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Design of Film Bulk Acoustic Wave Sensor for Internet of Things (IoT) Applications

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Abstract

The Internet of Things (IoT) is expanding quickly, which has increased demand for innovative sensing technologies that can provide real-time data for various applications. Film Bulk Acoustic Wave Resonators (FBARs) are miniature resonators that utilize the piezoelectric effect to create electrical signals using mechanical vibrations and vice versa. FBAR resonators have emerged as promising candidates for sensor applications in IoT due to their compact size, high sensitivity, and compatibility with microfabrication techniques. This paper presents design of FBAR sensor as gas and pressure sensor for IOT applications consisting of zinc oxide (ZnO) and Lithium niobate (LiNbO3) as piezoelectric film and Aluminum (Al) as top and bottom electrodes. The results show the superior performance of the proposed resonator. Based on the modeling results, the structure's resonance frequency is 12.02 and 10.36 GHz with a quality factor of 936.7 and 941.3 and an effective coupling coefficient of 18.35 and 18.27 % for ZnO and LiNbO3 respectively.

Keywords: FBAR, ZnO, LiNbO3, Al, IOT.

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Introduction

IoT is rapidly expanding with a wide variety of smart devices being developed to make our lives easier. These devices require sensors that are integrated into them to collect data. One such sensor is FBAR, which has been found to be an efficient and reliable sensing mechanism for a wide range of applications in IoT. FBAR technology is based on the piezoelectric effect, where a material generates an electric charge when subjected to mechanical stress. In an FBAR, a thin piezoelectric film is sandwiched between two metal electrodes, and an acoustic wave is generated in the film when an alternating electric field is applied to the electrodes. This acoustic wave can be used to detect changes in the environment, such as temperature, humidity, and pressure. FBARs are perfect for usage in IoT devices since they are lightweight, compact, and require very little power. [1, 2]

The piezoelectric stack structure that makes up the bulk acoustic wave (BAW) resonator consists of a piezoelectric sheet sandwiched between two metallic electrodes. The region where the upper and lower electrodes, the piezoelectric layer, and all three overlap in the thickness direction is known as the active area of the resonator. The active area needs to be entirely cut off from the substrate for the BAW resonator to work; otherwise, the piezoelectric film's generated acoustic waves will radiate into the substrate, preventing standing waves and, consequently, resonance. BAW resonators come in two different technology varieties. FBAR which is shown in Fig. 1a, is the first form and it is an air-cavity resonator. As shown in Fig. 1b, the other form of resonator is known as a solidly mounted resonator (SMR), and it is made by isolating the resonator from the substrate using an acoustic Bragg reflector[3, 4, 5]. The air-gap type FBAR was chosen over SMR because of its easier fabrication procedure. Due to its numerous advantages over competing devices, including their high sensitivity, simplicity of use, compact size, and low cost. FBARs are becoming more and more popular for a variety of applications. [6, 7]

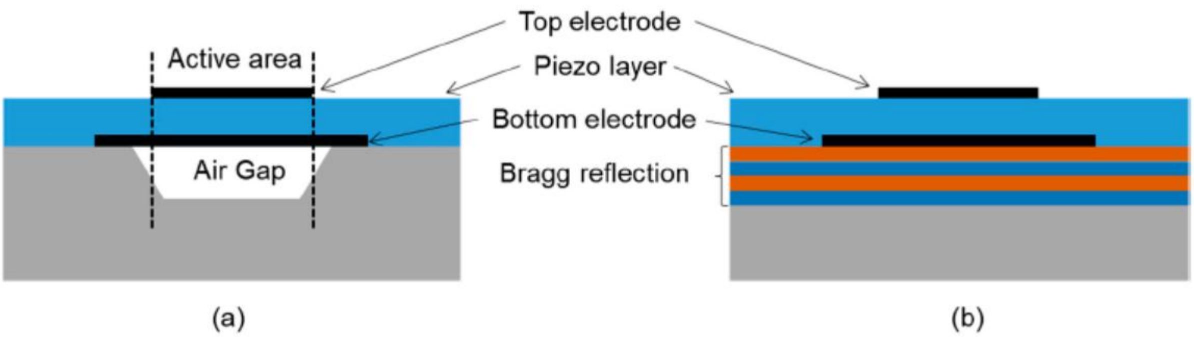


Fig.1 composition of (a) FBAR (b) SMR

IoT has many uses for the FBAR. There are many benefits to using FBAR resonators in IoT devices, including their high sensitivity, low power requirements, and small size. The demand for compact, low-power, and extremely sensitive sensors is anticipated to expand in the future, which will lead to an increase in the use of FBAR resonators in IoT devices. FBAR sensors offer several advantages over traditional sensors, such as low power consumption, high sensitivity, and small size. Additionally, FBAR sensors can be integrated with wireless communication technologies such as Bluetooth and Wi-Fi to enable real-time data transmission and remote monitoring. [8]

