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独特谐振模式下薄膜体声波谐振器的设计

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摘要：计算了四层复合结构的薄膜体声波谐振器（FBAR）的输入阻抗谱，各层采用的材料分别是 Al/AlN/Al/Si，其尺寸为 0.8 μm/1.9 μm/0.8 μm/100 μm，得出其有效机电耦合系数 k_{eff}^2随谐振模式的分布情况，从而得到最大 k_{eff}^2的独特谐振模式在 1～2 GHz 为第 40 阶谐振模式。从理论上探讨了各层的尺寸及材料属性对该独特谐振模式及其频移的影响，以及串联谐振品质因数 FOM 等滤波器设计的主要性能参数在该模式下的分布情况。实验结果表明，工作在独特谐振模式下的 FBAR 的性能依赖于各层材料尺寸，当压电层厚度从 0.2 μm 变到 4.3 μm 时，特殊谐振模式频率从 1.2 GHz 增加到 4.8 GHz；当基底厚度变厚时，有效机电耦合系数从 3.2%变到 0.8%，串联品质因数从 2 000 变到 700；而电极变厚后，有效机电耦合系数趋于一个稳定值。这些数据在实际设计过程中对滤波器的微调具有参考意义。

关　键　词：薄膜体声波谐振器；有效机电耦合系数；品质因数
中图分类号：TN752　　**文献标识码**：A

Design of thin film bulk acoustic resonator under unique mode

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Abstract：The spectra of input electric impedance for a four-layer (electrode/piezoelectric film/electrode/substrate) thin Film Bulk Acoustic Resonator (FBAR) with the materials of Al/AlN/Al/Si and the thickness of each layer of 0.8 μm/1.9 μm/0.8 μm/100 μm is researched by a transfer matrix method. The distribution of the effective coupling factor (k_{eff}^2) versus the mode order is derived，and a unique mode with maximum k_{eff}^2 is obtained in the 40th mode from 1 GHz to 2 GHz in simulation. The effects of various electrodes and the substrates on the distribution of unique mode and the frequency shift are studied，and the quality factor at series resonant frequency and the Figure of Merit (FOM) which are the main parameters to indicate the features of the crystal resonator in a filter design are investigated. Experimental results show that the performance of the FBAR working in the unique mode relies greatly on the sizes and the materials of layers. The unique mode shifts in a higher frequency are from 1.2 GHz to 4.8 GHz when the film thicknesses come from 0.2 μm to 4.3 μm in simulation; the k_{eff}^2 and Q_s are from 3.2% to 0.8% and from 2 000 to 700 in simulation，respectively when the substrate becomes thicker and the k_{eff}^2 of the unique mode declines and tends to a stable value when the e-

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lectrode becomes thicker. These conclusion gives some guidelines for the design of a proper FBAR.

Key words: Film Bulk Acoustic Resonator(FBAR); effective electromechanical coupling factor; quality factor

1 Introduction

Among frequency control/selection devices, the Film Bulk Acoustic Resonator (FBAR) consisting of a piezoelectric thin film on a high Q substrate in sandwich structures is an attractive candidate with high Q value reported to be the order of 1014. Because of its integration with CMOS process , it can be widely used in the field of wireless network, such as Voltage Controlled Oscillator (VCO)[1]. Several efforts for FBAR based on the oscillator with CMOS integrated circuits and discrete circuits have been reported with very impressive performance[2].

In an FBAR, there are a few tens to a few hundreds resonant modes in its frequency spectra, so it is our goal to choose the unique one with a maximum effective coupling factor k^2_{eff}, where k^2_{eff} is particularly used in the filter design literature as a convenient measure of bandwidth for bandpass filters and determines the insertion loss of the resonator used in the oscillator[3]. For the FBAR design and performance evaluation, it becomes important to precisely investigate the effects of the size and material properties of the main parameters under the unique mode.

In this paper, as the emphasis, the distribution of maximum k^2_{eff} under the unique mode and frequency shift as the thickness of substrate, the electrode and the piezo-film are comprehensively studied. Furthermore, under the unique mode of maximum k^2_{eff}, Quality factor, FOM, which is crucial parameters in filter and oscillator designs is evaluated in detail.

2 Performance parameters and simulation procedure

In order to deduced the performance parameters of the piezoelectric composite resonator, its input impedance Z_{in} should be derived first. And from the impedance spectrum, the series and parallel resonant frequencies f_{s} and f_{p} can be obtained, based on which the maximum k^2_{eff}, Q_{s} factor, and FOM can be derived.

