Gas Sensor with SAW Structures

A. Laposa, M. Husak, J. Kroutil and R. Vrba

Department of Microelectronics
Faculty of Electrical Engineering, Czech Technical University in Prague
Technicka 2, CZ – 166 27 Prague 6, CZECH REPUBLIC
husak@feld.cvut.cz

ABSTRACT

This work describes basic concept of chemical sensors based on surface acoustic wave (SAW). The aim is to depict basic physical concept and simulation rough draft for this type of sensors. By integrating a SAW measurement platform with a selective sensing layer, a desired chemical microsensor is constructed, which provides some of the functionality of an analytical instrument, but with extraordinary reduced cost, size, and power consumption.

The objective of this paper is presents gas sensors based on one-port and two-port interdigitated metal structures. The impulse response model is used for determination of IDT parameters and first order investigation, the transient analysis is performed on the devices to study the acoustic wave propagation and characterize the device in time and frequency domain. The effects of the various interdigital transducer (IDT) design, intermediate layer thickness and chemical sensitivity structure on the propagation characteristics is also investigated. Also, we present some results obtained from the device using automated measurement system for SAW oscillator frequency measurement.

Keywords: sensor, Gas sensors, SAW, IDT structure, measurement, oscillator.

1 INTRODUCTION

Surface acoustic wave (SAW) devices are microelectromechanical systems (MEMS) and as the name suggest, these waves travel very close to the surface of a piezoelectric substrate (to distance of one wavelength from the surface of the substrate). SAW's utilise Rayleigh waves, named after Lord Rayleigh [1], which in 1885 studied and correctly analytically described the propagation of earthquake waves on earth's surface. A mechanical wave is generated when an alternating electrical signal is applied to an interdigitated transducer (IDT) that is placed on top of a piezoelectric substrate. This mechanical wave propagates through or on the surface of the material, and it can be picked up and converted back into electrical signal by using another IDT placed in the path of wave propagation. Any changes in between the two IDTs will cause certain amount of attenuation and delay in the wave propagation and can then be correlated to the corresponding desired chemical element (which always has a certain amount of physical quantity) binded with the coated selective layer. And this is root idea of SAW device for sensing applications such as detecting physical, chemical and biochemical quantities.

SAW devices have been utilised in gas sensing applications since end of 70s [2], thus a lot of work has been done and in general, SAW sensors suffer from insufficient sensitivity and detection limit. However, we are looking to opposite direction, detect species of interest below the concentration levels and SAW sensors with reachable detection limits in the picogram range are almost ideal. In its simplest form, a SAW device appears as two comb-like metal structures deposited on a piezoelectric crystal surface (Figure 1) and chemical sensing is reached by detecting the mass loading when and thus perturbing the surface acoustic wave channel.

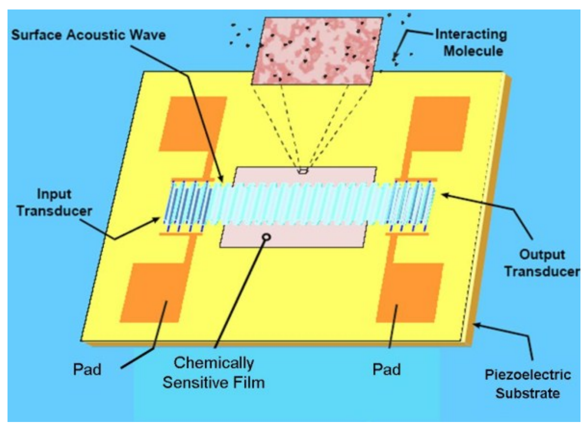


Figure 1: SAW device structure [3]

2. INTERDIGITAL TRANSDUCERS (IDT)

Two pair of symmetrical interdigital transducer (IDT) - invented by White/Voltmeter in 1965 - are the most usually used design for generating and receiving waves by exploiting the piezoelectric effect of the substrate as illustrated in figure 2. Design is quite simple, just two sets of closely spaced metal electrodes on a piezoelectric substrate. SAW acoustic wavelength λo is given by

$$\lambda_0 = \frac{v}{f_0} \quad (1)$$

where v is SAW velocity and fo is fundamental operating frequency. An electrode finger width is in a SAW IDT typically $\lambda o / 4$.

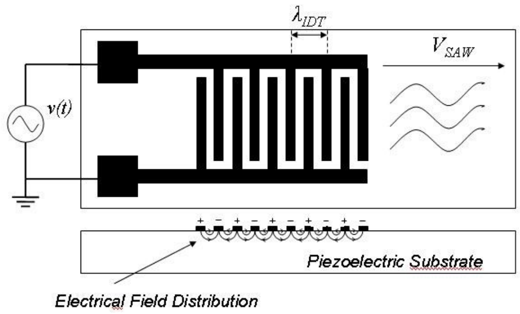


Figure 2: Structure of an IDT [3].

