High overtone acoustic resonator HBAR based on IDT's/c-tilted ZnO/Si for timing applications

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***Abstract*— In this paper, the frequency characteristics of high overtone bulk acoustic modes, generated by interdigital transducers IDT's on c-tilted ZnO/Si, are theoretically and experimentally investigated. The origin and characteristics of high overtone acoustic modes in ZnO piezoelectric layer on silicon substrate are discussed and one port HBAR resonator, based on c-axis tilted ZnO/Si, is fabricated and tested by network analyzer. The results achieved in this work are of interest in design and fabrication of radiofrequency sources and electronic timing devices based on thin film technology.**

Keywords*— *High overtone bulk acoustic modes, HBAR resonator, piezoelectric thin film, c-tilted ZnO, Frequency characteristics.

I. Introduction

High overtone bulk acoustic resonator HBAR is an electroacoustic device in which a piezoelectric thin layer, sandwiched between two electrodes, excite an acoustic wave in a high quality and low acoustic loss substrate, on which it's deposited. When the substrate is thicker than the deposited guiding layer, that is considered as a transducer, the generated acoustic wave propagates in the substrate and form stationary waves between surfaces at the top and the bottom of the substrate. The detected stationary waves from electrodes form frequency equidistant pulses (cardiogram like signal).

The main application of HBAR was in filters and oscillators [1]. Its high quality factor that can reach Q × f ≈ 1014 Hz [2], makes it the most-suitable to develop ultra-low phase noise oscillators for high frequency operating devices [3, 4]. Another application of HBAR's is the characterization of thin piezoelectric films [5, 6]. Among the researches that have been carried out to enhance HBAR characteristics [7-9], tilting piezoelectric material has shown its ability to enhance the performances of electroacoustic devices [10, 11]. To study HBAR based on c-tilted ZnO/Si, the origin of high overtone bulk acoustic modes in c-tilted ZnO on silicon substrate and their effect on the frequency spacing Δf of the HBAR resonator are discussed in details. The device is fabricated by radiofrequency rf growth of thin c-tilted ZnO on Si substrate and photolithography process to design IDT's on the ZnO free surface. Unlike the acoustic modes generated by simple metallic electrodes, the interdigital transducers IDT's allows to generate only the desired acoustic mode in the piezoelectric guiding layer, which ensure the control of the wave propagation direction and the frequency of the signal. Instead of surface acoustic modes, this study confirms the possibility to generate high overtone modes by interdigital transducers on ZnO/Si. The obtained results will contribute in design and fabrication of HBARs with controlled frequency, for high precision timing devices.

II. Origin of High Overtone Acoustic Modes in ZnO/Si

Bulk acoustic waves could be obtained by solving the equation of propagation without boundary conditions, in case of anisotropic and piezoelectric crystals, this equation takes the following form [12]:

$$\rho \frac{\partial^2 u_j}{\partial t^2} = c_{ijkl} \frac{\partial^2 u_j}{\partial x_i \partial x_l} + e_{kij} \frac{\partial^2 \emptyset}{\partial x_i \partial x_k} \quad (1)$$

$$e_{ikl} \frac{\partial^2 u_k}{\partial x_i \, \partial x_l} + \varepsilon_{ik} \frac{\partial^2 \emptyset}{\partial x_i \, \partial x_k} = 0 \quad i, j, k, l = 1,2,3$$

Where ρ is material density, ε_{kl} , e_{ikl} and c_{ijkl} are the material piezoelectric, dielectric and elastic constants, u_i is the particle displacements and Φ is the electric potential.

In case of unlimited anisotropic crystal, three bulk acoustic waves travels in the piezoelectric medium, depends upon the wave polarization compared to the propagation direction $\vec{n}$, a wave with longitudinal polarization and two waves polarized in the shear vertical and shear horizontal plan in respect to $\vec{n}$.

When the axis of a propagation form an angle with the direction of propagation, the waves are not pure anymore, and called in this case quasi-longitudinal QL and quasi-shear QS waves [12].

