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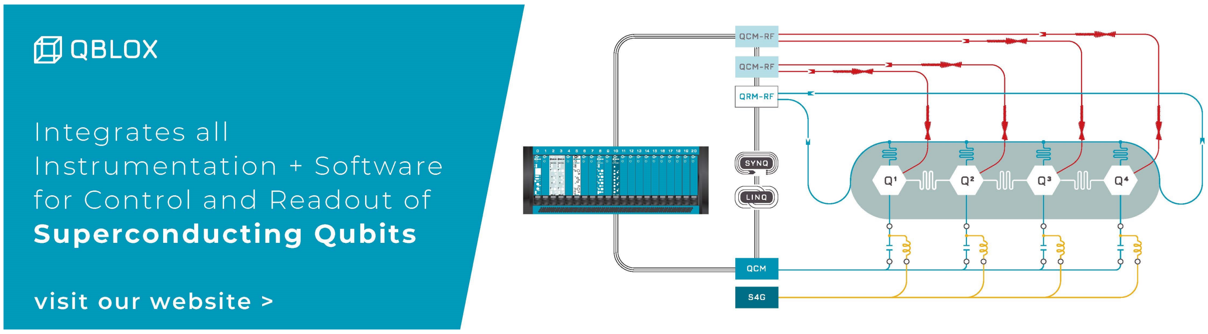

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Electrically tunable film bulk acoustic resonator based on Au/ZnO/Al structure

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An electrically tunable Au/N-ZnO/ZnO/Al film bulk acoustic resonator (FBAR) is proposed. The stack resonator is Au-piezoelectric ZnO layer-Al while Schottky diode junction is Au/N-ZnO semiconductor layer. The FBAR's resonance frequency changes as the junction capacitance decreases with reverse bias. Our experiments gave a frequency shift of ~30 kHz/V at 1.46 GHz, maximum insertion loss ~0.7 dB, and a very high Q factor above 1200. Circuit simulations indicated a tunable range of ~3.8 MHz from optimizing the FBAR's structure and doping concentration of N-ZnO. Electrical tunability decreases from 27 kHz/V to 1.5 kHz/V with temperatures from 30 °C to 105 °C. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4818157]

Film bulk acoustic resonator (FBAR) has been widely used in many wireless communication circuits[1,2] as one of the key components for oscillators, filters, and duplexers. This is because of its small size, very high quality (Q) factor of 2000–50 000 at radio frequencies (RF), and its technological advantages for process integration with the mainstream semiconductor manufacturing technologies.[3,4] With the diversified applications of wireless systems, an RF communication circuit now often needs to handle signals over a much wider frequency range. For these applications, the tunable FBAR is a promising key component for tunable RF circuits such as tunable filters and tunable oscillators. For example, a 30 MHz tunable range (at 2.4 GHz operation frequency), tunable filter can be used in a multi-mode cell phone and an MIMO (multiple-input and multiple-output) system where the tunable filter can be used to replace the multiple filters in these systems.

Several proposals for making the FBAR frequency tunable have been reported. Unlike the traditional FBAR with the operation frequency being determined by the external capacitor and inductor, Pang *et al*.[5] proposed to cascade the FBAR with a tunable cantilever capacitor which tunable frequency is about 1 MHz/V at 2.8 GHz under the bias voltage in the range of 0–6 V. Campanella *et al*.[6] also proposed a mass deposition method to achieve the tunable FBAR at high frequencies. However, in general, these methods are not cost effective for mass production.

Ferroelectric materials, such as barium strontium titanate (BST), which have a wider tunable frequency range of 0.12 MHz/V at 2.8 GHz for biasing voltage changing from 0 V to 600 V, were also used as the piezoelectric film in a FBAR.[7] Unfortunately, the BST film is not suitable for a standard integrated circuit process technology. Also, it has a low Q-factor (less than 200), and it requires a much larger biasing voltage for tuning.

In this paper, we proposed a tunable FBAR resonator structure with an embedded N-ZnO/Au Schottky diode that is compatible with the mainstream micro fabrication technology. This FBAR has a 3.8 MHz tuning frequency at 1.5 GHz by using a small bias, in the range 0 V–5 V, for tuning.