FBAR Design

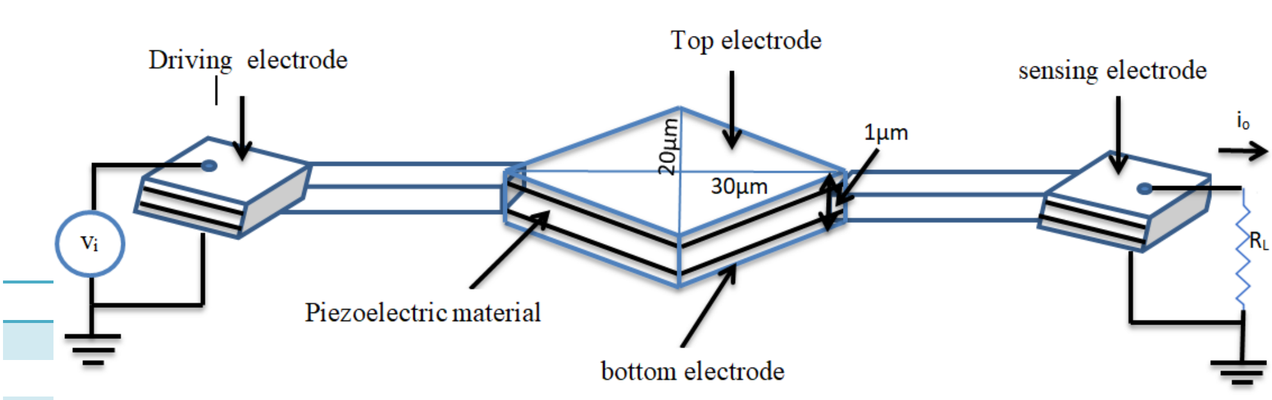
The effectiveness of the piezoelectric thin films is crucial to FBARs. Several requirements have been requested for the piezoelectric films to be used in FBARs in order to build a high-quality FBAR: High electromechanical coupling coefficient, good piezoelectric properties, highly ordered microstructures, simple production, and low cost are all desirable. [9]

In an IoT system, FBARs can be used to monitor various parameters such as temperature, pressure, humidity, and vibration. Since the FBAR is used as sensor, we will choose materials that can sense and has piezoelectric characteristics. In this paper, two materials will be used to sense dangerous gases and pressure. One example of a material that can sense dangerous gases and has piezoelectric characteristics is zinc oxide. zinc oxide has the ability to detect various gases, such as carbon monoxide and methane, and is often used in gas sensors[10]. Additionally, when it is subjected to mechanical stress, it exhibits piezoelectric properties, generating an electric charge. This makes it ideal for use in sensors and transducers, where it can detect the presence of gases and then convert the resulting signal into an electrical output. The second material that has the piezoelectric characteristics and can sense pressure is the Lithium niobate ($LiNbO_3$). $LiNbO_3$ is a high-performance piezoelectric material that can be used in acoustic and pressure sensors.[11, 12]

The choice of materials for the electrodes is essential since electrodes are required for the manufacturing of FBARs yet the performance of the FBAR is substantially impacted by the properties of the electrode materials. For high performance FBARs, materials having a high acoustic impedance mismatch with the piezoelectric thin film or substrate, a low mass density, and a high elastic modulus are necessary. Aluminum is used in this paper as electrode because it is an excellent conductor and is widely accessible. Aluminum exhibits a greater resonance frequency and has a much higher acoustic velocity than other electrodes. [13]

The geometry of the proposed FBAR is shown in Figure 2 and its dimension is shown in table1

