GHz frequency ZnO/Si SAW device

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***Abstract*—An GHz SAW device based on a ZnO/Si structure was developed by classical UV photolithography. Piezoelectric film optimization and specific interdigital transducers have been used to generate third harmonic guided wave at 2.5 GHz with Aluminum strip larger than 1 µm. 4 modes have been measured and theoretically identified thanks to an advanced finite element/boundary element based model. A good agreement is found between theory and experiments. The high frequency mode has been fully characterized, allowing for accurate design of SAW devices based on that mode.**

Keywords- ZnO; high frequency; FEA/BEM; elastic guided waves; thin piezoelectric films

I. INTRODUCTION

Zinc oxide (ZnO) is of great technological interest for the development of passive signal processing devices on different kind of substrate, and particularly Silicon. Many theoretical as well as technological works have been carried out on the ZnO layers deposited on dielectric, semi-conducting or piezoelectric substrates. Furthermore, ZnO has been widely investigated as a piezoelectric material for surface acoustic wave (SAW) devices [1,2], mainly because of the strength of its piezoelectric coupling coefficient. The centre frequency (f_0) of a SAW device is determined by the phase velocity (v_φ) of the acoustic propagation and the period (p) of the inter-digital transducers such as $f_0=v_\varphi/p$ (the acoustic wavelength λ is assumed equal to p in a first order approximation). In this work, we demonstrate the interest of the third harmonic generation to obtain high frequency SAW devices based on a ZnO/Si layered structure.

The ZnO films are deposited by a DC planar magnetron sputtering system on silicon Si(100) substrates. Aluminum inter-digital transducers (IDT) with uniform finger spacing and various spatial periods can be patterned by conventional contact UV photolithography and wet etching at the Si/ZnO interface or atop ZnO. The number of IDT pair fingers and the IDT aperture have been respectively fixed at 50 and 2 mm (always more than 100 λ). The metallization ratio (η) of IDT has been chosen to favour the generation of the 3rd harmonic. As a consequence, we show that sub-micrometric lithography is not required to develop SAW devices based on our compound Zno/Si substrate operating in GigaHertz range.

The experimental frequency characterization of the IDT response was performed using with a network analyzer (HP8752A). The measured frequencies are 665 Mhz, 971 MHz, 1.54 GHz and 2.47 GHz, corresponding respectively to the mode 0 harmonic 1, mode 1 harmonic 1, mode 0 harmonic 3, mode 1 harmonic 3 of the structure (higher modes have not been characterized).

A theoretical study has been carried out for this device to check the possibility to accurately analysed its operation, with the goal to demonstrate the possibility to efficiently design devices operating on such harmonic modes. It is based on a boundary integral method (BIM) of stacked materials coupled with finite element analysis (FEA) according to the celebrated Ventura's approach. The 4 above-mentioned modes are theoretically found in good agreement with experiments. The resonance frequencies deduced from harmonic admittance curves are predicted with a precision of about 1%, which is satisfactory considering the possible fluctuations of the film properties (process dependent). All the mode parameters are predicted and compared to those obtained experimentally. Moreover, the influence of the electrode on the 3rd harmonic mode parameters is reported, allowing for a better definition of the optimal working conditions of IDT under the considered operation mode.

II. EXPERIMENTAL APPROACH

A. Piezoelectric film optimization

Zinc oxide films elaborated by sputtering techniques are very sensitive to the deposition parameters: pressure, temperature, gas fraction, target-substrate distance [3,4]. The deposition conditions should therefore be optimized in order to obtain highly orientated ZnO films. These films were deposited by a DC planar magnetron sputtering system on silicon Si(100) substrates. The Zinc target (purity 99.99%) diameter was 107 mm (4 inch) and 6.35 mm thick. The distance between the cathode and the substrate holder was 80 mm. The deposition chamber was pumped down to a base pressure of 5.10^{-7} mbar by a turbomolecular pump prior to the introduction of the argon-oxygen gas mixture for ZnO thin film production. The gas discharge mixture was Ar/O_2 and the total pressure was varied from 2.10^{-3} to 2.10^{-2} mbar. The oxygen percentage in the Ar/O_2 gas mixture was varied from 30 to 70 %. The DC power delivered by the DC generator was respectively 60W, 120W and 180W. The substrate and the chamber wall were grounded and the substrate holder temperature wasn't heated before deposition. The crystallographic properties of films with same thickness were analyzed by X-Ray Diffraction (XRD) using the Cu Kα radiation. The atomic compositions of the ZnO films were determined by Energy Dispersive X-ray Spectroscopy (EDXS).