The schematic structure of the electrically tunable FBAR is shown in Fig. 1(a). It is composed of a 50 nm thick top Au electrode, a 50 nm thick N-type ZnO semiconductor layer, a 2 μm thick ZnO piezoelectric layer, and a 100 nm thick bottom Al electrode deposited on a 200 nm thick SiO_2 layer.[8] The supporting SiO_2 layer, also used as the stop layer during the deep reactive ion etching (DRIE), was deposited on a (100)-oriented Si substrate using the plasma enhanced chemical vapor deposition (PECVD). The top and bottom electrodes were deposited by DC sputtering. Both the N-type ZnO semiconductor layer and the ZnO piezoelectric layer were deposited by RF reactive sputtering but with different oxygen flow rates. For the N-ZnO film, the electron concentration was measured using the Hall effect, and it was $\sim 5 \times 10^{17}\,\mathrm{cm}^{-3}$. The bulk silicon under the FBAR was removed by DRIE. The size of the active area of the FBAR, i.e., the SiO_2/ZnO membrane, was $200 \times 200\,\mu\mathrm{m}^2$.

The electrical characteristics of the FBAR, as shown in Fig. 1(b), were measured with an Agilent E5071C network analyzer. Figure 2 shows frequency response characteristics of one of the FBAR. It has a resonant frequency of 1.46 GHz and a Q factor of 1510. The inset of Fig. 2 shows the shift of the resonant frequency under different reverse biases ranging from 0 to 5 V. The averaged resonant frequency tunability was 30 kHz/V with a maximum insertion loss of 0.7 dB.

In the structure shown as Fig. 1, we used the Au-piezoelectric ZnO layer-Al for the piezoelectric stack resonator and the Au/N-ZnO semiconductor layer for the Schottky diode which provided the tuning capability of the FBAR. The junction capacitance of the diode can be modified by the bias voltage, which in turn adjusts the resonance frequency of the FBAR.

Based on the equivalent circuit model of the Schottky diode given in Fig. 3(a) and the Modified Butterworth-Van Dyke (MBVD) model[9] shown in Fig. 3(b), an equivalent circuit is derived to model the proposed tunable FBAR structure in Fig. 3(c). The components, C_0, R_0, C_m, L_m, R_m, R_s,

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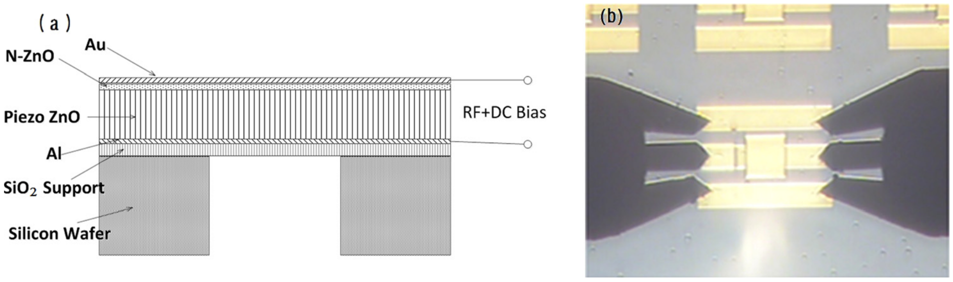

FIG. 1. (a) Schematic illustration of the structure of electrically tunable FBAR. (b) Final product under test.

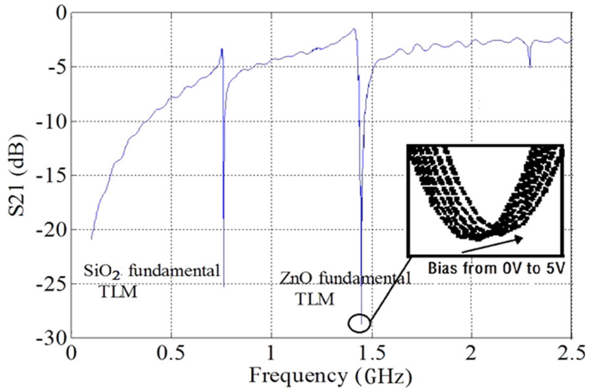

FIG. 2. Frequency response of the electrically tunable FBAR.