In both cases maximum coupling strength for

$$\lambda_{SAW} = \frac{v_{SAW}}{f} = 2p.....(\sim 1...10\mu m) \quad (2)$$

The metallization ratio

$$\eta = \frac{h}{(h+p)} \quad (3)$$

where h is the electrode width and p the gap between consequence electrodes - Figure 3.

The basic relation for SAW express that frequency shift is proportional to coupling coefficient, mass change and square of resonance frequency

$$\Delta f = -k f_0^2 \Delta m \quad (4)$$

where k electromechanical coupling coefficient, f_0. resonance frequency and Δ m. mass change. For example, if we assume the area 1 mm^2 & f_0 = 1 GHz , we will get $k f_0 \sim 10^7$ / kg, which implies to that 1 ppm of f deviation, this is equal to resolution 0.1 pg.

Most utilized interaction in SAW sensor applications is relation of SAW and mass loading – in other words, response due to changes in area/mass (mass/area) on the device surface. In the limit of a thin film the sensor is mass loaded and a frequency shift that depends on the mass of the layer is found. The mass of the layer is determined from the Sauerbrey equation.

$$\Delta m = m_0 \Delta f / f_0 \quad (5)$$

where m_0 is the mass of the electrode region of the resonator, f_0 is the initial natural frequency of the resonator and Δf the frequency shift after deposition. It is known that,

$$\frac{\Delta v}{v_0} = -c_{material} f_0 \rho_s \quad (6)$$

and thus, SAW incorporated in an oscillator loop

$$\frac{\Delta f}{f_0} = -c_{material} f_0 \rho_s \quad (7)$$

$$\Delta f = -c_{material} f_0^2 \rho_s \quad (8)$$

where $c_{material}$ is specific material constant, ρ_s density of substrate, Δv is velocity shift, v_0 is basic SAW velocity.

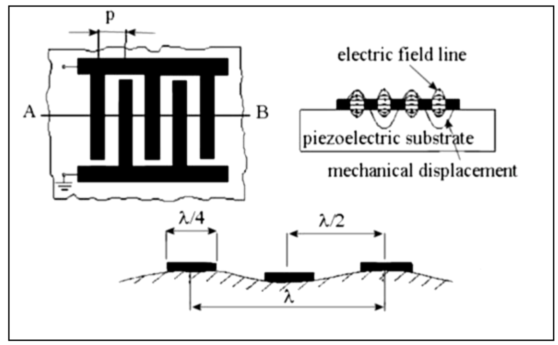


Figure 3: Top view on the right side and cross section view A-B on the left side [4].

The maximum frequency possible is determined by electrode width. At the centre frequency the electrodes have spacing λ/2, and width typically λ/4. Changes properties of chemical sensitive thin film perturb the mechanical properties of the wave propagation and its associated electrical field. Hence, this would result in changes in the velocity of acoustic wave propagation and its amplitude. In perturbation theory, these effects are described using the following equation [5]

$$\frac{\Delta v}{v} = \left(\frac{\pi h}{2\lambda}\right) \cdot \left[-\frac{\Delta\rho}{\rho}\left(\left(A_x^2 + A_y^2 + {}_z^2\right)\rho \upsilon_0^2\right) + \left(\frac{\left(1 - \frac{\Delta C_{44}}{C_{44}}\right)^2}{1 - \frac{\Delta C_{11}}{C_{11}}} - 1 \right) \left\{ 4A_z^2 \frac{C_{11}}{C_{11}} \right\} \right] \quad (9)$$

where υ_0 represents the velocity of the SAW in the particular piezoelectric substrate, Ax, Ay and Az the normalized mechanical displacements in the x-, y- and z-directions, respectively, C_{11} and C_{44} are the elastic constants of the film, h the thickness of the thin film, λ the wavelength of the SAW and ρ is the density of the film [5]. The values of the above elastic constants and density for example for Palladium thin film are as follows: C_{11}=190GPa, C_{44}=40GPa and ρ=12,023kg/m3 [5].

3 OSCILATOR CIRCUIT

SAW gas sensor testing can be performed using the oscillator circuit, Figure 4. The circuit used for realizing oscillator with commercially available one-port 434MHz SAW resonator can be seen on Figure 5. Single stage RF transistor amplifier has been used. The design uses surface mount components and the oscillators operate at 5V power supply. Tuning of the inductances and capacitors are crucial for the operation of these oscillators. In the one-port oscillator, the tank circuit L3, C3 and C4 are fine tuned by placing a short at the location of the SAW device [6] (in the Figure 5 represented by simplified universal equivalent circuit). The outputs of the oscillators was monitored by using a spectrum analyzer, but can be used also an oscilloscope and a frequency counter.

