{\bar{i}k},
\]

where \( d_{\bar{i}mn} \) are the tensor components of the piezoelectric coefficients in a new system of coordinates; \( a_{\bar{m}} \) \((\alpha = l, m, n; \beta = i, j, k)\) are the values of the rotation matrix; and summation is performed according to Einstein notation.

The matrices of rotation at the angle \( \alpha \) around the \( X \) axis and at the angle \( \varphi \) around the \( Y' \) axis are

\[
\begin{align*}
\mathbf{a}_1 &= \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & \sin \alpha \\
0 & -\sin \alpha & \cos \alpha
\end{pmatrix}; \\
\mathbf{a}_2 &= \begin{pmatrix}
\cos \varphi & 0 & \sin \varphi \\
0 & 1 & 0 \\
-\sin \varphi & 0 & \cos \varphi
\end{pmatrix}.
\end{align*}
\]

In the case of crystals with the point group \( 3m \), there are four independent components of the piezoelectric tensor, which can be written as follows in matrix representation:

\[
d_y = \begin{pmatrix}
0 & 0 & 0 & d_{15} & -2d_{22} \\
d_{31} & d_{31} & d_{33} & 0 & 0
\end{pmatrix},
\]

where \( d_{15} = 68 \) pC/N; \( d_{22} = 21 \) pC/N; \( d_{31} = \) 1 pC/N; \( d_{33} = 6 \) pC/N in the case of LiNbO\(_3\) crystals; \( d_{15} = 26 \) pC/N; \( d_{22} = 7 \) pC/N; \( d_{31} = -2 \) pC/N; and \( d_{33} = 8 \) pC/N in the case of LiTaO\(_3\) crystals [30].

The transverse piezoelectric effect, when the electric field is applied orthogonally to the wafer plane along the \( Y'' \) axis and the deformation occurs along the \( Z'' \) axis, corresponds to the piezoelectric modulus \( d_{23} \) (in matrix representation). In this case, to obtain the angular dependence of the transverse piezoelectric effect in the cut plane at the angle \( \alpha \), it is sufficient to consider the dependence \( d_{23}(\alpha = \) const, \( \varphi \)). Let us introduce matrix \( a_1 \) to Eq. (1). Then, after the first turn, we have

\[
d_{23}(\alpha) = -d_{15} \sin \alpha \cos^2 \alpha + d_{22} \sin^2 \alpha \cos \alpha + d_{31} \sin^3 \alpha + d_{33} \sin \alpha \cos^2 \alpha.
\] (2)

After plotting the dependence, we can determine the optimal cut angle of the crystal to design a piezoelectric actuator (Fig. 2).

Analysis of the plot in Fig. 2 shows that the largest value of the piezoelectric modulus is achieved in the \( Y + 140°-\)cut of LiNbO\(_3\) \((d_{23} = 30 \) pC/N\) and the \( Y + 137°-\)cut of LiTaO\(_3\) \((d_{23} = 9.6 \) pC/N\). Similar results were obtained in [25, 26], where the optimal cut was evaluated by the piezoelectric-coupling coefficient. It should be noted that the plot coincides with that given in [31], while Eq. (2) differs from the relationship for \( d_{23} \), which presumably indicates the presence of misprints in [31].

Let us consider the dependence of the piezoelectric modulus \( d_{23} \) on the second turn at the angle \( \varphi \) around the \( Y' \) axis. For this purpose, let us again transform the tensor \( d_y \) into the new coordinate system using the rotation matrix \( a_2 \). We obtain the following relationship:
\[ d_{23}(\alpha, \varphi) = \sin^2 \varphi (-d_{22} \cos \alpha + d_{33} \sin \alpha) \\
+ \cos^2 \varphi (-d_{15} \sin \alpha \cos^2 \alpha + d_{22} \sin^2 \alpha \cos \alpha) \\
+ d_{33} \sin^3 \alpha + d_{15} \sin \alpha \cos^2 \alpha. \]

Among the commercially available wafers, the \( Y + 128^\circ \)-cut of lithium niobate and the \( Y + 36^\circ \)-cut of lithium tantalite are closest to optimal. After setting the value of \( \alpha \) for these cuts and using Eq. (3), we can plot the angular distribution of the piezoelectric coefficient \( d_{23} \) (Fig. 3).