represent, respectively, the static capacitance, resistance due to medium loss, dynamic capacitance, dynamic inductance, resistance due to mechanical loss, and lead series resistance. The Schottky diode capacitance is C_j. The conventional MBVD model parameters can be extracted from measurement results.[9] The Schottky diode capacitance can be expressed as

$$C_j = A\left[\frac{e\varepsilon_s N_d}{2(V_{bi} + V_{rj})}\right]^{\frac{1}{2}}, \tag{1}$$

where A, e, ε_s, N_d, V_{bi}, and V_{rj} are the FBAR's active area, the electronic charge, the dielectric constant of ZnO, the doping concentration, the built-in potential, and the DC voltage across the junction, respectively. The voltage V_{rj} across the junction capacitance C_j can be calculated from

$$V_{rj} = \frac{C_0}{C_0 + C_j} \times V_r, \tag{2}$$

where C_0 is the static capacitance of FBAR and V_r is the applied DC reverse bias.

The proposed model is simulated using Advanced Design System (ADS), and the simulation results qualitatively agree with the measurements (see Fig. 4). In should be noted that in the current simplified model, several factors have been neglected. For example, one should note that the piezoelectric ZnO layer should also affect the characteristics of Au/N-ZnO Schottky diode and that was not included in the above model. As a result, when the bias voltage increases, the simulated results deviate from the experimental ones.

In Fig. 4, it is noted that large different characteristics were found for Devices 1 and 2. The devices were taken from the same wafer and have the identical processing conditions. They are different because of the different amount of surface states at the N-ZnO/Au interface. The interface states made the equivalent capacitance of the Schottky diode different and resulted in different tunable ranges of the frequency.

The present experimental results indicate that the tunable range is around 150 kHz, which may be too small in some applications. To increase the tunable range, the key is the variation in the junction capacitance C_j under reverse bias. As shown in Eq. (2), when the value of C_j is close to that of C_0, the FBAR's tunable range will reach maximum provided that the semiconductor layer is still not completely depleted under the bias voltage. According to Eq. (1) the junction capacitance of Schottky diode (C_j) depends on several parameters. Table I lists the possible frequency changes with feasible thicknesses, doping concentrations, and biases, which are from the simulation based on above model. One of largest frequency shifts of 3.8 MHz was found for the sample with 210 nm N-ZnO,

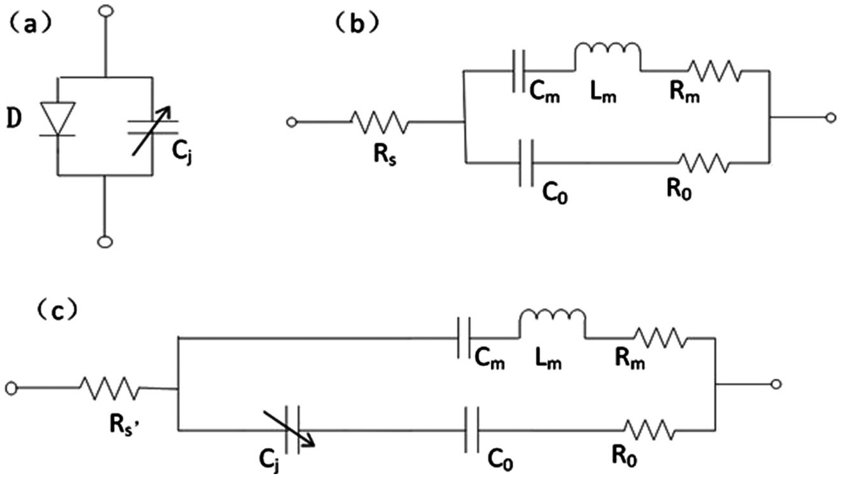

FIG. 3. (a) Schottky diode with a bias dependent junction capacitance; (b) MBVD equivalent model for the FBAR; and (c) proposed equivalent circuit model for the electrically tunable FBAR.