By solving equations system in Eq. 1, Fig. 1 displays the inverse of phase velocities V_i (Slowness curves), for different titling angles θ in the ZX plane, of ZnO deposited on Silicon Si substrate. The curves are plotted for both the guiding layer of ZnO and the substrate of Si and are separated by the interface ZnO/Si.

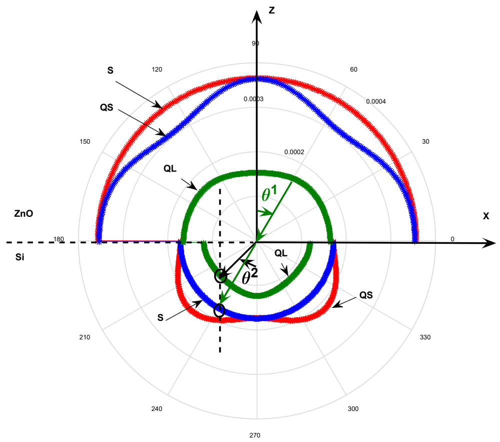

Fig. 1. Slowness curves of acoustic bulk wave velocities in ZnO/Si

Based on each wave polarisation in respect to the propagation direction X, the bulk waves are divided into quasi-longitudinal QL, shear S and quasi-shear QS waves. In case of ZnO, the first two waves are polarized in XZ plane when the shear wave is polarized in Z plane. On the contrary, the QL and S waves are polarized in ZX plane when the QS wave is polarized in Z plane for Si substrate.

When the quasi-longitudinal QL mode in ZnO is incident on the interface ZnO/Si under an angle θ_1, it leads to the generation of quasi-longitudinal and shear modes in the Si substrate under a critical angle θ_2 as explained in [8]. The quasi-shear mode QS in the substrate won't be generated due to its polarization in the YX plane, being Y the axis normal to the ZX plane.

A condition of reflection under the incident angle θ_1 obeys to Snell-Descarts law and is given by the following formula [12]:

$$\frac{1}{V_1}\sin\theta 1 = \frac{1}{V_2}\sin\theta 2 \qquad (2)$$

In which V_1 is the velocity of the incident QL wave in ZnO V_2 is the velocity of QL or S waves in Si. Fig. 2 shows the angles θ_1 for which the incident QL wave of ZnO will generate the transmitted QL and S waves in the substrate.

From Fig. 2, it's apparent that the transmitted shear wave S in the substrate is generated for all incident angles θ1 while the QL wave is only generated under angles θ_1 limited between -40° <θ1<40°. The transmission angle θ_2 must satisfy the condition $-1 < \sin(\theta 2) < 1$, so that the S and QL waves will be transmitted in the substrate. For -40° >θ1>40°, only S wave will be generated in the guiding layer. This confirms the direct relation between the transmitted wave in the substrate and the tilting angle θ.

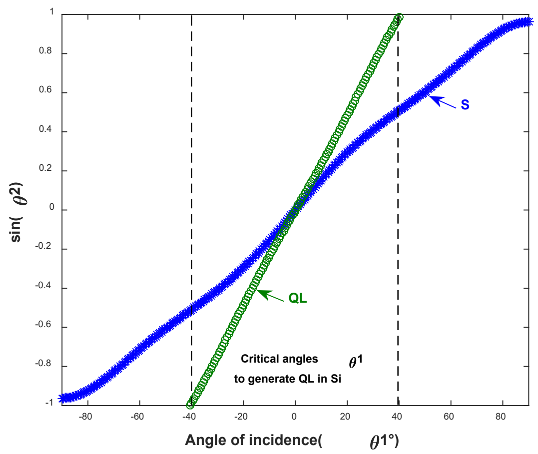

Fig. 2. Critical incidence angles to generate HBAR modes in the substrate (Si)

The transmitted waves in the substrate travel from the bottom of the substrate Si to the interface ZnO/Si, giving birth to stationary waves (high overtone modes) modulated by the resonant frequency of the incident wave from the ZnO layer, the modulation frequency f_m *(n)* for the incident acoustic mode *n* is given by the following formula [13]:

$$f_m(n) = n \,.\, \frac{V_{layer}}{2*h_{layer}} \qquad (3)$$

In which *n* is the order of the incident acoustic mode, it also represents the number of half-wavelength along the thickness of the guiding layer; V_{layer} and h_{layer} are, respectively, the acoustic velocity of the incident mode and the thickness of the piezoelectric layer.

