Magnetic field effect in piezoelectric resonators with HTS electrodes

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Abstract. Microwave (MW) impedance of a square-shaped piezoelectric (PE) resonator containing an AlN film with tilted c-axis and high temperature superconducting (HTS) electrodes was modelled for the case of propagation of longitudinal and shear acoustic waves (AW) across the resonator thickness. External DC magnetic field $B$ was assumed to be applied perpendicularly to the resonator surface. It was shown, that the magnetic field results in a decrease of the resonance frequency and an increase of the MW losses. The effect is due to a change of the MW impedance of HTS component under action of the magnetic field.

1. Introduction
Aluminim Nitride (AlN) is characterized by low losses, excellent piezoelectric (PE) characteristics and is attractive for use in microwave resonators, filters and sensors based on the resonance effect [1,2]. Thin films of AlN with tilted c-axis allow exciting in them the longitudinal and shear acoustic waves (LAW and ShAW, respectively) in the same configuration of the electrodes [3]. Although such devices mainly function at ambient temperatures, the attempts to make their cryogenically cooled versions are also important because it can reduce electrical losses in the devices. For example, AlN piezoelectric-on-silicon resonators functioning at 77 K and demonstrating high quality factors were reported in [4]. The use of high temperature superconducting (HTS) elements in such resonators at low temperatures leads to a significant decrease in the limit value of the quality factor caused by losses in the electrodes [5]. On the other hand, the application of external magnetic field causes a change of the characteristics of the HTS components [6, 7] and can lead to some adjustment of the device parameters. In this paper the magnetic field effect on the characteristics of the piezoelectric resonators with standard and inclined c-axis orientations, containing HTS electrodes, are modelled and analyzed in view of the importance of such devices for different applications.

2. Impedance of PE resonators with HTS electrodes for longitudinal and shear AW
A scheme of a square shaped PE resonator and coordinate systems $x, y, z$ and $x', y', z'$ related to the geometry of the resonator and to the symmetry of the hexagonal PE film are presented in figure 1. The resonator consists of PE film $l$, c-axis of which lay at the $x, y$ plane and is inclined at an angle $\theta$ with respect to the $z$-axis of the structure. The thickness of the resonator is significantly smaller of its
lateral dimensions. External magnetic field \( B \) is assumed to be applied perpendicularly to the resonator surface (figure 1). The MW electric field applied to HTS electrodes 2 of such an “inclined” resonator can excite the both longitudinal and shear acoustic waves (with the particle displacement nearly parallel to the \( z \)- and \( x \)-axis directions, respectively), propagating in the thickness direction \( z \). The AW motion equation in such a PE resonator can be obtained by taking into account of the transformation matrices [3] of the stiffness, piezoelectric and dielectric constant tensors from one coordinate system \( x’, y’, z’ \) to another system \( x, y, z \). The velocities of the longitudinal \( v_{1(L)} \) and shear \( v_{1(S)} \) AW propagating in the thickness direction are expressed by following formulas:

\[
v_{1(L,S)} = \left(2\rho_1 \right)^{1/2} \frac{c_{33}^{D} \pm \sqrt{\left(c_{33}^{D} - c_{33}^{E}\right)}}{c_{33}^{E}} + \left(4c_{33}^{D}\right)^{1/2},
\]

where \( c_{33}^{D} = c_{33}^{K} + \left(\varepsilon_3 / \varepsilon_3\right) \), \( c_{33}^{E} = c_{33}^{K} + \varepsilon_3 / \varepsilon_3\), \( c_{33}^{D} = c_{33}^{E} + \varepsilon_3 / \varepsilon_3\), \( c_{33}^{E} = c_{33}^{E} + \varepsilon_3 / \varepsilon_3\), \( c_{33}^{E}\) are the transformed stiffness, piezoelectric and dielectric constant tensors, respectively, \( \rho_1 \) is the density of the PE film. Electromechanical coupling constants for the longitudinal and shear AW can be presented in the following form:

\[
\begin{align*}
\left(k_{1(L)}^{(2)}\right)^2 & \approx \left(\varepsilon_3 / \varepsilon_3\right) / \varepsilon_3 \rho_1 \left(v_{1(L)}^{2}\right), \\
\left(k_{1(S)}^{(2)}\right)^2 & \approx \left(\varepsilon_3 / \varepsilon_3\right) / \varepsilon_3 \rho_1 \left(v_{1(S)}^{2}\right).
\end{align*}
\]

