Tunable Film Bulk Acoustic Wave Resonator Based on Magnetostrictive $Fe_{65}Co_{35}$ Thin Films

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Abstract — We have developed a Tunable Film Bulk Acoustic Wave Resonator (TFBAR) based on magnetostrictive $Fe_{65}Co_{35}$ thin films. The resonator layer stack consists of Pt/ZnO/$Fe_{65}Co_{35}$ layers for tuning of devices. When resonator is subject to magnetic field there is expansion in $Fe_{65}Co_{35}$ layer due to magnetostrictive effect. This expansion in $Fe_{65}Co_{35}$ layer induces strain, which alters the Young's modulus of magnetostrictive layer and this behavior is denoted as ΔE effect. In an unbiased condition, series (f_s) and parallel (f_p) resonance frequency are detected at 1.14 GHz and 1.187 GHz, respectively. When resonator was placed in magnetic field series and parallels both resonance frequencies are lower shifted by ~7MHz. Electromechanical coupling coefficient (k_t^2) was found 9.69% when there is no magnetic field and reduced to 9.53% with magnetic field. This reduction in k_t^2 is due to magnetic field induced strain in magnetostrictive $Fe_{65}Co_{35}$ layer. The proposed resonator is very promising and can be utilized for various reconfigurable microwave resonators, frequencies agile devices and magnetic sensors.

Index Terms — Acoustic resonators, magnetostriction, Piezoelectric devices, MEMS.

I. Introduction

Reconfigurable microwave resonator/filters make microwave transceivers adaptable to multiple bands of operation using a single filter, which is highly desirable in today's communications systems with evermore growing wireless applications. Tunable filters can replace the necessity of switching between several filters to have more than one filter response by introducing tuning elements embedded into a filter topology. $Fe_{65}Co_{35}$ thin films show magnetostrictive behavior and elastic modulus can be tuned by applied magnetic field. This effect is also regarded as ΔE effect. Size of RF/Microwave system (cellular radio or mobile phones) is continuously reducing due to competitive market and therefore goal of the RF/Microwave engineer to obtain small size, high performance and low cost reconfigurable integrated devices. Multiple functions are possible with a single tunable microwave resonator. Magnetostrictive $Fe_{65}Co_{35}$ can be integrated with Zinc oxide (ZnO) to maintain high quality factor (Q) and high figure of merit (FOM) with enhanced functionalities. Currently, acoustic wave resonators are available for single frequency of operation. Current progress of microwave communication systems indicates that these system has to be more user friendly i.e. adaptable and reconfigurable. The growing numbers of channels and bandwidth have to be agile (adaptable/reconfigurable). New functionality is needed in devices with enhanced performance to make them agile and cost effective.

Here, FBAR tuning is proposed based on ΔE effect. When resonator is placed in magnetic field, strain can be induced in $Fe_{65}Co_{35}$ thin film due to magnetostrictive effect. This result to a change in Young's modulus of magnetostrictive resonator. Device impedance and electromechanical resonance frequency (fs and fp) were tuned through dc magnetic field. Here, we have proposed a novel tunable film bulk acoustic wave resonator (TFBAR) based on magnetostrictive $Fe_{65}Co_{35}$ thin films.

Figure 1 shows the schematic sketch of Tunable Film Bulk Acoustic Wave Resonator (TFBAR) which was fabricated using bulk micromachining process. The resonator layer stack consists of various SiO_2/Pt/ZnO/$Fe_{65}Co_{35}$ layers. SiO_2 work as an isolation layer to isolate ground and signal electrodes. High magnetostrictive composition $Fe_{65}Co_{35}$ was utilized in the resonator for high tunability. Magnetic field induced frequency shift was monitored using vector network analyzer. The resonator materials properties and thickness are listed in Table I.

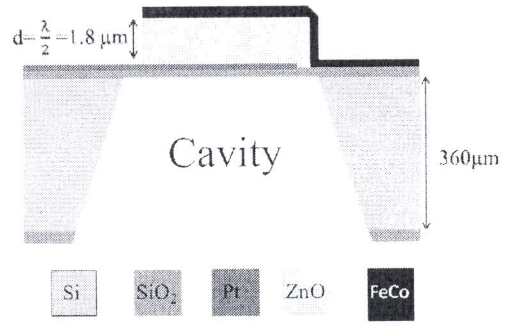

Fig.1. Schematic cross-section sketch of tunable FBAR.

II. Experimental Procedure

Magnetostrictive TFBAR structures was fabricated using a 3-inch diameter double side polished Si (100) wafers. The processing of TFBAR consists of five mask level fabrication process as shown in figure 2.

