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Design and Fabrication of SAW Resonators on Silicon Substrate Employing Transverse BAW in Patterned ZnO

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***Abstract*—The paper presents the design and fabrication of surface acoustic wave (SAW) resonators on silicon (Si) substrate employing transverse bulk acoustic wave (BAW) in periodically patterned ZnO thin film. Two types of resonators are fabricated and tested: Patterned-ZnO/Si and patterned-ZnO/SiO_2/Si. Transverse BAW excited in the ZnO pattern couples acoustically and transforms into surface wave in silicon substrate with a unique characteristic of high phase velocity and high coupling coefficient compared to conventional thin film SAW devices on silicon. The performance parameters of the proposed device are estimated through finite element simulations and SAW resonators are designed using equivalent circuit model, fabricated and tested. The measured S21 results show the excitation of surface mode at 285.12 MHz with an insertion loss of -29.72 dB and effective coupling coefficient of 15.16%.**

Keywords—resonator, hybrid transducer, SAW, BAW, thin film

I. INTRODUCTION

SAW devices are extensively used in wireless communications, sensing, and RFID applications. Till date SAW devices are essential components of mobile phones and serves as transceivers due to their superior performance compared to CMOS RF frontend transceivers [1-4]. The performance of SAW devices is mainly determined by phase velocity (v), electromechanical coupling coefficient (K^2), insertion loss, and temperature coefficient of frequency (TCF). SAW devices are also realized on non-piezoelectric substrates (e.g. silicon, diamond, and sapphire) using piezoelectric thin films like ZnO and AlN in conjunction with interdigital transducer (IDT) [5]. Many researchers proposed and implemented various layered structures for the realization of SAW devices with high phase velocity and high coupling coefficient [6-11]. However, piezoelectric thin film based SAW devices on silicon substrate exhibit a tradeoff between phase velocity and K^2, moreover the insertion loss of the layered devices primarily depends on the quality of the thin film and it is difficult to reproduce films with desired quality in bulk manufacturing.

Efficient methods for the transduction of surface waves on non-piezoelectric substrates using hybrid SAW/BAW transducers have been reported recently [13-15]. SAW transduction has been accomplished by the acoustic coupling of longitudinal BAW in piezoelectric pillars to the substrate. The fabrication of the reported devices requires multiple lithography processes and they exhibit low coupling coefficient (K^2). In this paper, we present the design and fabrication of SAW resonators on silicon substrate using patterned ZnO film to obtain high phase velocity and high K^2. The dispersion characteristics are estimated using FE simulations, resonators are fabricated with patterned-ZnO/Si and patterned-ZnO/SiO_2/Si configurations and the effect of addition of SiO_2 film is investigated.

II. DEVICE DESCRIPTION

The proposed device on Si substrate comprises of a periodically patterned c-axis oriented ZnO film positioned in the spaces of IDT structure, which resembles periodically placed BAW resonators excited with lateral electric field. Applying RF signal to IDT generates electric field that cuts through the ZnO pattern resulting in the excitation of dominant transverse BAW in each piezoelectric ZnO pattern, and the BAW couples acoustically with substrate resulting in the generation of surface waves. The type of surface mode generated can be either vertically or transversely polarized based on the orientation of ZnO and the type of BAW excited in ZnO [12]. The efficiency of mutual transduction of BAW and SAW depends on the acoustic impedance of piezoelectric and substrate materials as well as the wavelength of SAW and BAW [13-16].

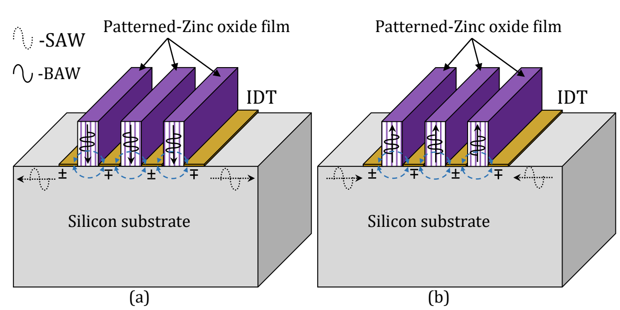

Fig. 1. 3D schematic of mutual transduction of transverse BAW and SAW in the proposed periodically patterned-ZnO/Si structure. (a) BAW to SAW conversion, and (b) SAW to BAW conversion.

