A Reference Book of

RECENT TRENDS IN SCIENCE AND TECHNOLOGY

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Dr. Siddheshwar D. Jadhav

Published by Deccan Education Society's Willingdon College, Sangli

Prarup Publication, Kolhapur

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ISBN Number: 978-81-948061-9-6

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(ISBN): 978-81-948061-9-6

1st Edition: 2022

(Publication Year)

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Publisher : Prarup Publications, Kolhapur, Maharashtra, India.

International Standard Book Number (ISBN): 978-81-948061-9-6

3. Electronics (EL)

EL-04 FEM Analysis of CMOS Compatible SAW Resonator For 2.45 GHz ISM Band Wireless Application.

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Abstract:

In this paper, CMOS compatible $ZnO/SiO_2/Si$ multilayer structures with different thicknesses of ZnO and SiO_2 are discussed and explained. This study investigates the use of buried IDT SAW device structure i.e. $ZnO/(IDT)/SiO_2/Si$ to increase coupling coefficient (K^2) and phase velocity (v_p) for Rayleigh mode .Zinc oxide (ZnO) has been used as a piezoelectric material and aluminium (Al) is chosen as an IDT electrode material. The $ZnO/(IDT)/SiO_2/Si$ structure was simulated using the two-dimensional finite-element method (2D-FEM). Based on simulation and study of SAW propagation characteristics like electromechanical coupling co-efficient and phase velocity are optimized for the 2.45GHz ISM band wireless application.

Keywords: SAW, ZnO, Multilayered, ISM band, Wireless application.

1. Introduction:

The SAW device has created immense applications in the field of mobile communication, such as delay lines, band pass filters, resonators, and duplexers. Typical SAW devices consist of metal interdigital transducers (IDTs) fabricated on a piezoelectric substrate. The IDT structure converts an electrical signal to an acoustic wave, which then propagates along the piezoelectric material. The piezoelectric substrate and IDT period mostly decide the resonance frequency of the SAW device. The resonance frequency dependence can be described by $f = v*\lambda$, where v is the acoustic velocity in the piezoelectric material and λ is the size of the period IDTs [1, 2]. SAW device parameters like quality factor (Q-factor), insertion loss (IL), electromechanical coupling factor (K^2), and phase velocity (vp) depend both on the properties of the substrate and the design of IDTs [3].

Conventional surface acoustic wave (SAW) devices are based on traditional bulk piezoelectric materials like lithium tantalite ($LiTaO_3$), lithium niobate ($LiNbO_3$), langasite ($La_3Ga_5SiO_{14}$), and quartz (SiO_2). These bulk piezoelectric materials suffer from their relatively low performance and are incompatible with integrating monolithic CMOS technology. However, CMOS compatibility and performance of SAW devices can be improved significantly by thin film technology [4] . In thin film technology, it is possible to combine high-velocity piezoelectric substrate materials like lithium tantalite ($LiTaO_3$), lithium niobate ($LiNbO_3$), and quartz (SiO_2) with non-piezoelectric substrates, such as Si, SiC, sapphire, and diamond, with a piezoelectric thin film. Zinc oxide (ZnO) is a very popular piezoelectric thin-film material because of its high strength piezoelectric coupling coefficient, CMOS compatibility, and ease of fabrication [5]. Nowadays, the 2.45GHz ISM band has received special attention to be used for Long Range (LoRa) and IoT wireless connectivity for medical wearable applications. It offers advantages such as small antenna size, high available bandwidth, and the availability of a large number of wireless technology standards such as Bluetooth, Zigbee, and Wi-Fi [6].

In this work, a buried IDT configuration with the multilayer $ZnO/SiO_2/Si$ structure was proposed for a 2.45GHz SAW resonator device.The effects of different ZnO and SiO2 film thicknesses on the resonance frequency and electromechanical coupling coefficient are analysed with the finite element method in COMSOL 5.5 Multiphysics software.