2.1 Input impedance of FBAR

For a four-layer FBAR[4], i. e. , a piezoelectric film sandwiched by two electrodes and deposited on a substrate, as shown in Fig. 1, the electric input impedance can be given by[5-6]

$$Z_{\mathrm{in}}=\frac{V}{I}=$$

$$\frac{1}{\mathrm{j}\omega C_0}\left[1-\frac{k_t^2}{\gamma}\frac{(z_1+z_2)\sin\gamma+\mathrm{j}2(1-\cos r)}{(z_1+z_2)\cos r+\mathrm{j}(1+z_1z_2)\sin\gamma}\right],(1)$$

Where $c_0=\varepsilon^s_{33}s/l$ is the clamped capacitor of the resonator with a area s, $z_0=s\rho v$ is the acoustic impedance of the piezoelectric layer with a density ρ, v is the longitudinal acoustic wave velocity in piezoelectric layer along the direction normal to the resonator surface; $\omega=2\pi f$ is the angular frequency , $\gamma=\omega l/v$ is the phase delay of the

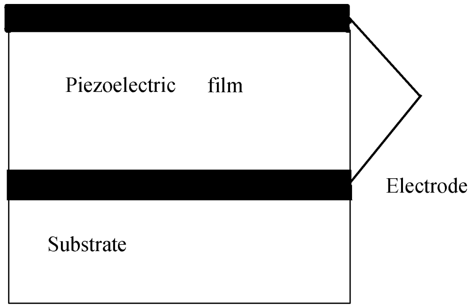

Fig. 1 Schematic of four-layer structure FBAR

acoustic wave in the piezoelectric film, k_t^2 is the electromechanical coupling coefficient of thin film piezoelectric material, $Z_1=\frac{F_0}{u_0}=\mathrm{j}Z_{e1}\tan\gamma_{e1}$, $Z_2=\frac{F_1}{u_1}=\mathrm{j}\,\frac{Z_{sb}\tan\gamma_{sb}+Z_{e2}\tan\gamma_{e2}}{1-(Z_{sb}/Z_{e2})\tan\gamma_{e2}\tan\gamma_{sb}}$, and $z_1=Z_1/Z_0$ and $z_2=Z_2/Z_0$ are the normalized acoustic loading impedance on both sides of the piezoelectric layer.

2.2 Performance parameters of unique mode

The performance parameters of a FBAR operating in the unique mode can be derived from f_s and f_p of the impedance spectrum. For the FBAR using as a frequency selection device, the BVD equivalent circuit parameters can be used to characterize its features, as shown in as Fig. 2. In this paper k_{eff}^2, Q_s in series resonant frequency , and FOM are emphasized. They can be defined as follows : (1) $k_{\mathrm{eff}}^2=(\frac{f_p^2-f_s^2}{f_p^2})$[7]; (2) $Q_s=\frac{f}{2}\left|\frac{\mathrm{d}\phi_{Z_{\mathrm{in}}}}{\mathrm{d}f}\right|_{f=f_s}$[6], where $\phi_{Z_{\mathrm{in}}}$ is the phase angle of input impedance; (3) $\mathrm{FOM}=Q_sC_1/2C_0=Q_s(f_p^2-f_s^2)/2f_s^2$.

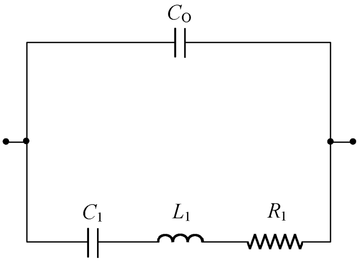

Fig. 2　BVD equivalent circuit of FBAR

2.3 Simulation procedure

The simulation procedure is as follows[8]:

(1) For a FBAR with fixed layer sizes and materials, calculate the input impedance spectrum, from which the series resonant frequency f_s, parallel resonant frequency f_p, and the phase angle $\phi_{Z_{\mathrm{in}}}$ of all modes can be calculated, and the distribution of k_{eff}^2 versus the mode orders can be obtained.

(2) The unique mode M with maximum $k_{\mathrm{eff}}^2(M)$ and its two resonant frequencies $f_s(M)$ and $f_p(M)$ can be obtained from the distribution.

(3) Q_s at the series resonant frequency and the FOM under the unique mode can be derived.

(4) The distribution of $k_{\mathrm{eff}}^2(M)$, Q_s, and FOM versus layer sizes can be studied by changing parameters of the electrodes, films and the substrates. In this paper, the effective thickness of substrate, that is the impedance ratio of substrate to that of film, is primarily studied.