TABLE I. DEPOSITION CONDITIONS OF ZNO BY DC PLANAR MAGNETRON SPUTTERING.

DC Power	100W
Pressure	2.10^{-3}mBar
Gas flow	30sccm
Temperature	< 200°C
Ar/O$_2$	30%-70%
Target	Zn (purity 99.99%)

B. *Experimental SAW device*

The optimized device is developed on Silicon with a 0.75µm ZnO thickness. The IDTs are made with aluminum (150nm) and included 40 finger pairs. The half spatial period is equal to $\lambda/2$=3.03µm divided into 1.16µm of metal and 1.87µm of space. The metallization ration is thus η=38% which makes possible to generate the third harmonic [5]. In the case of layered structures, the peak intensities strongly depends on the film thickness according to the dispersion curves.

The frequency response (figure 1) presents several peaks in the range 600MHz-2600MHz. These peaks correspond to different Rayleigh wave modes and the associated harmonics. In order to avoid any confusion, the delay time was measured. We can than extract four frequency values. The notation takes into account the mode (M) and the harmonic (h) so M1h3 corresponds to mode 1 and harmonic 3.

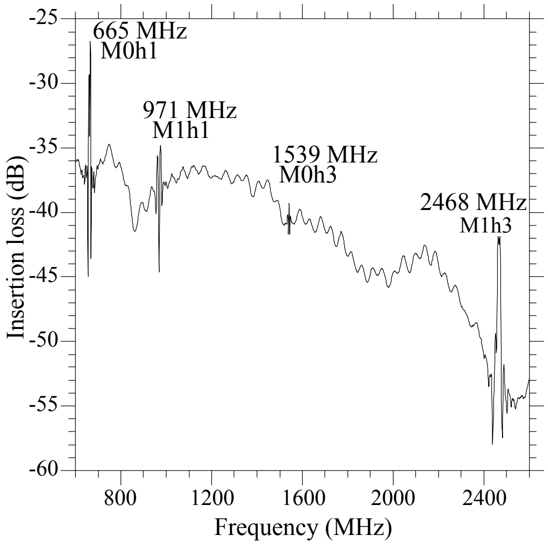


Figure 1. Transmission spectra of the ZnO/Si structure.

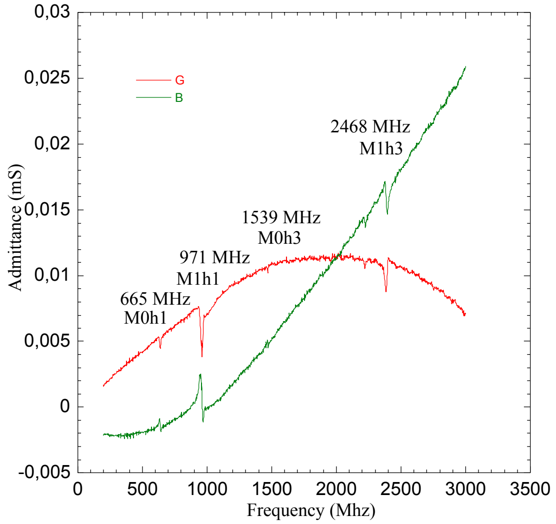


Figure 2. Admittance analysis of the ZnO/Si structure.