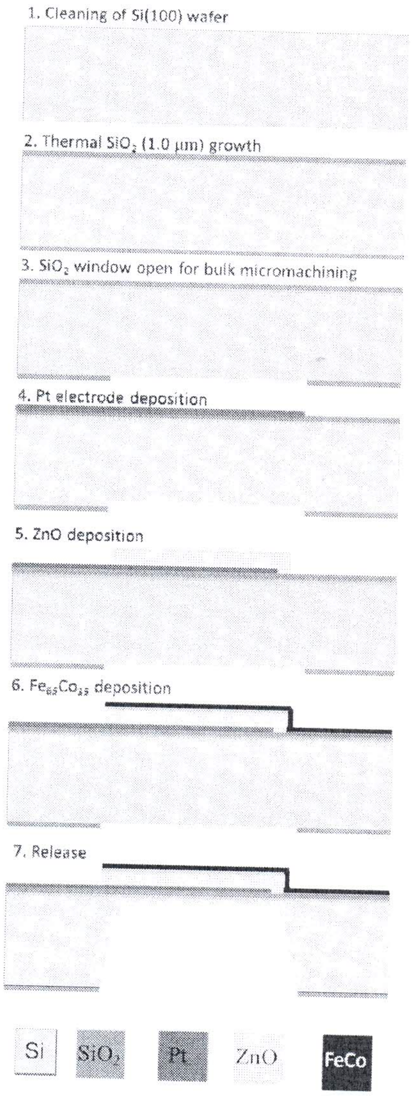

Fig.2. Fabrication process flow of tunable FBAR.

Initially, Si wafers were cleaned using standard process. Now, wafers are loaded in thermal oxidation furnace for growth of thermal silicon dioxide (SiO_2) ~1μm using a dry-wet-dry process sequence (step 1). Here, SiO_2 layer work as a masking layer during Si bulk micromachining during tetra-methyl-ammonium hydroxide (TMAH) etching and also works as an isolation layer between underlying Si and active magnetostrictive $Fe_{65}Co_{35}$ layer. Mask #1 was used to pattern SiO_2 layer and wet etched. Now, silicon windows are opened which will be used for bulk micromachining at later stage. Mask #2 was used to define bottom Platinum (Pt) electrode using a lift-off process. Piezoelectric zinc oxide (ZnO) layer was deposited using reactive sputter deposition process. Mask #3 was used to pattern ZnO thin film. Mask # 4 was employed to define the top magnetostrictive $Fe_{65}Co_{35}$ layer by lift-off process. Here, magnetic layer plays a dual role, it works as a

TABLE I
MATERIAL PROPERTIES OF VARIOUS LAYERS.

Material	Young Modulus (GPa)	Density (Kg/m³)	Poisons ratio (υ)	Acoustic velocity (m/s)	Thickness (μm)
SiO_2	73.1	2750	0.17	5600	1.0
Pt	168	21450	0.38	3300	0.2
ZnO	211	5680	0.3	6350	1.8
$Fe_{65}Co_{35}$	152	7860	0.27	5900	0.5

top electrode and also as a magnetostrictive layer to tune resonator. Contact pads are opened using mask # 5 and ZnO capacitor properties are measured using LCR meter. Special wafer holders are customized for single side wafer protection during Si bulk micromachining. This allows the TMAH wet etching only on the single side of wafer while protecting ZnO devices other side.

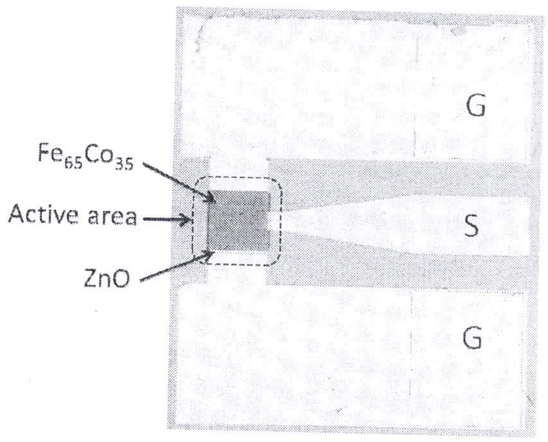

Fig. 3. Optical microscope image of a fabricated resonator.