2. Device Design, Model And Simulation Method

2.1. Saw Device Design

The generation of SAWs is govern by equation as

$$\nu\rho = \lambda * f0 \tag{1}$$

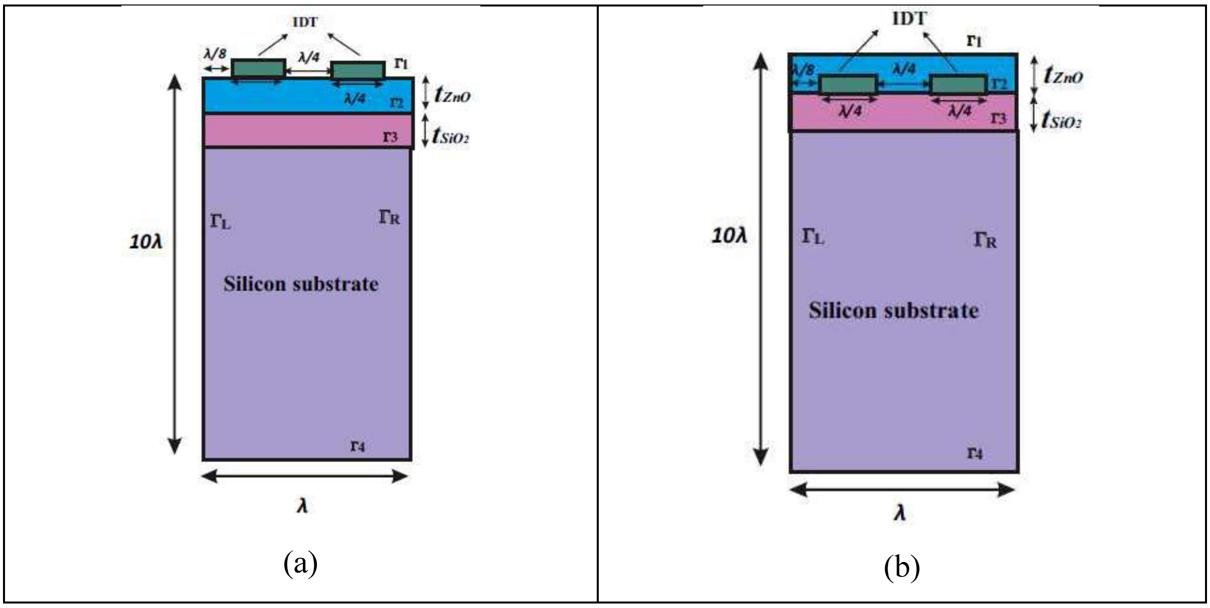

Figure 1. 2D geometry of the periodic unit cell used in Finite Element Method (FEM) simulation for (a) conventional IDT electrodes (IDT)/$ZnO/SiO_2/Si$ structure (b) buried IDT ZnO/(IDT)/SiO_2/Si structure electrodes.

where vρ is the wave acoustic velocity through the piezoelectric material, λ is the period of the metallic IDTs electrodes, and f0 is the applied radio frequency (RF) signal to an IDT. The width *w* of each finger of the metallic IDTs is a quarter of the wavelength λ ($w= \lambda/4$).

In this work, the vρ is 3600 m/s for a c-axis ZnO piezoelectric substrate. So, the wavelength (λ) for 2.45GHz ISM band frequency is calculated as

$\lambda = 3600/2.45*10^9 = 1.469\mu m$

The width of metallic IDT is given by

Width = $\lambda/4 = 0.36725\mu m$

2.2. Saw Device Model And Simulation Method

In SAW device model, the propagation is governed by differential equations. These equations must be solved along with design problems, including the geometric complexity of the device, the material properties, and the boundary conditions. The FEM provides, numerical solutions defined by associated differential equations. The couple piezoelectric constitutive equations (2) and (3) describe the relationship between the stress (T), strain (S), electric field (E), and electric displacement (D) of piezoelectric solid materials. [7, 8] .

$$T= [c_E] [S] - [e]E \quad (2)$$

$$D= [e][S] + [\varepsilon s]E \quad (3)$$

Where T represents the stress vector, S is the strain vector, E is the electric field vector, and D the electrical displacement vector. C_E, e, and εs are elasticity matrix, piezoelectric stress constant and dielectric permittivity constant, respectively. In this study, COMSOL Multiphysics uses the piezoelectric constitutes equation to solve the stress-charge problem using the finite element analysis method [[7, 8].

