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ZnO based film bulk acoustic resonator as infrared sensor

Ziyu Wang [a,b,c,1], Xiaotun Qiu [d,1], Shih Jui Chen [e], Wei Pang [f], Hao Zhang [f], Jing Shi [a,c], Hongyu Yu [b,d,*]

[a] School of Physics, Wuhan University, Wuhan, 430072, PR China
[b] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA
[c] Key Laboratory of Acoustic and Photonic materials and devices of Ministry of Education, Wuhan University, Wuhan, 430072, PR China
[d] School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287, USA
[e] Department of Electrical Engineering-Electrophysics, University of Southern California, Los Angeles, CA 90089, USA
[f] College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin, 300072, PR China

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ABSTRACT

This paper reported the investigation of an infrared (IR) sensitive, ZnO based Film Bulk Acoustic Resonator (FBAR). The resonant frequency of the FBAR decreased under IR illumination, and results demonstrated a linear dependence on IR intensity. The sensing mechanism is attributed to the temperature-dependent Young's modulus of the resonator material (ZnO), which subsequently shifts the resonant frequency. Thickness Field Excitation FBAR and Lateral Field Excitation (LFE) FBAR were fabricated and characterized with detection limits of 0.7 μW/mm^2 and 2 μW/mm^2, respectively, but the LFE FBAR exhibited higher IR sensitivity.

1. Introduction

Detection of infrared (IR) radiation is important in a wide range of scientific fields, including medicine, astrophysics, fire science and meteorology. There are two types of IR detectors currently available: photon detectors and thermal detectors. Traditionally, photon detectors are preferred for superior sensitivity. However, recent advances in micromachining techniques have made it possible to fabricate highly sensitive thermal IR detectors [1]. In fact, IR sensing technology that uses thermal detectors operating at room temperature now offers several advantages over conventional photon detectors, including reduced system costs, improved reliability, and instant operational possibilities.

The most common micromachined thermal detectors are microbolometers based on a resistive read-out principle [2]. While such sensors can reach high sensitivities in the infrared spectrum, they have drawbacks related to the nature of resistive sensing. For this reason, other options have been sought.

This study focused on a micro-bolometer based on a resonant read-out principle. The resonant frequency change output of this device offers several advantages over the usual resistance change output. First, a frequency read-out with resonators draws less power than a resistive read-out because no constant read-out current is needed. Second, the heat increase of the absorbing mass is detected directly in the resonator design, as opposed to resistive bolometers whose resistance change is primarily determined by the temperature increase of the IR absorber [2]. Third, potentially higher sensitivity can be achieved because frequency shifts can be measured with high accuracy. Recently, resonant IR sensors have been implemented by bulk micromachining quartz (detection limit of 0.37 μW/mm^2) [3] or silicon–germanium (SiGe) [4] as the sensing material.

Film bulk acoustic resonator (FBAR) is a kind of microwave acoustic device composed of a piezoelectric thin film (AlN or ZnO) and several electrodes; together they form a resonant structure. A resonance condition occurs if the thickness of the piezoelectric thin film (d) is equal to an integer multiple of half of the acoustic wavelength (λ). In recent years, FBAR has been developed both as filters [5] and as high-sensitivity mass, ultraviolet and humidity sensors [6–9].

Conventional FBAR uses thickness field excitation (TFE) to excite an acoustic wave in the resonator; this is called TFE FBAR (Fig. 1(a)). Reducing the thickness of the piezoelectric film enables the device to achieve a higher resonant frequency; as it does, the electrode layers constitute a greater portion of the resonator. By contrast, lateral field excitation (LFE) FBAR (Fig. 1(b)) does not have an electrode in the major acoustic path. For sensing applications, removing the electrode from the acoustic path means that sensing target can be directly in touch with the active region, which should increase the sensor's sensitivity.

* Corresponding author at: School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA. Tel.: +1 4807277454; fax: +1 4809650616.
E-mail address: hongyuyu@asu.edu (H. Yu).
[1] The first two authors contribute equally in this work.

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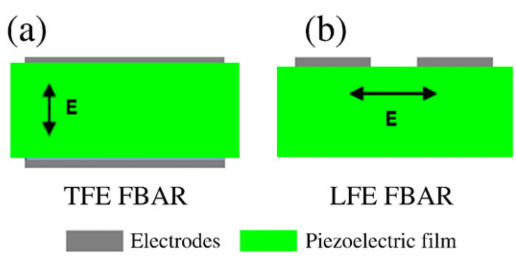

Fig. 1. The schematic structure of the film bulk acoustic resonator (FBAR): (a) thickness field excitation (TFE) FBAR; and (b) lateral field excitation (LFE) FBAR (the arrows in the drawing indicate the direction of the electrical filed inside the piezoelectric thin film).

