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SAW Resonator with Grooves for High Temperature Sensing Application

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Abstract — **Wireless passive surface acoustic wave (SAW) resonator has great potential in high temperature sensing applications. Nevertheless, degradation of metal electrodes and decrease of Q factors with rising temperature restrict the temperature upper limit of SAW resonators. From a structural perspective, a SAW resonator structure with grooved electrodes for interdigital transducers and groove-only grating for reflectors is proposed to improve the resonator performance at high temperatures. Quasi-3D periodic FEM models of platinum /trapezoidal-groove/langasite(0°, 22°, 30°) are established and the simulation results show that the grooved electrode is beneficial for electroacoustic coupling factor and pressure sensitivity. In addition, the groove-only grating with no metal reduces the negative effect of high temperature on resonator performance. It has been also verified by coupling-of-model theory that the spurious modes caused by structural difference can be suppressed.**

Keywords—SAW resonator; high temperature sensing; grooved electrode; langasite; FEM analysis.

I. Introduction

Surface acoustic wave (SAW) resonator is promising in harsh environments due to the capability of sensing without using cables or additional energy sources[1]. Especially for high temperature sensing applications, SAW resonators can be preferred because they are capable of being fabricated on piezoelectric materials such as langasite (LGS, $La_3Ga_5SiO_{14}$), which can work as the substrate up to its melting point at 1470°C, without phase transition or chemical decomposition[2]. However, unfavorable phenomena restrict the temperature upper limit of SAW resonators, the main one of which is the degradation of thin film metal electrodes caused by dewetting and agglomeration at high temperatures. Taking platinum film as an example, despite the high melting point of platinum (1768.3°C), it will be degraded above 700°C on LGS[3]. The degradation makes metal electrode discontinuous and therefore leads to an increase of electrical resistivity or even a failure. On the other hand, although LGS is a suitable material for high temperature applications, its increasing SAW propagation loss at high temperatures might cause difficulty in fabricating high Q factor SAW resonators[4]. Therefore, enhancing the temperature stability of the metal electrode and reducing the SAW propagation loss of the resonators are necessary for reliable SAW sensors in high temperature applications.

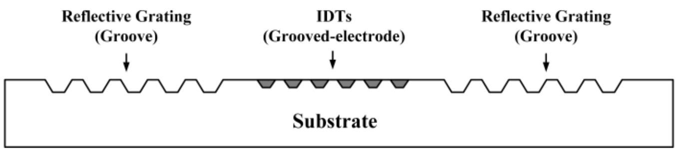
Research on high temperature SAW resonators has been developed for decades. A SAW resonator based on langasite with Platinum electrode has been fabricated and measured from room temperature up to 605°C, showing that Q factor of resonator decreases eminently with rising temperature[5]. The common methods for improving the resonator performance at high temperatures include: 1) using higher melting point metals as electrodes such as Iridium[6], 2) special design of the electrode. For example, composite metal materials and multilayer architecture have been applied to the electrodes of SAW resonators, which enable the resonators to survive for several hours above 1000°C[7,8]. It has been also reported that thicker electrodes are beneficial for temperature tolerance and Q factor of SAW resonators because of their better resistance to agglomeration and lower resistivity[9].

In this paper, a SAW resonator structure with grooved electrodes for interdigital transducers (IDTs) and groove-only grating for reflectors is proposed. Considering the available etching techniques of nanoscale grooves on LGS, quasi-3D periodic FEM models of Platinum/trapezoidal-groove/ LGS(0°,22°,30°) are established. The SAW propagation characteristics under the proposed structure, including the electromechanical coupling factor K^2, the reflection coefficient as well as the sensing sensitivity(pressure) are simulated and compared with those of the conventional structure. The results show that the grooved electrode brings about improvement of K^2 and pressure sensitivity, and the structurally optimized groove-only grating can provide a maximal and more reliable reflection coefficient. The admittance of finite length resonator is also considered to confirm the influence of structural difference between IDTs and reflection grating.

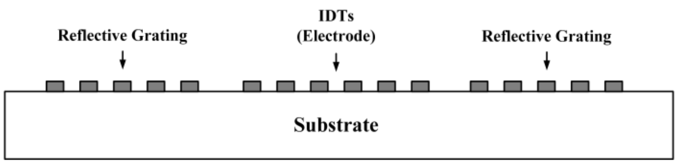
The remaining of paper is arranged as follows: In section II, the proposed resonator structure is analyzed qualitatively and modeled by finite element method. In section III, the relevant SAW propagation characteristics of the proposed structure are analyzed quantitatively according to the simulation results, and compared with the conventional structure. Then, optimized resonator parameters are given. Conclusions are summarized in section IV.