3 Results and discussion

The input impedance responses of a four- layer FBAR consisting of AlN film sandwiched by two Al electrodes on a Si substrate are shown in Fig. 3, in which the thickness of each layer is 0.8 μm/1.9 μm/0.8 μm/100 μm. Fig. 4 shows the distribution of k_{eff}^2 with mode orders, which can be seen that the 40th mode has maximum k_{eff}^2,

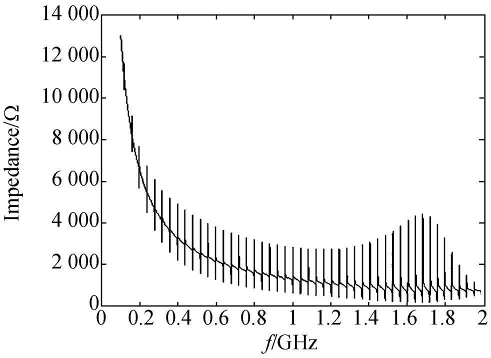

Fig. 3　Input impedance spectrum

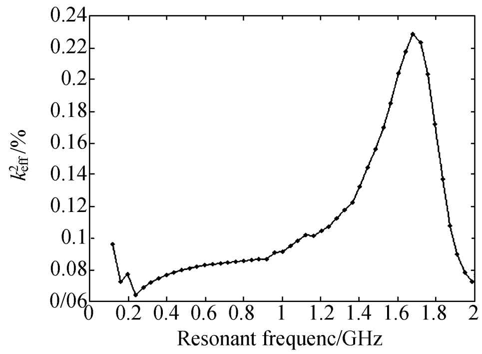

Fig. 4　k_{eff}^2 distribution of four-layer FBAR with a f_s of 1.680 0 GHz and a f_s of 1.681 9 GHz.

Fig. 5—7 are the simulation results of maximum k_{eff}^2 distribution with the different thicknesses of the piezo-films, electrodes, and substrates. It can be seen that the maximum k_{eff}^2 tends to raise when the film comes thicker, and a higher frequency can be gotten with a thinner film; the maximum k_{eff}^2 becomes smaller when the electrode comes thicker, and the operating frequency shows a periodically descend with electrode changes; when the film is deposited on a thicker substrate, maximum k_{eff}^2 comes smaller; and the operating frequency shows a disorder distribution.

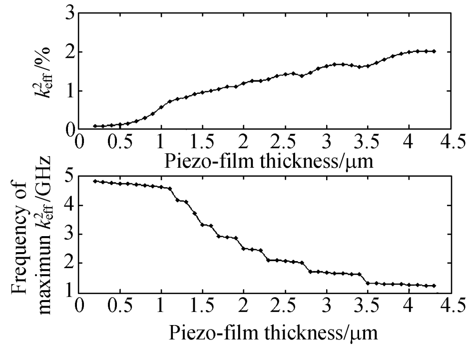

Fig. 5 Maximum k_{eff}^2 and operating frequency versus film thickness

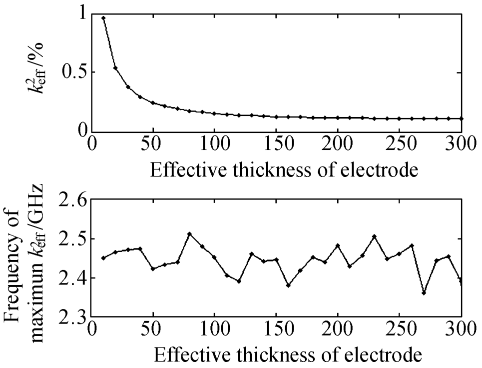

Fig. 6 Maximum k_{eff}^2 and operating frequency versus electrode thickness

Fig. 8—13 are the simulation results for the effective thickness of substrate and the thickness of electrode on the distribution of maximum k_{eff}^2, Q_s factor, and FOM. Three different kinds of

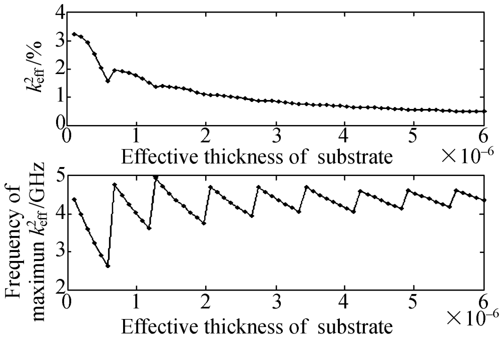

Fig. 7 Maximum k_{eff}^2 and operating frequency versus substrate effective thickness