Table 1: Dimensions of Proposed FBAR



Bottom electrode	Al	0.1

Fig.2 The Proposed FBAR Resonator

Butterworth-Van-Dyke (BVD) modeling is the equivalent circuit model for the FBAR resonator. The motional and static capacitance arms are two parallel branches that make up this structure. The series motional inductance Lm, capacitance Cm, and resistance Rm make up the motional arm. The parallel-plate capacitance Co created between the top and bottom

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electrodes of FBAR forms the static branch. the equivalent circuit model BVD of the proposed resonator is shown in fig.3.[14, 15, 16]

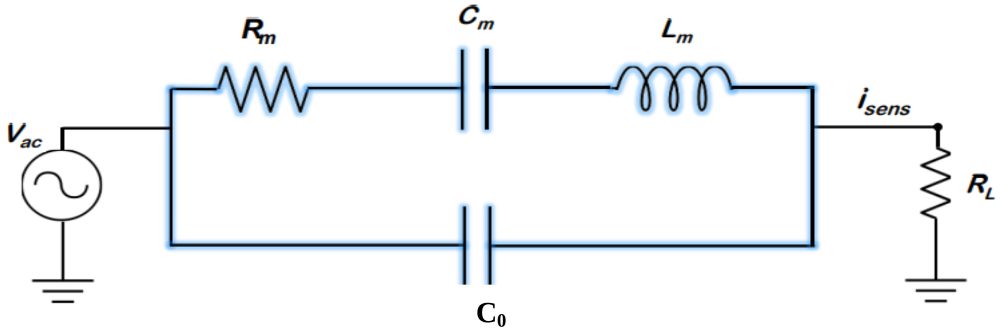

Fig.3 Equivalent Circuit of FBAR

This equivalent circuit resonates for two particular frequencies:[17]

$$f_s = \frac{1}{2\pi\sqrt{L_m C_m}} \tag{1}$$

$$f_p = \frac{1}{2\pi\sqrt{L_m \frac{C_m C_0}{C_m + C_0}}} \tag{2}$$

where f_s and f_p are known as the resonance and anti-resonance frequencies respectively.

The sensitivity of the FBAR depends on its resonance frequency when the resonance frequency increases the sensitivity also increases depending on the following equations:[18]

$$S = \frac{2 f_s^2}{\rho\, V_a} \tag{3}$$

Where ρ is the density and V_a is the acoustic velocity of the FBAR resonator.

The ability of a device in converting electrical energy into mechanical energy and back again is indicated by the effective electromechanical coupling coefficient The expression for K^2_{eff} is as below: [19, 20, 21]

$$K_{eff}^2 = \frac{\pi^2}{4} \frac{f_s}{f_p} \left[\frac{f_p - f_s}{f_p}\right] \tag{4}$$

The quality factor (Q) is the most crucial FBAR resonator parameter. Qs and Qp stand for the quality factors of series and parallel resonances, respectively. A resonator's capacity for precision and frequency stability increase with increasing Q. The proportion of stored to dissipated energy is known as a resonator's quality factor Q. It is an arbitrary integer that describes the resonator's quality.[22]

$$Q_s = \frac{2\pi f_s L_m}{R_m} \tag{5}$$

$$Q_p = \frac{1}{2\pi f_p C_0} \tag{6}$$

The parallel-plate capacitance Co, Cm, Rm and Lm are calculated by the design equations given below:[23, 24]

$$C_\circ = \frac{\varepsilon A}{t} \quad (7)$$

$$C_m = \frac{C_\circ 8 k_t^2}{(\pi)^2} \quad (8)$$

$$R_m = \frac{\eta}{C_m c_{33}} \quad (9)$$

$$L_m = \frac{1}{C_m w_s^2} \quad (10)$$

where ε is the permittivity of the piezoelectric material, A is the area of the resonator, t is the thickness of the piezoelectric layer, c_{33} is the Elastic modulus, η is the Damping loss factor and K_t^2 is the Effective coupling coefficient respectively.

Simulation Results

The simulation system which is utilized to design the resonance frequency, quality factor, effective electromechanical coupling coefficient (k_{eff}^2), figure of merit and MEMS-FBAR parameters such as (C0, Cm, Lm and Rm) has been designed and implemented to obtain these values from the FBAR properties parameters. In order to implement the proposed resonator the system shown in fig.4 is implemented in MatLab2021b Simulink and it consists of three key subsystems.

