Application of Bragg Reflection for Suppression of Spurious Transverse Mode Resonances in RF BAW Resonators

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Application of Bragg Reflection for Suppression of Spurious Transverse Mode Resonances in RF BAW Resonators

（RF BAW 共振子における不要横モード共振抑圧へのブラッグ反射の応用）

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ABSTRACT

In the BAW technologies, one of the cumbersome problems is the propagation of Lamb wave modes, which cause unwanted spurious resonances. This dissertation discusses use of periodic gratings to control excitation and propagation of Lamb modes in RF BAW devices from various aspects.

Firstly, the applicability of the Bragg reflection in periodic gratings placed on the FBAR top electrode in order to forbid lateral propagation of the spurious Lamb modes is discussed. Due to the Bragg reflection in periodic gratings, the stop band can be generated which plays the role in suppressing the spurious resonances. It is demonstrated that a spurious free resonance is obtainable provided that the grating period and height are set so that the stop band covers the frequency range where the lateral mode resonances occur.

Based on this technique method, secondly, the use of periodically slotted top electrode is discussed. In this case, the Bragg reflection can be generated in periodic slots. The results show that lateral propagating modes can be suppressed well and $Q$ factor can be enhanced when the structure is properly designed.

Next, it is indicated that the slotted FBAR structure can be used to realize a coupled resonator filter (CRF), where evanescent modes in the periodic structure are used for the coupling between adjacent electrodes. It is shown that wideband CRFs are realizable when the period, thickness, and width of slotted electrodes are properly set.
Although both gratings and slots are effective to suppress the spurious resonances and improve the $Q$ factor, achieved effective electromechanical coupling factor $k_e^2$ is somewhat low compared with the original FBAR structure.

Finally, it is demonstrated that the $Q$ value at the anti-resonance frequency is enhanced without changing $k_e^2$ by employing the Bragg reflector placed on the top surface near the side edges of FBAR structure.
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Chapter 1

BACKGROUND
A tremendous growth in telecommunication industry over the past few decades drives the subsequent development in demand for high frequency components. Bulk acoustic wave (BAW) devices entered the RF (radio frequency) field as an irreplaceable component for many communication systems such as cellphones, satellite receivers, mobile computers and so on. In this chapter, the motivation of the present work is given in section 1.2, along with a brief introduction to the BAW technology in section 1.1.

1.1 Introduction

Vast growth of the RF filter market gives more stringent requirements on insertion loss, operating frequency, size, price, and so on. Bulk acoustic wave (BAW) resonators represented by quartz resonators [1-4] have been widely used even in the modern digital communications for the clock generation. Since they employ mechanically thinned quartz plate, their resonance frequencies are usually lower than 30 MHz.

The film BAW technology using a piezoelectric thin film was proposed nearly simultaneously by three research groups of Nakamura [5], Grudkowski [6] and Lakin [7] in 1980. This technique evolved in a surprising speed until now, and is now widely used as frontend filters and duplexers in wireless communication equipment [8-9].

The film BAW resonators and filters are miniature and operate in a GHz range. Most importantly, they can be integrated with active RF circuits [10]. The main part of film BAW resonator consists of a resonating piezoelectric film (such as ZnO and AlN) between two metal electrodes. When the voltage signal is applied, the main resonance of the thickness
extension (TE) vibration is excited. Due to the determination of resonance frequency by the piezoelectric film thickness, therefore, the thin film technology enables BAW devices to operate in a high frequency and brings BAW devices so popular in the present telecommunication fields.

There are two typical configurations for the film BAW resonator to confine the energy within the active region. One is the membrane structure which confines the energy using large difference in acoustic impedance at the air interface, which is commonly named as film bulk acoustic wave resonator (FBAR) [11-15] (see Fig. 1.1).

FIG. 1.1. FBAR configuration which air cavity is formed by etching substrate.

Another possibility to confine the energy as shown in Fig. 1.2 is to use the Bragg reflector mirror below the bottom electrode, where the mirror consists of a series of alternating low and high acoustic impedance with the thicknesses close to a quarter wavelength [16]. This type of resonator is commonly named as solidly mounted resonator (SMR). This type of structure is very attractive due to its better mechanical robustness compared to the above FBAR configuration. However, SMR devices generally exhibit lower electromechanical coupling and quality factors than the FBAR counterpart. They are owed to energy penetration into the Bragg reflector and transmission into the substrate.
The main resonance of FBAR and SMR is caused by the TE vibration of the piezoelectric film sandwiched in between two metal electrodes. Their composite structure also acts as a waveguide for laterally propagating plate modes, namely Lamb modes [17], which cause unwanted spurious resonances [18]. They are called the transverse resonances, which will be discussed in detail in Chapter 2, and their suppression without deteriorating the main resonance is one of the major concerns for the design of RF BAW resonators.

Various techniques have been proposed for the suppression. Apodization of the top shape as shown in Fig. 1.3 is an example [19-22]. It extends the path length of lateral modes, and smears out their resonance peaks. However, since lateral modes are not trapped, their energy will be finally dissipated.

FIG. 1.2. Solidly mounted resonator which employs the Bragg reflection layers technique.

FIG. 1.3. A top view of apodized FBAR structures.
The piston mode operation is also well known [23-24], where the resonator rims are specifically designed; a narrow border block is added so that loops of all the resonance modes locate at the resonator edge as shown in Fig. 1.4. This design makes only a main mode electrically active.

![Fig. 1.4. The cut-off frequency diagram and displacement profile of piston mode resonator with border region.](image)

Although usefulness of these techniques is well recognized, they are not effective to suppress energy leakage through top and bottom metal electrodes extended for the electrical interconnection [25]. This loss causes deterioration of the quality factor $Q$ of the main resonance.

This work is aimed at suppressing the spurious transverse modes and enhancing the quality factor $Q$ by the Bragg reflection caused by

1) Periodic grating placed on the top electrode,
2) Periodically slotted top electrode, and
3) Periodic gratings placed near the side edges.
1.2 Outline of this research

In Chapter 2, propagation of Lamb waves in a plate is introduced. Propagation of Lamb modes is clarified. Laterally propagating Lamb waves cause spurious resonances and/or lateral energy leakage, which deteriorate the device performance.

In Chapter 3, we discuss applicability of the Bragg reflection in a periodic grating placed on the top electrode of the FBAR structure in order to forbid lateral propagation of the spurious Lamb modes. Firstly, the simulation setup using ANSYS is presented. Secondly, the finite element (FE) analysis is performed for two representative structures, namely, Mo/ZnO/Mo and Ru/AlN/Ru, on which the first-order symmetric Lamb mode exhibits the “Type-I” and “Type-II” dispersion, respectively. It is demonstrated theoretically that for both cases, the stop band is generated by the Bragg reflection, and a spurious free resonance is obtainable provided that the grating period and height are set so that the stop band covers the frequency range where the lateral mode resonances occur. Thirdly, use of different materials for gratings is also investigated. The results suggest that a spurious free resonance is also available by employing other grating metals.

In the design, the Bragg reflection plays the role to control lateral propagation of Lamb modes. In Chapter 4, we continue to discuss use of periodic slots, which are formed by slotting the top electrode in FBAR structure, for suppressing the spurious resonances. This technique is employed again for Mo/ZnO/Mo FBAR structure. The results demonstrate that lateral wave propagation is controlled well by the Bragg reflection, and spurious transverse resonances can be suppressed when the structure is properly designed. Next, more importantly, it is shown that the slotted top electrode structure provides a possibility to realize wideband coupled resonator filters (CRFs) and balun function. These functions are strongly demanded in the FBAR community.
Chapter 5 discusses applicability of the Bragg reflector placed on the top surface near the FBAR side edges for the enhancement of the $Q$ factor. The results suggest that the $Q$ factor at anti-resonance frequency is enhanced without changing the effective electromechanical coupling factor.

At last in Chapter 6, conclusions obtained by the present studies are summarized and outlook are given for next study.
References


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Chapter 2

TRANSVERSE MODES IN FBAR STRUCTURE
In this chapter, Lamb wave propagation in a plate is outlined and the propagation behavior of Lamb wave in the FBAR structure is discussed. Spurious transverse resonances accompanying with the main resonance are clarified.

2.1 Acoustic wave propagation in FBARs

2.1.1 Lamb wave in plate

In a plate structure, which is defined as infinite laterally but finite vertically, since longitudinal (L) and shear vertical (SV) waves cannot satisfy free boundary conditions at the top and bottom surfaces, their coupling occurs there. In other words, these two waves are reflected and converted to each other at the surfaces periodically, and Lamb waves are constructed. Due to the structural symmetry with respect to its center, the Lamb wave modes can be further categorized into symmetric (S\textsubscript{n}) and anti-symmetric modes (A\textsubscript{n}).

Investigation of Lamb waves usually starts by performing a so-called dispersion analysis. The theoretical derivation of dispersion relation in a single isotropic plate can be found from B. A. Auld’s book [1]. The dispersion equation for symmetric modes is given by

\[ \tan(k_{sv}b/2) = -\frac{4\beta^2k_lk_{sv}}{(k_{sv}^2 - \beta^2)^2}, \]  

(2.1)

while that for anti-symmetric modes is given by

\[ \tan(k_{sv}b/2) = \frac{(k_{sv}^2 - \beta^2)^2}{4\beta^2k_lk_{sv}}, \]

(2.2)

where \( b \) is the thickness of the plate, \( \beta \) is the wavenumber of Lamb modes, and \( k_{sv} \) and \( k_l \) are the wavenumbers of the SV and L waves in the plate, respectively.
Fig. 2.1 shows the calculated dispersion for Lamb modes in an isotropic steel plate including the real and pure imaginary $\beta$. The $v_{SV}$ denotes the SV wave velocity. The frequencies giving $\beta = 0$ are called cut-off frequencies. The cut-off frequency of the $S_1$ mode corresponds to the main resonance frequency of the thickness extension mode. These Lamb modes are allowed to propagate when they satisfy the transverse resonance condition in the waveguide structure.

Techniques based on effective acoustic impedance [3], transfer matrix scheme [4-6], finite element method (FEM) [7], were proposed to calculate dispersion relation of Lamb modes in multilayer isotropic/anisotropic plates.
2.1.2 Transverse modes in FBAR structure

FBAR structures shown in Fig. 1.1 and Fig. 1.2 are multilayer plates, and Lamb waves can propagate then. Although both of ZnO and AlN films are mainly used as the main part of FBAR, the dispersion behavior in the ZnO film composite structure shown in Fig. 2.2 is quite different from that in the AlN film FBAR structures as shown in Fig. 2.3. It should be noted that there is also an infinite number of real and complex branches of higher order modes not shown in the graph. For the branches with real $\beta$, five Lamb modes labeled the symmetric $S_0$, $S_1$, and $S_2$ modes and the anti-symmetric modes $A_0$ and $A_1$ can be seen, but $S_1$ mode exhibits different dispersion behavior. The $S_1$ mode branch in Fig. 2.2 exhibits positive group velocity that is defined as $v_g = \frac{d\omega}{d\beta}$, called the “Type-I” dispersion. Instead it takes negative group velocity in Fig. 2.3, which called the “Type-II” dispersion. The waves with negative group velocity is called backward waves in which the phase velocity is opposite to the group velocity [8].

For the branches with imaginary $\beta$, it denotes that the displacements of these modes will decay exponentially. They are called evanescent modes.
FIG. 2.2. Typical dispersion curves exhibited “Type-I” feature in ZnO FBAR structure.

FIG. 2.3. Typical dispersion curves exhibited “Type-II” feature in AlN FBAR structure.
The difference between “Type-I” and “Type-II” behaviors combined with evanescent modes will lead to the difference in the FBAR design for energy trapping [9-10], suppression of spurious modes [11-12], CRFs (in section 4.2), sensors [8], and so on.

As discussed in Chapter 1, the main resonance of FBAR is caused by the TE vibration of piezoelectric film sandwiched in between two metal electrodes. This main resonance frequency corresponds to the cut-off frequency of $S_1$ mode. Besides the main resonance, Lamb waves close to the main resonance are easily launched in lateral directions. This laterally traveling Lamb modes cause unwanted spurious resonances. They are called transverse resonances.

Fig. 2.4 and Fig. 2.5 show the typical admittance characteristics of the ZnO and AlN FBARs, respectively. It is seen clearly that spurious transverse resonances appear above the main resonance frequency $f_r$ for the ZnO FBAR, while they appear below the main resonance frequency $f_a$ for the AlN FBAR.

FIG. 2.4. Typical admittance characteristics of the ZnO FBAR structure.
From the dispersion diagrams shown in Fig. 2.2 and Fig. 2.3, it is easy to understand that spurious modes are caused by the “Type-I” and “Type-II” dispersion for ZnO and AlN film resonators, respectively. In real devices, due to the discontinuous boundaries and edges, these excited transverse modes are able to induce new Lamb modes, for instance, $A_0$, $S_0$, and $S_1$ modes from the reflection and mode conversion [2].

These spurious modes cause unwanted and aggravating ripples in the filter pass band and they also can reduce the $Q$ factor due to energy conversion to these lateral modes. Therefore their suppression without deteriorating the main resonance is one of the major concerns for the design of RF BAW resonators.
2.2 Discussion

This chapter discussed the spurious transverse resonances in FBARs caused by the laterally propagating Lamb modes. Although usefulness of these techniques discussed in Chapter 1 is well recognized, they are not effective to suppress energy leakage through top and bottom metal electrodes extended for the electrical interconnection [13]. This loss causes deterioration of the quality factor $Q$ of the main resonance (see Fig. 2.6) taking piston mode resonator as an example.

To this end, other novel techniques are required to circumvent this problem. Next chapter, we propose a new structure to suppress the spurious transverse resonances and energy leakage.

FIG. 2.6. Energy loss due to the electrical interconnection even border region is applied.
Chapter 2 Transverse modes in FBAR structure

References


Chapter 2 Transverse modes in FBAR structure


Chapter 3

SUPPRESSION OF TRANSVERSE MODES

USING PERIODIC GRATINGS
This chapter discusses applicability of the Bragg reflection in a periodic grating placed on the top electrode of the FBAR structure in order to forbid lateral propagation of the spurious Lamb modes. The FEM analysis is performed for two representative structures, namely, Mo/ZnO/Mo and Ru/AlN/Ru, on which the first-order symmetric Lamb mode exhibits the “Type-I” and “Type-II” dispersion, respectively. It is demonstrated theoretically that for both cases, the stop band is generated by the Bragg reflection, and a spurious free resonance is obtainable provided that the grating period and height are set so that the stop band covers the frequency range where the lateral mode resonances occur.

### 3.1 FEM simulation setup

Fig. 3.1 shows the periodic structure discussed in this paper, where $p$, $w$, $h_g$, $N_p$ and $L$ are the period, width, height, and the number of the surface gratings and total length of the structure, respectively. Thicknesses of the piezoelectric layer and the electrodes are designated by $h_p$ and $h_e$, respectively. In the following analysis, $w$ is fixed at $p/2$.

The FEM analysis was carried out by ANSYS Multiphysics 13.0 (ANSYS, Inc., Canonsburg, PA) with reading an ANSYS parametric design language (APDL) script into the batch mode. Parametric input, data evaluation, and calculation flow control were performed by MATLAB 7.7 (The MathWorks, Inc., Natick, MA).
In the simulation, harmonic analysis in frequency domain was performed, where the sinusoidal voltage $V$ with the frequency $f$ was applied between the top and bottom electrodes. The electric potential of all the nodes of the individual electrode was coupled to keep the voltage at the electrode constant for a given time. The absorption mechanism [1] was adapted at both ends to decrease the reflection and mode conversion there.