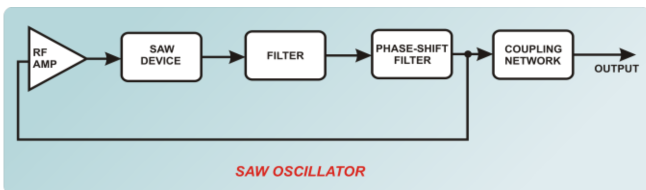


Figure 4: Oscillator block diagram.

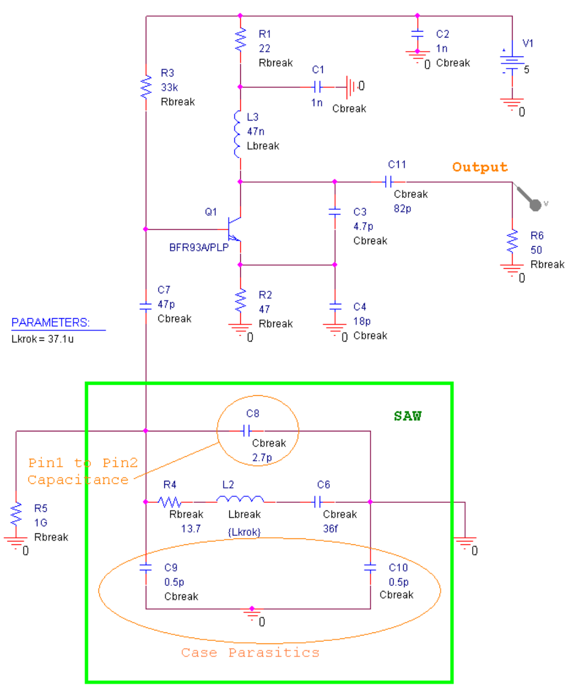


Figure 5: Oscillator circuits with one-port SAW resonator device.

Figure 6 shows PCB with SAW oscillator circuits and fabricated SAW sensors, which is connected to 50Ω input of spectrum analyzer by SMA connector, impedance matching is done by 47nH air coil.

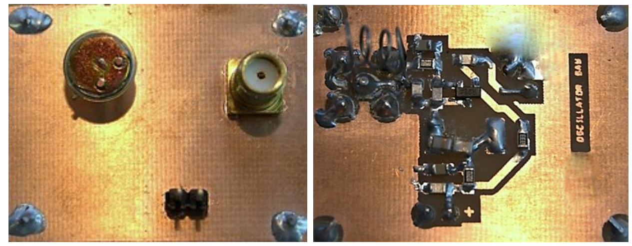


Figure 6: PCB with SAW oscillator circuits and fabricated SAW sensors.

4 SAW STRUCTURES

Surface acoustic wave (SAW) sensors, which are sensitive to a variety of surface changes, have been widely used for chemical and physical sensing. All acoustic wave devices and sensors use a piezoelectric material (PVDF, guartz SiO_2, $LiTaO_3$, $LiNbO_3$, PZT) creates a mechanical stress. Piezoelectric acoustic wave sensors apply an oscillating electric field to create a mechanical wave, which propagates through the substrate and is then converted back to an electric field for measurement.

Two pair of symmetrical interdigital transducer (IDT) are the most usually used design for generating and receiving waves by exploiting the piezoelectric effect of the substrate as is illustrated in Figure 7.

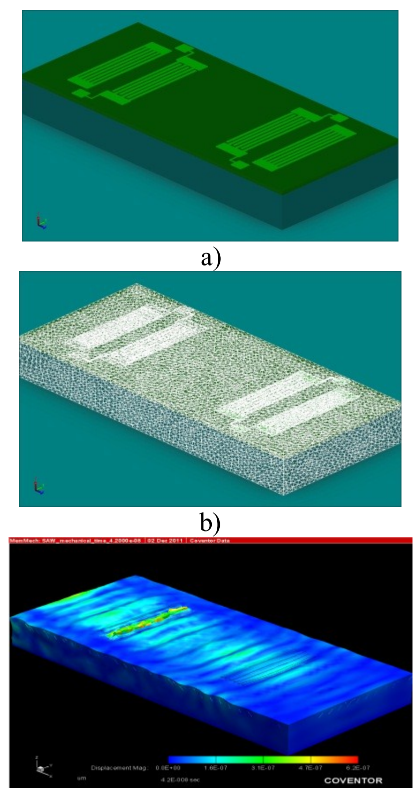


Figure 7: Simplified top view of two port SAW delay line and 3-D graphical represent showing wave propagation from left to right of the structure.

The effects of the various interdigital transducer (IDT) design (one port or two port resonators, two port delay lines), intermediate layer and coating structure on the propagation characteristics is also investigated (see Figure 7 and Figure 8).