III. Simulation and Results

Two dimensional (2D) model is considered for the investigation of characteristics of surface waves generated in patterned-ZnO/Si and patterned-ZnO/SiO_2/Si configurations. Since *c*-axis oriented ZnO exhibits minimal shear coupling coefficient along *c*-axis vis-à-vis insignificant existence of shear horizontal surface modes [17], the 2D model is sufficient to obtain the characteristics of SAW generated in the structure. Uniform IDT with metallization ratio of 0.5 and λ = 8 μm is considered and located on the top surface of the substrate. ZnO thin film of thickness h_{ZnO} is patterned along the aperture of IDT to fill spaces between fingers. Perfectly matched layer (PML) considered at the bottom of the silicon substrate acts as an absorbing medium to suppress unwanted responses due to acoustic reflections from bottom surface of the substrate and fixed boundary constrain is applied to the bottom surface of PML [17].

The result shows the generation of surface wave due to acoustic coupling of various modes of transverse BAW in ZnO pattern. The generated surface mode is represented as VP_{T0}, which means vertically polarized surface mode in the substrate due to the acoustic coupling of 0th transverse BAW in ZnO pattern. The displacement profile of surface mode VP_{T1} generated in the structure is shown in Fig. 2(a). The displacement profiles and characteristics of all surface modes generated in the structure are vividly detailed in our previous publication [17].

The dispersion characteristics of surface modes generated in the patterned-ZnO/Si configuration are shown in Fig. 2(b-d). The results show that the surface mode VP_{T0} at h/λ = 0.13 exhibits maximum K^2 of 8.37% which is 2.5 times greater than the maximum coupling coefficient in conventional SAW devices fabricated with ZnO film on silicon substrate [18]. The surface mode VP_{T1} exhibits unique characteristic of high phase velocity (5272 m/s) and high coupling coefficient (6.4%) with TCF of -14.7 ppm/°C and K^2 is increased by a factor of 1.8 as compared to reported conventional thin film ZnO/IDT/Si SAW device [18]. Fig. 2 (e-g) depict the characteristics of surface modes generated in the patterned-ZnO/SiO_2/Si configuration with SiO_2 film thickness to wavelength ratio (h_{SiO2}/λ) of 0.2.

The dispersion characteristics of patterned-ZnO/SiO_2/Si show decrease in coupling coefficient values compared to patterned-ZnO/Si, due to the large acoustic impedance difference between ZnO pattern and SiO_2, however the TCF characteristics are improved significantly. Interestingly, the phase velocity of VP_{T2} mode varies minimally over a wide range of h_{SiO2}/λ (0.12–0.3) with a K^2 of 1.26% and TCF < -1 ppm/°C.

Two-port SAW resonators are designed with patterned-ZnO/Si and patterned-ZnO/SiO_2/Si configurations using equivalent circuit model [19]. The number of finger pairs and the aperture length of IDT are chosen in such a way that the resistance of IDT matches with the source and load impedances of 50 Ω.

IV. Device Fabrication

As aluminum is reactive with the etchants used for ZnO patterning, we considered gold (100 nm) for IDT structure and chromium (10 nm) for better adhesion of gold with silicon substrate. (002) oriented ZnO films are deposited over the