It is clear from Fig. 3 that the transverse piezoelectric modulus changes sign in the \( Y + 128^\circ \)-cut wafer plane of lithium niobate. This implies that the wafer is elongated in one direction and contracts in the other direction when an electric field is applied. Also, the deformation along the \( Z'' \) axis is higher than along the \( X'' \) axis. Knowing that the displacement of the edge of the piezoelectric bimorph is directly proportional to the piezoelectric modulus [32], we can presume that the bidomain wafer of this section will deform in a saddle-like form. Let us now consider the angular dependence of the piezoelectric coefficient \( d_{23} \) for the \( Y + 36^\circ \)-cut wafer of lithium tantalate. The piezoelectric modulus has the same sign in all directions in the wafer plane and changes insignificantly. This allows us to conclude that a bidomain crystal of lithium tantalate of this orientation will possess a convex form in the deformed state under the applied electric field.

**MATERIALS AND METHODS**

Bidomain crystals were prepared from \( Y + 128^\circ \)-cut polished round wafers of lithium niobate with the diameter of 40 mm and thickness of 1 mm. It is known that, depending on the way of bidomain structure formation, the appearance of the boundary between two domains may differ [18, 24]. In particular, during the preparation of bidomain crystals using stationary external heating [19] there is no sharp domain wall but the wide polydomain region. In contrast, when annealing with the out-diffusion of lithium is used for the bidomain structure formation [17], the domain boundary is sharp.

The specimens of two types of bidomain structures were studied. To prepare specimens of the first type, the crystals were annealed in a ULVAC VHC-P610 infrared furnace at 1150°C according to the procedure described in detail in [19] (stationary external heating). In this case, the domains are formed under the action of internal electric fields generated by the temperature gradient upon the cooling of the crystal, so the bidomain structure has a head-to-head appearance with the polydomain region between macrodomains. The specimens of the second type were prepared using the procedure suggested in [17] by annealing in a muffle furnace in air under the conditions of lithium out-diffusion from the crystal. The bidomain structure, which was obtained during this process, also possesses a head-to-head form; however, the boundary between the domains is sharp.

To control the bidomain structure, witness crystal samples \( 10 \times 10 \times 1 \) mm\(^3\) in size were also annealed.
together with the wafers. After the formation of a bidomain structure, polished angle laps were prepared from these crystals and etched in the mixture of nitric and hydrofluoric acid according to the procedure described in [33] to visualize the domain structure. The photographs of the etched polished angle laps are given in Fig. 4.

The bidomain structure formed using stationary external heating is less sharp and the interdomain region possesses a clear polydomain appearance. The boundary between domains is in the center of the wafer and deviates from the mean plane by 15–20% of the thickness (Fig. 4a). The domain structure obtained using long annealing with lithium out-diffusion from the crystal demonstrates a clear contrast between domains and lies in the middle of the wafer (Fig. 4b).

After the formation of a bidomain structure in the specimens, we deposited copper electrodes with a thickness of ~100 nm on the crystals’ faces using magnetron sputtering.

To measure the deformation, round specimens with a bidomain structure were fastened in a special holder fixing them pointwise in the center (Fig. 5). The specimen fastened in the holder was placed under the objective of the microscope and focused on the end of the bidomain structure. The displacement of the crystal edge was measured after applying a DC electric field of 980 V. Each subsequent measurement was carried out by rotating the crystal in the holder at 5°.

**RESULTS AND DISCUSSION**

In Figs. 6a and 7a, the angular dependences of the deviation of the edges of $Y + 128^\circ$-cut bidomain wafers of lithium niobate, which were obtained using stationary external heating and long annealing, respectively, are given. As follows from Figs. 6a and 7a, the bend of the wafer is nonuniform and the maximum displacement of the edge is achieved in the directions orthogonal to the $X''$ axis, which confirms the calculations given above.
The deformation plots repeat the form of the plot of the angular dependence of the piezoelectric modulus $d_{33}$ with the exactness up to a constant (on average, $3.1 \times 10^5$ m N C$^{-1}$ and $3.6 \times 10^5$ m N C$^{-1}$ in the case of stationary external heating and long annealing, respectively). This indicates a linear form of the dependence of the transverse piezoelectric modulus and the displacement of the wafer edge in the direction for which this modulus was calculated. The divergence between the constants is ~14%.

In Figs. 6b and 7b, the results of modeling the shape deformed under the action of the electric field of the bidomain wafers, which were obtained on the assumption that the dependence of the deflection of the wafer edge on the distance from its center is quadratic, are given [32]. Analysis of the experimental results and modeling indicates that the $Y + 128^\circ$-cut bidomain crystal of lithium niobate is deformed in a saddle-like manner when an electric field is applied. It is expected that the deformation of the crystal with a bidomain structure, which is formed by stationary external heating, is slightly less than for a crystal exposed to long annealing with lithium outdiffusion, due to the mentioned differences in the domain structure appearance. At the same time, the maximum deviations of the wafer edges with a bidomain structure, which are formed after stationary external heating and long annealing, differ by less than 14%. Consequently, the presence of the polydomain region in the middle of the bidomain wafer weakly affects the maximum deformation of the actuator at the same voltage.