III. THEORETICAL ANALYSIS

We briefly describe here our model based on the theoretical approach proposed by Ventura et al. for infinite periodic electrode gratings atop semi-infinite substrates widely described in [6,7] and extended to the simulation of such transducers atop any layered media (assuming flat interfaces between each layer). The electrode contribution is described using a finite element analysis benefiting from all the advances performed in that field. The compound substrate is simulated via its Green's function inserted in the above-mentioned boundary integral method (BIM), here again taking advantage of recent developments devoted to the numerical stabilization of the corresponding calculation [8]. This point is essential when computing the response of a device consisting in piezoelectric, dielectric or metallic layers with various thickness in the range [a few µm: a few tenth of nm] deposited on a semi-infinite or a thick substrate. Both calculations are mixed along the method described in [6,7], allowing for the derivation of the harmonic admittance of the considered structure. One can then extract from this result typical characteristic of the waves that can be excited and detected by the IDTs, such as phase velocity (or slowness), electromechanical coupling, propagation losses and diffraction of the wave on the electrodes. Although the model can treat intrinsic material losses as imaginary parts of the physical constants, these leakage sources have been neglected in this work because almost no data are available concerning ZnO (which is assumed to be one of the principle leakage source of the device). The only leakage phenomena that can occur are then related to wave radiation into the bulk (semi-infinite substrate assumption). The shapes of the mode have be en identified using another approach [9] that gives easily access to that kind of information.

Figure 3 shows the harmonic admittance of the implemented structure (i.e. all geometrical parameters strictly equal the experimental one, see section II.*B*), providing a quite easy identification of the excited modes. One can see that all the measured contributions are theoretically predicted with a fine degree of accuracy. The main source of discrepancy between theoretical results and measures come from the very poor knowledge of the ZnO actual electro-acoustic properties, which of course principally condition the guided wave characteristics.

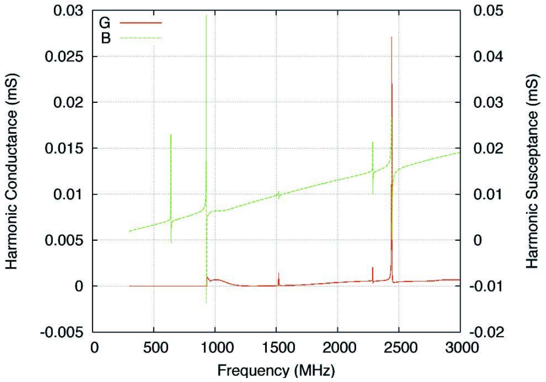


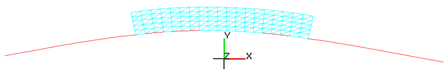
Figure 3. Harmonic admittance of the IDT structure devoted to 3rd harmonic excitation

Table II compares the measured and computed resonance frequencies, emphasizing the reliability of the computation (resonance frequencies predicted with a precision better than 5%).

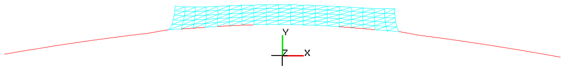
TABLE II. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICALLY PREDICTED RESONANCE FREQUENCIES.

Experiments (MHz)	665	971	1539	2225	2468
Theory (MHz)	640	932	1520	2281	2441

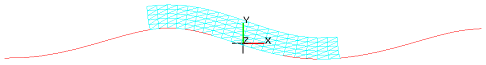
The next figures show the shape of the excited mode. It can be noted that all the mode at 2.2 GHz is a 5th harmonic of the first mode, very weakly coupled. The two first modes actually correspond to fundamental modes, whereas the modes at 1.5 and 2.4 GHz exhibit a 3rd harmonic vibration shape (i.e. 3 wavelength in one electrical period).



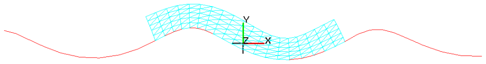
(a)



(b)



(c)



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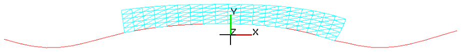
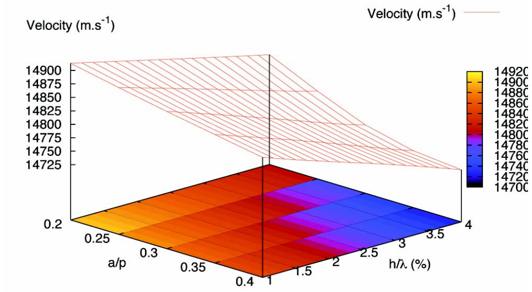