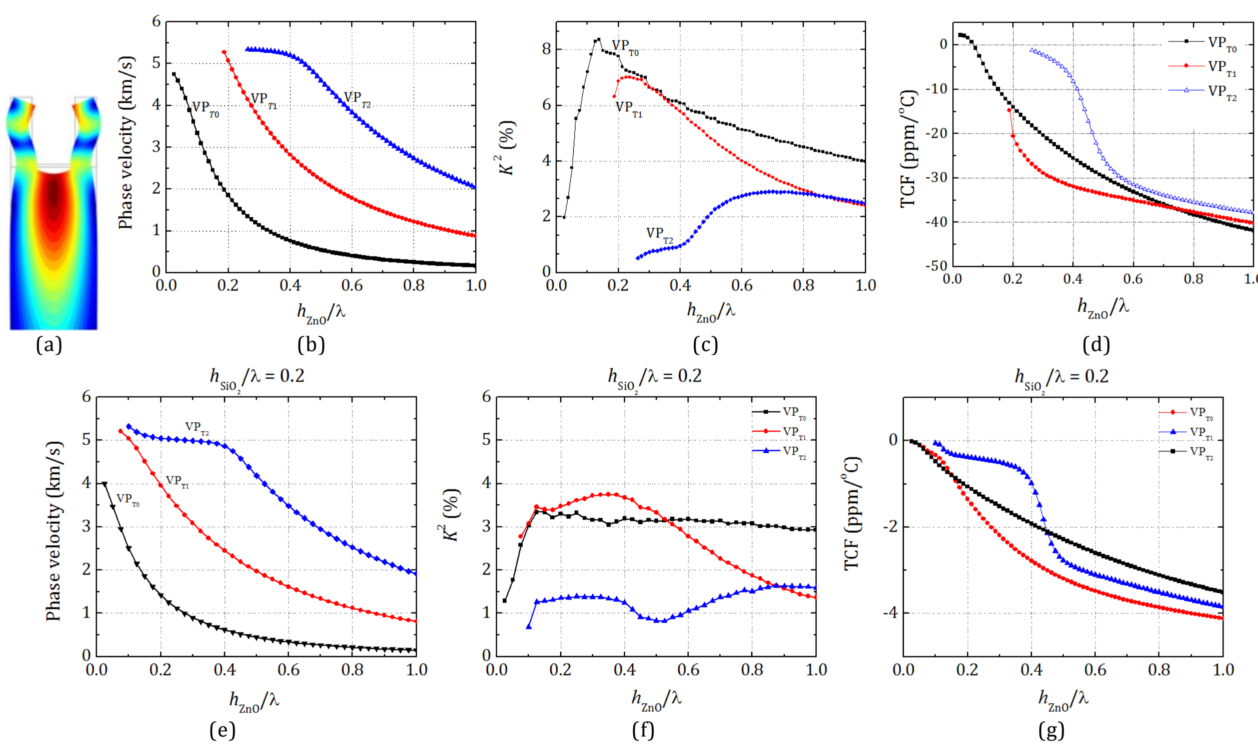

Fig. 2. (a) Displacement profile of VP_{T1} surface mode generated in the silicon substrate due to the acoustic coupling of 1st higher order transverse mode in ZnO pattern, (e-g) Phase velocity, K^2 and TCF dispersion characteristics of various surface modes generated in the patterned-ZnO/Si structure, and (d-f) dispersion characteristics of patterned-ZnO/SiO_2/Si structure.

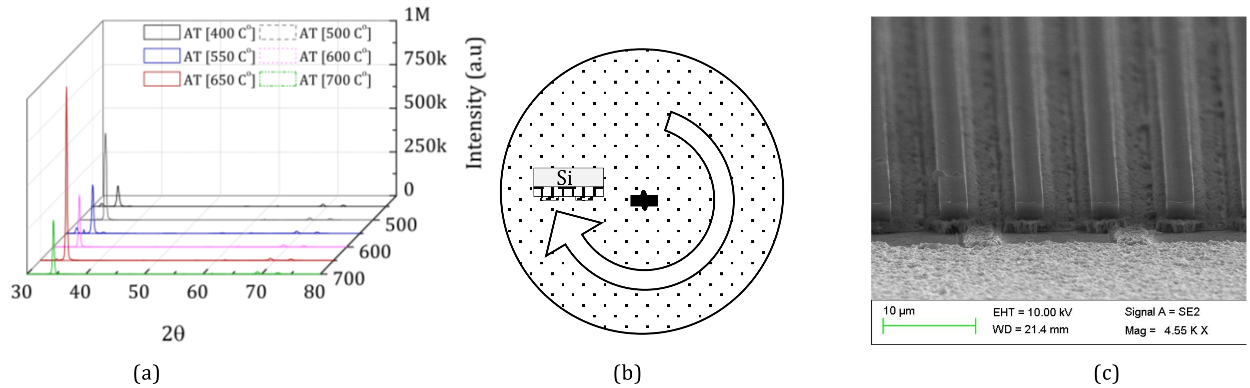

Fig. 3. (a) XRD analysis of ZnO film on silicon substrate annealed at different temperatures, (b) top view illustration of ZnO etching with convection flow using magnetic stirrer, and (c) SEM image of patterned ZnO structure on actual device.

samples using 2 inch commercial sputtering target of 99.99% pure ZnO using RF sputtering system with argon flow of 20 sccm. The ZnO film depositions are carried out to obtain thicknesses in range of 3.8– 4.3 µm and 3–3.2 µm for devices on silicon and silicon with oxide film respectively. The annealing temperature is optimized through various trial runs on test samples at different temperatures. XRD analysis is carried out on all the test samples to validate the orientation of ZnO as well as to find the optimum annealing temperature. The XRD results of all test samples are shown in Fig. 3 (a). The intensity peak observed at 34.4° confirms the (002) orientation of ZnO film and a relative maximum intensity value of the peak is observed at 650℃, the optimum temperature for annealing the deposited ZnO films.

The critical part of the fabrication process is the patterning of ZnO film using wet etching process, since the device performance is precisely determined by the dimensions and positioning of ZnO pattern. Variety of chemical recipes and different photoresists are examined to obtain desired ZnO pattern, that requires dominant vertical etching and less lateral etching. Based on the initial trials and reported literature [20], to enhance the vertical etch rate of ZnO, a convection flow of the etchant solution perpendicular to the sample surface is employed using mechanical stirring and the etching process with convection flow is illustrated in Fig. 3(b). Dilute acetic acid of 0.2 M and SiO_2 hard mask on ZnO film along with conventional flow of speed 1.6 m/s is the best choice for desired ZnO pattern and also suitable for bulk processing of devices. Overall fabrication process involves only two UV lithography steps one for IDT development and the other to have a hard mask for the patterning of ZnO film. The SEM image of the actual two port SAW resonator is shown in Fig. 3 (c).