After the FEM analysis, the ANSYS post-processor gives total charge $q$ on the top electrode. Then the admittance $Y$ is given by $2\pi f q/V$.

### 3.2 “Type-I” dispersion case

#### 3.2.1 Mo/ZnO/Mo FBAR structure

The analysis is performed for the Mo/ZnO/Mo structure shown in Fig. 3.2, where the first-order symmetric Lamb mode exhibits the “Type-I” dispersion.
Chapter 3 Suppression of transverse modes using periodic grating

Fig. 3.3 shows, as an example, calculated admittance $Y$ of the Mo/ZnO/Mo structure without the surface grating in decibels, namely, $20\log_{10}|Y/B_0|$, where $B_0=2\pi f_r C_0$, $f_r$ is the main resonance frequency, and $C_0$ is the shunt capacitance. In this calculation, $h_p$ and $h_e$ were set at 1.52 μm and 0.1 μm, respectively. The main resonance giving $|Y|^{-1}$~0 is seen at $f_r=1.637$ GHz, and the anti-resonance giving $|Y|\sim0$ is seen at $f_a=1.714$ GHz. The effective electromechanical coupling factor $k_e^2$ given by [2]

$$k_e^2 = \frac{\pi}{2} \frac{f_r}{f_a} \left[ \tan \left( \frac{\pi}{2} \frac{f_r}{f_a} \right) \right]^{-1}$$

is estimated as 10.6% for this case.

Series of spurious resonances are seen at frequencies above $f_r$. They are due to lateral propagation of eigen Lamb modes [2-4].
In this case, finite $Q$ of resonant peaks is due to energy transfer to the absorption mechanism. Thus the lateral energy confinement at $f=f_r$ and $f=f_a$ can be understood qualitatively from the resonance $Q (Q_r)$ and anti-resonance $Q (Q_a)$, respectively. It should be noted that $|Y/B_0|$ at $f=f_r$ and $f=f_a$ are approximately given by $Q_r k_e^2$ and $1/Q_a k_e^2$, respectively.

The ANSYS post-processor also gives out-of-plane displacements $u_z(x)$ at the bottom surface. Then their spectrum $U_z$ in the wavenumber ($\beta_x$) domain is readily obtained by applying the Fast Fourier Transform (FFT) to $u_A(x)$. The dispersion relation of the Lamb modes is given by calculating $|U_z|$ as a function of $f$ and assigning $|U_z|$ to brightness at a point ($\beta_x, f$).

Fig. 3.4 shows calculated $|U_z|$ as a two-dimensional function of $\beta_x$ and $f$ on the Mo/ZnO/Mo structure without the surface grating. Three lines correspond to the dispersion relation of propagating eigen Lamb modes. The branch labeled as $S_1$ exhibits the cut-off ($\beta_x=0$) at $f=1.637$ GHz, which corresponds to the main thickness extension resonance. The $S_1$ mode exhibits so-called the “Type-I” dispersion where $f$ increases with an increase in $\beta_x$ near the cut-off. The spurious resonances appeared in Fig. 3.3 are mainly caused by the $S_1$ mode at this region.

Due to the structural symmetry, only symmetric modes appear in this figure. It should be noted that 0-th order symmetric mode $S_0$ and second-order thickness shear mode $TS_2$ are hardly excited electrically in this configuration. They may be generated mainly by the mode-conversion of the electrically excited $S_1$ mode at the absorption mechanism.
3.2.2 Impact of Mo grating

Next, it is shown how resonance characteristics are influenced by the Mo grating placed on the top surface of the Mo/ZnO/Mo structure (see Fig. 3.5).

Fig. 3.6 shows the admittance $Y$ when $p$ and $h_g$ are set at 12.6 $\mu$m and 0.1 $\mu$m, respectively. Due to the mass loading of the Mo grating, $f_r$ and $f_a$ slightly decrease to 1.558 GHz and 1.609 GHz, respectively. From these values, $k_e^2$ is calculated as 7.6%, which is
somewhat smaller than the value of 10.6% when the surface grating is not given. This reduction may be due to non-uniformity of the lateral field distribution caused by the Bragg reflection.

From comparison of this figure with Fig. 3.3, it is clear that transverse spurious resonances are completely suppressed by the placement of surface grating. In addition, $|Y|$ at the anti-resonance becomes extremely small. In other words, $Q_a$ is enhanced. This enhancement is due to reduction of the energy leakage toward the absorption mechanism originated from the forbidden lateral propagation.

Fig. 3.7 shows calculated $|U_z|$ for this case. Due to periodicity of the structure, the identical dispersion curves appear periodically with a period of $2\pi/p=0.5$ rad/µm. A stop band, where lateral wave propagation is forbidden and only vertical wave propagation is allowed, is
found in the frequency range from 1.557 to 1.635 GHz, above the cut-off due to its “Type-I” characteristic. The stop band is caused by the Bragg reflection of the grating structure.

**FIG. 3.7.** Calculated spectrum $|U_z|$ in Mo/ZnO/Mo structure with Mo surface grating ($p=12.6$ μm and $h_g=0.1$ μm).

**FIG. 3.8.** Displacement pattern in one period in Mo/ZnO/Mo structure with Mo surface grating ($p=12.6$ μm and $h_g=0.1$ μm).
Fig. 3.8 shows the displacement pattern at resonance frequency in one period obtained from ANSYS post-processor by applying the periodic boundary condition. From it, we can recognize a thickness vibration with lateral field distribution.

We also investigated the cases when \( h_g \) is increased. The result indicated that although the spurious modes can be suppressed well because the stop band width increases with \( h_g \) in general, too large \( h_g \) deteriorates resonance characteristics.

Fig. 3.9 shows, as an example, calculated \( Y \) when \( h_g \) is increased to 0.15 \( \mu m \). In this case, \( k_{c2}^2 \) is further reduced to 6.3% due to further enhancement of the lateral energy concentration. Although spurious resonances above \( f_r \) are well suppressed, another spurious resonance appears below \( f_r \). This may be caused by the coupling of the \( S_1 \) mode with other Lamb modes such as \( S_0 \).

![Admittance vs Frequency Graph](image)

**FIG. 3.9.** Calculated admittance of the Mo/ZnO/Mo structure with Mo surface grating (\( p=12.6 \mu m \) and \( h_g=0.15 \mu m \)).
Therefore, the grating pitch and thickness should be set so that the stop band covers only the frequency range where the lateral mode resonances occur.

The lateral wavenumber $\beta$ is $\pi/p$ at the stop band edges, and the stop band width increases with $h_g$. Thus $p$ should be set so that the stop band locates in the frequency range where the spurious resonances occur, and $h_g$ should be set so that the stop band fully covers the frequency range.

3.3 “Type-II” dispersion case

3.3.1 Ru/AlN/Ru FBAR structure

Fig. 3.10 shows calculated admittance $Y$ of the Ru/AlN/Ru structure without the surface grating. In this calculation, $h_\theta$ and $h_\varepsilon$ were set at 1.0 $\mu$m and 0.3 $\mu$m, respectively. The main resonance is seen at $f_r=2.057$ GHz and its anti-resonance is located at $f_a=2.115$ GHz. From these values, $k_z^2$ is estimated as 6.6%. In this case, several small spurious resonances are seen at frequencies below $f_r$. They are due to lateral propagation of eigen Lamb modes.

Fig. 3.11 shows calculated $|U_z|$ as a two-dimensional function of $\beta_x$ and $f$ on the Ru/AlN/Ru structure without the surface grating. Two lines correspond to the dispersion relation of propagating eigen Lamb modes. In this case, the $S_1$ mode exhibits so called the “Type-II” dispersion where $f$ decreases with $\beta_x$ near the cut-off. The spurious resonances appeared in Fig. 3.10 are mainly caused by the $S_1$ mode at this region.
Chapter 3 Suppression of transverse modes using periodic grating

FIG. 3.10. Calculated admittance of the Ru/AlN/Ru structure.

FIG. 3.11. Calculated spectrum $|U_j|$ in the Ru/AlN/Ru structure.
3.3.2 Impact of Cu grating

Next, we discuss how resonance characteristics are influenced by the placement of the Cu grating on the Ru/AlN/Ru structure.

Fig. 3.12 shows the admittance when $p$ and $h_g$ are set at 5.65 μm and 0.2 μm, respectively. Due to the mass loading of the Cu grating, the resonance frequency $f_r$ slightly decreases to 1.994 GHz and 2.035 GHz for $f_a$. From these values, $k_e^2$ is estimated as 4.9%, which is somewhat smaller than the value of 6.6% obtained when the surface grating is not given. This $k_e^2$ decrease can be explained again by the lateral field concentration.

It can be seen clearly that transverse resonances are suppressed well also for this case.

FIG. 3.12. Calculated admittance in the Ru/AlN/Ru structure with Cu surface grating ($p=5.65$ μm and $h_g=0.2$ μm).
Fig. 3.13 shows calculated $|U_z|$ for this case. A stop band where propagation of transverse modes is forbidden is seen from 1.93 GHz to 1.96 GHz, below the cut-off frequency due to its “Type II” dispersion.

![Image](image_url)

**FIG. 3.13.** Calculated spectrum $|U_z|$ in the Ru/AlN/Ru structure with Cu surface grating ($p=5.65$ $\mu$m and $h_g=0.2$ $\mu$m).

### 3.3.3 Impact of Ru grating

Fig. 3.14 shows the Calculated admittance in the Ru/AlN/Ru structure with the Ru surface grating ($p=9.42$ $\mu$m and $h_g=0.25$ $\mu$m). It can be seen clearly that all the spurious transverse modes were suppressed well. Compared with Fig. 3.12, the quality factor $Q$ at the resonance frequency for this case is a bit higher than that of the Cu grating. The reason may be due to
high impedance of Ru which offers good energy confinement, while evaluated $k_e^2$ of 3.44% is somewhat lower than that of the Cu grating.

FIG. 3.14. Calculated admittance in the Ru/AlN/Ru structure with Ru surface grating ($p=9.42$ μm and $h_g=0.25$ μm).
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3.4 Discussion

This chapter discussed applicability of the Bragg reflection in a periodic grating placed on the top electrode of the FBAR structure in order to forbid lateral propagation of the $S_1$ mode. The FEM analysis was performed for two representative structures, namely, Mo/ZnO/Mo and Ru/AlN/Ru, on which the $S_1$ mode exhibits the “Type-I” and “Type-II” dispersions, respectively.

It was demonstrated theoretically that for the both cases, the stop band is generated due to the Bragg reflection, and a clean resonance is obtainable provided that the grating period and height are set so that the stop band covers the frequency range where the lateral mode resonances occur.

This work is done based on the 2D simulation. For the simulation or real device fabrication, the configuration of grating does not like interdigital electrodes, but the square blocks shown in Fig. 3.15. Therefore the 2D simulation in this work will enable the guide in real device fabrication.

FIG. 3.15. 3D model of periodic gratings placed on the surface top electrode in FBAR structure.
References


Chapter 4

SLOTTED ELECTRODE IN FBAR STRUCTURE
In Chapter 3, it was shown that use of the Bragg reflection to forbid propagation of the Lamb modes in the FBAR structure with the periodic surface grating. In this chapter, we propose use of the periodically slotted top electrodes for generating the Bragg reflection. This slotted electrode also provides the possibility to realize various electrical interconnections which opens the door to design coupled resonator filters (CRFs).

### 4.1 Suppression of spurious transverse resonance

#### 4.1.1 Introduction

From an analogy to the idea used in Chapter 3, it seems possible to generate the Bragg reflection by slotting the top electrode periodically (see Fig. 4.1).

![Fig. 4.1. Slotted top electrode on the FBAR structure.](image)

Fig. 4.2 shows the device structure used for the analysis, where $p$, $w$, $h_s$, $N_p$ and $L$ are the period, width, thickness, the number of the slotted top electrodes and total length of the
structure, respectively, and $h_p$ and $h_e$ designate the thicknesses of the piezoelectric layer and bottom electrode. The metallization ratio $m$ is defined as $w/p$. In the following analysis, ZnO and Mo are chosen as the piezoelectric layer and electrode materials, respectively.

In the simulation, harmonic analysis in frequency domain was performed. The absorption mechanism [1] discussed in Chapter 3 was adapted at both ends to decrease the reflection and mode conversion there.

The sinusoidal voltage with the frequency $f$ was applied to all the slotted top electrodes while the bottom electrode was grounded.

In the following sections, the resonance characteristics in Mo/ZnO/Mo FBAR structures with slotted electrodes will be discussed.

4.1.2 Slotted electrode Mo/ZnO/Mo FBAR structure

Fig. 4.3 shows the calculated admittance $Y$ when $h_s$, $h_p$, $h_e$, $p$, and $m$ are set as 0.1 μm, 1.52 μm, 0.1 μm, 3.125π μm and 0.7, respectively. Due to the decreased mass loading, $f_r$ and $f_a$ slightly increase to 1.689 GHz and 1.742 GHz, respectively. From the figure, it is seen that
spurious resonances appeared in Fig. 3.4 are completely suppressed and only a clean thickness resonance is visible.

FIG. 4.3. Calculated admittance of the Mo/ZnO/Mo FBAR structure with slotted top electrodes.

FIG. 4.4. Dispersion curves for the Mo/ZnO/Mo FBAR structure with slotted top electrodes.
Fig. 4.4 shows the dispersion curves for this case. Due to the structural periodicity, the identical dispersion curves appear periodically with a period of $2\pi/p = 0.64$ rad/µm. It is clear that the $S_1$ mode branch is partially disappeared due to the Bragg reflection.

These results indicate that the slotted top electrode is effective to control propagation of lateral modes similar to the grating placed on the top electrode.

### 4.2 Coupling resonator filters design

The filter function is realized by interconnecting multiple RF BAW resonators to the ladder or lattice topology [2]. The “ladder”-type filter offers the flat pass band and steep transition bands with the unbalanced termination for the input and output ports, however achievable out-of-band rejection is usually limited [2]. On the other hand, the “lattice”-type filter exhibits good out-of-band rejection far from the pass band, however the cut-off characteristic is gradual [3]. It should be noted that the “lattice”-type filter operates only with the balanced termination, and does not fit to the current RF front-end where the antenna port is usually unbalanced.

Coupled resonator filters (CRFs) [4] [5] are known to offer low insertion loss in the pass band and good out-of-band rejection far from the pass band, and flatness of the pass band and steepness of transition bands are enhanced when multiple CRFs are cascaded. Furthermore, the cascade connection can be also used to realize the balanced to unbalanced conversion and/or impedance conversion functions [5].
A design principle for the CRF is [6]: (a) the resonance frequency for $Y_i$ (or $Y_a$) coincides with the anti-resonance frequency for $Y_a$ (or $Y_i$), and (b) the shunt capacitance $C_0$ is set at circa $G_0/\omega_k$, where $G_0$ is the real part of admittance and $\omega_k$ is the resonance frequency.