In this contribution, the excitation and propagation characteristics of the SAW device in the multilayer composite structure of $ZnO/SiO_2/Si$ were investigated theoretically by finite element (FEM) analysis.

In general, SAWs require a large number of uniform interdigital electrodes for transduction from one type of energy to acoustic energy. This uniform periodic IDT with a metallization ratio of 0.5 allows us to model the device using half the spatial period of the IDT using periodic boundary conditions [2].

Figure 1 depicts the two-dimensional (2D) cross-section schematic of the SAW device built by the composted ZnO structure, where t_{ZnO}, t_{Al}, and t_{SiO2} denote ZnO thickness, Al electrode thickness, and SiO_2 thickness, respectively.Eigen frequency analysis was used to determine the resonance frequencies and anti-resonance frequencies for Rayleigh modes of deformation in the multilayer system. The material constants of ZnO film, dielectric SiO_2, and Si substrate used in the device model were taken from literature [9, 10], and given in Table 1.The mechanical and electrical periodic boundary conditions that have been set in both the x- and y-directions to simulate the infinite length of the device model are listed in Table 2.

Table 1. Material properties used in the simulation [9] [10].

	Symbol	ZnO	SiO_2	Si
Density(Kg/m^3)		5610	2200	2330
Elastic Constants(GPa)	C_{11}	1.57	78.5	166
	C_{12}	0.89	16.1	64
	C_{13}	0.83	16.1	64
	C_{33}	2.08	78.5	166
	C_{44}	0.38	31.2	80
	C_{66}	0.34	31.2	80
Piezoelectric Constant(C/m^2)	e15	-0.59	-	-
	e31	-0.61	-	-
	e33	1.14	-	-
Dielectic Constant(10^{-11} F/m)	ε11	3.3468	3.32	10.62
	ε 33	3.3468	3.32	10.62
Poisson ratio		0.33	0.17	0.27

Table 2. Device boundary condition used in the simulation

	Mechanical Boundary Conditions	Electrical Boundary Conditions
Γ1	Free	Zero charge
Γ2, Γ3	Free	Continuity
Γ4	Fixed ground	
ΓL, ΓR	Periodic boundary condition at left side and right side	

The efficiency of the energy conversion between the acoustic signal and electric signal and vice a versa is estimated by the electromechanical coupling coefficient (K^2) parameter and is given with series and parallel resonance frequency [7] as

$$K^2=\frac{\pi^2}{4}\frac{fs-fp}{fs} \qquad (4)$$

where fs and fp are series and parallel resonance frequencies of the SAW structure extracted with Eigenfrequency simulation analysis using COMSOL Multiphysics simulation software.

3. Results And Discussion:

In this section, we study the effect of ZnO film thickness and thickness variation of the SiO_2 buffer layer on the performance of SAW characteristics with a two-dimensional (2D) finite element method (FEM). The device performance of the proposed SAW device has been investigated in terms of the electromechanical coupling coefficient (K^2) and phase velocity.

3.1(IDT)/ZnO/SiO_2/Si Structure

Figure 2a,b displays the (IDT)/ZnO/SiO_2/Si the simulation results of the Phase velocity(Vp) and Coupling coefficient (K^2) of Rayleigh modes in (IDT)/ZnO/SiO_2/Si with varying the normalized thickness of the ZnO film $t_{(ZnO/\lambda)}$. To avoid the mass loading effect, the thicknesses of metallic IDT Al electrodes are kept negligible. As it is shown in Figure 2a, in Rayleigh mode, the phase velocity (νρ) decrease monotonically with the increase of the ZnO thickness. The maximum phase velocity (Vp) of 3729 m/s is obtained at $t_{(ZnO/\lambda)}$ is and it will be reduced below 2700 m/s when the normalized thickness of $t_{(ZnO/\lambda)}$ is more than 0.5. It is observed that, the influence of SiO_2 buffer layer thicknesses on Vp and K^2 for the Rayleigh mode is negligible.