This paper presented an investigation of differences in the IR sensitivity for the TFE and LFE FBAR. We tested an IR sensing device that used both TFE and LFE ZnO film based FBAR. The design, fabrication and characterization of the FBAR sensor were described, and the mechanism for FBAR frequency response to IR was discussed.

2. Theory

The principle for using a resonator to detect IR radiation is grounded in that the Young's modulus of the resonator material depends on temperature [4]. Power from an IR source is absorbed by the resonating element and subsequently converted to heat, leading to a temperature increase that further changes the Young's modulus. For a resonator operating in bulk mode, a change in the Young's modulus generally translates into a shift of the resonant frequency.

The resonant frequency of the FBAR can be determined from the following two equations:

$$v = \sqrt{\frac{E}{\rho}} \tag{1}$$

$$f = \frac{v}{2d} \tag{2}$$

where E, ρ and d are the Young's modulus, density and thickness of the ZnO film, respectively. The variable v represents the acoustic velocity within the ZnO film and f is the resonant frequency of the FBAR. As temperature increases with the absorption of IR, the Young's modulus decreases due to material softening. Although the mass density also decreases with temperature, the acoustic velocity decreases as temperature increases, owing to the dominant effect of the Young's modulus, which results in a drop in resonant frequency.

The dependence of the material properties on temperature can be characterized as follows. We adopted a linear variation of the Young's modulus (E), thickness (d), and density (ρ) according to Eqs. (3), (4), and (6), respectively; Eq. (5) links the density to thermal expansion.

$$E = E_o(1 + \alpha\Delta T). \tag{3}$$

$$d = d_o(1 + \beta\Delta T). \tag{4}$$

$$d\rho / dT = -3\beta\rho_o. \tag{5}$$

$$\rho = \rho_o(1 - 3\beta\Delta T). \tag{6}$$

The temperature difference, the temperature coefficient of Young's modulus, and the thermal expansion coefficient are defined as ΔT, α and β, respectively.

Taking Eqs. (3), (4), and (6) into Eqs. (1) and (2), we have

$$v = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{E_o(1 + \alpha\Delta T)}{\rho_o(1 - 3\beta\Delta T)}} = v_o\sqrt{\frac{1 + \alpha\Delta T}{1 - 3\beta\Delta T}} \tag{7}$$

$$f = \frac{v}{2d} = \frac{v_o}{2d_o}\frac{\sqrt{(1 + \alpha\Delta T)/(1 - 3\beta\Delta T)}}{1 + \beta\Delta T}. \tag{8}$$

For ZnO [10,11], we use

$$\alpha = -99.7 \times 10^{-6}/K$$
$$\beta = 3.53 \times 10^{-6}/K.$$

Thus, we have

$$f \approx \frac{v_o}{2d_o}\sqrt{1 + \alpha\Delta T} \quad (|\alpha| \gg |\beta|). \tag{9}$$

The frequency shift Δf is

$$\Delta f = f_o - f = f_o\left(1 - \sqrt{1 + \alpha\Delta T}\right) \approx -\frac{1}{2}f_o\alpha\Delta T. \tag{10}$$

Eq. (10) shows that the resonant frequency shifts linearly with the temperature. The coefficient ($\alpha/2$) is generally defined as the temperature coefficient of resonant frequency (TCF) of the resonator [12].

The IR power W received by the FBAR when thermal balance is achieved can be expressed as

$$W = C\frac{dT}{dt} + G\Delta T. \tag{11}$$

In the above equation, C is thermal capacitance and G is thermal conductance. At steady state,

$$W = G\Delta T. \tag{12}$$

Thus, W is proportional to ΔT. Since IR intensity I is proportional to W, I is proportional to ΔT and Δf. Thus, a linear relationship can be expected between IR intensity and the resonant frequency of the FBAR.