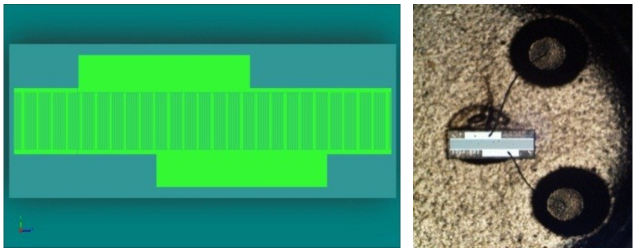


Figure 8: Model of one port SAW resonator and fabricated device.

5 RESULTS AND CONCLUSIONS

Also, a comparison is provided between the measured and simulated frequency response (see Figure 9). Results indicate that with increasing the gas concentration the wave velocity decreases and the attenuation of the wave is reduced and our methodology provides powerfull tools to tune optimal design parameters.

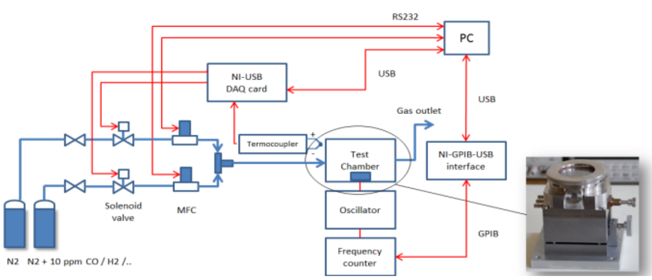
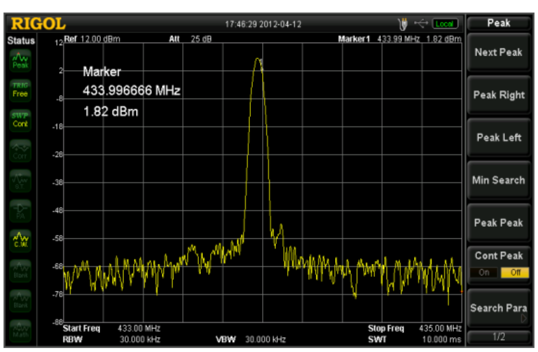
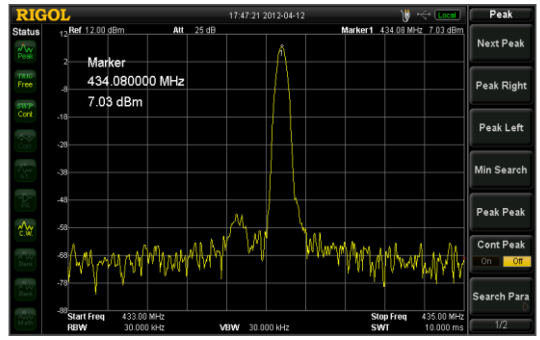


Figure 9: Measurement setup.

Figure 10 demonstrates the spectral response of the SAW sensor for different concentration of acetone.



a)



b)

Figure 10 shows the spectral response of the SAW sensor for different concentration of acetone.

6 ACKNOWLEDGEMENT

This research has been supported by the Czech Science Foundation project No. 102/09/1601 "Intelligent Micro and Nano Structures for Microsensor Realized Using Nanotechnologies" and partially by The Ministry of Interior of the Czech Republic research program No. VG20102015015, partially by project No: CZ.1.05/2.1.00/03.0094 “Regional Innovation Center of Electrical Engineering”.

REFERENCES

[1] H. Wohltjen: Mechanism of operation and design considerations for surface acoustic wave device vapour sensors, Sensors and Actuators, Vol. 5, pp. 307-325, 1984

[2] H. Wohltjen, R. Dessy, Surface acoustic wave probe for chemical analysis. Part I: Introduction and instrument description, Analytical Chemistry, vol. 51, no. 9, pp. 1458-1475,1979.

[3] L. Rufer, T. Lalinsky, D. Grobelny, S. Mir1, G. Vanko, Z. Őszi, Z. Mozolova, and J. Gregus: GaAs and GaN based SAW chemical sensors: Acoustic part design and Technology, presentation on ASDAM 2006, Oct. 16-18 2006, Smolenice, Slovakia.

[4] IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society, Teaching Resources in Ultrasonics, available at http://www.ieee-uffc.org/edmain.asp , September 2007

[5] V.I. Anisimkin, I.M. Kotelyanskii, V.I. Fedosov, C. Caliendo, P. Verardi, E. Verona, Analysis of the different contributions to the response of SAW gas sensors, in: Proceedings of the IEEE Ultrasonics Symposium, 1995, pp. 515–518.

[6] Nimal, A.T., Singh, M., Mittal, U. & Yadava, R.D.S. A comparative analysis of one-port Colpitt and two-port Pierce SAW oscillators for DMMP vapor sensing. Sensors and Actuators B: Chemical 114, 316-325 (2006).