Temperature-Compensated Structure For Saw Pressure Sensor In Very High Temperature

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***Abstract*—This paper concerns the design and the analysis of a Surface Acoustic Wave (SAW) pressure sensor that is capable to work in high temperature (up to 800^0C) environment. Novel structures of the device are also presented for self-temperature compensation. Special attention is made on the different possible multilayer structures that could be used, the behavior of the sensor, the electromechanical coupling factor, the wave velocity as well as the required RF matching circuit. These parameters are critical issues for this special SAW sensor.**

I. INTRODUCTION

Surface Acoustic Wave (SAW) devices play a key role not only in today's telecommunication systems but also in many industrial applications. Although the telecommunication industry is the largest user of these devices, SAW based sensors have many attractive features to be explored. Due to their small size, high sensitivity to external physical parameters and from the properties of the film deposited on the SAW substrate, they can react very fast to the changes in the environmental conditions. In SAW pressure sensor, the pressure induced static stress and strain, so modified the wave velocity, and, therefore, the frequency. The pressure can be obtained by measuring frequency change. An important characteristic is the linear relationship between the frequency variation and the pressure [4]. Besides, the effect of frequency variation by temperature change [5], [6] is derived from that properties of materials are affected by temperature variation. For pressure application, this sensitivity must be avoided. Usually, temperature compensation can be done by using one port InterDigital Transducer (IDT) and at least three reflectors to create several propagation paths of different lengths [7], [8].In this work, we have developed a pressure sensor with aluminum nitride (AlN) layer and SiO_2 on a silicon (Si) substrate. The piezoelectric layer AlN is required to generate the elastic wave.

The multilayers structure AlN/SiO2/Si is proposed for self temperature compensation and for applications in very high temperature (up to 800^0C). AlN is chosen because its deposit process is compatible with electronic process and it has good behavior at high temperature.

This paper is organized as follows. Section II presents the design method for SAW device, methods for calculating center frequency, wave velocity, electromechanical coupling coefficient, transfer function as well as self temperature compensated structure for SAW pressure sensor. Results and comments from section II are also introduced in section III. Conclusion is given in section IV.

II. DEVICE DESIGN

A. *The center frequency, wave velocity and electromechanical coupling factor*

The important three parameters of the SAW material, the center frequency, the phase velocity, and the electromechanical coupling factor (K^2) were calculated numerically.

The center frequency is determined by the period of the IDT fingers and the acoustic velocity. The governing equation that determines the operation frequency is

$$f_0 = v_{SAW} / \lambda \tag{1}$$

where λ is the wavelength at f_0, determined by the periodicity of the IDT. For the technology being used in this paper

$$\lambda = p = \text{finger width} \times 4 \tag{2}$$

where the finger width is determined by the design rule of the technology which sets the minimum metal to metal distance, f_0 center frequency of the device, v_{SAW} surface acoustic wave velocity.

The wave velocity and therefore, the frequency are determined by matrix method proposed by Cambel and Jones (1968) and Ingerbrigtsen (1969).

Fig. 1 shows the wave velocity of structure AlN/SiO2(1.3µm)/Si(4µm).

Electrical conditions in the matrix method are used to calculate the electromechanical coupling factor K as follows:

$$K^2 = 2(v_0 - v_s)/v_0 \quad (3)$$

where v_0, v_s are respectively velocities when the plane of IDTs is electrically open or short-circuit.

Figs. 2 and 3 show the electromechanical coupling factor K in different-thickness structures $AlN/SiO_2/Si$.

B. Analytical methods

To analyse the device, some behavior models and Finite Element Method (FEM) are used. Today, with FEM tools, to simulate the complete devices, simulation time would be very large or the necessary computer resources would exceed the available amount. Besides, there is existence of the number of references for behavior models. So, they are used for analysing the device. As the behavior models, the equivalent circuit model, Coupling-Of-Mode (COM) model, and P-matrix model are widely used. The difference in these models is how one period IDT is expressed in a three-port element shown in Fig. 4, where $U_{+/-}(x)$ is the SAW amplitude propagating to the (+/-) x direction; V and I are the applied voltage and current, respectively.