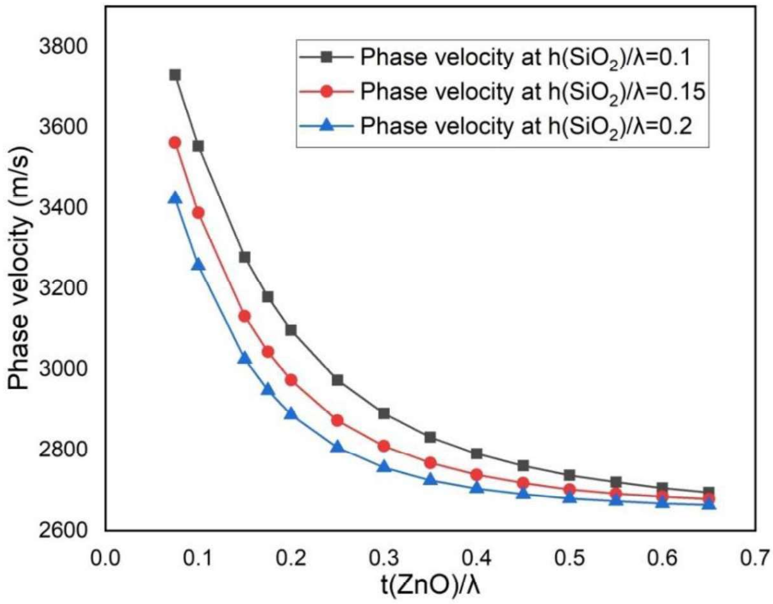

Figure 2a: Simulated phase velocity of the (IDT)/ZnO/SiO_2/Si structure at different normalized thicknesses of the ZnO film when metallic IDT $h_{Al}/\lambda = 0.05$.

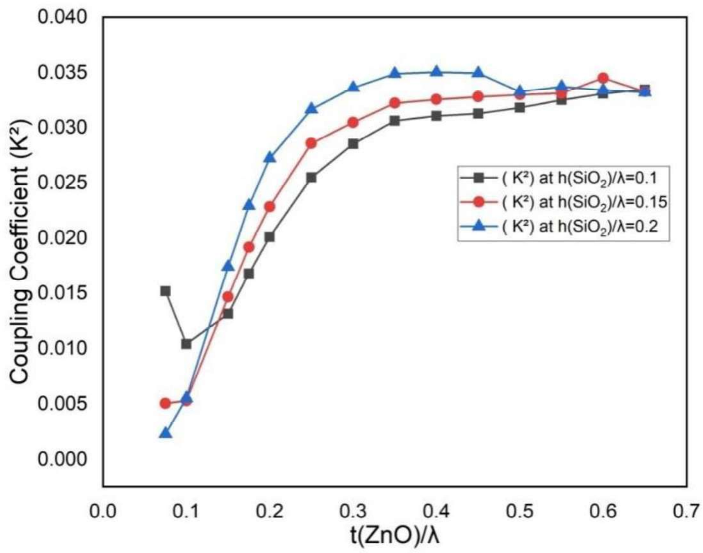

Figure 2b.Simulated coupling coefficient (K^2) of the (IDT)/ZnO/SiO_2/Si structure at different normalized thicknesses of the ZnO film when metallic IDT $h_{Al}/\lambda = 0.05$.

3.2. ZnO/(IDT)/SiO2/Si Structure

To investigate the mechanisms behind the improvement of coupling coefficient (K^2) for the Rayleigh mode in buried IDTs ZnO/(IDT)/SiO_2/Si structure , propagation characteristic of SAW device were simulated. In buried IDT electrode structure, IDTs are embedded under the piezoelectric layer. It is observed from Figure 3a , the phase velocity of buried IDTs ZnO/(IDT)/SiO_2/Si structure has same characteristic nature of conventional IDT saw device, but buried IDT structure exhibits a larger K^2 as compared to conventional structure. The enhancement of K^2 can be realized as compared to conventional structures, due to energy degradation in non-piezoelectric IDT electrodes being decreased while acoustic energy is efficiently excited in piezoelectric films [11].