3. Results and discussion

3.1. TFE FBAR IR sensor

The schematic structure of the TFE FBAR IR sensor is shown in Fig. 2. The device was fabricated on top of a SiN (0.6 μm) diaphragm. A sputtered ZnO film (1.2 μm) was used as both the IR sensitive layer and the piezoelectric actuation layer for the FBAR sensor. The top and bottom electrodes were both made of Al (0.2 μm). The fabrication process of the FBAR was as follows. First, a SiN layer was deposited on

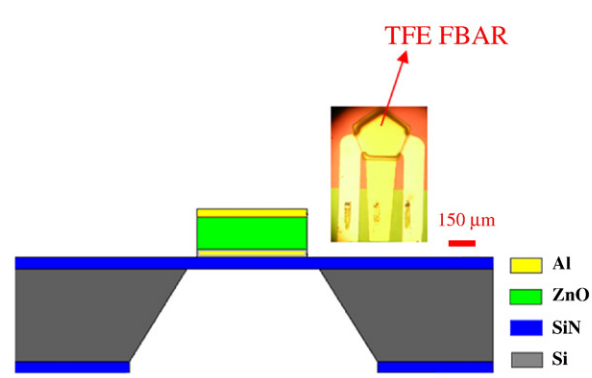

Fig. 2. Schematic cross-section view of the TFE FBAR with a photograph of the top view of a fabricated device.

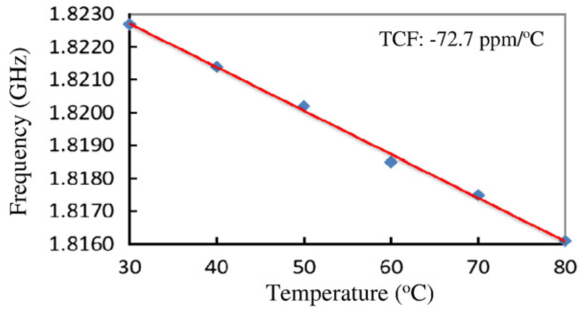

Fig. 3. The frequency response of the TFE FBAR to temperature.

a Si wafer (100) with low-pressure chemical vapor deposition. Then the Si wafer was etched anisotropically from the backside by potassium hydroxide (KOH) to form the cavity. Next, the bottom Al electrode was deposited by electron-beam (e-beam) evaporation and patterned on top of the SiN film using wet etching. ZnO was radio-frequency sputtered and etched to form the desired pattern. The last step was e-beam deposition and patterning of the top Al electrode by lift-off.

IR radiation was generated by a halogen lamp (peak wavelength at 750 nm). The intensity of IR received by the detector was calibrated using an IR power meter (Thorlabs, Newton, NJ). The temperature stabilization time was 2 min. An HCC214S hot chuck system (INSTEC, Boulder, CO) was employed to adjust the temperature of the FBAR for TCF measurement. The resonant frequency was measured by setting a marker in the network analyzer (Agilent E5071C, Agilent, Santa Clara, CA) to the point where the imaginary part of the impedance was zero. A LabVIEW program (National Instruments, Austin, TX) was employed to track the position of the zero point and record the corresponding frequency (the sampling rate was 1 s). For each measurement, around 10 points were recorded. From these data, the noise floor can be obtained and by averaging the data, the resonant frequency in each case can be calculated.

The TFE FBAR had a noise floor of 1.1 ppm at 1.8 GHz, which was suitable for integration with a wireless sensor network. The quality factor (Q) of the FBAR was about 150. Fig. 3 illustrates the frequency response of the TFE FBAR to temperature. In agreement with Eq. (10), a linear relationship was obtained with a measured TCF of −72.7 ppm/°C. The resonant frequency response to different IR intensities is shown in Fig. 4. As discussed in Section 2, a linear relationship was observed. The detection limit was 0.7 μW/mm^2.

3.2. LFE FBAR IR sensor

The schematic structure of the LFE FBAR IR sensor is shown in Fig. 5. Like the TFE FBAR, this device was also fabricated on top of a SiN (0.6 μm) diaphragm with a sputtered ZnO film (1.2 μm) used as both the IR sensitive layer and the piezoelectric actuation layer. The top

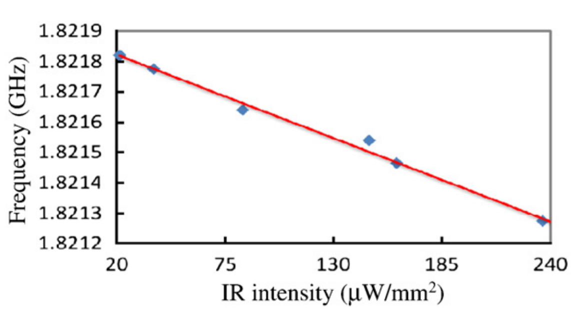

Fig. 4. The relationship between the resonant frequency and IR intensity for the TFE FBAR. A linear relationship was observed with a detection limit of 0.7 μW/mm^2.