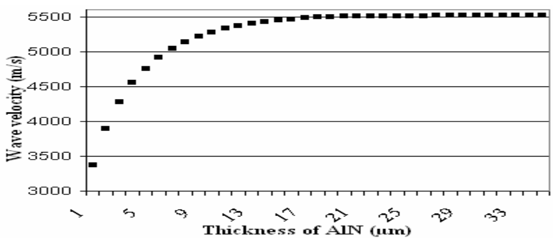


Figure 1. Wave velocity in structure AlN/SiO2(1.3µm)/Si(4µm) with different thicknesses of AlN

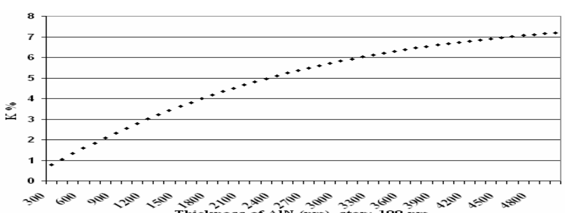


Figure 2. Electromechanical coupling factor in structure AlN/SiO2(1.3µm)/Si(4µm) with different thicknesses of AlN

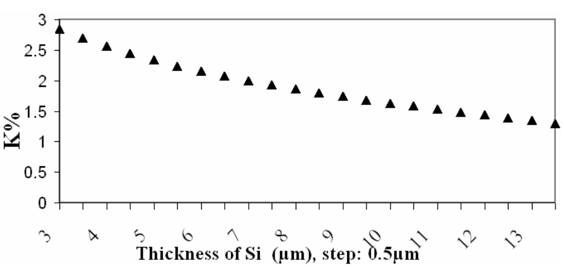


Figure 3. Electromechanical coupling factor in structure AlN(1µm)/SiO2(1.3µm)/Si with different thicknesses of Si

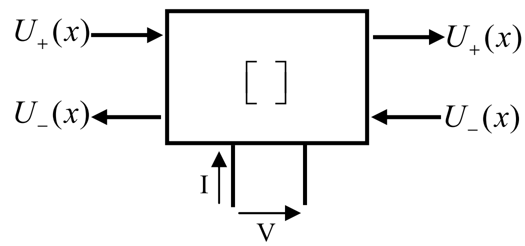


Figure 4. Three-port element for one period IDT

The equivalent-circuit model is chosen because it is simple and it can determine the frequency response, impedance parameters and transfer characteristics of SAW device. This allows the designer to determine the major dimensions and parameters in number of fingers, finger width, aperature, delay line distance.

There are two different circuit models for analysing IDT [9]. Both of them are based on the bulk-wave three-port models originally published by Mason [1]. The crossed field model is selected for the modeling of the devices because it was shown in the literature that the crossed field model yielded better agreement than the experiment when compared to the in-line model when K is small. In our device, AlN is used as piezoelectric layer and K in any our different configurations are less than 7.2% (Figs. 3 and 4).

Each IDT is represented by a three-port network shown in Fig. 5 [9], where

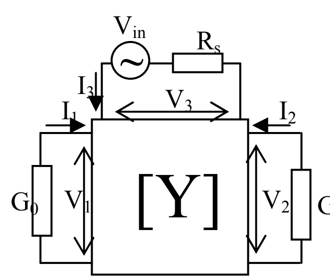
G_0 the electrical characteristic admittance of a one-period IDT, $G_0 = 1/Z_0 = K^2 C_s f_0$ (mho) (4)

Z_0 electrical characteristic impedance;

K electromechanical coupling factor;

C_s static capacitance of one periodic section;