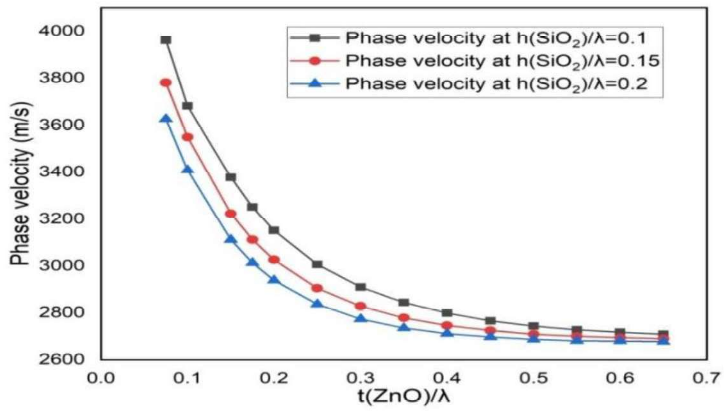

Figure 3a.Simulated phase velocity of the ZnO/(IDT)/SiO_2/Si structure at different normalized thicknesses of the ZnO film when metallic IDT $h_{Al}/\lambda = 0.05$.

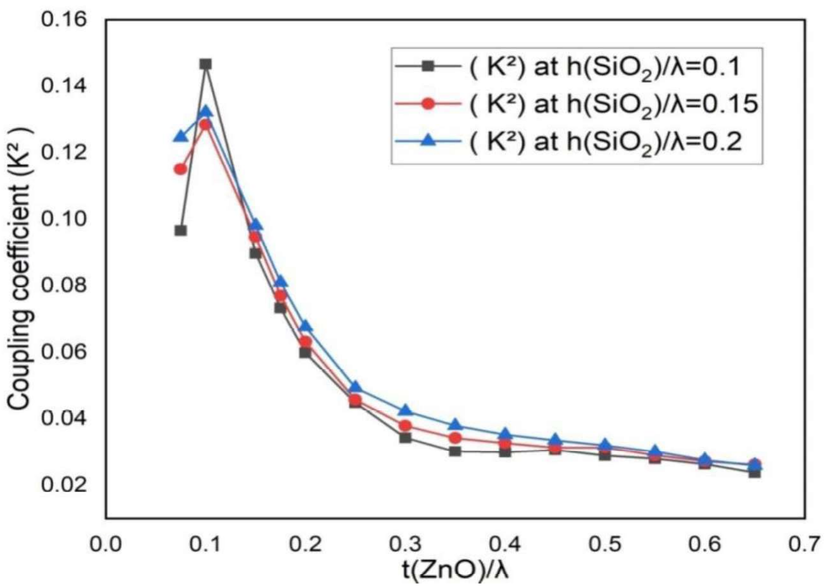

Figure 3b. Simulated coupling coefficient (K^2) of the ZnO/(IDT)/SiO_2/Si structure at different normalized thicknesses of the ZnO film when metallic IDT $h_{Al}/\lambda = 0.05$.

4. Conclusions:

In summary, we proposed a buried metallic IDT configuration which significantly improve the coupling factor (K^2) of Rayleigh mode in ZnO/(IDT)/SiO_2/Si structure. We used 2D FEM to optimize SAW device parameters like ZnO normalized thickness, SiO_2 normalized thickness, and metallization ratio for 2.45GHz ISM band frequency using COMSOL Multiphysic Software. We found that a buried IDT configuration gives the maximum K^2 value of 0.147%, which is the best performance compared to the conventional SAW structure. It is investigated that, the influence of SiO_2 dielectric layer thicknesses on phase velocity (vp) and coupling coefficient (K^2)for the Rayleigh mode is negligible. The enhanced performance promises to meet the requirements of various RF fields, such as the fabrication of high-frequency and wideband SAW devices with miniaturized size.

5. Acknowledgements:

This work has been financially supported by Shivaji University, Kolhapur under the Research Initiation Scheme SU/C&U.D Section/54/562.

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