The MW impedance \( Z_{in} \) of the resonator (figure 1) can be represented as follows using Mason and transmission line models:

\[
Z_{in}^{(L,S)} = 2Z_{EM} + \frac{1}{j\omega C_{0}^{(L,S)}} \left[1 - \left(k_{1}^{(2)}\right)^2 / \tan\left(k_{1}^{(2)}\right) / \phi_{1}^{(2)}\right],
\]

where \( Z_{EM} \) is the MW impedance of the electrode; \( \phi_{1}^{(L,S)} = k_{1}^{(L,S)} d_{1}/2; \) \( \phi_{2}^{(L,S)} = j\left(Z_{2}^{(L,S)} / Z_{0}^{(L,S)}\right) \tan(k_{2}^{(L,S)} d_{2}) \) is dimensionless acoustic impedance of electrodes 2 with respect to the longitudinal and shear AW; \( Z_{0}^{(L,S)} = \rho_1 v_{1(L,S)}, Z_{2}^{(L,S)} = \rho_2 v_{2(L,S)} \) are the characteristic AW impedances of the PE layer and of the electrodes; \( \rho_2 \) is the density of the electrode material 2; \( C_{0}^{(L,S)} = v_{33}^{E}Sd_{1} \) is the capacitance and \( S \) is the area of the structure; \( v_{33}^{E} \) is the relative dielectric constant of PE measured in \( z \) direction; \( \varepsilon_3 = 8.854 \times 10^{-12} \text{ F/m} \); \( \omega = 2\pi f \) is the frequency of the applied MW field; \( k_{1}^{(L,S)} = \omega v_{1(L,S)} / \omega v_{1(L,S)} \); \( k_{2}^{(L,S)} = \omega v_{2(L,S)} / \omega v_{2(L,S)} \) are wave vectors in the PE and electrode media, respectively; \( d_{1} \) and \( d_{2} \) are thicknesses of PE film 1 and electrodes 2; \( f^2 = -1. \) MW impedance of HTS electrodes \( Z_{EM} \) can be described by formulas (2) and (3) from [5]. External DC magnetic field leads to an increase of the impedance of HTS materials [6].

3. Modelling results and discussion

The MW impedance of a square-shaped (~220 \( \times \) 220 \( \mu \)m\(^2\)) PE resonator with inclined \( c \)-axis was modeled for the case of propagation of longitudinal and shear AW across the resonator thickness and of DC magnetic field applied perpendicularly to the resonator plane. The parameters of PE were assumed to be similar to those of AlN material (see, for example [8]). The imaginary part of the LAW and ShAW velocity \( v_{1(L,m)}^{(2,m)} \) and \( v_{1(S,m)}^{(2,m)} \) in PE (which characterizes the acoustic losses) was chosen to be...
small \((0.0000056 \text{ m/s} \text{ and } 0.0000031 \text{ m/s}, \text{ respectively})\) in order to obtain information on \(Q\)-factor mainly caused by MW losses in the HTS electrodes. Parameters of YBCO electrode used in the model were \(\rho_2 = 6300 \text{ kg/m}^3\), \(v_2 = 5040 \text{ m/s}\) (for the longitudinal AW) and \(v_2 = 2400 \text{ m/s}\) (for the shear AW) and its electromagnetic parameters were taken from [5]. The thickness of the HTS electrode was chosen to be small \(d_2 = 20 \text{ nm}\), in order to have stronger magnetic field effect on the impedance. By taking into account the results of [6, 8] we described the effect of magnetic field \(B\) on the penetration depth of the HTS electrodes by an approximate formula \(\lambda_L(B) = \lambda_{LO} + NB\), where \(N \sim 10^{-8} \text{ m/T}, \lambda_{LO} = 0.2 \times 10^{-6} \text{ m}\).