N the number of sections in IDT;



$$[Y] = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{12} & Y_{11} & -Y_{13} \\ Y_{13} & -Y_{13} & Y_{33} \end{bmatrix}$$

$$Y_{11} = -jG_0 \cot g(4N\alpha)$$

$$Y_{12} = \frac{jG_0}{\sin(4N\alpha)}$$

$$Y_{13} = -jG_0 tg\alpha$$

$$Y_{33} = jN(2\omega C_0 + 4G_0 tg\alpha)$$

$$\alpha = \frac{\pi}{2}\frac{f}{f_0}, C_0 = \frac{C_s}{2}$$

Figure 5. Three-port equivalent admittance network representation for an IDT in the crossed field model

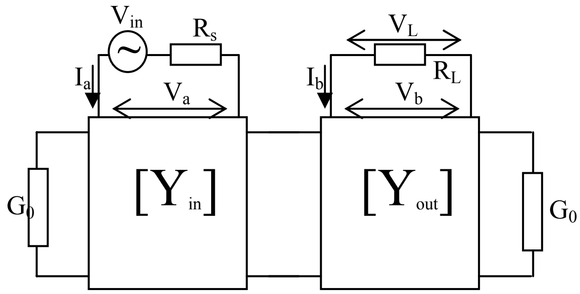


Figure 6. Equivalent circuit for SAW device

Applying the circuit theory for the current voltage relations on input and output, transfer function is calculated for SAW device (Fig. 6) and is modeled in Matlab

$$H(f)=\frac{V_L}{V_{in}}=\frac{y_{ab}R_L}{(1+y_{aa}R_s)(1+y_{bb}R_L)-y_{ab}^2R_sR_L} \quad (5)$$

Where

$$y_{aa}=j2\pi fC_T+G_a(f)$$

$$y_{bb}=j2\pi fC_T^{out}+G_a^{out}(f)$$

$$y_{ab}=8NMG_0\frac{\sin x}{x}\frac{\sin y}{y}e^{j\pi(1-(N+M)\frac{f-f_0}{f_0}}$$

$$G_a(f)=8N^2G_0\left(\frac{\sin x}{x}\right)^2;x=N\pi\frac{f-f_o}{f_0}$$

$$G_a^{out}(f)=8M^2G_0\left(\frac{\sin y}{y}\right)^2;y=M\pi\frac{f-f_o}{f_0}$$

$$C_T=NC_s;C_T^{out}=MC_s$$

N, M the number of sections in input and output IDTs respectively.

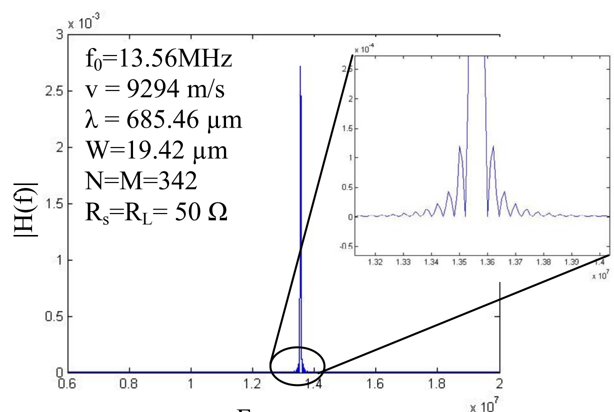


Figure 7. Amplitude of transfer function for SAW device

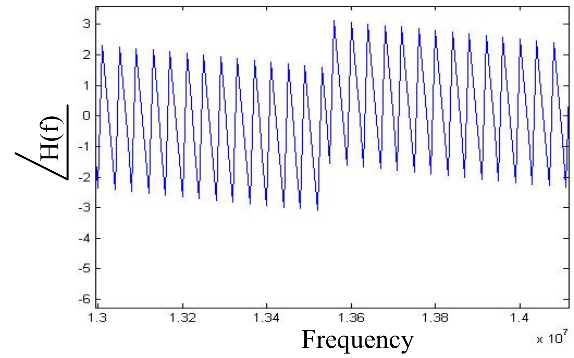


Figure 8. Phase of transfer function for SAW device

C. *Temperature stability*

Temperature stability is a critical issue for SAW sensor. Table I presents the temperature coefficients of AlN, Si and SiO_2. The temperature coefficient of mass density p of Si also is presented in [2]:

$p(T)= p_m -1.69.10^{-4}(T-T_m) - 1.75.10^{-7}(T-T_m)^2$ (g/cm^3) (6)

T_m= 1687 (K), p_m=2.56 (g/cm^3) at T_m (7)

The temperature dependence of Young's modulus of AlN also is presented in literature (Fig. 9).