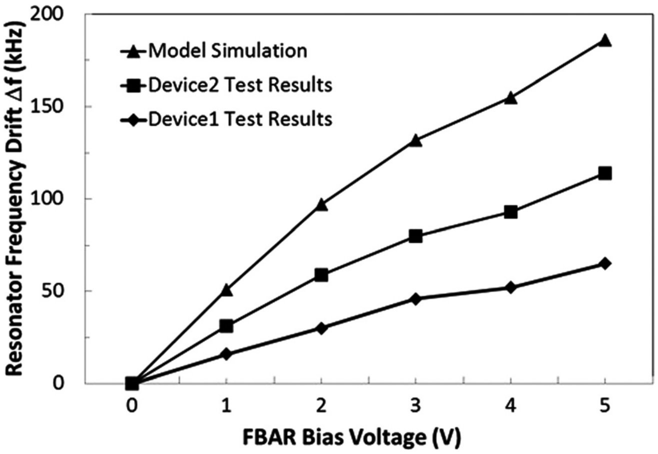

FIG. 4. Comparison of measured results with simulations using the proposed circuit model and the ADS tool.

TABLE I. Effects of device parameters on the maximum frequency shift.

Case	Thickness of N-ZnO layer (nm)	Doping concentration ($\times 10^{16}\,\text{cm}^{-3}$)	Bias voltage (V)	Frequency shift (kHz)
I	50	25	−5.0	118
II	50	20	5.0	130
III	100	7	−5.0	431
IV	110	4	5.0	600
V	210	1	−5.0	1530
VI	210	1	5.0	3810

dopant concentration of $1.0 \times 10^{16}\,\text{cm}^{-3}$, and bias of $+5$ V. Thus a thick N-ZnO layer with small doping concentration is preferred in order to have a larger frequency shift. However, the low-doping thick N-ZnO layer will lead to a large voltage drop across the FBAR. Therefore, the device parameters need to be optimized based on the specific application. Since the junction capacitance of the Schottky diode are different under reverse bias and forward bias, the tunable frequency range of the FBAR will be different. Also, it seems that a reverse bias can result in a wider tunable range than a forward bias one.

Although ZnO FBAR has a small negative temperature coefficient for the resonant frequency (TCF), the temperature characteristics is still needed to be considered for actual applications in some systems.[2,3] Temperature also has significant effect on the capacitance (C_j) of the Schottky diode which in turn affects the tuning range of the FBAR. Figure 5 shows FBAR tunable frequency at different temperatures. With increasing temperature, the FBAR's resonator frequency and its tunable range decrease. The tunability of the FBAR is negligible for temperature above $80\,^{\circ}\text{C}$. This negligible tunability change at higher temperatures is related to the temperature dependence of the Schottky diode. The intrinsic carrier concentration in the N-ZnO increases with temperature, which also makes the bias effect weaker.

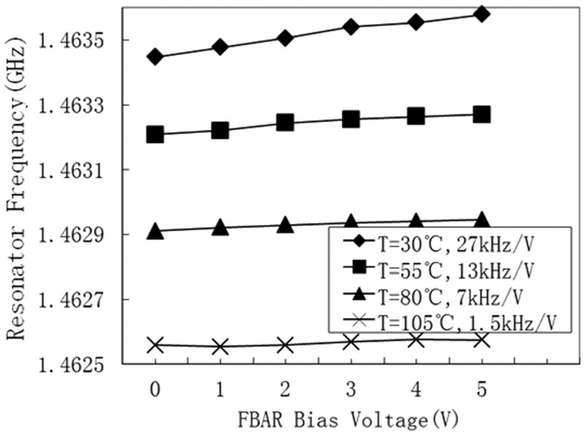

FIG. 5. Temperature effects on the frequency tuning range of the proposed FBAR.

In conclusion, a method for realizing electronically tunable FBAR resonators has been proposed by incorporating a thin N-type ZnO semiconductor layer on the top of the ZnO piezoelectric layer of the FBAR resonator. By varying the biasing of the Au/N-ZnO Schottky diode, a shift of the resonance frequency was obtained. An equivalent circuit model of this tunable FBAR was developed to model the device characteristics. The model agreed qualitatively with the experimental results. Finally, the effect of temperature on the resonance frequency of the FBAR was studied, and it was shown that a too high temperature is detrimental to its frequency tunability.

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