Velocities \(v_1(L), v_1(S)\) of LAW and ShAW propagating across the thickness of AlN film, modelled for different inclination angles \(\theta\) of c-axis are presented in figure 2. The maximal velocities are observed for inclination angles \(\theta = 0^\circ\) (longitudinal AW) and \(\theta \approx 30^\circ\) (shear AW) although there is not a strong dependence of the velocities on the orientation. Modelled electromechanical coupling coefficients \(k_{t(L)}, k_{t(S)}\) of the longitudinal and shear AW as function of the inclination angle \(\theta\) are shown in figure 2 too. The maximal coupling coefficients are obtained for longitudinal and shear AW in the resonators with \(\theta = 0^\circ\) and \(\theta \approx 30^\circ\), respectively, and there is not big difference between their values. Local maximums of \(k_{t(L)}, k_{t(S)}\) with less magnitudes occur at \(\theta \approx 65^\circ\) and \(\theta = 0^\circ\) for above types of AW.

![Figure 2](image-url)  
**Figure 2.** Velocities (1,2) and electromechanical coupling coefficient (3,4) of longitudinal (1,3) and shear (2,4) AW modeled for the case of AlN crystal as function of the inclination angle \(\theta\).

![Figure 3](image-url)  
**Figure 3.** Impedance \(|Z_{\text{tot}}|\) of an AlN resonator with HTS YBCO electrodes modeled for \(T = 77 \text{ K}, d_1 = 2.5 \mu\text{m}\) and \(\theta = 30^\circ\). Peaks 1 and 2 correspond to the resonance of LAW and ShAW, respectively.

Microwave impedances \(|Z_{\text{tot}}|\) of the AlN resonators with inclined c-axis were modeled for the LAW and ShAW regimes by taking into account the effect of HTS electrodes. Frequency dependence of such MW impedance of a resonator with the thickness \(d_2 = 2.5 \mu\text{m}\) and the inclination angle \(\theta \approx 30^\circ\) (where \(k_{t(S)}\) is close to its maximal value) is shown in figure 3 for the case of \(B = 0\). Peaks observed at \(f \sim 1.2\) and \(f \sim 2.1 \text{ GHz}\) correspond to the shear AW and longitudinal AW resonances, respectively, and according to the results, the both resonances can be easily excited. Minimum (inverse peak) and maximum (conventional peak) of the impedance are observed at the resonance and antiresonance frequencies \(f_r, f_a\), respectively. Quality factor of the resonance peak 1 is higher than that of the peak 2, due to lower microwave losses in HTS electrodes at lower frequency.

Results of modeling of resonance frequency \(f_r\) and quality factor \(Q\) of the resonators with several thicknesses are presented in figure 4. Shear AW resonances occur at lower frequency as compared with longitudinal AW resonances for the same resonator. Quality factor of the resonators is high at lower frequencies for both the longitudinal and the shear AW resonances. This is due to the fact, that the thickness (or volume) of resonators with lower \(f_r\) is greater and stores more mechanical energy. Furthermore, at low frequencies the losses of HTS materials are smaller too. Figure 4 also shows
changes in the resonance frequency $f_r$ of longitudinal and shear AW for PE resonators with standard and inclined $c$-axes under action of the external DC magnetic field of $B=100$ mT applied perpendicularly to the HTS electrodes. Magnetic field leads to a decrease of the resonance frequency, especially, in the case of resonators with high value of $f_r$. The effect is caused by increase of the kinetic inductance of HTS elements (electrodes) of the resonator in magnetic field $B$.