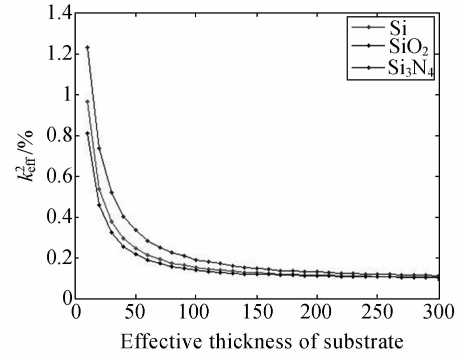

Fig. 8 Maximum k_{eff}^2 on different substrates

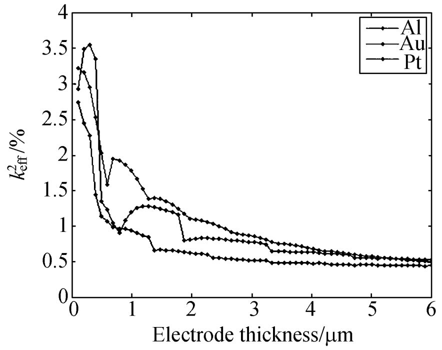

Fig. 9 Maximum k_{eff}^2 on different electrodes

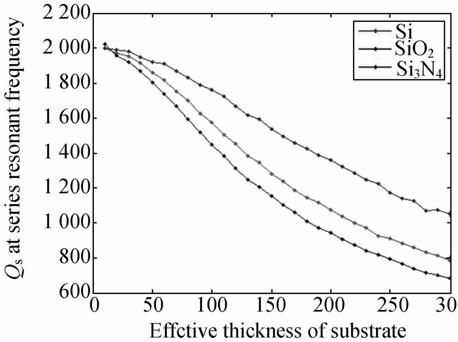

Fig. 10 Q_s distribution on different substrates substrate and electrode materials are used in the calculation. It can be seen that the three parameters drop smoothly with the increase of the substrate thickness, and decline vibrantly with the electrode coming thicker. And the performance parameters of a better FBAR deposited on a SiO_2 substrate with a larger acoustic impedance and sandwiched by a Pt electrode with a smaller acoustic impedance than other candidates[9] are gotten. The effect of electrodes on k_{eff}^2 and FOM seems more obvious than that of substrates, and the effect of the substrates on Q_s are greater than that of the electrodes.

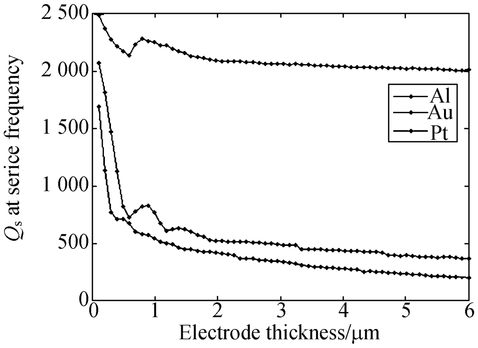

Fig. 11 Q_s distribution on different electrodes

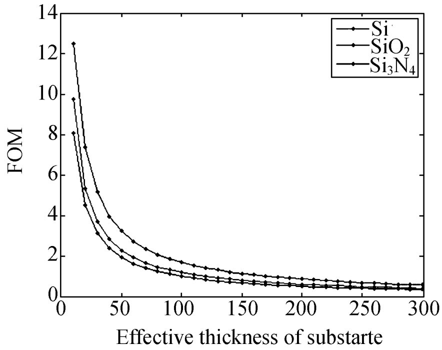

Fig. 12 FOM distribution for substrate sizes

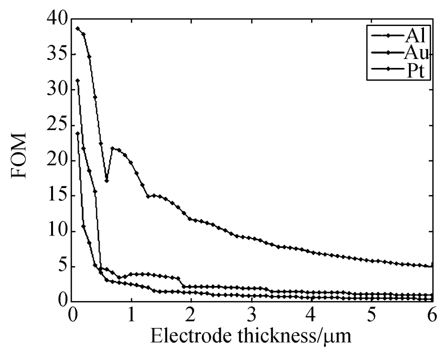

Fig. 13 FOM distribution on different electrodes

4 Conclusions

Based on the input impedance spectrum of a four-layer FBAR, a unique mode with maximum k_{eff}^2 can be chosen, and the performance parameters of the unique mode, such as the k_{eff}^2, Q_s, and FOM are discussed in the numerical simulation in detail. It can be found that they rely greatly on the property of each layer.

(1) When the film thickness comes thinner (from 0.2 μm to 4.3 μm in simulation), the unique mode shifts to a higher frequency (from 1.2 GHz to 4.8 GHz in simulation), which means that a higher operating frequency can be obtained, but the k_{eff}^2 tends to drop down.

(2) The k_{eff}^2, Q_s, and FOM of the unique mode decline when the substrate becomes thicker (k_{eff}^2 from 3.2% to 0.8%, Q_s from 2 000 to 700 in simulation), because some energy is absorbed by substrate. And a better parameter value can be obtained with a higher acoustic impedance.

(3) The k_{eff}^2 of the unique mode declines and tends to reach a stable value when the electrode becomes thicker, because its mass load effect can not be neglect when it comes thicker. Its thickness can be adjusted to get a higher or lower operating frequencies.

The simulation results above can give us a guideline in the design of a proper FBAR with the best operating performance, which is still to be confirmed in experiment.

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