II. Structure and Methods

The schematic diagram of the proposed SAW resonator structure is shown in figure 1(a). As a comparison, figure 1(b) shows a conventional structure. In the proposed structure, the electrode discontinuity due to dewetting and agglomeration at high temperatures can be reduced. Since all metal electrodes are located in the grooves, the thicker metal electrode is possible and the dispersion of dewetted electrodes is confined to a small area. The electrode thickness is the same as the groove depth, because the electrodes are supposed to be protected by grooves but too deep grooves have proven to be not conducive to improving K^2 and pressure sensitivity. Furthermore, the reflection coefficient of IDTs is deceased by grooved electrode, thus the interference distortion of internal reflection on the acoustic standing wave field in IDTs is reduced[10,11]. For reflector grating, there is no metal so that no degradation exists, which leads to a more stable Q factor at high temperatures. Summary above, compared with the conventional structure, the negative effects of high temperature on grooved electrode and groove-only grating can be slighter.



(a) The proposed resonator structure.



(b) The conventional resonator structure.

Fig. 1. The schematic diagrams of two structures used in this work.

In order to analyze the propagation characteristics, quasi-3D periodic FEM models are established, in which the IDTs and reflection grating are separately modeled. Specifically, the FEM models for IDTs and reflector grating of the conventional structure are same, shown in figure 2(a). And figure 2(b) and 2(c) illustrate the models for IDTs and reflector grating of the proposed structure, respectively.

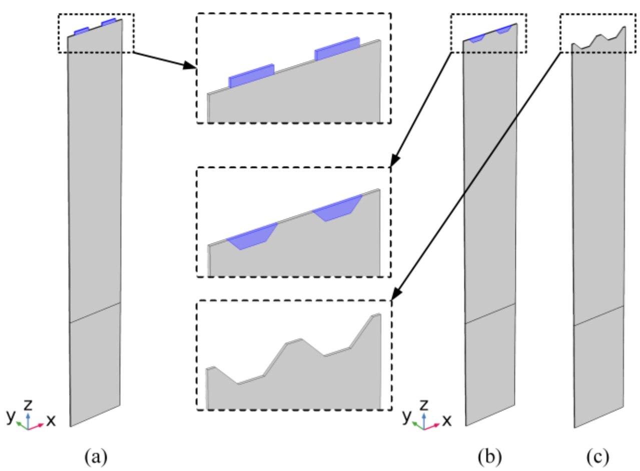


Fig. 2. Quasi-3D periodic FEM models: (a) IDTs and reflection grating of conventional structure; (b) IDTs of the proposed structure; (c) Reflection grating of the proposed structure.

All models in figure 2 are set as infinite periodic extension in both direction *x* and direction *y*. The bottom surface of each model is fixed and the lower layer is set as perfect match layer (PML) to eliminate the effects of reflection from the bottom surface. The platinum electrode is used in above models. And LGS (0°, 22°, 30°) is determined as the substrate, for this cut is resistant to heating[12] with high K^2 and pressure sensitivity simultaneously. The material constants are obtained from [13]. In addition, coupling-of-model (COM) theory is used to consider the admittance of finite length resonators for a more practical design.

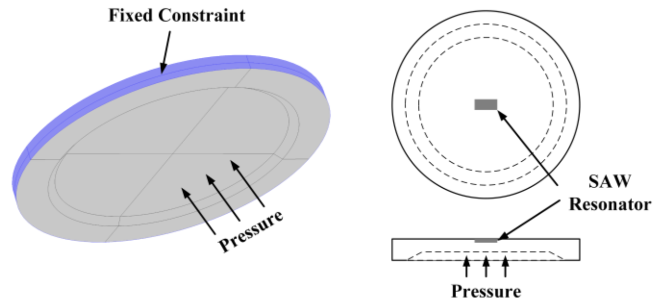


Fig. 3. Sensitive model for simulating pressure sensitivity.

Figure 3 shows the FEM model used to simulate and evaluate the influence of the grooved electrode on pressure sensitivity. The model is a thin disk with fixed periphery. The disk bottom is under pressure, which is thinned for a higher pressure sensitivity. SAW resonators are placed at the center of the upper surface. This sensitive structure makes the strain or stress transmitted to SAW resonators as large and uniform as possible.

III. Results and Discussion

Based on the above FEM models, K^2, reflection coefficient and pressure sensitivity are simulated and analyzed. The IDTs models are applied for simulation of K^2 and pressure sensitivity, while the reflector grating models are applied for reflection coefficient.