When designing devices based on bidomain crystals, it is necessary to assume the form of the dependence of the transverse piezoelectric modulus $d_{33}$ on the turn in the wafer plane for the $Y + 128^\circ$-cut LiNbO$_3$ (Fig. 3a) and the saddle-like deformation of the wafer in the DC.
external electric field. In particular, the use of these structures in the mode of the direct piezoelectric effect (in mechanoelectrical transducers of low-power generators, sensitive elements of magnetic-field sensors, and vibration, oscillation, and pulsation sensors) while bending through an angle will lead to the formation of charges with the opposite signs at various points of the crystal surface and a decrease in the operating characteristics (the transformation coefficient of the energy of the mechanical deformation in the electrical signal). When bidomain crystals are utilized as actuators, the saddle-like character of a deformation can also be harmful. One example is that a beam-focusing mirror surface cannot be formed based on this structure. The solution of this problem can be found by the choice of another cut of the crystal; in particular, we can choose the section with the angular dependence of a piezomodulus, which is similar to lithium tantalate (Fig. 3b) or use several galvanically isolated electrodes, which are located as sectors along the wafer surface.

**CONCLUSIONS**

The character of the deformation of $Y + 128^\circ$-cut bidomain single crystals of lithium niobate has been analyzed. The analytical dependences of piezoelectric modulus $d_{33}$ on the rotation angle of the crystal cut with the $3m$ symmetry have been obtained. A bidomain structure has been formed in two $Y + 128^\circ$-cut round wafers of LiNbO$_3$ using stationary external heating and long annealing with lithium out-diffusion. The etched angle laps with a visualized domain ferroelectric structure have been studied. Using the point central fastening, the displacements of the edges of the bidomain wafers have been studied at various rotation angles around the line orthogonal to the wafer plane and the DC electric field of 980 V. The linear form of the dependence of the bidomain wafer edge’s displacement in a DC electric field on the transverse piezoelectric modulus $d_{33}$ in the direction under study has been stated. The proportionality constants were on average $3.1 \times 10^5$ N C$^{-1}$ and $3.6 \times 10^5$ N C$^{-1}$ in the case of stationary external heating and long annealing, respectively. The shape of the bidomain crystal surface deformed under stress has been simulated in the approximation of the quadratic dependence of the displacement of the edge on the radial distance to the center of the wafer. The saddle-like character of the deformation of wafer with the maximum displacement of the edge in the direction perpendicular to the crystallographic $X$ axis of the crystal in the standard orientation has been discovered. The results must be considered when designing devices with piezoelectric bidomain elements, such as actuators; mechanoelectrical generators; and vibration, oscillation, and pulsation sensors.

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**REFERENCES**

1. Volk, T.R. and, Wöhlecke, M., *Lithium Niobate: Defects, Photorefractive and Ferroelectric Switching*, vol. 115 of *Springer Series in Materials Science*, Berlin, Heidelberg: Springer, 2009. doi:10.1007/978-3-540-70766-0

2. Arizmendi, L., Photonic applications of lithium niobate crystals, *Phys. Status Solidi A*, 2004, vol. 201, no. 2, pp. 253–283. doi:10.1002/pssa.200303911

3. Wooten, E.L., Kiss, K.M., Yi-Yan, A., Murphy, E.J., Lafaw, D.A., Hallemeyer, P.F., Maack, D., Attanasio, D.V., Fritz, D.J., McBrien, G.J., and Bossi, D.E., A review of lithium niobate modulators for fiber–optic communications systems, *IEEE J. Sel. Top. Quantum Electron.*, 2000, vol. 6, no. 1, pp. 69–82. doi:10.1109/2944.826874

4. Gualtieri, J.G., Kosinski, J.A., and Ballato, A., Piezoelectric materials for acoustic wave applications, *IEEE Trans. Ultrason. Ferroelecr. Freq. Control*, 1994, vol. 41, no. 1, pp. 53–59. doi:10.1109/58.265820

5. Scott, J.F., *Ferroelectric Memories*, Vol. 3 of *Springer Series in Advanced Microelectronics*, Berlin, Heidelberg: Springer, 2000. doi:10.1007/978-3-662-04307-3