The frequency spacing *Δf* between two adjacent overtone modes is calculated from the velocity of the wave that travels from the ZnO/Si interface then be reflected from the bottom side of the substrate, without taking into consideration the thickness of the guiding layer, it can be calculated using the following formula [14]:

$$\Delta f = \frac{V_{sub}}{2*h_{sub}} \qquad (4)$$

In which V_{sub} is the acoustic velocity of longitudinal wave in the substrate [15] and h_{sub} is the thickness of the substrate.

III. EXPERIMENTAL SETUP

c-tilted ZnO thin film was reactively sputtered on silicon Si (001) substrate using Zn target (99.999%) in Ar/O2 atmosphere at a temperature 200°C, the rf-power was 200 W, and the pressure was 3.5 mTorr. The ZnO layer on Si substrate shows good surface quality and adhesion as shown in Fig. 3.

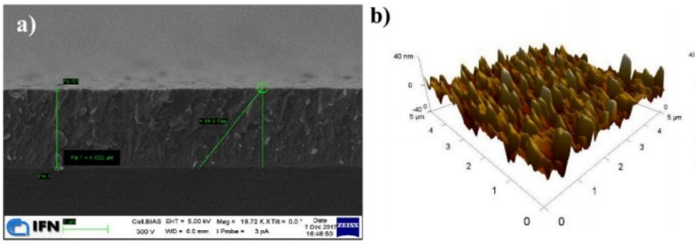

Fig. 3. Characteristics of the deposited ZnO on Si a) SEM cross section of the sputtered ZnO and b) Atomic force microscopy AFM of the free ZnO surface

Fig. 3-a shows a good crystal quality with a c-axis tilted about 34°, this tilting starts from about a thickness of h_{ZnO} = 1 µm, while Fig. 3-b shows the good surface quality of the deposited ZnO with small roughness.

After the deposition process, the ZnO free surface is coated with photoresist (OR 1A) using a spinner under a velocity (3000 Tr/min) for 40 s and baked under (T=185 °C) for 5 min, this allow to get a very thin layer of OR 1A (some hundreds of nm). Then, a second photoresist (1811) is added under the same velocity for 60 s and a second bake is performed under (T=115 °C) for 60s.

The photoresist film was exposed in mask aligner under a hard contact for 20 s, then it was developed in (DC 26 developer) for about 80 s to get the final pattern before depositing the Aluminum Al metal to get the IDT's. Fig. 4 shows the different followed steps for IDT's microfabrication process on the free surface of ZnO using photolithography technic.

After the photolithography process, Aluminum Al metal was sputtered on the wafer using rf magnetron for 10 min, then a lift off of the residual photoresist is performed using (micro-strip 2001) solution under temperature.

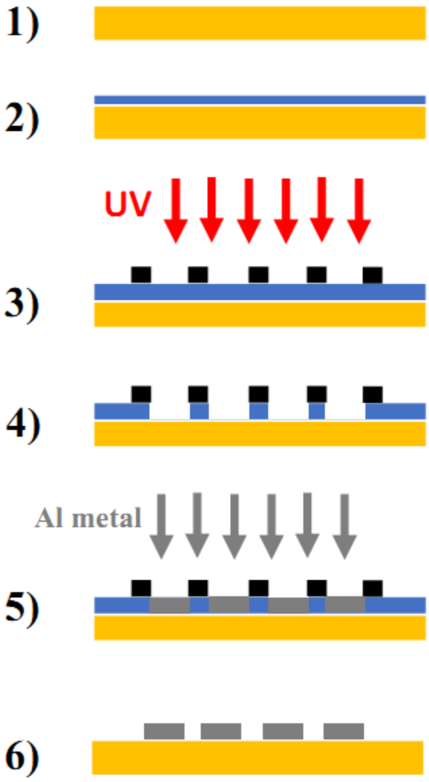

Fig. 4. Different steps for IDT's microfabrication

This allows to get the final design transferred on the free surface of ZnO. The number of IDT's is N= 20 and the aperture W has a length of 60 λ [16]. The image of the obtained IDT's is shown in Fig. 5, with a wavelength λ=20µm.