The relationship between K^2 and relative electrode thickness of both two structures are shown in figure 4. The K^2 of conventional structure reaches maximum 0.91% at relative electrode thickness 0.05, and the K^2 peak of grooved-electrode structure reaches 1.18% at relative electrode thickness 0.09. Larger K^2 leads to wider bandwidth. And for SAW sensing application, it is beneficial to a wider sensing range. Compared with conventional structure, the grooved electrode increases the K^2 maximum. The increase might result from the decreased IDT internal reflection and the larger area of piezoelectric excitation. More importantly, the maximum is at a thicker thickness, making it possible to improve temperature tolerance and sensing range at the same time.

The relationship between pressure sensitivity and relative electrode thickness are illustrated in figure 5, the results in which are obtained with the sensitive structure shown in figure 3. The pressure sensitivity at each relative electrode thickness is an average frequency shift from 0 bar to 10 bar, without considering nonlinearity. It shows that the pressure sensitivity of both structures decreases with increasing electrode thickness, but the grooved electrode slows down this reduction. From another aspect, the pressure sensitivity is increased by grooved electrodes, especially under thicker electrodes. For example, the pressure sensitivity of the grooved electrode is 40% higher than that of conventional structure at relative electrode thickness 0.07, which means a higher measurement accuracy.

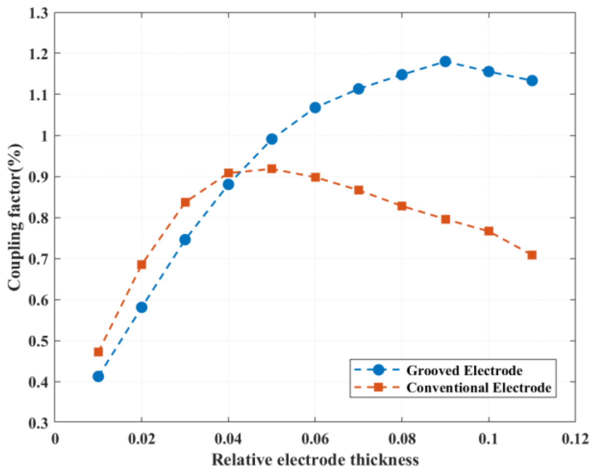


Fig. 4. Relation between K^2 and electrode thickness.

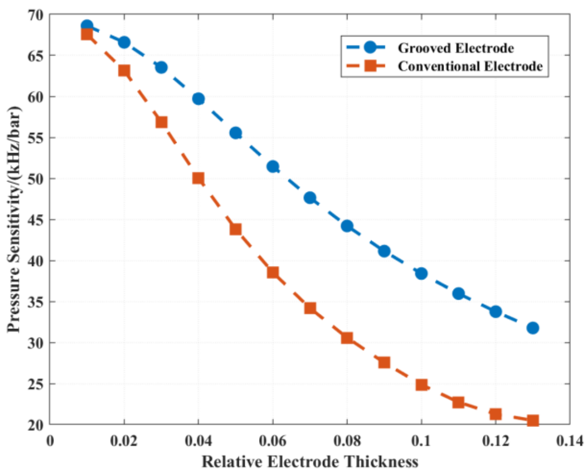


Fig. 5. Relation between pressure sensitivity and electrode thickness.

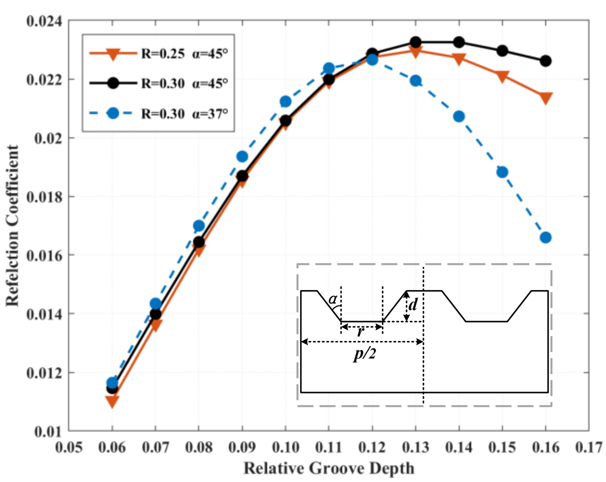
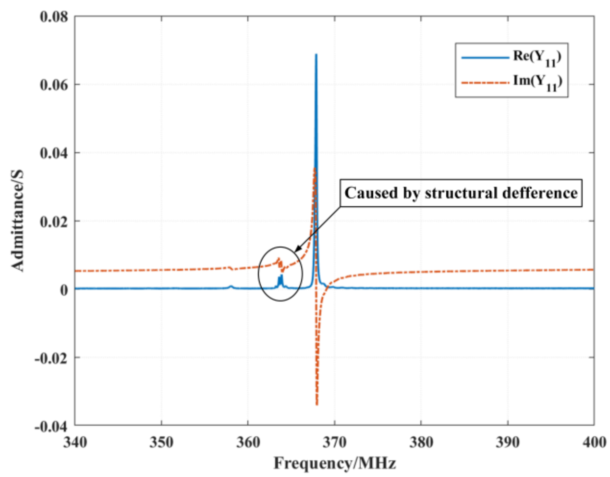