### 4.3 FBAR-based CRF design

The conventional CRF is realized by sandwiching the multilayer reflector in between two stacked resonators in order to weaken the acoustic coupling between the resonators [4] [5], where, however, the coupling is very delicate and hard to control in fabrication see, Fig. 4.5. Later, a single and unique coupling layer has been developed to simplify the fabrication process [7-9].

Laterally coupled BAW filters fabricated on a thin-film acoustic mirror were reported where the lateral evanescent field caused by the cut-off of the thickness resonance is responsible to the coupling between closely spaced narrow resonators [10-12] (see Fig. 4.6).
or two resonators placed in parallel [13] (see Fig. 4.7). Application of this design is not simple for structures exhibiting so-called “type-II” dispersion because the resonance frequency for the coupling region is required to be lower than that of the resonator region [14].

![Diagram of CRF design by laterally placed narrow resonators on mirror reflector layers.](image1)

FIG. 4.6. CRF design by laterally placed narrow resonators on mirror reflector layers.

![Diagram of CRFs design by only two parallel resonators.](image2)

FIG. 4.7. CRFs design by only two parallel resonators.

This section is aimed at discussing a possibility to realize wideband CRFs using the lateral coupling controlled by the Bragg reflection. Fig. 4.8 shows the device configuration discussed in this paper, where narrow FBAR sections are aligned periodically, and are electrically connected alternately. The acoustic coupling between adjacent resonators is caused by the evanescent mode in the periodic structure, and the coupling strength is controlled by the slot period and width.
The structure shown in Fig. 4.8 seems equivalent to that used in Lamb wave resonators (LWRs) [15-16]. Since polarity between adjacent electrodes is opposite for the case, laterally propagating Lamb waves are predominantly excited, and their resonance frequencies are mostly determined by the electrode period. In contrast, they are mostly determined by the film thickness in the present case because the thickness vibration is predominantly excited due to the electrode mutual connection.

Let us express the electric characteristics of the CRF structure shown in Fig. 4.8 as the following admittance matrix:

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix} = \begin{pmatrix}
Y_{11} & Y_{12} \\
Y_{12} & Y_{22}
\end{pmatrix} \begin{pmatrix}
V_1 \\
V_2
\end{pmatrix},
\]

where \(V_n\) and \(I_n\) are the voltage and current applied to the electric port \(n\), where \(n=1,2\). Due to the structural symmetry, \(Y_{22}=Y_{11}\) in this case. When the CRF is terminated by the impedance \(G_0\), the transfer function \(S_{21}\) is given by

\[
S_{21} = \frac{2G_0Y_{12}}{(Y_{11} + G_0)(Y_{22} + G_0)^2 - Y_{12}^2}.
\]

When \(V_2=V_1\), all FBAR sections vibrate in phase (see Fig. 4.9) while adjacent FBAR sections vibrate in anti-phase when \(V_2= -V_1\) shown in Fig. 4.10.
Let us define $Y_i = Y_{11} + Y_{12}$ and $Y_a = Y_{11} - Y_{12}$, which correspond to the input admittances for these in-phase and anti-phase resonance modes, respectively.

Fig. 4.11 shows $Y_i$ and $Y_a$ of a CRF designed under this principle. In this calculation, $h_s$, $h_p$, $h_e$, $p$, and $m$ were set as 0.09 $\mu$m, 1.52 $\mu$m, 0.09 $\mu$m, $2\pi$ $\mu$m and 0.52, respectively. It can be seen that the anti-resonance frequency of $Y_i$ coincides with the resonance frequency of $Y_a$. 
FIG. 4.11. Admittance characteristic of designed CRF.

FIG. 4.12. Calculated transfer function S21 of the designed CRF.
Fig. 4.12 shows the transfer function $S_{21}$ of the designed CRF. It is seen that a relatively flat and wide pass-band is realized. Relatively large spurious peaks are seen at 1.73 GHz and 1.86 GHz. They are due to spurious resonances in $Y_a$, which are also seen in Fig. 4.11.

Achieved out of band rejection is somewhat limited at frequencies far from the pass band. Main reasons are the electrostatic coupling between adjacent electrodes and influence of spurious resonances far from the main resonance. They may be suppressed under optimal design.

It is expected that CRFs are also realizable when the both the top and bottom electrodes are slotted as shown in Fig. 4.13. Electrical isolation between electric ports can be used to realize the balanced-to-unbalanced and/or impedance conversion functions [5]. However, since the underneath layer critically influences to quality of the piezoelectric layer at the deposition, non-uniform bottom electrode may not fit to the current FBAR/SMR fabrication process.

![FIG. 4.13. CRF configuration using slotted top and bottom electrode.](image)
4.4 Discussion

This Chapter investigated influence of the slotted top electrode placed on the FBAR structure for the realization of CRFs.

First, it was shown that, similar to the surface grating, the slotted top electrodes cause the Bragg reflection and can be used to suppress transverse modes.

Then it was shown that the slotted top electrodes can be used to design wideband CRFs. A CRF was designed, and its performance was demonstrated.
References


Chapter 5

Enhancement of Q Factor with the Bragg Reflector in FBAR Structure
This chapter discusses an applicability of the Bragg reflector placed on the top surface near the side edges of the film bulk acoustic resonator (FBAR) structure for the enhancement of the $Q$ factor. The finite element analysis is performed for Ru/AlN/Ru structure. It is demonstrated theoretically that the $Q$ factor is enhanced clearly at anti-resonance frequency when the grating thickness and period are set appropriately.

5.1 Introduction

One of the remaining issues in the FBAR technology is the suppression of the lateral leakage of acoustic energy for further enhancement of the FBAR performance. In addition to the main resonance caused by the thickness extension vibration of the piezoelectric film sandwiched in between two metal electrodes, lateral Lamb wave propagation causes spurious transverse resonances. In addition, the main Lamb modes reached at FBAR rims are often leaked away to peripherals and/or converted to other modes [1-2]. This is expected to be one of the main loss mechanisms near the anti-resonance frequency for current AlN-based FBARs [3-4].

In Chapters 3 and 4, use of periodic gratings and slots was proposed for the suppression of Lamb wave propagation in the FBAR structure [5-6]. Although effectiveness of these methods was demonstrated, they also cause considerable reduction of the effective electromechanical coupling factor $k_e^2$ due to non-uniform field distribution.

This chapter discusses the use of the Bragg reflector placed on the top surface near the FBAR rims for the $Q$ enhancement near the anti-resonance frequency, see Fig. 5.1. The Bragg reflector is designed so that only one lateral Lamb mode is reflected and others are
leaked out. The grating period is chosen so that the Bragg frequency of the target Lamb mode is close to or coincident with the anti-resonance frequency.

![Bragg reflector configuration in FBAR structure.](image)

In this study, the FEM is employed for the analysis. The symmetric boundary condition (Sym. BC) is applied to the center of the structure, and only a half of the structure is considered in the simulation for reduction of computational time. The absorption mechanism [7] is adapted to the outside of the Bragg grating to avoid the reflection and the mode conversion there.

The simulation is performed for an AlN plate sandwiched in between two Ru electrodes with/without the Ru grating reflector. It is shown that the $Q$ factor at anti-resonance frequency is enhanced when the grating period and height are set so that the Bragg frequency for the Lamb mode is close to the anti-resonance frequency.

### 5.2 Simulation setup

Fig. 5.2 shows the FBAR structure with the Bragg reflector discussed here, where $p$ and $h_g$ are the period and the height of the grating (Ru is chosen as a material), respectively. $L$ is the
length of the top electrode in active region. The thicknesses of the AlN film and Ru electrodes are fixed at the value 1.0 µm and 0.3 µm, respectively. In the following analysis, the width of grating is fixed at $p/2$.

In the simulation, harmonic analysis in frequency domain is performed. The absorption mechanism is adapted at the left end to decrease the reflection and mode conversion there. The Symmetric BC is applied at the middle of the structure for reduction of computational time.

### 5.3 Analysis

#### 5.3.1 Structure with Si substrate

Fig. 5.3 shows the calculated admittance $Y$ of the Ru/AlN/Ru structure with/without the Ru Bragg reflector in decibels, namely, $20 \log_{10} |Y/B_0|$, where $B_0 = 2\pi f C_0$, $f$ is the main resonance frequency, and $C_0$ is the shunt capacitance. In this calculation, $p$, $h_g$ and $L$ were set at 0.9π, 0.2 µm and 91.6 µm, respectively. The number of grating was given 12.
It is seen that location of the resonance and anti-resonance frequencies remains unchanged with the Ru reflector, namely, \( k_e^2 \) is unchanged. This is because the design given for the active region unchanged. It is seen clearly that the dip at \( f = f_a \) becomes deep when the Bragg reflector is given while the peak height at \( f = f_r \) is scarcely changed. It should be noted that the dip depth at \( f = f_a \) and the peak height at \( f = f_r \) are proportional to the anti-resonance \( Q_a \), \( Q_r \), and the resonance \( Q, Q_r \), respectively.

The \( Q_a \) with/without the Bragg reflector were evaluated as 4,100 and 2,600, respectively. The estimation was carried out by fitting the calculated \( Y \) with the equation [8]

\[
Y \approx \frac{1 - (f/f_a)^2 + jQ_a^{-1}}{ja} \approx \frac{Q_a^{-1}}{a} + \frac{2j f - f_a}{f_a},
\]

where \( a \) is a constant, which is estimated from the gradient of \( \text{Im}[Y] \) at \( f - f_a \).

![Admittance graph](image)

**FIG. 5.3.** Calculated admittance of the Ru/AlN/Ru structure with/without Ru Bragg grating reflector.

Fig. 5.4 and Fig. 5.5 show the spectrum of the surface amplitude \( u_s \) in the wavenumber \( (\beta_s) \) domain calculated for the FBAR structures with/without the Bragg reflector, respectively.
When the reflector is not given, three lateral transverse modes labeled as $S_1$, $S_0$ and $A_0$ are seen. They are caused by the reflection and the mode conversion at the discontinuous boundary (see Fig. 5.4). It should be noted here that all the plotted surface amplitudes in this chapter are normalized with $S_1$ mode obtained when the reflector is not given. On the other hand, as shown in Fig. 5.5, the $A_0$ mode is completely suppressed when the Bragg reflector is applied. This explains why $Q_a$ was enhanced when the Bragg reflector was applied. Here the amplitude of $S_0$ mode becomes slightly large. This may be due to the partial energy conversion of the incident $S_1$ mode to the $S_0$ mode in the Bragg reflector.

FIG. 5.4. Calculated surface amplitudes of individual modes of FBAR structure without Bragg grating reflector at the anti-resonance frequency.
5.3.2 Structure without Si substrate

The case when the Si substrate was removed was also investigated. Fig. 5.6 and Fig. 5.7 show the calculated admittance $Y$ and the spectrum of the Ru/AlN/Ru structure without the Si substrate. In order to discuss influence of the Si substrate, in this calculation, $p$, $h_g$ and $L$ were kept at the same value with above case.

Comparison of Fig. 5.6 with Fig. 5.3 indicates that $Q_a$ was not enhanced by the substrate removal. Comparison of Fig. 5.7 with Fig. 5.4 indicates that, it does not influence intensity of the spurious modes $S_1$, $S_0$ and $A_0$. It demonstrated that the discontinuous boundary at the substrate scarcely influence the lateral wave propagating.

FIG. 5.5. Calculated surface amplitudes of individual modes of FBAR structure with Bragg grating reflector at the anti-resonance frequency.
FIG. 5.6. Calculated admittance of the Ru/AlN/Ru structure without Si substrate.

FIG. 5.7. Calculated surface amplitudes of individual modes of FBAR structure without Si substrate at the anti-resonance frequency.
5.3.3 Structure with double-side Bragg reflectors

We also investigated the case when double-side Bragg reflectors as shown in Fig.5.8 are employed to enhance the $Q_a$ factor. In this case, the $A_0$ mode will not be generated automatically due to the structural symmetry.

![Diagram of double-side Bragg reflectors on FBAR structure.]

**FIG. 5.8.** Double-side Bragg reflectors on FBAR structure.

Fig. 5.9 and Fig. 5.10 show the calculated admittance $Y$ and the spectrum of the Ru/AlN/Ru structure with the double-side Ru Bragg reflectors. In this calculation, $p$, $h_g$ and $L$ were set at the same value with the previous cases. Compared with Fig. 5.3, it can be known from the depth at $f=f_a$ that $Q_a$ factor is enhanced a little. This enhancement is due to case that $S_1$ mode is completely suppressed when the Bragg reflector is applied. The results shows that the impact of the $S_1$ mode is not significant for $Q_a$. It should be noted that double-side Bragg reflectors may not fit to the current FBAR fabrication process.

Other attempts by changing the grating period were failed to suppress the $S_0$ mode. The reason may be due to generation of $S_0$ mode from the reflection among gratings or between gratings and top electrode.
FIG. 5.9. Calculated admittance of the Ru/AlN/Ru structure with double-side Bragg reflectors.

FIG. 5.10. Calculated surface amplitudes of individual modes of FBAR structure with double-side Bragg reflectors at the anti-resonance frequency.
5.4 Discussion

This chapter discussed an applicability of the Bragg reflector placed on the top surface near the side edges of the FBAR structure for the enhancement of the $Q_a$ factor. The finite element analysis was performed for Ru/AlN/Ru structure with Ru grating reflector. It was demonstrated theoretically that the $Q_a$ is enhanced without changing $k_e^2$ when the grating thickness and period are set properly. Based on these results, they showed that Si substrate is useful to suppress lateral spurious modes, and the impact of $S_1$ mode is not significant for $Q_a$. 
References


Chapter 6

CONCLUSIONS AND OUTLOOK
6.1 Conclusion

In the BAW technologies, one of the cumbersome problems is the propagation of Lamb wave modes, which cause unwanted spurious resonances. This dissertation discussed use of periodic gratings to control excitation and propagation of Lamb modes in RF BAW devices from various aspects.

Brief introduction of BAW technologies and their current status were given in Chapter 1, and it was revealed why the suppression of Lamb modes is crucial for further enhancement of BAW device performances. Then various techniques proposed for the purpose were reviewed in Chapter 2.

In Chapter 3, we discussed applicability of the Bragg reflection in a periodic grating placed on the top electrode of the FBAR structure in order to forbid lateral propagation of the spurious Lamb modes. Due to the Bragg reflection in periodic gratings, the stop band was induced which plays the role in suppressing the spurious transverse resonances. It should be noted that the grating period determines the location of the stop band by wavenumber $\beta=\pi/p$, and the grating thickness is set for controlling the width of the stop band. Based on these two rules, the propagation of spurious modes could be forbidden.

According to this technique principle, we demonstrated in Chapter 4 that use of periodically slotted top electrodes are also able to produce the same result, namely the suppression of the spurious transverse resonances. In addition, wide pass-band CRFs are obtainable in FBAR structure. This technique needs to control the coupling by the period, thickness, and metallization ratio.
Although both gratings and slots are effective to suppress the spurious transverse resonances and improve the $Q$ factor, achieved $k_e^2$ is somewhat low compared with the original FBAR structure. Finally, in Chapter 5, we demonstrated theoretically that the $Q_a$ is enhanced without changing $k_e^2$ by employing the Bragg reflector placed on the top surface near the side edges of FBAR structure.