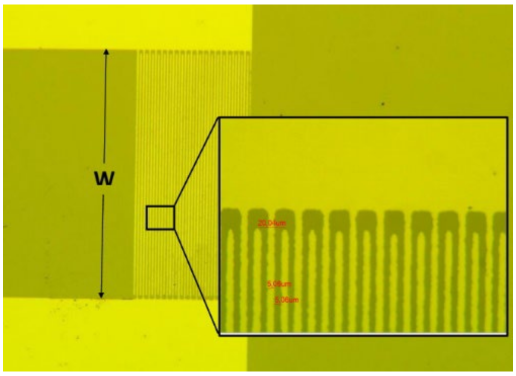

Fig. 5. Image of the IDT's patterned on the free surface of ZnO

The HBAR scattering parameter S11 was measured with a network analyzer of type (Agilent N5230A), connected to a microprobe station (Cascade-SUMMIT 9101), as shown in Fig. 6. For the adopted IDT's design, and with a thickness of the piezoelectric layer hZnO = 4 µm, the frequency of modulation is calculated from Eq. 3 for a shear velocity (VQS = 2780 m/s at θ=34°), and its f_m = 340 MHz.

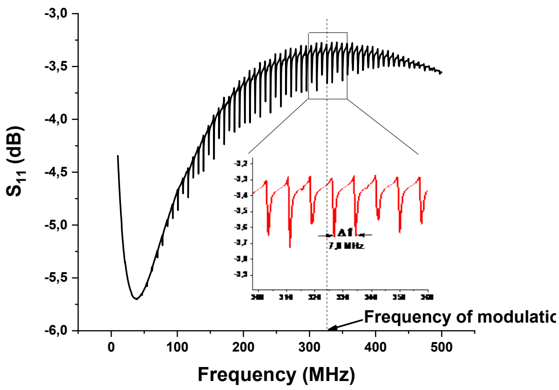

Fig. 6. Scattering parameters of HBAR based on c-tilted 34° ZnO/Si for h_{ZnO} = 4µm

Fig. 6 shows the high overtone modes modulated in the frequency range (0-500 MHz). The obtained results are for thin piezoelectric c-tilted 34° ZnO layer with h_{ZnO} = 4µm, deposited on Si substrate (001) of a thickness h_{sub} = 500 µm. It appears that the measured frequency shift between two adjacent overtones is Δf = 7.8 MHz and the modulation frequency is found to be f_m = 330 MHz. The measured values correspond exactly to the predicted results, and can be affected by the material properties of both the piezoelectric guiding layer and the substrate, the crystal cuts and the tilting angle θ of the piezoelectric crystal. The study will carried on to analyze θ > 40°, and the effect of tilting angle on the nature of the acoustic wave generated e.g. surface acoustic wave, and on the frequency characteristics of HBARs.

IV. Conclusion

In this paper, we theoretically and experimentally studied an HBAR resonator based on high overtone bulk acoustic modes on c-tilted ZnO/Si. The frequency spacing Δf of the overtone modes generated by IDT's is investigated under a tilting angle of 34° and a thickness of ZnO of 4 µm.

The obtained results confirms the possibility to generate high overtone modes by IDT's on c-axis tilted ZnO/Si, instead of surface acoustic modes. Based on bulk acoustic waves in the guiding layer and the substrate, it's possible to control the frequency characteristics and the type of acoustic modes, not only by changing the substrate material but also by tilting the c-axis of the guiding layer. The effect of the c-axis tilting angle (0°, θ°,90°), the substrate material and the design of IDT's will be studied in the future to help in the design, the fabrication and the enhancement of HBARs as timing sources based on thin film technology and easy for monolithic integration with electronic devices.

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