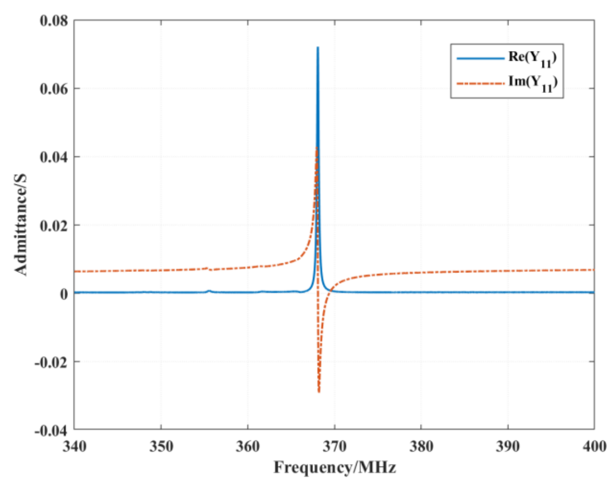
Fig. 6. Reflection coefficient with different groove structures.

Large reflection coefficient is important to high Q factor resonators. Although the reflection coefficient of conventional metal grating is larger than that of groove-only grating, the uncertainty of reflection coefficient due to metal degradation causes instability in resonator performance at high temperatures. In contrast, the high temperature performance of groove-only grating is more reliable. In order to improve the more reliable reflection coefficient as much as possible, the influence of groove structure on reflection coefficient has been studied. The structural variables taken into account include the inclination, relative depth and relative bottom width of groove.

Figure 6 shows the influence of groove structure on reflection coefficient, where p represents the period of grating, α and R represent the dip angle and the relative bottom width $2r/p$, respectively. The maximum reflection coefficient of the groove-only grating reaches 0.023 when the relative groove depth, the dip angle and the relative bottom width are 0.13, 45° and 0.30, respectively. In addition to improving the Q factor, large reflection coefficient is also conducive to reduce the number of reflectors. The propagation loss therefore will decrease due to the shorter propagation distance.



(a) Y_{11} of a resonator without special design.



(b) Y_{11} of the resonator with the optimized parameters.

Fig. 7. Admittance of finite length SAW resonators with the proposed structure.

To verify the admittance of the proposed asynchronous SAW resonator in finite length condition, COM theory is applied to the simulation of Y_{11}. Due to the structural difference between the IDTs and reflection grating, the influence of the spurious modes near the resonance frequency, shown in figure 7(a), are more obvious. Therefore, careful design of resonator structure for spurious mode suppression is necessary. The figure 7(b) shows the simulation result with a group of optimized resonator parameters as following. The periods of IDTs and grating are 6 μm and 6.54 μm, respectively. The IDTs has 80 grooved electrodes of 420 nm thickness while each reflection grating has 300 grooves of 850 nm depth. And the dip angle and relative bottom width of all grooves in IDTs and grating are 45° and 0.30, respectively. It demonstrates the spurious modes caused by structural difference are suppressed. Additionally, if more than one resonance peaks exist, it has been proven that adjustment of groove depth and electrode thickness is able to change the amplitudes of resonance peaks, which is useful to suppress or enhance certain resonance modes.

Although the proposed SAW resonator structure is expected to perform better at high temperatures, it might be difficult to manufacture. The main challenge is that the etching process on LGS can hardly meet the groove design requirements, whether using wet etching or dry etching. In addition, depositing metal film electrodes in grooves also requires high process precision. Fortunately, these problems are hopeful to be solved because of the mature etching process on quartz and the structural similarity between quartz and LGS.

IV. Conclusion

This work proposes a SAW resonator structure with grooved IDTs and groove reflection grating on LGS, aiming to reduce the negative effects of high temperature. The simulation based on quasi-3D periodic FEM models demonstrates that the grooved electrode contributes to higher K^2 and pressure sensitivity under thick electrodes. Despite the decreased reflection of groove-only grating, a reflection coefficient of 0.23 is obtained by structural adjustment and the Q factor of SAW resonators can be more stable at high temperatures. The simulation based on COM theory demonstrates that the spurious modes caused by structural difference between IDTs and reflectors can be suppressed by special design. In general, the proposed resonator structure achieves an excellent balance between high temperature tolerance and resonator performance, which is beneficial to the practicality of SAW resonators in high temperature sensing applications.

Acknowledgment

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