III. RESULTS AND DISCUSSION

Figure 3 shows the microscopic image of a fabricated tunable FBAR. Active area of resonator consists of Pt/ZnO/$Fe_{65}Co_{35}$ multilayer stack as highlighted and visible in figure 3. Various layer colors are clearly visible. The device was designed according to on-wafer probe measurement in ground-signal-ground (GSG) kind of configuration with ground and signal line with separation gap of 100μm. Figure 4 shows the resonator impedance with frequency. Initially, resonator was tested without magnetic field and impedance was plotted with frequency. Resonance peaks are observed corresponding to series resonance frequency (f_s) and parallel resonance frequency (f_p). Series resonance frequency refers to the resonance frequency where minimum impedance (Z_{min}) was observed. At parallel resonance frequency maximum impedance (Z_{max}) was observed. Resonance frequency (ω_n) of FBAR resonator is given as

$$\omega_n = (n+1)\frac{\pi}{2}\frac{v}{d}, \quad n = 0,1,2 \ldots \qquad (1)$$

where resonator consisting of a piezoelectric plate of thickness 2d, sandwiched between two electrodes. Composite material has acoustic wave velocity v, which is multiple half-wavelength ($\lambda/2$) resonance established in thickness mode of device. Acoustic wave velocity (v) depends on material equivalent elastic modulus (E_{eq}) and equivalent density (ρ_{eq}) as follows:

$$v = \sqrt{\frac{E_{eq}}{\rho_{eq}}} \qquad (2)$$

Magnetostrictive $Fe_{65}Co_{35}$ based FBAR shows shift in resonance frequency due to strain induced change in elastic modulus. In small strain regime, due to applied magnetic field in small there is strain in magnetic film and material softens and results to decrease in elastic modulus. This effect is called ΔE effect and acoustic wave velocity (u) is reduced and expresses as

$$u = \sqrt{\frac{E_{eq} - \Delta E}{\rho_{eq}}} \qquad (3)$$

Here, it is assumed that material density is constant when magnetic field is applied on FBAR device. Due to ΔE effect, ~7 MHz shift was observed in resonance as shown in figure 4.

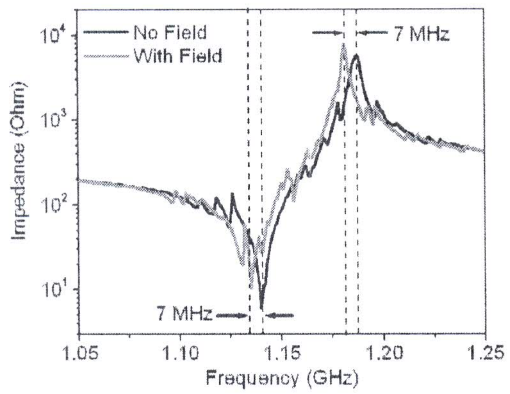

Fig. 4. Response of tunable FBAR, which shows ~7MHz shift in resonance frequency.

IV. CONCLUSION

Tunable Film Bulk Acoustic Wave Resonator (TFBAR) is developed based on magnetostrictive $Fe_{65}Co_{35}$ thin films. The resonator shows tuning due to magnetostrictive $Fe_{65}Co_{35}$ layer. Due to magnetic field there is strain in $Fe_{65}Co_{35}$ layer and that results to ΔE effect and shows tunability. Series (f_s) and parallel (f_p) resonance frequency are tuned with magnetic field and shifted by ~7MHz. Electromechanical coupling coefficient (k_t^2) was reduced. The proposed tunable resonator is very promising and can be utilized for various frequencies agile/reconfigurable devices.

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REFERENCES

[1] T. Nan, Y. Hui, M. Rinaldi and N. X. Sun, "Self-Biased 215 MHz magnetoelectric NEMS Resonator for Ultra-Sensitive DC Magnetic Field Detection," *Sci. Rep.*, vol. 3, pp. 1985 (1-6), 2013.

[2] A. Ludwig and E. Quandt, "Optimization of ΔE effect in thin films and multilayers by magnetic field annealing," *IEEE Trans. on Mag.*, vol. 38, pp. 2829-2831, 2002.

[3] Ken-ya Hashimoto, "RF Bulk Acoustic Wave Filters for Communications" in 2009 ARTECH HOUSE.

[4] Priyanka Joshi, Jitendra Singh, Ramakant Sharma, V.K. Jain and Jamil Akhtar, "A facile approach to fabricate ZnO thin film based micro-cantilevers" *Microelectronic Engineering*, vol. 187-188, pp.50-57, 2018.

[5] S.R. Dong, X. L. Bian, H. Jin, N.N. Hu, J. Zhou, H. Wong and M.J. Deen, "Electrically tunable film bulk acoustic resonator based on Au/ZnO/Al structure", *Appl. Phys. Lett.*, vol. 103, pp. 062904 (1-3), 2013.

[6] B. Gojdka, R. jahns, K. Meurish, H. Greve, R. Adelung, E. Quandt, R. Knochel and F. Faupel, "Fully integrable magnetic field sensor based on delta-E effect", *Appl. Phys. Lett.*, vol. 99, pp. 223502 (1-3), 2011.