6.2 Outlook

The dissertation based on numerical simulation gave the analysis of the suppression of transverse spurious resonances. These techniques should be validated experimentally, and applicability to future volume production should be discussed. The phononic crystal technology [1] [2] [3] may be used as the stop band mechanism, the core of this thesis, to design resonators and filters, and this will open doors to develop new type of functional acoustic wave devices.
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Conference Proceedings


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FIG. 5.1. Bragg reflector configuration in FBAR structure

FIG. 5.2. Performed Bragg reflector FBAR structure by FEM analysis

FIG. 5.3. Calculated admittance of the Ru/AlN/Ru structure with/without Ru Bragg grating reflector

FIG. 5.4. Calculated surface amplitudes of individual modes of FBAR structure without Bragg grating reflector at the anti-resonance frequency

FIG. 5.5. Calculated surface amplitudes of individual modes of FBAR structure with Bragg grating reflector at the anti-resonance frequency

FIG. 5.6. Calculated admittance of the Ru/AlN/Ru structure without Si substrate

FIG. 5.7. Calculated surface amplitudes of individual modes of FBAR structure without Si substrate at the anti-resonance frequency

FIG. 5.8. Double-side Bragg reflectors on FBAR structure

FIG. 5.9. Calculated admittance of the Ru/AlN/Ru structure with double-side Bragg reflectors

FIG. 5.10. Calculated surface amplitudes of individual modes of FBAR structure with double-side Bragg reflectors at the anti-resonance frequency
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APDL</td>
<td>ANSYS parametric design language</td>
</tr>
<tr>
<td>BAW</td>
<td>Bulk acoustic wave</td>
</tr>
<tr>
<td>BC</td>
<td>Boundary condition</td>
</tr>
<tr>
<td>CRF</td>
<td>Coupled resonator filter</td>
</tr>
<tr>
<td>FBAR</td>
<td>Film bulk acoustic resonator</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>LMR</td>
<td>Lamb wave resonator</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>SMR</td>
<td>Solidly mounted resonator</td>
</tr>
<tr>
<td>SV</td>
<td>Shear vertical</td>
</tr>
<tr>
<td>TE</td>
<td>Thickness extension</td>
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**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_n )</td>
<td>Asymmetric ( n )-th Lamb mode</td>
</tr>
<tr>
<td>( b )</td>
<td>The thickness of the isotropic plate</td>
</tr>
<tr>
<td>( B_0 )</td>
<td>Real part of admittance</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Wavenumber</td>
</tr>
<tr>
<td>( C_0 )</td>
<td>Static capacitance</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
</tr>
<tr>
<td>( f_r )</td>
<td>Resonance frequency</td>
</tr>
<tr>
<td>( f_a )</td>
<td>Anti-resonance frequency</td>
</tr>
<tr>
<td>( h_e )</td>
<td>Thickness of the electrode</td>
</tr>
<tr>
<td>( h_g )</td>
<td>Thickness of the grating</td>
</tr>
<tr>
<td>( h_p )</td>
<td>Thickness of the piezoelectric film</td>
</tr>
<tr>
<td>( h_s )</td>
<td>Thickness of the slotted electrode</td>
</tr>
<tr>
<td>( j )</td>
<td>Imaginary number</td>
</tr>
<tr>
<td>( k )</td>
<td>Spring constant</td>
</tr>
<tr>
<td>( k_c )</td>
<td>Coupled spring constant</td>
</tr>
<tr>
<td>( k_e^2 )</td>
<td>Effective electromechanical coupling factor</td>
</tr>
<tr>
<td>( k_l )</td>
<td>The wavenumber of the longitudinal waves</td>
</tr>
<tr>
<td>( k_{sv} )</td>
<td>The wavenumber of the shear vertical waves</td>
</tr>
<tr>
<td>( L )</td>
<td>Length of the structure, specific length of active region</td>
</tr>
<tr>
<td>( m )</td>
<td>Metallization ratio/spring mass</td>
</tr>
<tr>
<td>( N_p )</td>
<td>Number of the grating/number of the slotted electrode</td>
</tr>
</tbody>
</table>
\( p \) \hspace{1cm} \text{Period} \\
\( q \) \hspace{1cm} \text{Charge} \\
\( Q \) \hspace{1cm} \text{Quality factor} \\
\( Q_a \) \hspace{1cm} \text{Quality factor at anti-resonance frequency} \\
\( Q_r \) \hspace{1cm} \text{Quality factor at resonance frequency} \\
\( S_a \) \hspace{1cm} \text{Symmetric} \ n \text{-th Lamb mode} \\
\( u_z \) \hspace{1cm} \text{Displacements in} \ z \text{ direction} \\
\( V \) \hspace{1cm} \text{Voltage} \\
\( v_{sv} \) \hspace{1cm} \text{Velocity of the shear vertical waves} \\
\( W \) \hspace{1cm} \text{Width of the grating} \\
\( Y \) \hspace{1cm} \text{Admittance}
ACKNOWLEDGEMENT

How time flies! Just like acoustic wave, its fast velocity does not allow me to have enough time to share my feelings with all of you.

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APPENDIX-A

SPRING MASS SYSTEM
Here, the general mechanical model of three-spring two-mass system is given with the aim to generate the understanding of CRFs for the Chapter 4 as the supplement.

![Diagram of a three-spring two-mass system](image)

**FIG. A. 1.** Spring mass system with coupling state.

Fig. A.1 shows the discussed configuration of three-spring two-mass system, where $k$ and $m$ are the spring constant and mass of balls, respectively. $k_c$ is the coupled spring constant between two balls. Based on the model, the motion equation can be written as

\[
\begin{align*}
    m\ddot{x}_1 + kx_1 + k_c(x_1 - x_2) &= 0, \\
    m\ddot{x}_2 + kx_2 - k_c(x_1 - x_2) &= 0.
\end{align*}
\]  

(A-1)

Writing (A-1) in matrix form gives

\[
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_2
\end{bmatrix} = \frac{1}{m} \begin{bmatrix}
    - (k + k_c) & k_c \\
    k_c & - (k + k_c)
\end{bmatrix} \begin{bmatrix}
    x_1 \\
    x_2
\end{bmatrix},
\]  

(A-2)

Let us assume the harmonic displacement as the form

\[
x_n = x_n \exp(j \omega t).
\]  

(A-3)

Substituting (A-3) in (A-2), we can get

\[
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_2
\end{bmatrix} = \begin{bmatrix}
    \omega^2 - \frac{(k + k_c)}{m} & k_c \\
    k_c & \omega^2 - \frac{(k + k_c)}{m}
\end{bmatrix} \begin{bmatrix}
    x_1 \\
    x_2
\end{bmatrix} = \begin{bmatrix}
    0 \\
    0
\end{bmatrix}.
\]  

(A-4)
From the displacements for existence of non-trivial solutions, the determinant must be zero, namely

\[
\begin{vmatrix}
\omega^2 - \frac{(k + k_c)}{m} & \frac{k_c}{m} \\
\frac{k_c}{m} & \omega^2 - \frac{(k + k_c)}{m}
\end{vmatrix} = 0. \tag{A-5}
\]

Equation (A-5) gives

\[
\left( \omega^2 - \frac{(k + k_c)}{m} \right)^2 = \left( \frac{k_c}{m} \right)^2. \tag{A-6}
\]

From equation (A-6), frequency solutions are

\[
\omega_1 = \sqrt{\frac{(k + 2k_c)}{m}}, \tag{A-7}
\]

\[
\omega_2 = \frac{k}{m}, \tag{A-8}
\]

where negative solution of frequency was taken out.

Substituting the solution (A-7) in equation (A-4)

\[
\begin{bmatrix}
k_c & k_c \\
\frac{m}{m} & \frac{m}{m} & \frac{k_c}{m} & \frac{k_c}{m}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} = \frac{k_c}{m} \begin{bmatrix}
1 & 1 \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} = 0. \tag{A-9}
\]

Namely, \( x_1 = -x_2 \), the eigenvalue and its associated eigenvector are

\[
\omega_1 = \sqrt{\frac{(k + 2k_c)}{m}}, \ x_1 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}. \tag{A-10}
\]

This corresponds to masses moving in opposite direction, namely symmetrical vibration.

Substituting the solution (A-8) in equation (A-4)

\[
\begin{bmatrix}
-k_c & k_c \\
\frac{m}{m} & \frac{m}{m} & -\frac{k_c}{m} & \frac{k_c}{m}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} = \frac{k_c}{m} \begin{bmatrix}
-1 & 1 \\
1 & -1
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} = 0. \tag{A-11}
\]

Namely, \( x_1 = x_2 \), the eigenvalue and its associated eigenvector are
\[ \omega_i = \sqrt{\frac{k}{m}}, \quad \mathbf{x}_i = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \]  

This solution corresponds to masses moving in same direction, namely anti-symmetrical vibration.

CRF physical model can be analogous to two spring-coupled masses system simply. Due to the symmetry of structure shown in Fig. 4.8, its vibration resonance can be categorized into two types: one of the two resonant modes is symmetric with respect to the center of the structure; instead, another is anti-symmetric. Coupled factor \( k_c \) in equation (A-7) and (A-8) determines the strength between two resonances. If \( k_c \) is too small, it means they vibrate separately without any coupled between them shown in Fig. A.2. which cannot enable the CRFs design. In CRFs design, the coupling between two resonators is essential and it need to be set appropriately according to their resonance characteristics.

![Spring mass system without coupling state.](image)

FIG. A. 2. Spring mass system without coupling state.
APPENDIX-B

ANSYS SCRIPT
Finite element (FE) software are very popular between researchers in the university and engineers in the companies, due to their powerful capability to simulate and solve complex structures and multi-physics problems. Although it has been well recognized how these simulation techniques are effective, it does not seem that they are extensively employed in actual device design. This is because a lot of knowledge and efforts are required for the development of FE software.

In my research work, ANSYS is chosen as simulation tool due its flexible and efficient capabilities for multi-physics models, however, it not so easy to learn ANSYS and know how to operate and use APDL script for the beginners, especially for the ones who are studying in the piezoelectric acoustic fields. Lots of ANSYS learners sent me emails and searched for the possible helps.

From this point of view, with the permission of my supervisor, I would like to share my APDL scripts with them. I believe that these APDL scripts will be helpful for them. I would also be pleased to accept the validation of my scripts from world-wide readers.

Furthermore, the main ANSYS scripts should be included since they are also the most important parts for this study work. All the simulation results in the thesis are based on them. Therefore it is necessary to include these ANSYS scripts in the thesis.

In this part, the main ANSYS scripts include:

1) Main body,
2) Macro file: Material constants,
3) Macro file: Absorption mechanism,
4) Macro file: Periodic boundary conditions, and
5) Macro file: Extraction of node displacements.

Other macro files are not included here since I believe the excluded ones can be done by readers themselves.
B.1 Main Body

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!! Simulation of Piezoelectric Acoustic Devices !!!!!!
!!!! Author: Jiansong Liu !!!!!!
!!!! Supervised by Prof. Ken-ya Hashimoto !!!!!!
!!!! Date: 2013/07/16 !!!!!!
!!!! Version: 2014A !!!!!!
!!!! Price: 0 $ !!!!!!
!!!! Note: N/A !!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

finish
clear
/title, Simulation for 2D Piezoelectric BAW devices
/filename, Resonator_BAW2D2
/CONFIG, NPROC, 4
/CONFIG, NRES, 10000

!!!!!!!!!!!! Enter into preprocessor !!!!!!!!!!!!!
/prep7

/units, user,1e6,1,1,1,273.15,1e12,1e6,1e12
emunit, epzro, 8.854e-6

pi=3.1415926535

!!!!!!!!!!!!!!!!!!!!!!!! Read file from MATLAB !!!!!!!!!!!!!

*create, Ratio
*dim, lengthratio, array, 1, 2
*vread, lengthratio(1,1), ratiomatlab, txt, , jik, 2, 1
(f4.0, f7.4)
*end

/input, Ratio

!!!!!!!!!!!!!!!!!!!!!!!! Definition of parameters !!!!!!!!!!!!!
wavelength=1.8*pi ! Wavenumber of the grating
period=wavelength/2 ! period of the grating
thick=1.0 ! Thickness of AlN film
electrnum=1 ! top electrode numbers
Mratio=0.5 ! metallization ratio
IDTwidth=Mratio*period ! the width of IDT/Grating
IDTspace=period-IDTwidth ! Gap between IDT
IDTthick=0.15 ! thickness of IDT/Grating
MidGrthick=0.05
SecondTopEthick=0.1
Topelectrthick=0.3  ! Top electrode
Botelectrthick=0.3  ! Bot. electrode
width=electrnum*period
width_FBAR=91.5624
! width_FBAR=MidGrNum*period
This parameter uses for Mode-7

!!-------------------------------------------------------------------
leftwidth=IDTspace/2  ! left port of IDT block
rightwidth=IDTspace/2  ! right port of IDT block
gap=leftwidth*4  ! gap=1*period/4
gap1=leftwidth*4
! leftwidth=wavelength*lengthratio(1,2)
! rightwidth=wavelength*lengthratio(1,2)

!!---------------------- Overlap Border Region ------------------------
! Sunkendepth=Topelectrthick*0.1
! Sunkenwidth=period

! Overlapthick=Topelectrthick*2
! Overlapwidth=period*2

!!-------------------------- Si substrate Para -------------------------
AlN_Si_L=2*period
TopE_Si_L=AlN_Si_L
BotE_Si_L=AlN_Si_L
Si_L=2*period
Si_T=10*thick

!!-------------------------------------------------------------------
frqstr=1.95e9  ! the start frequency
frqend=2.25e9  ! the end of frequency
modnum=200  ! mode number
steps=300  ! Frequency steps
voltagePlus=1  ! applied volt. on top electr.
voltageMins=1
! elesize=wavelength/40
elesize=0.15

!!!!!!!! Insert Damper Layer !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
InsertDamper=0  ! 0 = Do not insert damper layer
! 1 = Insert damper layer
dampernum=10
widthdamper=7*thick

sidecheck=1  ! 1= damper on left side
! 2= damper on two sides
! 3= damper on right side

!!!!!!!!!!!!!!!! Periodic BC parameter !!!!!!!!
PeriodBC=0  ! 0 = Do not apply ---
! 1 = Apply periodic boundary condition
!!-----------------------------------------------------------------------------------------------------------
! 1=p=wavelength/2  For short circuit
p=-1
! -1=2p=wavelength For Open and harmonic circuit
!!-----------------------------------------------------------------------------------------------------------

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Symmetric BC %%%%%%%%%%%%
! 0 = Do not apply ----
SymSignal=2
! 1 = Apply symmetric BC with overboder area
! 2 = only Apply symmetric BC
!!-----------------------------------------------------------------------------------------------------------
Sym=1
! 0 = Antisymmetric BC
! 1 = Symmetric BC
!!-----------------------------------------------------------------------------------------------------------