V. Device Characterization

S-parameters of the fabricated patterned-ZnO/Si SAW resonators are obtained using network analyzer (Agilent E8361A) and RF probe station (Cascade Microtech Summit 9000). The following four resonance modes are observed and identified based on the zero crossings in the phase plot. Mode 1 at 92.93 MHz with an insertion loss (IL) of -26.25 dB, Mode 2 at 136.034 MHz with IL -30.94 dB, Mode 3 at 285.12 MHz with IL -29.72 dB and effective coupling coefficient (k^2_{eff}) of 15.16%, and Mode 4 at 318.61 MHz with IL -31.43 dB. Mode 1, Mode 2, Mode 3 and Mode 4 correspond to VP_{T0}, VP_{L0}, VP_{T1}, and VP_{T2} respectively, identified through the simulation of two port SAW resonator on silicon substrate as fabricated. The reason behind the significance of VP_{L0} mode is the shift of ZnO pattern during fabrication, which leads to increase in-line

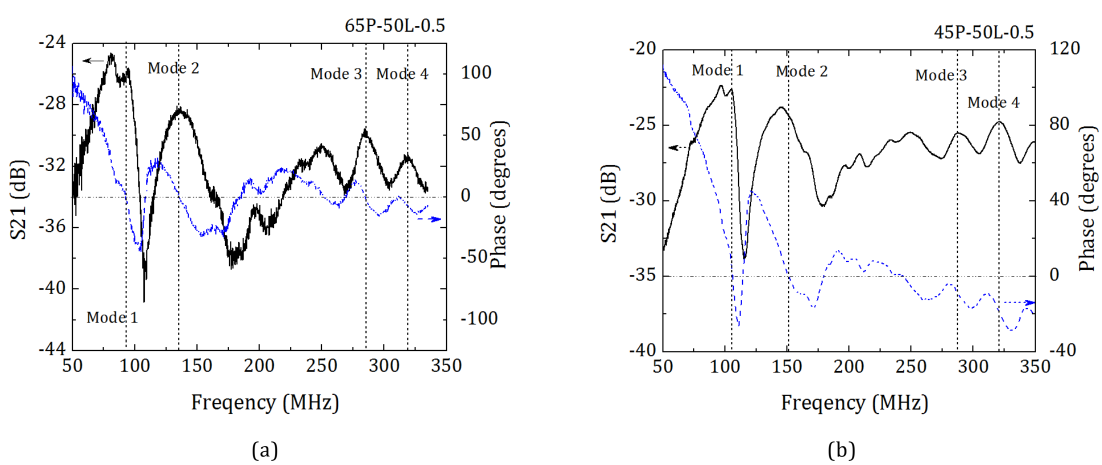

Fig. 4. (a) S21 magnitude and phase plots of tested two port SAW resonator on plain silicon wafer without an oxide layer and the resonance modes are identified through zero crossings in the phase plot and (b) S21 characteristics of two port SAW resonator fabricated on silicon substrate with an oxide thickness of 1.73 µm.

electric field along the ZnO pattern and results in strong perturbation of longitudinal modes in the pattern which couple acoustically to the silicon substrate to generated dominant VP_{L0} mode. As the ZnO pattern aligns more towards and onto the IDT, the VP_L modes become predominant [14-15].

S21 characteristics of patterned-ZnO/SiO_2/Si two port SAW resonator show Mode 1 at 106.063 MHz with IL -22.73 dB, Mode 2 at 145.344 MHz with IL -23.77 dB, Mode 3 at 288.220 MHz with IL -25.47 dB, Mode 4 at 320.840 MHz with IL -24.74 dB. From the S21 characteristics of both the devices, it is evident that the oxide film supports the wave guiding of generated surface modes and also reduces the electromagnetic feed-through between input and output IDTs.

VI. CONCLUSION

Transduction of surface waves on silicon substrate by employing transverse BAW in pattern-ZnO has been validated through simulation and experiments. The obtained results show the excitation of surface wave with unique nature of high coupling coefficient and high phase velocity. The effective coupling coefficient of patterned-ZnO/Si structure is significantly improved in comparison with the reported hybrid SAW/BAW devices. Employing the SiO_2 film in patterned-ZnO/Si structure decreases the coupling coefficient however it improves the TCF characteristics and also reduces the electromagnetic feed-through. The experimental results are promising and the performance can be improved with better fabrication technology. In addition, the proposed SAW resonators are viable for the monolithic integration with CMOS circuits and bulk manufacturing.

VII. ACKNOWLEDGMENT

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