Both AlN and Si have negative temperature dependence of coefficient elastic constants and mass density. On the contrary, SiO_2 has positive temperature dependence coefficient of elastic constants and negative temperature dependence coefficient of mass density. So, temperature compensated structures of SAW sensor are constructed based on these properties. Our self temperature compensated structure must include multilayers Si, AlN and SiO_2.

From (1), temperature coefficient of frequency (TCF)

$$TCF=\frac{1}{f_0}\frac{df}{dT}=\frac{dv}{vdT}-\frac{1}{D}\frac{dD}{dT} \quad (8)$$

where D distance between 2 fingers which have the same potential.

$\frac{dv}{vdT}\approx\frac{v(t+5^0C)-v(t-5^0C)}{v(t).10}$ is obtained by substituting velocity calculated at temperature t, (t+5) and (t-5).

$\frac{1}{D}\frac{dD}{dT}=\alpha_a$, where α_a is the thermal expansion coefficient of AlN, $\alpha_a=4.2.10^{-6}(^0C^{-1})$ in structure where IDTs are on the AlN surface. So,

$$TCF\approx\frac{v(t+5^0C)-v(t-5^0C)}{v(t).10}-\alpha_a \quad (9)$$

Fig. 10 shows the frequency shift versus temperature change in no pressure applied condition with structures composed of three layers: AlN(1µm)/ SiO2(0.5; 0.7; 0.9; 1.1 and 1.3µm)/Si(4µm). The best self temperature compensated structure can be obtained with AlN(1µm)/ SiO2(1.3µm)/Si(4µm) in which TCF= -0.8 ppm/0C.

To show the importance of self temperature compensated structure in SAW pressure sensor, frequency shift due to a temperature and pressure variation are compared. The pressure dependence of frequency shift is calculated from the perturbation method proposed by H.F.Tiersten [14],[15].

Fig. 11 shows the frequency variation versus pressure in structure AlN(1µm)/SiO2(0.9µm)/Si(4µm). The frequency change versus temperature variation of 500C in structure AlN(1µm)/SiO2(0.9µm)/Si(4µm) is shown in Fig. 12.

TABLE I. TEMPERATURE COEFFICIENTS OF MATERIALS

Temperature coefficients		Si	SiO_2	AlN
Elastic constants ($x\ 10^{-4}\ K^{-1}$)	(1/C11)(dC11/dT)	-0. 53	2. 39	-0. 37
	(1/C12)(dC12/dT)	-0. 98		
	(1/C13)(dC13/dT)	-0. 75	5. 84	
	(1/C33)(dC33/dT)	-0. 53	2. 39	-0. 37
	(1/C44)(dC44/dT)	-0. 42	1. 51	-0. 57
Mass density ($x\ 10^{-6}\ K^{-1}$)	(1/p)(dp/dT)	-2. 6	-1. 65	-13.7