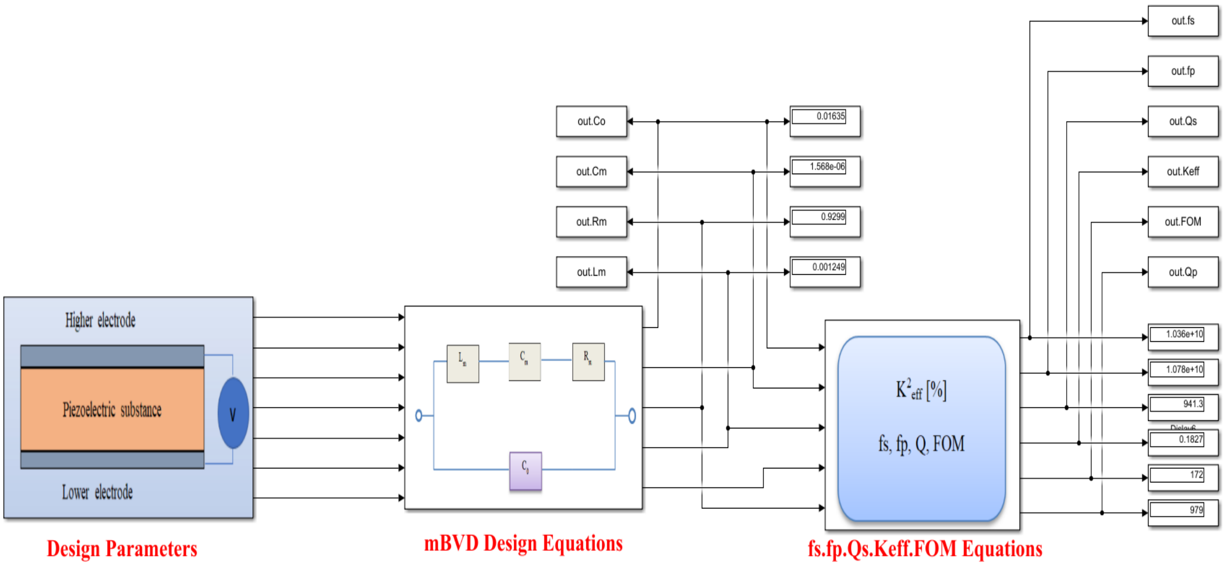

Fig. 4: Demonstration of the FBAR Design Lab Simulink

The first subsystem is the design parameters in which the characteristics of the proposed resonator is defined which is the area of the resonator, the thickness of the piezoelectric layer, the acoustic velocity, Piezoelectric constant (e_{33}), Elastic modulus(c_{33}), Relative permittivity and Damping loss factor(η). The characteristics of the top and bottom electrode and the piezoelectric layer are shown in table 2 and 3.

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Table 2 Characteristics of Al Material[25]

Properties of Al material	Aluminum (Al)	unit
Density	2700	kg/m^3
Thermal conductivity	237	W/(m·K)
Young's modulus	70	GPa
Poisson's ratio	0.35	1
Resistivity (ρ)	2.65×10^{-8}	ohm m
Acoustic velocity	6300	m/s

Table3 Characteristics of LiNbo3 and ZnO Piezoelectric Material[26, 27]

Properties	LiNbo3	ZnO	Unit
Piezoelectric constant (e_{33})	**1.33**	**1.32**	**c/m^2**
Acoustic velocity (v_a)	**3980**	**6630**	**m/s**
Elastic modulus(c_{33})	**203**	**211**	**Gpa**
Relative permittivity($\in_r$)	**43.6**	**8.54**	**epsilon**
density	**4700**	**5680**	**Kg/m^3**
Poisson ratio	**0.25**	**0.36**	**-**
Damping loss factor	**0.0005**	**0.001**	**Kg/Sm**
Effective coupling coefficient K_t^2	**20**	**9**	**%**

The second subsystem is a MATLAB function and it is used to calculate the parameters of the electrical equivalent circuit of FBAR resonator which is Cm, Lm, Rm, C0 depending on their equations. The third subsystem is also a MATLAB function and is used to calculate the frequencies, the quality factors and the effective electromechanical coupling depending on the value of the output parameters in the second subsystem.