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Electrode material %%%%%%%%%%%%
! 1=AlN
Film=1
! 2=ZnO
! 3=ScAlN
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Electrode material %%%%%%%%%%%%
! 4=Al  2700
! 5=Ru 12450
TopElectrode=5
! 6=Cu  8900
BotElectrode=5
! 7=Pt  21450
IDTelectrode=5
! 8=Mo 10280
HeavyElectrode=9
! 9=Au 19300
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Substrate material %%%%%%%%%%%%
! 10=6H-SiC
Substrate=12
! 11=3C-SiC
! 12=Si
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Circuit Options %%%%%%%%%%%%%%%%%
! 0=Open circuit
! 1=Short circuit
! 2=Harmonic
circuit=2
! 3=Harmonic +++- for GPE structure
! 4=Harmonic +++ for GPE structure
! 5=Harmonic +++- for GPG structure
! 6=Harmonic top+and bot-for GPG structure
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Analysis Options %%%%%%%%%%%%%%%%%
! 0=Static
analysis=2
! 1=Modal
! 2=Harmonic
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Model Options %%%%%%%%%%%%%%%%%
! 1 structure like E/P/E
! 2 structure like Gr./E/F/E
! 3 structure like Gr./E/F/E/Gr.
! 4 structure like Gr./F/E
! 5 structure like E/Gr./F/E
! 6 structure like Gr./Film/Gr.
buildmodel=8
! 7 structure like GEPE+EEPE
8 structure like GEPE+EPE
9 structure like GP+EPE with double side
10 structure like GEPE+GEPE
11 structure like GPE+EPE
12 structure like GP+EPE
13 structure like GPE+EPE with Substrate
14 structure like E/P/E with Substrate

Elements Type
Filmele=1
Electrele=2

ele, Filmele, plane223, 1001, 2 ! element type of piezo. layer
ele, Electrele, plane183, 2 ! element type of electrode layer

Input Material Properties
! input the material constants
/input, 'E:\Simulation\Macros\materialscons', mac

Model Options

!!!-------------------- For the case of Model-1 --------------------
*if, buildmodel, eq, 1, then
   /input, 'E:\Simulation\Macros\Model_EPE', mac
!!!-------------------- For the case of Model-2 --------------------
*elseif, buildmodel, eq, 2
   /input, 'E:\Simulation\Macros\Model_GEPE', mac
!!!-------------------- For the case of Model-3 --------------------
*elseif, buildmodel, eq, 3
   /input, 'E:\Simulation\Macros\Model_IDT_EPE_IDT', mac
!!!-------------------- For the case of Model-4 --------------------
*elseif, buildmodel, eq, 4
   /input, 'E:\Simulation\Macros\Model_GPE', mac
!!!-------------------- For the case of Model-5 --------------------
*elseif, buildmodel, eq, 5
   /input, 'E:\Simulation\Macros\Model_EGPE', mac
!!!-------------------- For the case of Model-6 --------------------
*elseif, buildmodel, eq, 6
   /input, 'E:\Simulation\Macros\Model_GPG', mac
!!!-------------------- For the case of Model-7&8--------------------
*elseif, buildmodel, eq, 7, or, buildmodel, eq, 8
   *if, SymSignal, eq, 0, then
      /input, 'E:\Simulation\Macros\Model_GEPE_Left', mac
      /input, 'E:\Simulation\Macros\Model_EEPE', mac
      *elseif, SymSignal, eq, 2
         /input, 'E:\Simulation\Macros\Model_GEPE_Right', mac
         /input, 'E:\Simulation\Macros\Model_EEPE', mac
   *endif
!!!-------------------- For the case of Model-9 --------------------
*elseif, buildmodel, eq, 9
   *if, SymSignal, eq, 0, then
      /input, 'E:\Simulation\Macros\Model_GEPE_Left_Double', mac
   *endif
!!!-------------------- For the case of Model-10--------------------
*elseif, buildmodel, eq, 10
   /input, 'E:\Simulation\Macros\Model_GEPE_Right_Double', mac

!!!------------------------ For the case of Model-11------------------------
*endif

!!!------------------------ For the case of Model-12------------------------
*endif
*elseif, SymSignal, eq, 2
*/input,'E:\Simulation\Macros\Model_GEPE_Left_Double',mac
*/input,'E:\Simulation\Macros\Model_GEPE_Middle',mac
*/input,'E:\Simulation\Macros\Model_GEPE_Right',mac
*endif

!!-------------------------- For the case of Model-10---------
*elseif, buildmodel, eq, 10
  *if, SymSignal, eq, 0, then
  */input,'E:\Simulation\Macros\Model_GEPE_Left',mac
  */input,'E:\Simulation\Macros\Model_GEPE_Middle',mac
  */input,'E:\Simulation\Macros\Model_GEPE_Right',mac
  *elseif, SymSignal, eq, 2
  */input,'E:\Simulation\Macros\Model_GEPE_Left',mac
  */input,'E:\Simulation\Macros\Model_GEPE_Middle',mac
  *endif

!!-------------------------- For the case of Model-11---------
*elseif, buildmodel, eq, 11
  *if, SymSignal, eq, 0, then
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  */input,'E:\Simulation\Macros\Model_GP_Right',mac
  *elseif, SymSignal, eq, 2
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  *endif

!!-------------------------- For the case of Model-12---------
*elseif, buildmodel, eq, 12
  *if, SymSignal, eq, 0, then
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  */input,'E:\Simulation\Macros\Model_GP_Right',mac
  *elseif, SymSignal, eq, 2
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  *endif

!!-------------------------- For the case of Model-13---------
*elseif, buildmodel, eq, 13
  *if, SymSignal, eq, 0, then
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  */input,'E:\Simulation\Macros\Model_GP_Right',mac
  *elseif, SymSignal, eq, 2
  */input,'E:\Simulation\Macros\Model_GP_Left',mac
  */input,'E:\Simulation\Macros\Model_EPE_Middle',mac
  *endif

!!-------------------------- For the case of Model-15---------
*elseif, buildmodel, eq, 14
  *if, SymSignal, eq, 0, then
*elseif, SymSignal, eq, 2
*endif

!!!%%%%%%%%%%%%%%%%%%%%%%%% Insert Absorption Layer %%%%%%%%%%%%%%%%%%
*if, InsertDamper, eq, 1, then
    /input,'E:\Simulation\Macros\Model_EPE_Si',mac
    /input,'E:\Simulation\Macros\Model_EPE_Substrate',mac
*endif

!!!%%%%%%%%%%%%%%%%%%%%%%%% Mesh Setting %%%%%%%%%%%%%%%%%%
*if, buildmodel, eq, 1, then
    allsel, all
esize, elesize
!!------------------------------------------------------------
elseif,buildmodel,eq,2
    lsel,s,loc,y,-Botelectrthick+1.0e-6,
thick+Topelectrthick+IDTthick
lesize,all,elesize
lsel,s,length,, IDTwidth
lsel,a,length,, IDTspace
lsel,a,length,, leftwidth
lesize,all,elesize
!!$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$
*if, InsertDamper, eq, 1, then
    lsel,s,loc,x,-dampernum*widthdamper, 0
    lsel,a,loc,x,width,width+dampernum*widthdamper
lesize,all,elesize
*endif
!!------------------------------------------------------------
elseif,buildmodel,eq,3
    lsel,s,loc,y,-Botelectrthick-IDTthick,
thick+Topelectrthick+IDTthick
lesize,all,elesize
lsel,s,length,, IDTwidth
lsel,a,length,, IDTspace
lsel,a,length,, leftwidth
lesize,all,elesize
!!$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$ 
*if, InsertDamper, eq, 1, then
    lsel,s,loc,x,-dampernum*widthdamper, 0
    lsel,a,loc,x,width,width+dampernum*widthdamper
lesize,all,elesize
*endif
!!------------------------------------------------------------
elseif,buildmodel,eq,4,then
lsel,s,loc,y,-Botelectrthick, thick+IDTthick
lesize,all,elesize
lsel,s,length,,IDTwidth
lsel,a,length,,IDTspace
lsel,a,length,,leftwidth
lesize,all,elesize
!!$$$$$$$ mesh for absorption layers $$$$$$$$$$$
*if,InsertDamper,eq,1,then
  lsel,s,loc,x,-dampernum*widthdamper,0
  lsel,a,loc,x,width,width+dampernum*widthdamper
lesize,all,elesize
*endif
!!------------------------------------------------------------
*else
  if,buildmodel,eq,5
    lsel,s,loc,y,0, thick+IDTthick
    lesize,all,elesize
    lsel,s,length,,IDTwidth
    lsel,a,length,,IDTspace
    lsel,a,length,,leftwidth
    lesize,all,elesize
    !!$$$$$$$ mesh for absorption layers $$$$$$$$$$$
    *if,InsertDamper,eq,1,then
      lsel,s,loc,x,-dampernum*widthdamper,0
      lsel,a,loc,x,width,width+dampernum*widthdamper
      lesize,all,elesize
    *endif
    !!------------------------------------------------------------
  *elseif,buildmodel,eq,6,or,buildmodel,eq,8
    lsel,s,loc,y,-Botelectrthick,thick+IDTthick
    lesize,all,elesize
    lsel,s,length,,IDTwidth
    lsel,a,length,,IDTspace
    lsel,a,length,,leftwidth
    lesize,all,elesize
    !!$$$$$$$ mesh for absorption layers $$$$$$$$$$$
    *if,InsertDamper,eq,1,then
      lsel,s,loc,x,-dampernum*widthdamper,0
      lsel,a,loc,x,width,width+dampernum*widthdamper
      lesize,all,elesize
    *endif
    !!------------------------------------------------------------
  *elseif,buildmodel,eq,7,or,buildmodel,eq,8
    lsel,s,loc,y,-Botelectrthick,thick+Topelectrthick+IDTthick
    lesize,all,elesize
    lsel,s,length,,IDTwidth
    lsel,a,length,,width_FBAR
    lsel,a,length,,leftwidth
    lesize,all,elesize
    !!$$$$$$$ mesh for absorption layers $$$$$$$$$$$
    *if,InsertDamper,eq,1,then
      lsel,s,loc,x,-dampernum*widthdamper,0
      lsel,a,loc,x,width,width+dampernum*widthdamper
      lesize,all,elesize
    *endif
    !!------------------------------------------------------------
  *endif
  !--------------------------------------------------------------------------
*if, SymSignal, eq, 0, then
  lsel, s, loc, x, -dampernum*widthdamper, 0
  lsel, a, loc, x, 2*width+width_FBAR, 2*width+width_FBAR+
  dampernum*widthdamper
  lesize, all, elesize
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, -dampernum*widthdamper, 0
  lesize, all, elesize
*endif
*endif

!!-------------------------------------------------------------------------------
*elseif, buildmodel, eq, 9
  lsel, s, loc, y, -IDTthick, thick+IDTthick
  lesize, all, elesize
  lsel, s, length,, IDTwidth
  lsel, a, length,, width_FBAR
  lsel, a, length,, leftwidth
  lsel, a, length,, gap
  lesize, all, elesize
!!$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$
*if, InsertDamper, eq, 1, then
  *if, SymSignal, eq, 0, then
    lsel, s, loc, x, -dampernum*widthdamper, 0
    lsel, a, loc, x, 2*width+width_FBAR, 2*width+width_FBAR+
    dampernum*widthdamper
    lesize, all, elesize
  *elseif, SymSignal, eq, 2
    lsel, s, loc, x, -dampernum*widthdamper, 0
    lesize, all, elesize
  *endif
*endif

!!-------------------------------------------------------------------------------
*elseif, buildmodel, eq, 10
  lsel, s, loc, y, -Botelecrthick,
  thick+Topelecrthick+SecondTopEthick+MidGrthick
  lesize, all, elesize
  lsel, s, length,, IDTwidth
  lsel, a, length,, leftwidth
  lesize, all, elesize
!!$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$
*if, InsertDamper, eq, 1, then
  *if, SymSignal, eq, 0, then
    lsel, s, loc, x, -dampernum*widthdamper, 0
    lsel, a, loc, x, 2*width+width_FBAR, 2*width+width_FBAR+
    dampernum*widthdamper
    lesize, all, elesize
  *elseif, SymSignal, eq, 2
    lsel, s, loc, x, -dampernum*widthdamper, 0
    lesize, all, elesize
  *endif
*endif
*elseif, buildmodel, eq, 11
  lsel, s, loc, y, -Botelectrthick, thick+IDTthick
  lesize, all, elesize
  lsel, s, length,, IDTwidth
  lsel, s, length,, width_FBAR
  lsel, s, length,, gap
  lsel, s, length,, leftwidth
  lesize, all, elesize

  !$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$$
  *if, InsertDamper, eq, 1, then
    *if, SymSignal, eq, 0, then
      lsel, s, loc, x, -dampernum*widthdamper, 0
      lsel, a, loc, x, 2*width+width_FBAR, 2*width+width_FBAR +
      dampernum*widthdamper
      lesize, all, elesize
    *elseif, SymSignal, eq, 2
      lsel, s, loc, x, -dampernum*widthdamper, 0
      lesize, all, elesize
    *endif
  *endif

  *elseif, buildmodel, eq, 12
  lsel, s, loc, y, -Botelectrthick, thick+IDTthick
  lsel, s, loc, y, thick+1.0e-6, thick+IDTthick-1.0e-6
  lesize, all, elesize
  lsel, s, length,, IDTwidth
  lsel, a, length,, width_FBAR
  lsel, a, length,, leftwidth
  lesize, all, elesize

  !$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$$
  *if, InsertDamper, eq, 1, then
    *if, SymSignal, eq, 0, then
      lsel, s, loc, x, -dampernum*widthdamper, 0
      lsel, a, loc, x, 2*width+width_FBAR, 2*width+width_FBAR +
      dampernum*widthdamper
      lesize, all, elesize
    *elseif, SymSignal, eq, 2
      lsel, s, loc, x, -dampernum*widthdamper, 0
      lesize, all, elesize
    *endif
  *endif

  *elseif, buildmodel, eq, 13
  lsel, s, loc, y, -Botelectrthick, thick+IDTthick
  lesize, all, elesize
  lsel, s, length,, IDTwidth
  lsel, a, length,, width_FBAR
  lsel, a, length,, leftwidth
  lsel, a, length,, AlN_Si_L
  lesize, all, elesize

  !$$$$$$$$ mesh for absorption layers $$$$$$$$$$$$$$$
*if, InsertDamper, eq, 1, then
  *if, SymSignal, eq, 0, then
    lsel, s, loc, x, -dampernum*widthdamper, 0
    lsel, a, loc, x, 2*width+width_FB, 2*width+width_FB +dampernum*widthdamper
    lesize, all, elesize
  *elseif, buildmodel, eq, 14
    allsel, all
    esize, elesize
*endif
*endif

*elseif, buildmodel, eq, 14
  allsel, all
  esize, elesize
*endif

!!!$$$$$$$$$$$$$$$$$$$$$$$$$ Enter Into Solution Part $$$$$$$$$$
/solu

!!!%%%%%%%%%%%%%%%%%%%% Apply Loads %%%%%%%%%%%%%%%%%%

!!------------------------ For the case of Open Circuit ----------------
*if, circuit, eq, 0, then
  lsel, s, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottom, node, 0, num, min
  !d, bottom, volt, 0
  lsel, s, loc, y, thick
  nsll, s, 1      ! selects all the nodes on the selected line.
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
  d, topelectrode, volt, 0
  allsel, all

!!------------------------ For the case of Short Circuit ----------------
*elseif, circuit, eq, 1
*elseif, circuit, eq, 2

!!---------------------- For the case of Harmonic Circuit
  *if, buildmodel, eq, 7, or, buildmodel, eq, 8, then