Magnetic field leads to a decrease of the quality factor $Q$ of the resonators too, provoked by increase of MW losses in HTS electrodes. Change of the inverse quality factor $Q^{-1}$ (which characterizes microwave losses) in perpendicular magnetic field $B=100$ mT for AlN resonators with different thickness are shown in figure 5 for the longitudinal AW. It is seen, that the effect of magnetic field on the MW losses is stronger for the case of resonators with higher resonance frequency $f_r$ (i.e. for the case of thinner resonators). It can be also noted, that some additive factors, such as defects of HTS material, the structure of the magnetic vortices can enhance magnetic field effect in the resonators affecting the quality factor and the resonance frequency.

Tables 1 and 2 summarize the results of modelling for above resonators and effect of magnetic field on them. Quality factors were computed under the assumption of negligibly small losses in the PE part of the resonator as it was mentioned above. For this reason, the obtained $Q$ -values are high (especially in the case of lower frequencies) and can be considered as the values of $Q$ -factors limited by the MW losses in the HTS electrodes. In the case of higher resonance frequencies it is necessary using of thicker (~ 100 nm) HTS electrodes in order to obtain higher values of limiting quality factor.

**Table 1.** Modeled quality factor $Q$, resonance frequency $f_r$ and its change in AlN resonators (at $\theta = 0^\circ$, longitudinal AW resonances) with 20 - nm thick HTS YBCO electrodes.

| Resonator thickness, µm | Quality factor | Resonance frequency $f_r$ at 0 T, GHz | $f_r(0\text{mT}) - f_r(100\text{mT})$, MHz |
|------------------------|---------------|--------------------------------------|----------------------------------------|
| 2.5                    | 599000        | 2.06494                              | 0.035                                  |
| 1.25                   | 35179         | 4.00305                              | 0.45                                   |
| 0.8                    | 5275          | 6.032                                | 3                                      |
| 0.58                   | 974           | 7.967                                | 17                                     |
Table 2. Modeled quality factor $Q$, resonance frequency $f_r$ and its change in AlN resonators (at $\theta = 30^\circ$, shear AW resonances) with 20 - nm thick HTS YBCO electrodes.

| Resonator thickness, µm | Quality factor $Q$ | Resonance frequency $f_r$ at 0 T, GHz | $f_r$(0mT)-$f_r$(100mT), MHz |
|------------------------|--------------------|---------------------------------------|----------------------------|
| 2.5                    | 3640619            | 1.1871345                             | 0.0145                     |
| 1.25                   | 202199             | 2.30332                               | 0.065                      |
| 0.8                    | 40863              | 3.4796                                | 0.5                        |
| 0.58                   | 10510              | 4.6313                                | 1.7                        |

It is seen, that the change of the resonance frequencies of the longitudinal and shear AW in these resonators under action of the magnetic field $B=100$ mT can reach from several tens kHz to nearly twenty MHz, in dependence on the thickness (resonance frequency) of the resonators (tables 1 and 2).

4. Conclusions
Microwave impedance of PE resonators, containing an AlN component with tilted c-axis and HTS electrodes was modelled for the longitudinal and shear AW regimes with taking into account the effect of DC magnetic field $B$ applied perpendicularly to the resonator. Shear AW resonances occur at lower frequency as compared with longitudinal AW resonances for the same resonator. The limiting $Q$-factor of such resonators caused by electric losses in HTS electrodes can be very high at 77 K and decreases drastically with increasing of the frequency. It was shown that the magnetic field $B$ leads to a decrease of the resonance frequency $f_r$ and quality factor $Q$. A change of the resonance frequencies of the longitudinal and shear AW in these resonators under action of the magnetic field $B=100$ mT can reach from several tens kHz (in thicker resonators with $f_r \sim 2$ GHz) to nearly twenty MHz (in thinner resonators with $f_r \sim 8$ GHz).

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