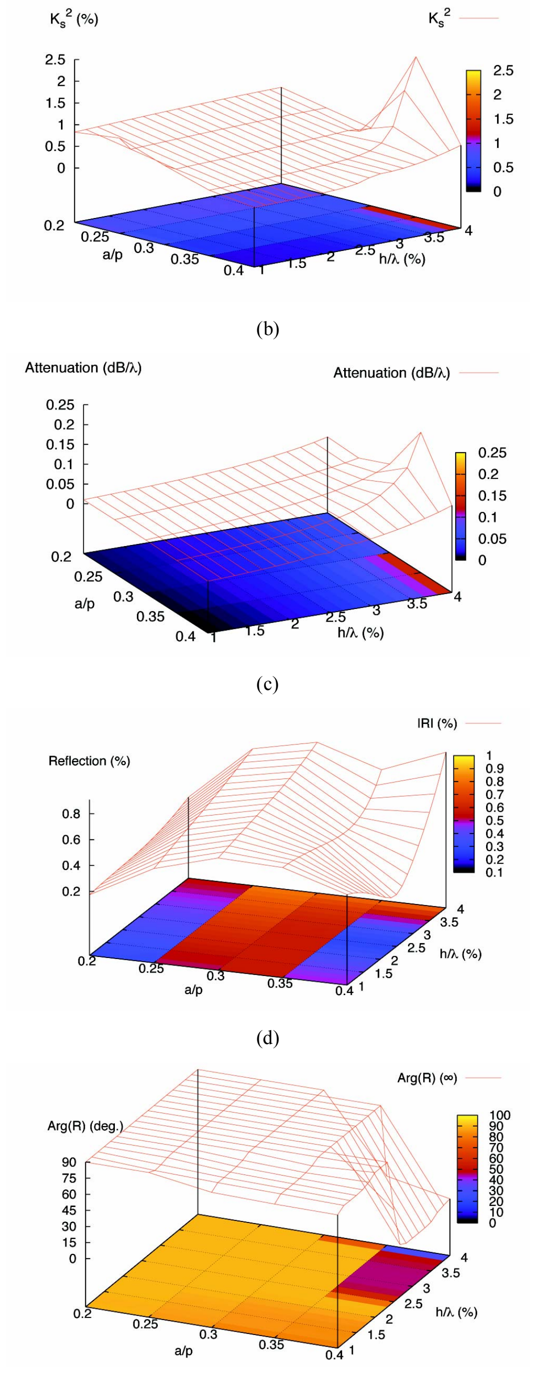
(e)

Figure 4. Shape of the five excited modes corresponding to the measured response (a) 640 MHz (b) 932 MHz (c) 1520 MHz (d) 2281 MHz (e) 2441 MHz

We finally report here the characteristics of the 3rd harmonic needed for any mixed matrix based design [6]. These are namely the phase velocity of the wave under the grating, the electromechanical coupling factor, the reflection coefficient (magnitude and phase) and the attenuation factor. From those plot, one can easily deduce that for this ZnO thickness (with a grating period of 3µm), the best configuration occurs for very thin metal thickness (h/λ=1%) and metallisation ration (a/p=0.3). In this configuration, attenuation smaller than 10^{-2} dB/λ as well as coupling close to 1% may occur. Such values are sufficient to develop narrow band SAW device in the 2.5 GHz region.



(a)



(b)

(c)

(d)

(e)

Figure 5 Characteristics of the 3rd harmonic mode for mixed matrix simulation (a) phase velocity (b) electromechanical coupling (c) attenuation (d) magnitude of the reflection (e) phase of the reflection

IV. CONCLUSION

A good agreement is found between theory and experiments, allowing for the accurate analysis of the experimental device response and the characteristics of the 3rd harmonic mode. Pseudo-velocities as high as 15000 $m.s^{-1}$ have been obtained with a theoretical coupling coefficient of about 1% at h/l near 1% and a/p equal to 0.25. In that case, the propagation is almost non lossy and the reflection coefficent is close to the one on (ST,X) quartz. Note that the resonance occurs at the end of the stopband (phase of the reflection coefficient close to 90°). This mode is then completely analyzed (all its characteristics can be deduced from theoretical FEA-BIM analysis), allowing for the design of actual devices using COM or Mixed Matrix approaches. The quality of the theoretical analysis also enables one to accurately identify the material constants (elastic, piezoelectric, dielectric) providing then a reliable set of parameter for improved designs. It is then demonstrated that one can easily reach the GHz frequency range using standard lithography process.

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