6. Cross, L.E., Ferroelectric materials for electromechanical transducer applications, *Mater. Chem. Phys.*, 1996, vol. 43, no. 2, pp. 108–115. doi:10.1016/0254-0584(95)01617-4

7. Lu, Y.L., Lu, Y.Q., Cheng, X.F., Luo, G.P., Xue, C.C., and Ming, N.B., Formation mechanism for ferroelectric domain structures in a LiNbO$_3$ optical superlattice, *Appl. Phys. Lett.*, 1996, vol. 68, no. 19, pp. 2642–2644. doi:10.1063/1.116267

8. Antipov, V.V., Bykov, A.S., Malinkovich, M.D., and Parkhomenko, Yu.N., Formation of bidomain structure in lithium niobate single crystals by electrothermal method, *Ferroelectrics*, 2008, vol. 374, no. 1, pp. 65–72. doi:10.1080/00150190802427127

9. Grilli, S., Ferraro, P., De Nicola, S., Finizio, A., Pierattini, G., de Natale, P., and Chiarini, M., Investigation on reversed domain structures in lithium niobate crystals patterned by interference lithography, *Opt. Express*, 2003, vol. 11, no. 4, pp. 392–405. doi:10.1364/OE.11.000392

10. Dierolf, V., and Sandmann, C., Direct-write method for domain inversion patterns in LiNbO$_3$, *Appl. Phys. Lett.*, 2004, vol. 84, no. 20, pp. 3987–3989. doi:10.1063/1.1753057

11. Zhang, X., Dongfeng, X., and Kenji, K., Domain switching and surface fabrication of lithium niobate single crystals, *J. Alloys Compd.*, 2008, vol. 499, nos. 1–2, pp. 219–223. doi:10.1016/j.jallcom.2006.02.091

12. Nutt, A.C., Gopalan, V., and Gupta, M.C., Domain inversion in LiNbO$_3$ using direct electron–beam writing, *Appl. Phys. Lett.*, 1992, vol. 60, no. 23, pp. 2826–2830. doi:10.1063/1.106837
13. Miyazawa, S., Ferroelectric domain inversion in Ti-diffused LiNbO$_3$ optical waveguide, *J. Appl. Phys.*, 1979, vol. 50, no. 7, pp. 4599–4603. doi 10.1063/1.326568

14. Rosenman, G., Kugel, V.D., and Shur, D., Diffusion-induced domain inversion in ferroelectrics, *Ferroelectrics*, 1995, vol. 172, no. 1, pp. 7–18. doi 10.1080/00150199508018452

15. Chen, J., Zhou, Q., Hong, J.F., Wang, W.S., Ming, N.B., Feng, D., and Fang, C.G., Influence of growth striations on para-ferroelectric phase transitions: mechanism of the formation of periodic laminar domains in LiNbO$_3$ and LiTaO$_3$, *J. Appl. Phys.*, 1989, vol. 66, no. 1, pp. 336–341. doi 10.1063/1.348379

16. Malinkovich, M.D., Bykov, A.S., Kubasov, I.V., Kiselev, D.A., Ksenich, S.V., Zhukov, R.N., Temirov, A.A., Timushkin, N.G., and Parkhomenko, Yu.N., Formation of bidomain structure in lithium niobate plates for beta-electric actuator production by a stationary external heating method, *Russ. Microelectron.*, 2016, vol. 45, no. 8, pp. 582–586. doi 10.1134/S0023476116080096

17. Kugel, V.D. and Rosenman, G., Domain inversion in heat-treated LiNbO$_3$ crystals, *Appl. Phys. Lett.*, 1993, vol. 62, no. 23, pp. 2902–2904. doi 10.1063/1.109191

18. Kubasov, I.V., Kislyuk, A.M., Bykov, A.S., Malinkovich, M.D., Zhukov, R.N., Kiselev, D.A., Ksenich, S.V., Temirov, A.A., Timushkin, N.G., and Parkhomenko, Yu.N., Bidomain structures formed in lithium niobate and lithium tantalate single crystals by light annealing, *Crystallogr. Rep.*, 2016, vol. 61, no. 2, pp. 258–262. doi 10.7868/S0023476116020120

19. Bykov, A.S., Grigoryan, S.G., Zhukov, R.N., Kiselev, D.A., Ksenich, S.V., Kubasov, I.V., Malinkovich, M.D., and Parkhomenko, Yu.N., Formation of bidomain structure in lithium niobate plates by the stationary external heating method, *Russ. Microelectron.*, 2014, vol. 43, no. 8, pp. 536–542. doi 10.1134/S0036739714080034

20. Kubasov, I., Malinkovich, M., Bykov, A., Kiselev, D., Temirov, A., and Ksenich, S., Bimorph single-crystal piezoelectric actuators for scanning probe microscopy, in *Proceedings of the 24th International Conference on Materials and Technology, Portoroz, Slovenia*, 2016, p. 124.