    *if, SymSignal, eq, 0, then
      lsel, s, loc, x, 0, 2*width+width_FBAR
      lsel, r, loc, y, 0
      nsll, s, 1
      cp, 1, volt, all
      *get, bottomelectrode, node, 0, num, min
      d, bottomelectrode, volt, 0
    *elseif, SymSignal, eq, 2
      lsel, s, loc, x, 0, width+width_FBAR
      lsel, r, loc, y, 0
      nsll, s, 1
      cp, 1, volt, all
      *get, bottomelectrode, node, 0, num, min
      d, bottomelectrode, volt, 0
    *endif

  *elseif, buildmodel, eq, 9

    *if, SymSignal, eq, 0, then
      lsel, s, loc, x, 0, 2*width+width_FBAR
      lsel, r, loc, y, 0
      nsll, s, 1
      cp, 1, volt, all
      *get, bottomelectrode, node, 0, num, min
      d, bottomelectrode, volt, 0
    *elseif, SymSignal, eq, 2
      asel, s, loc, y, thick, thick+IDTthick
      asel, r, loc, x, 0, width
      lsla, s
      lsel, r, loc, y, thick
      nsll, s, 1
      cm, topgrating, node
      asel, s, loc, y, 0, -IDTthick
      asel, r, loc, x, 0, width
      lsla, s
lsel, r, loc, y, 0
nsll, s, 1
cm, bottomgrating, node
lsel, s, loc, x, width-gap1+gap, width+gap+width_FBAR
!lsel, s, loc, x, width, width+gap+width_FBAR
lsel, r, loc, y, 0
nsll, s, 1
cm, bottomele, node
cmssel, s, bottomele
!cmssel, a, topgrating
!cmssel, a, bottomgrating
cp, 1, volt, all
*get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

*elseif, buildmodel, eq, 10

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, 0, 2*width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

*elseif, buildmodel, eq, 11

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, width, 2*width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif
*elseif, buildmodel, eq, 12

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, width, 2*width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, width, width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

*elseif, buildmodel, eq, 13

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, width, 2*width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, AlN_Si_L+width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

*elseif, buildmodel, eq, 14

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, width, 2*width+width_FBAR
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
  *get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, AlN_Si_L+width
  lsel, r, loc, y, 0
  nsll, s, 1
  cp, 1, volt, all
*get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

*else

lsel, s, loc, x, 0, width
lsel, r, loc, y, 0
nsll, s, 1
cp, 1, volt, all
*get, bottomelectrode, node, 0, num, min
d, bottomelectrode, volt, 0
*endif

!!!!!!!!!!!!!!!!!!!! Plus voltage !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

*if, buildmodel, eq, 1, or, buildmodel, eq, 2, then

lsel, s, loc, x, 0, width
lsel, r, loc, y, thick
nsll, s, 1
cp, 2, volt, all
*get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus

*elseif, buildmodel, eq, 4, or, buildmodel, eq, 5

asel, s, loc, y, thick, thick+IDTthick
lsla, s
lsel, r, loc, y, thick
nsll, s, 1
cp, 2, volt, all
*get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus

*elseif, buildmodel, eq, 7, or, buildmodel, eq, 8

*if, SymSignal, eq, 0, then
    lsel, s, loc, x, 0, 2*width+width_FBAR
    lsel, r, loc, y, thick
    nsll, s, 1
cp, 2, volt, all
*get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*elseif, SymSignal, eq, 2
    lsel, s, loc, x, 0, width+width_FBAR
    lsel, r, loc, y, thick
    nsll, s, 1
cp, 2, volt, all
*get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*endif

*elseif, buildmodel, eq, 9

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, 0, 2*width + width_FBAR
  lsel, r, loc, y, thick
  nsll, s, 1
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, width + width_FBAR
! lsel, s, loc, x, width + width_FBAR
  lsel, r, loc, y, thick
  nsll, s, 1
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*endif

*elseif, buildmodel, eq, 10

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, 0, 2*width + width_FBAR
  lsel, r, loc, y, thick
  nsll, s, 1
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, width + width_FBAR
  lsel, r, loc, y, thick
  nsll, s, 1
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*endif

*elseif, buildmodel, eq, 11

*if, SymSignal, eq, 0, then
  lsel, s, loc, x, width, 2*width + width_FBAR
  lsel, r, loc, y, thick
  nsll, s, 1
  cp, 2, volt, all
  *get, topelectrode, node, 0, num, min
d, topelectrode, volt, voltagePlus
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, width, width + width_FBAR
  lsel, r, loc, y, thick
nsll,s,1
cp,2,volt,all
*get,topelectrode,node,0,num,min
d,topelectrode,volt,voltagePlus
*endif
*elseif,buildmodel,eq,12
  *if,SymSignal,eq,0,then
  lsel,s,loc,x,width,2*width+width_FBAR
  lsel,r,loc,y,thick
  nsll,s,1
  cp,2,volt,all
  *get,topelectrode,node,0,num,min
  d,topelectrode,volt,voltagePlus
*elseif,SymSignal,eq,2
  lsel,s,loc,x,width,width+width_FBAR
  lsel,r,loc,y,thick
  nsll,s,1
  cp,2,volt,all
  *get,topelectrode,node,0,num,min
  d,topelectrode,volt,voltagePlus
*endif
*elseif,buildmodel,eq,13
  *if,SymSignal,eq,0,then
  lsel,s,loc,x,width,2*width+width_FBAR
  lsel,r,loc,y,thick
  nsll,s,1
  cp,2,volt,all
  *get,topelectrode,node,0,num,min
  d,topelectrode,volt,voltagePlus
*elseif,SymSignal,eq,2
  lsel,s,loc,x,AlN_Si_L+width,AlN_Si_L+width+width_FBAR
  lsel,r,loc,y,thick
  nsll,s,1
  cp,2,volt,all
  *get,topelectrode,node,0,num,min
  d,topelectrode,volt,voltagePlus
*endif
*elseif,buildmodel,eq,14
  *if,SymSignal,eq,0,then
  lsel,s,loc,x,width,2*width+width_FBAR
  lsel,r,loc,y,thick
  nsll,s,1
  cp,2,volt,all
  *get,topelectrode,node,0,num,min
d,topelectrode,volt,voltagePlus
*elseif,SymSignal,eq,2
  lsel,s,loc,x,AlN_Si_L,AlN_Si_L+width
cp,2,volt,all
  *get,topelectrode,node,0,num,min
d,topelectrode,volt,voltagePlus
*endif

!!--------------------- For GPE model with +++ Harmonic ----
*elseif,circuit,eq,3
  /input,'E:\Simulation\Macros\HarmonicCircuit_GPE_++,',mac
!!--------------------- For GPG model with ++- Harmonic ----
*elseif,circuit,eq,4
  /input,'E:\Simulation\Macros\HarmonicCircuit_GPG_+-',mac
!!--------------------- For GPG model with ++- Harmonic ----
*elseif,circuit,eq,5
  /input,'E:\Simulation\Macros\HarmonicCircuit_GPG_++-',mac
!!--------------------- For GPE model with ++- Harmonic ----
*elseif,circuit,eq,6
  /input,'E:\Simulation\Macros\HarmonicCircuit_GPG_++-',mac
*
!!! Apply Periodic BC--2 ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*if,PeriodBC,eq,1,then
  *if,buildmodel,eq,1,or,buildmodel,eq,2,then
    /input,'E:\Simulation\Macros\PeriodicBC_IDT_EPE_IDT',mac
  *elseif,buildmodel,eq,4
    /input,'E:\Simulation\Macros\PeriodicBC_GPE',mac
  *elseif,buildmodel,eq,5
    /input,'E:\Simulation\Macros\PeriodicBC_EGPE',mac
  *elseif,buildmodel,eq,6
    /input,'E:\Simulation\Macros\PeriodicBC_GPG',mac
  *endif
*endif

!!! Apply Symmetric BC ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*if, SymSignal, eq, 1, then
   /input, 'E:\Simulation\Macros\SymmetricBC', mac
*endif

*if, SymSignal, eq, 2, then
   /input, 'E:\Simulation\Macros\SymmetricBC', mac
*endif

!!!!!!!!!!!!!!!! Static Analysis !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

*if, analysis, eq, 0, then
   antype, static

!!!!!!!!!!!!!!!!!!!!!!!! Modal Analysis !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

*elseif, analysis, eq, 1
   antype, modal ! select modal analysis
   modopt, lanb, modnum, frqstr, frqend ! set the start frequency
   ! modopt, lanb, modnum
   mxpand, modnum

*else

!!!!!!!!!!!!!!!!!!!!!!!! Harmonic Analysis !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

   antype, harmonic ! select modal analysis
   hroute, on ! set the start frequency
   harfrq, frqstr, frqend ! the range of frequency
   nsubst, steps ! steps
   kbc, 1 ! specifies stepped (1), ramped (0)

*endif

allsel, all

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Solve !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

solve
finish
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Enter into Postprocessor $$$$$$$
/post1

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Static Analysis !!!!!!!!!!!!!!!!!!!!!!!!!!!!!

*if, analysis, eq, 0, then
   *get, C1, node, topelectrode, rf, chrg
   *get, C2, node, bottomelectrode, rf, chrg
   Cs=abs(C1) ! C=Q/V
!!!%%%%%%%%%%%%%%%%%%%%%%%%% Modal analysis %%%%%%%%%%%%%%%%%%%
*elseif,analysis,eq,1
  *dim,frq,array,modnum,1
  *dim,waveratio,array,modnum,1
  *do,j,1,modnum,1
    *get,frq(j,1),mode,j,freq   ! get the modal frequency
   !*get,mcoeff(j,1),mode,j,mcoef  ! get the modal frequency
    waveratio(j,1)=lengthratio(1,2)
  *endo

!!!-------- -- Extract Modal displacement ---------
/input,'E:\Simulation\Macros\ExtractDispModal',mac

!!!%%%%%%%%%%%%%%%%%%% Harmonic analysis %%%%%%%%%%%%%%%%%%%
*else
  *dim,frq,array,steps,1
  !*dim,mcoeff,array,steps,1
  *do,j,1,steps,1
    set,1,j
    *get,frq(j,1),active,,set,freq ! get the Harmonic frequency
   !*get,mcoeff(j,1),mode,j,mcoef  ! get the modal frequency
  *endo

!!!-------- Extract Surface Displacements -------
/input,'E:\Simulation\Macros\ExtractDispHarmonic',mac

!!!----- ----- Extract Electrical Parameters -------
/input,'E:\Simulation\Macros\ElectricalParameters',mac
*endif

!!!$$$$$$$$$$$$$$$$$$ FINISH $$$$$$$$$$$$$$$$$$$$$$$$$$
### B.2 Macro file: Material Constants

<table>
<thead>
<tr>
<th>Material Code</th>
<th>Material Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AlN</td>
</tr>
<tr>
<td>2</td>
<td>ZnO</td>
</tr>
<tr>
<td>3</td>
<td>ScAlN</td>
</tr>
<tr>
<td>4</td>
<td>Al</td>
</tr>
<tr>
<td>5</td>
<td>Ru</td>
</tr>
<tr>
<td>6</td>
<td>Cu</td>
</tr>
<tr>
<td>7</td>
<td>Pt</td>
</tr>
<tr>
<td>8</td>
<td>Mo</td>
</tr>
<tr>
<td>9</td>
<td>Au</td>
</tr>
<tr>
<td>10</td>
<td>6H-SiC</td>
</tr>
<tr>
<td>11</td>
<td>3C-SiC</td>
</tr>
<tr>
<td>12</td>
<td>Si</td>
</tr>
<tr>
<td>13</td>
<td>SiO2</td>
</tr>
<tr>
<td>14</td>
<td>Tungsten (W)</td>
</tr>
<tr>
<td>15</td>
<td>...</td>
</tr>
</tbody>
</table>
matcount=1

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
!! Piezoelectric AlN (material number: 1 )
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

AlN=matcount  ! Set number for AlN

! Independent stiffness coefficients for constant E [GPa*1e-6]
c11=345e3  $c12=125e3 $c13=120e3 $c33=395e3 $!c44=118e3
c44=105e3 $c66=110e3

! Independent piezoelectric coefficients
e31=-0.58 $e33=1.55 $e24=-0.48

! Relative permittivity
epsxx=9.0395 $epsyy=9.0395 $epszz=10.7345

! Density [kg/um^3]
density=3260e-18

! Damper
constdamp=1/500

! Generating normal form of matrix
c11e=c11 $c12e=c12 $c13e=c13 $c14e=0 $c15e=0 $c16e=0 $c22e=c11
  c23e=c13 $c24e=0 $c25e=0 $c26e=0 $c33e=c33 $c34e=0 $c35e=0
  c36e=0 $c44e=c44 $c45e=0 $c46e=0 $c55e=c44 $c56e=0
  c66e =(c11-c12)/2

! Write to ANSYS-material table
! normal matrix has to be changed due to different annotation in ANSYS
! ({x, y, z, xy, yz, xz} instead of {x, y, z, yz, xz, xy})
! and due to 2D-xy-plane223 x=x, y=z, z=y, so 1=1, 2->3, 2->3, 4->5, 5->4, 6=6

tb,anel,Aln  !{x , z, y, xz, yz, xy}
tbdatal, 1,c11e,c13e,c12e,c15e,c14e,c16e!
tbdatal, 7,    c33e,c23e,c35e,c34e,c36e!
tbdatal,12,    c22e,c25e,c24e,c26e!
tbdatal,16,    c55e,c64e,c45e!
tbdatal,19,    c44e,c46e!
tbdatal,21,    c66e!

!! Tensor of piezoelectric coefficients
! Generating normal form of matrix
e11t=0 $e12t=0 $e13t=0 $e14t=0 $e15t=e24 $e16t=0 $e21t=0
e22t=0 $e23t=0 $e24t=e24 $e25t=0 $e26t=0 $e31t=e31
  e32t=e31 $e33t=e33 $e34t=0 $e35t=0 $e36t=0

! Write to ANSYS-material table
tb,piez,Aln

tbdatal, 1,e11t,e31t,e21t!
tbdatal, 4,e13t,e33t,e23t!
!! Tensor of relative permittivity
!Generating normal form of matrix
epsXXs=epsxx $epsXYs=0$ $epsXZs=0$ $epsYYs=epsxx$
epsYZs=0 $epsZZs=epszz

! Write to ANSYS-material table
tb,dper,Aln $!$ Permittivity matrix
tbdata, 1,epsXXs,epsZZs,epsYYs !$
tbdata, 4,epsXZs,epsYZs,epsXYs !$

mp,dens,Aln,density $!$ Density of AlN
!mp,dmpr,Aln,constdamp

!! Independent stiffness coefficients for constant E [GPa*1e-6]
c11=209.6e3 $c12=120e3$ $c13=104.6e3$ $c33=210.6e3$ $c44=42.3e3$
c66=44.8e3
! Independent piezoelectric coefficients [pC/um^3]
e31=-0.573 $e33=1.321$ $e24=-0.48$
! Relative permittivity
epsxx=7.57 $epsyy=7.57$ $epszz=9$
! Density [kg/um^3]density=5610e-18
! Generating normal form of matrix
c11e=c11 $c12e=c12$ $c13e=c13$ $c14e=0$ $c15e=0$ $c16e=0$ $c22e=c11$
c23e=c13 $c24e=0$ $c25e=0$ $c26e=0$ $c33e=c33$ $c34e=0$ $c35e=0$
c36e=0 $c44e=c44$ $c45e=0$ $c46e=0$ $c55e=c44$ $c56e=0$
c66e=(c11-c12)/2 $!$c66
! Write to ANSYS-material table
tb,anel,ZnO $!$ {x, z, y, xz, yz, xy}$
tbdata, 1,c11e,c13e,c12e,c15e,c14e,c16e !
tbdata, 7, c33e,c23e,c35e,c34e,c36e !
tbdata,12, c22e,c25e,c24e,c26e !
tbdata,16, c55e,c64e,c45e !
tbdata,19, c44e,c46e !
tbdata,21, c66e !