The results of the MATLAB Simulink is shown in table 4 which is the resonance frequency, quality factor, effective electromechanical coupling when ZnO and LiNbo3 are used as piezoelectric layer and Al as top and bottom electrode.

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Table4 The specifications for FBAR resonators using ZnO and LiNbo3 piezoelectric layers and Al as top and bottom electrodes

Parameters	ZnO	LiNbo3	Unit
f_s	12.02	10.36	GHz
f_b	12.5	10.78	GHz
Q_s	936.7	941.3	-
Q_p	974.4	979	-
K^2_{eff}	18.35	18.27	%
C_0	0.003202	0.01635	F
C_m	1.509e-6	1.568e-6	F
L_m	0.001182	0.001249	H
R_m	1.888	0.9299	Ω

Finally, Table 5 compares the results of proposed FBAR resonator parameters with the results of previous published papers. From the comparison above, it is plain to see that the designed FBAR performs better, making it a suitable choice for next sensing applications.

Table 5 Performance Comparison of Proposed Resonator with Previous Resonators

Ref.	Year of publication	piezoelectric material	f_r	$k^2_{eff}[\%]$	Q	Sensor function
[28]	2018	ZnO	1.75 GHz	4.154	59.8	Sense gases
[29]	2019	ZnO	239 MHz	-	1300	Sense gases
[30]	2020	ZnO	1.39 GHz	8.6	923	Sense gases
[31]	2020	LiNbo3	5 GHz	-	300	Sense pressure
[32]	2021	ZnO	1.7432 GHz	8.92	28.61	Sense gases
[33]	2022	ZnO	2400 MHz	-	900	Sense gases
This paper	2023	ZnO	12.02 GHz	18.35	936.7	Sense gases
		LiNbo3	10.36 GHz	18.27	941.3	Sense pressure

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Conclusions

The frequency, quality factor, coupling coefficient, and BVD parameter for the piezoelectric layers ZnO and LiNbo3 as well as the top and bottom electrodes of Al have been constructed and simulated for the film bulk acoustic wave resonator (FBAR). The proposed FBAR resonator is designed to be used as sensor in IOT applications. ZnO and LiNbo3 have the ability to sense dangerous gases and pressure in addition to have piezoelectric characteristics therefore it is good choice for using in design FBAR sensor. The choice of electrodes are also important for the design of FBAR because the performance of the FBAR is impacted by the characteristics of the electrode materials. Aluminum is used in this paper as top and bottom electrode because It is a powerful conductor and it is readily available.

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تصميم حساس بالموجات الصوتية الحجمية الرقيقة لتطبيقات إنترنت الأشياء

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الخلاصة

التوسع السريع لإنترنت الاشياء أدى إلى زيادة الطلب على تقنيات الاستشعار المبتكرة التي يمكن أن توفر بيانات في الوقت الفعلي لمختلف التطبيقات. رنانات الموجات الصوتية ذات الاغشية الرقيقة (FBARs) هي رنانات مصغرة تستخدم التأثير الكهرو إجهادي لإنشاء إشارات كهربائية باستخدام الاهتزازات الميكانيكية والعكس صحيح. ظهرت رنانات FBAR كمتحسسات واعدة لتطبيقات الاستشعار في إنترنت الأشياء نظرًا لحجمها الصغير وحساسيتها العالية وتوافقها مع تقنيات التصنيع الدقيق. يقدم هذا البحث تصميم مستشعر FBAR لتطبيقات انترنت الاشياء التي تتكون من أكسيد الزنك (ZnO) و ليثيوم نيوباتيت (LiNbO3) كمواد كهروضغطية والالمنيوم كأقطاب كهربائية علوية وسفلية. تظهر النتائج الأداء المتفوق للرنان المقترح. بناءً على نتائج النمذجة ، فإن تردد الرنين هو ١٢.٠٢ و ١٠.٣٦ جيجاهرتز مع عامل جودة ٩٣٦.٧ و ٩٤١.٣ ومعامل الاقتران الفعال ١٨.٣٥ و ١٨.٢٧٪ لـــ أكسيد الزنك و ليثيوم نيوباتيت على التوالي.

الكلمات الدالة: أكسيد الزنك, ليثيوم نيوباتيت, الالمنيوم, انترنت الاشياء. ,جهاز الرنين الصوتي الحجمي ذو الأغشية الرقيقة.