21. Blagov, A.E., Bykov, A.S., Kubasov, I.V., Malinkovich, M.D., Psarevski, Yu.V., Targonski, A.V., Eliovich, I.A., and Kovalchuk, M.V., An electromechanical X-ray optical element based on a hysteresis-free monolithic bimorph crystal, *Instrum. Exp. Tech.*, 2016, vol. 59, no. 5, pp. 728–732. doi 10.1134/S0020441216050043

22. Kubasov, I., Kislyuk, A., Malinkovich, M., Kiselev, D., Chichkov, M., Ksenich, S., Temirov, A., Bykov, A., and Parkhomenko, Yu., A novel high-temperature vibration sensor based on bidomain lithium niobate crystal, in *Proceedings of the 7th International Advances in Applied Physics and Materials Science Conference and Exhibition, Oludeniz, Turkey*, 2017, in press.

23. Vidal, J., Turutin, A.V., Kubasov, I.V., Malinkovich, M.D., Parkhomenko, Yu.N., Kheleva, S.P., Khoklin, A.L., and Sobolev, N.A., Equivalent magnetic noise in magnetoelectric laminates comprising bidomain LiNbO$_3$ crystals, *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, 2017, vol. 99, p. 1. doi 10.1109/TUFFC.2017.2694342

24. Kubasov, I.V., Timoshina, M.S., Kiselev, D.A., Malinkovich, M.D., Bykov, A.S., and Parkhomenko, Yu.N., Interdomain region in single-crystal lithium niobate bimorph actuators produced by light annealing, *Crystallogr. Rep.*, 2015, vol. 60, no. 5, pp. 700–705. doi 10.1134/S1063774515040136

25. Nakamura, K., Ando, H., and Shimizu, H., Bending vibrator consisting of a LiNbO$_3$ plate with a ferroelectric inversion layer, *Jpn. J. Appl. Phys.*, 1987, vol. 26, no. S2, pp. 198–200. doi 10.7567/JJAPS.26S2.198

26. Nakamura, K. and Shimizu, H., Hysteresis-free piezoelectric actuators using LiNbO$_3$ plates with a ferroelectric inversion layer, *Ferroelectrics*, 1989, vol. 93, no. 1, pp. 211–216. doi 10.1080/00150198908017348

27. Crawley, E.F. and Lazarus, K.B., Induced strain actuation of isotropic and anisotropic plates, *AIAA J.*, 1991, vol. 29, no. 6, pp. 944–951. doi 10.2514/3.10684

28. Bent, A.A., Hagood, N.W., and Rodgers, J.P., Anisotropic actuation with piezoelectric fiber composites, *J. Intell. Mater. Syst. Struct.*, 1995, vol. 6, no. 3, pp. 338–349. doi 10.1177/1045389X9500600305

29. Huang, G.L. and Sun, C.T., The dynamic behaviour of a piezoelectric actuator bonded to an anisotropic elastic medium, *Int. J. Solids Struct.*, 2006, vol. 43, no. 5, pp. 1291–1307. doi 10.1016/j.ijsolstr.2005.03.010

30. Warner, A.W., Onoe, M., and Coquin, G.A., Determination of elastic and piezoelectric constants for crystals in class (3m), *J. Acoust. Soc. Am.*, 1967, vol. 42, no. 6, pp. 1223–1231. doi 10.1121/1.1910709

31. Shur, Y.Y., Batulin, I.S., Mingaliev, E.A., Zorikhin, D.V., Udalov, A.R., and Greshnyakov, E.D., Hysteresis-free high-temperature precise bimorph actuators produced by direct bonding of lithium niobate wafers, *Appl. Phys. Lett.*, 2015, vol. 106, no. 5, p. 053116. doi 10.1063/1.4907679

32. Smits, J.G., Dalke, S.I., and Cooney, T.K., The constituent equations of piezoelectric bimorphs, *Sens. Actuators A: Phys.*, 1991, vol. 28, no. 1, pp. 41–61. doi 10.1016/0924-4247(91)80007-C

33. Nassau, K., Levinstein, H.J., and Loiacono, G.M., The domain structure and etching of ferroelectric lithium niobate, *Appl. Phys. Lett.*, 1965, vol. 6, no. 11, pp. 228–229. doi 10.1063/1.1754147

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