! Tensor of piezoelectric coefficients
e11t=0 $e_{12}t=0$ $e_{13}t=0$ $e_{14}t=0$ $e_{15}t=e_{24}$ $e_{16}t=0$ $e_{21}t=0$ $e_{22}t=0$ $e_{24}t=e_{24}$ $e_{25}t=0$ $e_{26}t=0$ $e_{31t}=e_{31}$ $e_{32t}=e_{33}$ $e_{34t}=0$ $e_{35t}=0$ $e_{36t}=0$

! Write to ANSYS-material table
tb,piez,ZnO !
tbdata, 1,e11t,e31t,e21t !
tbdata, 4,e13t,e33t,e23t !
tbdata, 7,e12t,e32t,e22t !
tbdata,10,e15t,e35t,e25t !
tbdata,13,e14t,e34t,e24t !
tbdata,16,e16t,e36t,e26t !

!! Tensor of relative permittivities
! Generating normal form of matrix
epsXXs=epsxx $epsXYs=0$ $epsXZs=0$ $epsYYs=epsxx$ $epsYZs=0$
epsZZs=epszz

! Write to ANSYS-material table
tb,dper,ZnO ! Permittivity matrix
tbdata, 1,epsXXs,epsZZs,epsYYs !
tbdata, 4,epsXZs,epsYZs,epsXYs !

mp,dens,ZnO,density ! Density of AlN
!mp,dmpr,ZnO,constdamp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
Piezoelectric ScAlN (material number: 3)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
matcount=matcount+1 ! Set number for ScAlN
ScAlN=matcount

! Independent stiffness coefficients for constant E [GPa*1e-6]
c11=169e3 $c_{12}=61.2e3$ $c_{13}=58.8e3$ $c_{33}=211e3$ c44=51.5e3 c66=53.9e3

! Independent piezoelectric coefficients [pC/um^3]
e31=-1.58 $e_{33}=4.42$ $e_{24}=-1.31$
! Relative permittivity
epsXX=30.49 $epsYY=30.49$ $epsZZ=30.27$
! Density [kg/um^3]
density=3760e-18!! Damper
!constdamp=1/1000

! Generating normal form of matrix
c11e=c11 $c_{12e}=c_{12}$ $c_{13e}=c_{13}$ $c_{14e}=0$ $c_{15e}=0$ $c_{16e}=0$
c22e=c11 $c_{23e}=c_{13}$ $c_{24e}=0$ $c_{25e}=0$ $c_{26e}=0$ $c_{33e}=c_{33}$
c34e=0 $c_{35e}=0$ $c_{36e}=0$ $c_{44e}=c_{44}$ $c_{45e}=0$ $c_{46e}=0$
c55e=c44 $c_{56e}=0$ $c_{66e}=c_{66}$
! Write to ANSYS-material table
tb,anel,ScAlN  !{x , z, y, xz, yz, xy}
tbdata, 1,c11e,c13e,c12e,c15e,c14e,c16e!
tbdata, 7,  
         c33e,c23e,c35e,c34e,c36e!
tbdata,12, c22e,c25e,c24e,c26e!
tbdata,16,  c55e,c64e,c45e!
tbdata,19, c44e,c46e!
tbdata,21, c66e!
!! Tesor of piezoelectric coefficients
e11t=0  $e12t=0  $e13t=0  $e14t=0  $e15t=e24  $e16t=0  
e22t=0  $e23t=0  $e24t=e24  $e25t=0  $e26t=0  $e31t=e31  $e32t=e31  
e33t=e33  $e34t=0  $e35t=0  $e36t=0

! Write to ANSYS-material table
tb,piez,ScAlN    !
tbdata, 1,e11t,e31t,e21t!
tbdata, 4,e13t,e33t,e23t!
tbdata, 7,e12t,e32t,e22t!
tbdata,10,e15t,e35t,e25t!
tbdata,13,e14t,e34t,e24t!
tbdata,16,e16t,e36t,e26t!

! Tensor of relative permittivities
epsXXs=epsxx  $epsXYs=0  $epsXZs=0  $epsYYs=epsxx  $epsYZs=0  
epsZZs=epszz

! Write to ANSYS-material table
tb,dper,ScAlN    ! Permittivity matrix
tbdata, 1,epsXXs,epsZZs,epsYYs!
tbdata, 4,epsXZs,epsYZs,epsXYs!

mp,dens,ScAlN,density    ! Density of ScAlN
! Damping of ScAlN
!mp,dmpr,ScAlN,constdamp

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Electr. material Aluminium (Al) (number: 4 )
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matcount=matcount+1
Al=matcount

mp,ex,Al,7e4          ! Al Young's modulus
mp,ey,Al,7e4
mp,ez,Al,7e4

mp,nuxy,Al,0.35        ! Al poisson ratio
mp,nuxz,Al,0.35
mp,nuyz,Al,0.35
mp,dens,Al,2700e-18  ! Al density

!mp,dmpr,Al,constdamp

mp,perx,Al,1    ! relative permittivity
mp,pery,Al,1
mp,perz,Al,1

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Electr. material Ruthenium (Ru) (material number: 5)
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matcount=matcount+1
Ru=matcount

mp,ex,Ru,44.7e4
mp,ey,Ru,44.7e4
mp,ez,Ru,44.7e4

mp,nuxy,Ru,.3
mp,nuxz,Ru,.3
mp,nuyz,Ru,.3

mp,dens,Ru,12450e-18
!

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Electr. material Ruthenium (Cu) (material number: 6)
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matcount=matcount+1
Cu=matcount

mp,ex,Cu,12e4
mp,ey,Cu,12e4
mp,ez,Cu,12e4

mp,nuxy,Cu,.34
mp,nuxz,Cu,.34
mp,nuyz,Cu,.34

mp,dens,Cu,8940e-18
!mp,dmpr,Cu,constdamp
mp,perx,Cu,1
mp,pery,Cu,1
mp,perz,Cu,1

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Electr. material Platinum (Pt)    (material number: 7 )
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
matcount=matcount+1
Pt=matcount

mp,ex,Pt,16.8e4
mp,ey,Pt,16.8e4
mp,ez,Pt,16.8e4

mp,nuxy,Pt,.38
mp,nuxz,Pt,.38
mp,nuyz,Pt,.38

mp,dens,Pt,21450e-18
!mp,dmpr,Pt,constdamp

mp,perx,Pt,1
mp,pery,Pt,1
mp,perz,Pt,1

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!! Electr. material Molybdenum (Mo)    (material number: 8 )
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
matcount=matcount+1
Mo=matcount

mp,ex,Mo,32.9e4
mp,ey,Mo,32.9e4
mp,ez,Mo,32.9e4

mp,nuxy,Mo,.31
mp,nuxz,Mo,.31
mp,nuyz,Mo,.31

mp,dens,Mo,10280e-18
!mp,dmpr,Mo,constdamp

mp,perx,Mo,1
mp,pery,Mo,1
mp,perz,Mo,1
Electrical material: Gold (Au) (material number: 9)

```
matcount=matcount+1
Au=matcount

mp,ex,Au,7.9e4
mp,ey,Au,7.9e4
mp,ez,Au,7.9e4

mp,nuxy,Au,.44
mp,nuxz,Au,.44
mp,nuyz,Au,.44

mp,dens,Au,19300e-18

!mp,dmpr,Au,constdamp

mp,perx,Au,1
mp,pery,Au,1
mp,perz,Au,1
```

Substrate: 6H-SiC (material number: 10)

```
matcount=matcount+1
SixHSiC=matcount

! Independent stiffness coefficients for constant E [GPa*1e-6]
c11=759e3  $c12=275e3  $c13=264e3  $c33=869e3  $c44=231e3  
c66=53.9e3
e31=-0.2  $e33=0.398  $e24=-0.198
epsxx=9.66  $epsyy=9.66  $epszz=10.33
density=3217e-18       ! Density [kg/um^3]

! Generating normal form of matrix
c11e=c11  $c12e=c12  $c13e=c13  $c14e=0  $c15e=0  $c16e=0 
c22e=c11  $c23e=c13  $c24e=0  $c25e=0  $c26e=0  $c33e=c33 
c34e=0c35e=0  $c36e=0  $c44e=c44  $c45e=0  $c46e=0  $c55e=c44  
c56e=0  $c66e=c66
```

```
tb,anel,SixHSiC  ![x, z, y, xz, yz, xy]
tbdata, 1,c11e,c13e,c12e,c15e,c14e,c16e !
tbdata, 7, c33e,c23e,c35e,c34e,c36e !
tbdata,12, c22e,c25e,c24e,c26e !
tbdata,16, c55e,c64e,c45e !
tbdata,19, c44e,c46e !
tbdata,21, c66e !
```
!! Tensor of piezoelectric coefficients

e_{11t}=0 \ e_{12t}=0 \ e_{13t}=0 \ e_{14t}=0 \ e_{15t}=e_{24} \ e_{16t}=0 \\
e_{22t}=0 \ e_{23t}=0 \ e_{24t}=e_{24} \ e_{25t}=0 \ e_{26t}=0 \ e_{31t}=e_{31} \ e_{32t}=e_{31} \\
e_{33t}=e_{33} \ e_{34t}=0 \ e_{35t}=0 \ e_{36t}=0

! Write to ANSYS-material table
tb,piez,SixHSiC     
  tbd,ata, 1,e_{11t},e_{31t},e_{21t} 
  tbd,ata, 4,e_{13t},e_{33t},e_{23t} 
  tbd,ata, 7,e_{12t},e_{32t},e_{22t} 
  tbd,ata,10,e_{15t},e_{35t},e_{25t} 
  tbd,ata,13,e_{14t},e_{34t},e_{24t} 
  tbd,ata,16,e_{16t},e_{36t},e_{26t}

!! Tensor of relative permittivities

\epsilon_{XXs}=\epsilon_{xx} \ $\epsilon_{XYs}=0 \ $\epsilon_{XZs}=0 \ $\epsilon_{YYs}=\epsilon_{xx} \ $\epsilon_{YZs}=0 \\
\epsilon_{ZZs}=\epsilon_{zz}

! Write to ANSYS-material table
tb,dper,SixHSiC     ! Permittivity matrix
  tbd,ata, 1,\epsilon_{XXs},\epsilon_{ZZs},\epsilon_{YYs} 
  tbd,ata, 4,\epsilon_{XZs},\epsilon_{YZs},\epsilon_{XYs} 

mp,dens,SixHSiC,density     ! Density of 6H-SiC

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%!  Substrate 3C-SiC (material number: 11 )
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matcount=matcount+1
ThreeCSiC=matcount

! Independent stiffness coefficients
$c_{11}=390e3 \ $c_{12}=142e3 \ $c_{13}=142e3 \ $c_{33}=390e3 \ $c_{44}=256e3 \\
c_{66}=256e3 \\
e_{14}=-0.349 \\
\epsilon_{xxx}=6.52 \ $\epsilon_{yy}=6.52 \ $\epsilon_{zz}=6.52 \\
density=3210e^{-18}

! Generating normal form of matrix
$c_{11e}=c_{11} \ $c_{12e}=c_{12} \ $c_{13e}=c_{13} \ $c_{14e}=0 \ $c_{15e}=0 \ $c_{16e}=0 \ $c_{22e}=c_{11} \\
c_{23e}=c_{13} \ $c_{24e}=0 \ $c_{25e}=0 \ $c_{26e}=0 \ $c_{33e}=c_{33} \ $c_{34e}=0 \ $c_{35e}=0 \\
c_{36e}=0 \ $c_{44e}=c_{44} \ $c_{45e}=0 \ $c_{46e}=0 \ $c_{55e}=c_{44} \ $c_{56e}=0 \ $c_{66e}=c_{66}

tb,anel,ThreeCSiC ![x , z, y, xz, yz, xy]
  tbd,ata, 1,c_{11e},c_{13e},c_{12e},c_{15e},c_{14e},c_{16e} 
  tbd,ata, 7, c_{33e},c_{23e},c_{35e},c_{34e},c_{36e} 
  tbd,ata,12, c_{22e},c_{25e},c_{24e},c_{26e} 
  tbd,ata,16, c_{55e},c_{64e},c_{45e}
!! Tensor of piezoelectric coefficients
!---------------------------------------------
$e_{11t}=0$  $e_{12t}=0$  $e_{13t}=0$  $e_{14t}=e_{14}$  $e_{15t}=0$  $e_{16t}=0$
$e_{21t}=0$  $e_{22t}=0$  $e_{23t}=0$  $e_{24t}=0$  $e_{25t}=14$  $e_{26t}=0$
$e_{31t}=0$  $e_{32t}=0$  $e_{33t}=0$  $e_{34t}=0$  $e_{35t}=0$  $e_{36t}=e_{14}$

! Write to ANSYS-material table

tb, piez, ThreeCSiC  !
tbdata, 1, $e_{11t}$, $e_{31t}$, $e_{21t}$  !
tbdata, 4, $e_{13t}$, $e_{33t}$, $e_{23t}$  !
tbdata, 7, $e_{12t}$, $e_{32t}$, $e_{22t}$  !
tbdata, 10, $e_{15t}$, $e_{35t}$, $e_{25t}$  !
tbdata, 13, $e_{14t}$, $e_{34t}$, $e_{24t}$  !
tbdata, 16, $e_{16t}$, $e_{36t}$, $e_{26t}$  !