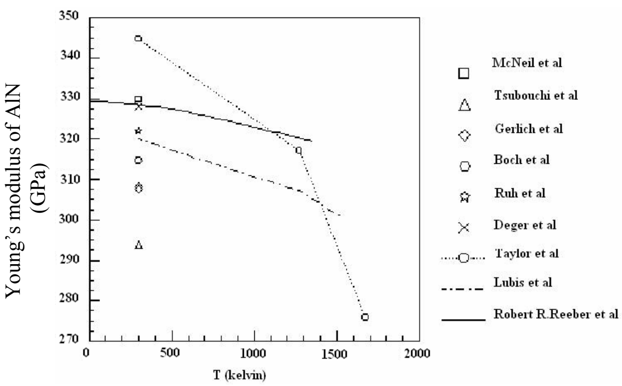


Figure 9. Young's modulus of AlN

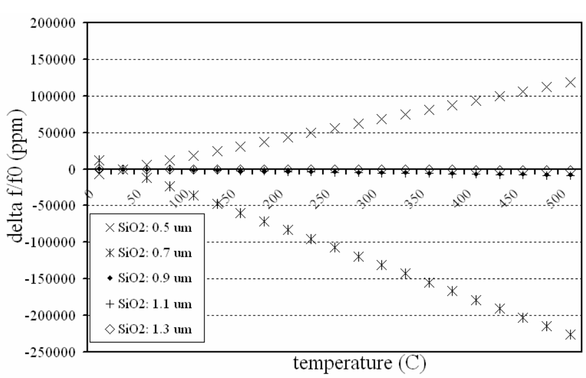


Figure 10. Calculated frequency shift versus temperature change of (0-500^{0}C)

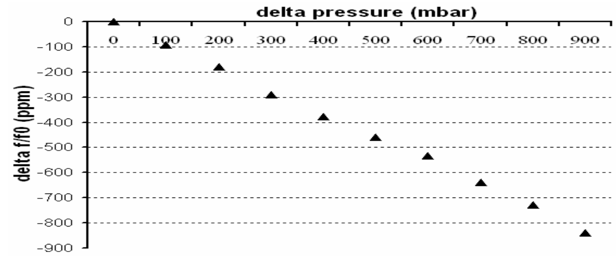


Figure 11. Calculated frequency variation versus pressure, structure AlN(1µm)/SiO2(0.9µm)/Si(4µm)

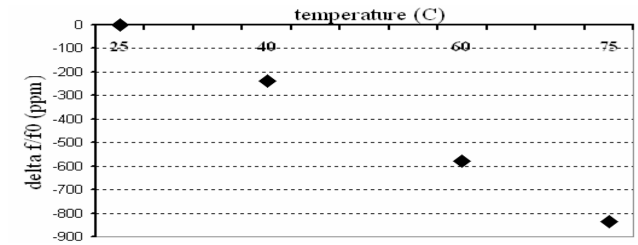


Figure 12. Calculated frequency change versus temperature variation of 500C, structure AlN(1µm)/SiO2(0.9µm)/Si(4µm)

III. RESULTS AND COMMENTS

Figs. 11 and 12 show that frequency shift due to a temperature variation of 50 0C is equivalent to a pressure variation of 0-900 mbar in structure AlN(1µm)/ SiO2(0.9µm)/Si(4µm). So, it is very important to determine the thickness of every layer in multilayers structure for seft temperature compensation used in pressure sensor applications. However, self temperature compensated structure AlN(1µm)/ SiO2(1.3µm)/Si(4µm) has electromechanical coupling factor, wave velocity smaller than no-temperature compensated structure, for instance AlN(1.2µm)/SiO2(1.3µm)/Si(4µm); AlN(1µm)/SiO_2(1.3µm)/Si(3µm) (shown in Figs. 1, 2 and 3). In SAW device, one of the most important purposes in designing SAW device is to increase the center frequency. So, at the same lithographic resolution for fabricating IDT, to increase the center frequency, increasing the SAW velocity is taken into account.

Besides, with self temperature compensated structure, the pressure sensitivity is also considered and compared with another structures. The pressure sensitivity is better with thinner layers thickness by the acknowledged equation:

$$\Delta f \propto \frac{P}{h^2} \quad (10)$$

where P: the pressure, and h: layers thickness.

IV. CONCLUSION

The design, calculation and modeling of SAW sensor are presented. By using three materials AlN, Si and SiO2, a self temperature compensated structure has been obtained with AlN(1µm)/SiO2(1.3µm)/Si(4µm). However, compromising between temperature compensated structure, wave velocity, electromechanical coupling factor and pressure sensitivity is also taken into account.

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