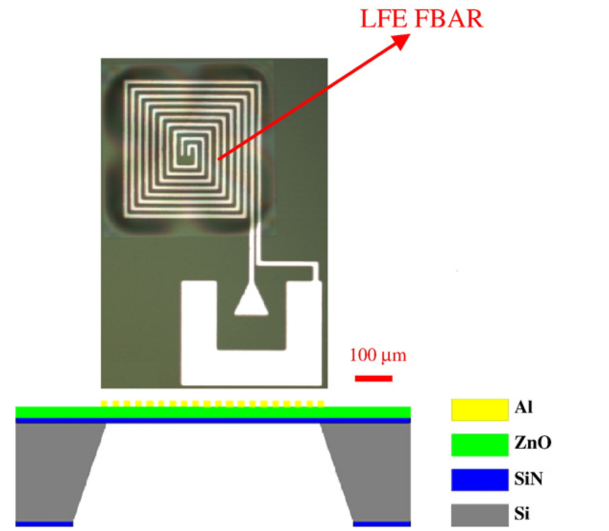

Fig. 5. Schematic cross-section view of the LFE FBAR with a photograph of the top view of a fabricated device.

electrode was made of Al (0.2 μm). The fabrication process was almost identical to the one described in Section 3.1, except for the lack of a bottom electrode and ZnO patterning steps. The measured resonant frequency of the LFE FBAR was around 860 MHz, with a noise floor of 29 ppm. The large noise floor was due to the small Q of the LFE FBAR (around 50). The poor quality factor may be a result of weak interaction between the electrical field and the piezoelectric material from the current electrode design [13,14]. Additional efforts to optimize the electrodes are underway to improve the performance of the FBAR.

Fig. 6 illustrates the relationship between the resonant frequency and IR intensity for the LFE FBAR. These results demonstrated a linear relationship with a detection limit of 2 μW/mm^2. The TCF of the LFE FBAR is shown in Fig. 7 (−37.4 ppm/°C).

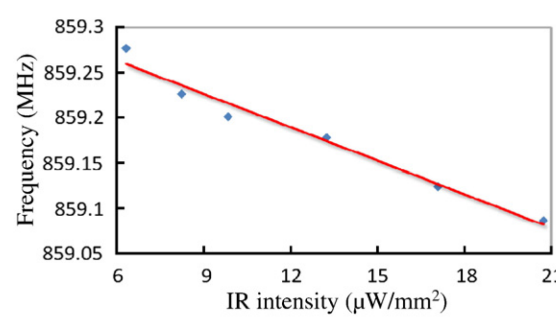

Fig. 6. The relationship between the resonant frequency and IR intensity for the LFE FBAR. A linear relationship was observed with a detection limit of 2 μW/mm^2.

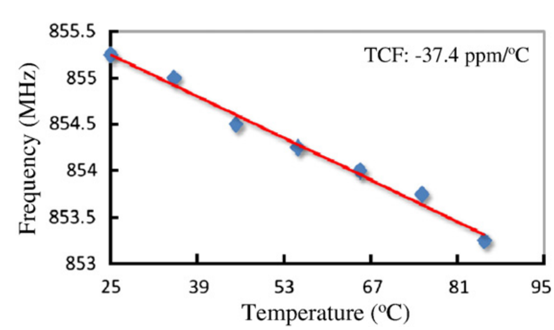

Fig. 7. The frequency response of the LFE FBAR to temperature.

3.3. Comparison between TFE and LFE FBAR IR sensors

As discussed in Section 2, the IR sensitivity of bulk resonators fabricated with the same material depends mainly on their TCF. Generally, a resonator with a larger TCF should have a higher sensitivity towards IR. IR sensitivity was, however, higher for the LFE FBAR (12.3 kHz/(μW/mm^2)) than for the TFE FBAR (3 kHz/(μW/mm^2)), despite the fact that the TCF was twice as large in the later case. This result was attributed to the different structures of these two devices. In the TFE FBAR, the top electrode reflected most of the IR radiation [3], resulting in less IR absorption for the FBAR, and therefore a smaller IR sensitivity.

4. Summary

In this paper, we presented an IR sensing device using ZnO film based FBAR. The resonant frequency of the FBAR decreased linearly as IR intensity falling on the device increased. The sensing mechanism is based on the fact that the Young's modulus of the ZnO depends on temperature. As temperature increases with IR absorption, the Young's modulus decreases due to material softening, decreasing the acoustic velocity for a resulting drop in resonant frequency. The sensitivity of the FBAR relies on its TCF. In our study, the TFE FBAR possessed a larger TCF, but showed lower IR sensitivity (3 kHz/(μW/mm^2)) when compared with the LFE FBAR (12.3 kHz/(μW/mm^2)). This result was due to the reflection of IR radiation from the top electrode on the TFE FBAR. This study has demonstrated the feasibility of using FBAR as a potential IR detector.

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