!! Tensor of relative permittivities
! Generating normal form of matrix
$\varepsilon_{XXs}=\varepsilon_{xx}$  $\varepsilon_{XYs}=0$  $\varepsilon_{XZs}=0$  $\varepsilon_{YYs}=\varepsilon_{xx}$
$\varepsilon_{YZs}=0$  $\varepsilon_{ZZs}=\varepsilon_{zz}$

! Write to ANSYS-material table

tb, dper, ThreeCSiC  ! Permittivity matrix
tbdata, 1, $\varepsilon_{XXs}$, $\varepsilon_{ZZs}$, $\varepsilon_{YYs}$  !
tbdata, 4, $\varepsilon_{XZs}$, $\varepsilon_{YZs}$, $\varepsilon_{XYs}$  !

mp, dens, ThreeCSiC, density  ! Density of 3C-SiC

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 
!%%%%            Substrate Si  (material number: 12 ) 
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
matcount = matcount + 1
Si = matcount
! Independent stiffness coefficients for constant E [GPa*1e-6]
c11 = 165.7e3  $c_{12}=63.9e3$  $c_{13}=63.9e3$  $c_{33}=79.56e3$  $c_{44}=79.56e3$
c66 = 79.56e3
e14 = 0
$\varepsilon_{xx}=11.7$  $\varepsilon_{yy}=11.7$  $\varepsilon_{zz}=11.7$
density = 2230e-18  ! Density [kg/um^3]

! Generating normal form of matrix
$c_{11e}=c_{11}$  $c_{12e}=c_{12}$  $c_{13e}=c_{13}$  $c_{14e}=0$  $c_{15e}=0$  $c_{16e}=0$
c_{22e}=c_{11}  $c_{23e}=c_{13}$  $c_{24e}=0$  $c_{25e}=0$  $c_{26e}=0$
c_{33e}=c_{33}  $c_{34e}=0$  $c_{35e}=0$  $c_{36e}=0$
c_{44e}=c_{44}  $c_{45e}=0$  $c_{46e}=0$  $c_{55e}=c_{44}$  $c_{56e}=0$
c_{66e}=c_{66}

tb, anel, Si  !{x , z, y, xz, yz, xy}
!! Tensor of piezoelectric coefficients

e11t=0 $e12t=0 $e13t=0 $e14t=e14 $e15t=0 $e16t=0 $e21t=0

e22t=0 $e23t=0 $e24t=0 $e25t=e14 $e26t=0 $e31t=0 $e32t=0

e33t=0 $e34t=0 $e35t=0 $e36t=e14

! Write to ANSYS-material table
tb,piez,Si

tbdata, 1, e11t, e31t, e21t

tbdata, 4, e13t, e33t, e23t

tbdata, 7, e12t, e32t, e22t

tbdata,10, e15t, e35t, e25t

tbdata,13, e14t, e34t, e24t

tbdata,16, e16t, e36t, e26t

!! Tensor of relative permittivities
! Generating normal form of matrix
epsXXs=epsxx $epsXYs=0 $epsXZs=0 $epsYYs=epsxx

epsYZs=0 $epsZZs=epszz

! Write to ANSYS-material table
tb,dper,Si

! Permittivity matrix
tbdata, 1, epsXXs, epsZZs, epsYYs

tbdata, 4, epsXZs, epsYZs, epsXYs

mp,dens,Si,density      ! Density of Si

! Generating normal form of matrix
c11e=c11 $c12e=c12 $c13e=c13 $c14e=0 $c15e=0 $c16e=0 $c22e=c11
c23e=c13 $c24e=0 $c25e=0 $c26e=0 $c33e=c33 $c34e=0 $c35e=0 $c36e=0

c55e,c64e,c45e
c44e,c46e
c66e

c11e,c13e,c12e,c15e,c14e,c16e
c33e,c23e,c35e,c34e,c36e
c22e,c25e,c24e,c26e
c55e,c64e,c45e
c44e,c46e
c66e
! Write to ANSYS-material table
tb,anel,SiO2 !{x, z, y, xz, yz, xy}
tbdata, 1,c11e,c13e,c12e,c15e,c14e,c16e!
tbdata, 7, c33e,c23e,c35e,c34e,c36e!
tbdata,12, c22e,c25e,c24e,c26e!
tbdata,16, c55e,c64e,c45e!
tbdata,19, c44e,c46e!
tbdata,21, c66e!

!! Tensor of piezoelectric coefficients
e11t=0 $e12t=0 $e13t=0 $e14t=e14 $e15t=0 $e16t=0 $e21t=0 $e22t=0 $e23t=0 $e24t=0 $e25t=e14 $e26t=0 $e31t=0 $e32t=0 $e33t=0 $e34t=0 $e35t=0 $e36t=e14

! Write to ANSYS-material table
tb,piez,SiO2 

tbdata, 1,e11t,e31t,e21t !
tbdata, 4,e13t,e33t,e23t !
tbdata, 7,e12t,e32t,e22t !
tbdata,10,e15t,e35t,e25t !
tbdata,13,e14t,e34t,e24t !
tbdata,16,e16t,e36t,e26t !

!! Tensor of relative permittivities
epsXXs=epsxx $epsXYs=0 $epsXZs=0 $epsYYs=epsxx $epsYZs=0 $epsZZs=epszz

! Write to ANSYS-material table
tb,dper,SiO2 ! Permittivity matrix
tbdata, 1,epsXXs,epsZZs,epsYYs !
tbdata, 4,epsXZs,epsYZs,epsXYs !

mp,dens,SiO2,density ! Density of SiO2

!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Substrate W (material number: 14)
!%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matcount=matcount+1
W=matcount

mp,ex,W,41.1e4
mp,ey,W,41.1e4
mp,ez,W,41.1e4

mp,nuxy,W,0.28
mp,nuxz,W,0.28
mp,nuyz,W,0.28
mp, dens, W, 19250e-18

mp, perx, W, 1
mp, pery, W, 1
mp, perz, W, 1
Definition of the damper materials

Q_{start}=1000  ! quality factor of first damper layer
Q_{end}=10  ! quality factor of last damper layer

*dim,Q,array,dampernum,
*dim,dampvalue,array,dampernum,
*do,i,1,dampernum,1
  Q(i)=BY YOURSELF
  dampvalue(i)=BY YOURSELF

!-------------------------------piezoelectric film-------------------------------
mpcopy,,Film,Film*NUMBER+i
HOW YOU WILL DO IT NEXT
HOW YOU WILL DO IT NEXT

!-------------------------------Top electrode-------------------------------
mpcopy,,TopElectrode,TopElectrode*NUMBER+i
HOW YOU WILL DO IT NEXT
HOW YOU WILL DO IT NEXT

!-------------------------------Bottom electrode-------------------------------
mpcopy,,BotElectrode,BotElectrode*NUMBER+i
HOW YOU WILL DO IT NEXT
HOW YOU WILL DO IT NEXT

*enddo

Definition of the geometry model

"widthdamper" needs to be denoted in Main codes

"sidecheck" needs to be denoted in Main codes

sidecheck=1, damper on right side
sidecheck=2, damper on two sides
sidecheck=3, damper on left side

allsel,all
*get,areanum,area,,count

Left side
*if,sidcheck,eq,1,then
!------------------ EPE or IDT/EPE or IDT/EPE/IDT structures
*if,buildmodel,eq,1,or,buildmodel,eq,2,then
 *do,i,1,dampernum,1
  areanum=areanum+1
  rectng,-i*widthdamper,(l-i)*widthdamper,0,thick
  asel,s,,,areanum,,,0
  aatt,Film*NUMBER+i,,,Filmele
  areanum=areanum+1
  rectng,-i*widthdamper,(l-i)*widthdamper,thick,thick+Topelectrthick
  asel,s,,,areanum,,,0
  aatt,TopElectrode*NUMBER+i,,,Electrele
  areanum=areanum+1
  rectng,-i*widthdamper,(l-i)*widthdamper,-
  Botelectrthick,0
  asel,s,,,areanum,,,0
  aatt,BotElectrode*NUMBER+i,,,Electrele
*enddo
*elseif,buildmodel,eq,4
 *do,i,1,dampernum,1
  areanum=areanum+1
  rectng,-i*widthdamper,(l-i)*widthdamper,0,thick
  asel,s,,,areanum,,,0
  aatt,Film*NUMBER+i,,,Filmele
  areanum=areanum+1
  rectng,-i*widthdamper,(l-i)*widthdamper,-
  Botelectrthick,0
  asel,s,,,areanum,,,0
  aatt,BotElectrode*NUMBER+i,,,Electrele
*enddo
*elseif,buildmodel,eq,7,or,buildmodel,eq,8
allsel,all
 *get,areanumber,area,,count
 *get,arealist,area,,num,max
 *do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(l-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,,Filmele
  arealist=arealist+1
  rectng,-i*widthdamper,(l-i)*widthdamper,thick,thick+Topelectrthick
  asel,s,,,arealist,,,0
  aatt,TopElectrode*NUMBER+i,,,Electrele
  aatt,TopElectrode,,Electrele
  arealist=arealist+1
rectng,-i*widthdamper,(1-i)*widthdamper,-
Botelectrthick,0
asel,s,,,arealist,,,0
aatt,BotElectrode*NUMBER+i,,Electrele
!aatt,BotElectrode,,Electrele
*endo
*elseif,buildmodel,eq,9
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,Filmele
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,thick,thick+Topelectrthick
  asel,s,,,arealist,,,0
  aatt,TopElectrode*NUMBER+i,,Electrele
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,-
  Botelectrthick,0
  asel,s,,,arealist,,,0
  aatt,BotElectrode*NUMBER+i,,Electrele
*enddo
*elseif,buildmodel,eq,10
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,Filmele
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,thick,thick+Topelectrthick
  asel,s,,,arealist,,,0
  aatt,TopElectrode*NUMBER+i,,Electrele
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,-
  Botelectrthick,0
  asel,s,,,arealist,,,0
  aatt,BotElectrode*NUMBER+i,,Electrele
*enddo
*elseif,buildmodel,eq,11
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
arealist=arealist+1
rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
asel,s,,,arealist,,,0
aatt,Film*NUMBER+i,,,Filmele
arealist=arealist+1
rectng,-i*widthdamper,(1-i)*widthdamper,-
BotElectrothick,0
asel,s,,,arealist,,,0
aatt,BotElectrode*NUMBER+i,,,Electrele
*enddo
*elseif,buildmodel,eq,12
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,,Filmele
*enddo
*elseif,buildmodel,eq,13
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,,Filmele
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,-
  BotElectrothick,0
  asel,s,,,arealist,,,0
  aatt,BotElectrode*NUMBER+i,,,Electrele
*enddo
*elseif,buildmodel,eq,14
allsel,all
*get,areanumber,area,,count
*get,arealist,area,,num,max
*do,i,1,dampernum,1
  arealist=arealist+1
  rectng,-i*widthdamper,(1-i)*widthdamper,0,thick
  asel,s,,,arealist,,,0
  aatt,Film*NUMBER+i,,,Filmele
  ! arealist=arealist+1
  !rectng,-i*widthdamper,(1-i)*widthdamper,thick,thick+Topelectrothick
  ! asel,s,,,arealist,,,0
  ! aatt,TopElectrode*NUMBER+i,,,Electrele
  arealist=arealist+1
rectng,-i*widthdamper,(1-i)*widthdamper,-
Botelectrthick,0
asel,s,,,arealist,,,0
aatt,BotElectrode*NUMBER+i,,Electrele
*endo
*endif

!------------------------------------------------- Two sides -------------------------------
*elseif,sidecheck,eq,2,then
... (I believe you can do it by yourself)
!------------------------------------------------- Right side -------------------------------
*else
... (I believe you can do it by yourself)
*endif

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! Finsh !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
B.4 Macro file: Periodic Boundary Condition

!$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
!$$$$        Periodic Boundary Conditions                $$$$$
!$$$$                                                    $$$$$
!$$$$                 Jiansong Liu                      $$$$$
!$$$$                                                    $$$$$
!$$$$               Chiba University                    $$$$$
!$$$$                                                    $$$$$
!$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

!$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

%%%%%% Apply the periodic BC by CE command %%%%%%%

!------ Obtain the node number on the left side ------------
allsel,all
nsll
*get,
*get,
*dim,
*do,
   I BELIEVE YOU CAN DO IT NOW!!
*enddo
/out
*vwrite
/out

!------ Obtain the node number one the right side ----------
allsel,all
nsll
*get,
*get,
*dim,
*do,
   YOU CAN DO IT!!
*enddo
/out
*vwrite
/out
!!!-----------------------------------------------------------------------
*do,j,1,rightnode,1
   *if,j,lt,3,then
       ce,j,0,leftcode(j),ux,1,rightcode(j),ux,p
       ce,j+NUMBER0,0,leftcode(j),uy,1,rightcode(j),uy,p
ce, j+5000, 0, leftcode(j), volt, 1, rightcode(j), volt, p
*else
  ce, j, 0, leftcode(j), ux, 1, rightcode(rightnode-(j-3)), ux, p
  ce, j+1000, 0, leftcode(j), uy, 1, rightcode(rightnode-(j-3)), uy, p
  ce, j+5000, 0, leftcode(j), volt, 1, rightcode(rightnode-(j-3)), volt, p
*endif
*enddo

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ Finish ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
B.5 Macro file: Extraction of Node Displacements

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%%%Output node coord. and mode dipl. of the surface -------

finish
/post1

*if,InsertDamper,eq,1,then
  *if,buildmodel,eq,1,then
    lsel,s,loc,x,0,width
    lsel,r,loc,y,thick+Topelectrthick
  *elseif,buildmodel,eq,2
    lsel,s,loc,x,0,width
    lsel,r,loc,y,thick+Topelectrthick
  *elseif,buildmodel,eq,3
    lsel,s,loc,x,0,width
    lsel,r,loc,y,thick+Topelectrthick
  *elseif,buildmodel,eq,7,or,buildmodel,eq,8
    *if,SymSignal,eq,0,then
      lsel,s,loc,x,0,2*width+width_FBAR
      lsel,r,loc,y,thick+Topelectrthick
    *elseif,SymSignal,eq,2
      lsel,s,loc,x,width+width_FBAR
      lsel,r,loc,y,thick+Topelectrthick
    *endif
  *elseif,buildmodel,eq,9
    *if,SymSignal,eq,0,then
      lsel,s,loc,x,0,2*width+width_FBAR
      lsel,r,loc,y,thick+Topelectrthick
    *elseif,SymSignal,eq,2
      lsel,s,loc,x,width+gap,width+gap+width_FBAR
      lsel,r,loc,y,thick
    *endif
  *elseif,buildmodel,eq,10
    *if,SymSignal,eq,0,then
      lsel,s,loc,x,0,2*width+width_FBAR
      lsel,r,loc,y,thick+Topelectrthick

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*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, width + width_FBAR
  lsel, r, loc, y, thick + Topelectrthick
*endif
*elseif, buildmodel, eq, 11
*if, SymSignal, eq, 0, then
  lsel, s, loc, x, 0, 2*width + width_FBAR
  lsel, r, loc, y, thick
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, width, width + width_FBAR
  lsel, r, loc, y, thick
*endif
*elseif, buildmodel, eq, 12
*if, SymSignal, eq, 0, then
  lsel, s, loc, x, 0, 2*width + width_FBAR
  lsel, r, loc, y, thick
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, 0, width + width_FBAR
  lsel, r, loc, y, thick
*endif
*elseif, buildmodel, eq, 13
*if, SymSignal, eq, 0, then
  lsel, s, loc, x, AlN_Si_L + width, AlN_Si_L + width + width_FBAR
  lsel, r, loc, y, thick
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, AlN_Si_L + width, AlN_Si_L + width + width_FBAR
  lsel, r, loc, y, thick
*endif
*elseif, buildmodel, eq, 14
*if, SymSignal, eq, 0, then
  lsel, s, loc, x, AlN_Si_L, AlN_Si_L + width
  lsel, r, loc, y, thick
*elseif, SymSignal, eq, 2
  lsel, s, loc, x, AlN_Si_L, AlN_Si_L + width
  lsel, r, loc, y, thick
*endif
*else
  lsel, s, loc, x, 0, width
  lsel, r, loc, y, thick
*endif
*elseif, InsertDamper, eq, 0, then
  *if, buildmodel, eq, 1, then
    lsel, s, loc, y, thick + Topelectrthick
*elseif, buildmodel, eq, 2
  lsel, s, loc, y, thick + Topelectrthick
*elseif, buildmodel, eq, 3
  lsel, s, loc, y, thick + Topelectrthick
*elseif, buildmodel, eq, 9
  lsel, s, loc, x, width, width + width_FBAR
I BELIEVE YOU CAN DO IT!!

*enddo
/out,

*enddo