Actuated Micro-Sensor for Magnetic Field Detection Based on Piezoresistor Transduction

Waddah Abdelbagi Talha, Mohammed A. A. Emaleeh, John Ojur Dennis

Abstract— one of the techniques used to measure the external magnetic field is by the transduction of the deflection produced by the Lorentz force into electrical signal using Piezoresistor technology. It is stated that the piezoresistive effect in silicon depends strongly on the crystal orientation, doping type, and concentration. In this paper the piezoresistive property of the Polysilicon is used as Piezoresistor transducer to study the transduction procedures. The results obtained observe the response of the different samples of piezoresistor transducer to transfer the deflection of the cantilever to electrical signal (voltage output). The sensitivity of the system is calculated for different samples at a fixed value of the applied force the percentage rate of change of the resistivity (ΔRp %) for different values of the cantilever deflections were obtained. It is observed that the change in resistance of the piezoresistor increases nonlinearly with the increase of the cantilever displacement. The Polysilicon Piezoresistor in Whetstone's bridge configuration is used to transducer the response of the cantilever to electrical measurements at various voltages. Various dimensions of the cantilever were considered in the measurements. The highest sensitivity of the measurements (64mV/mT) is obtained for a thin beam of 0.6 µm polysilicon embedded in 2 µm thick silicon cantilever beam.

Keywords- Lorentz force; Polysilicon Piezoresistor; Bulk Micromachining; Wheatstone bridge.

I. INTRODUCTION

Although electrostatic actuators are widely used in MEMS, electromagnetic force (the Lorentz force) is still an alternative to power micro machines. Micro coils are less efficient due to the scale effect, but if a permanent magnet is used, the result is a quite scale-independent magnetic field strength [1]. The actuation of U-shaped cantilever in a magnetic field is based on the principle of Lorentz force. As shown in Figure-1 this force is generated when Aluminum U-shaped cantilever carrying an electrical current is placed in a magnetic field. Each of the moving charges in the wire, which comprise the current, experiences the Lorentz force, and together they can create a macroscopic force on the wire given, in the case of a straight and stationary wire, by the equation

$$\vec{F} = \vec{I}L \times \vec{B} \qquad (1)$$

Where $\vec{F}$ is the force, measured in Newton's, I is the current in the wire, measured in amperes, **B** is the magnetic flux density vector, measured in tesla and **L** is the length of the wire (measured in meters).

The Lorantz force acting on a U-shaped cantilever is used to bend and deflect it in different modes accordingly to direction of an external magnetic field and current through the cantilever. Figure 1 shows a case where the external magnetic field and the current through the wire are perpendicular to one another at the base of the U-shaped cantilever while they are parallel or antiparallel to each other at the arms. In this situation, the Lorentz force will act on the base of the U- shaped cantilever according to the magnetic field right hand rule while no force acts on the arms. If therefore a direct current is used the deflection will be up as indicated in figure.1 this situation called static mode. If, however, an alternating current is used the cantilever will vibrate up and down this motion is called dynamic mode. The response of a vibrating system will depend on the relationship between the frequency of the externally applied periodic force and the natural frequency of the vibration system. For instance if a mass on a spring is moved and then released, it will oscillate at its natural frequency. When a periodic force is applied at this frequency, the amplitude of the response (maximum displacement) will increase dramatically to the highest displacement of the cantilever, indicating to the highest sensitivity of the sensor. This phenomenon is known as resonance and is the fundamental principle applied in all resonating sensors [2]. The principles of the transformation of a deformation in a micro cantilever into an electrical output and the electronic interface circuits needed for such purposes. The transfer of a deformation in a mechanical construction by an external load to an electrical signal is called transduction. Piezoresistivity is a material property where the bulk resistivity of a material is influenced by the mechanical stress applied to it. Silicon, especially in the monocrystalline form, exhibits a high piezoresistivity [3-4]. Combined with excellent mechanical properties, this makes it a preferable material for mechanical sensors. Whereas metals show a change in resistance due to mechanical stress or strain mainly because of geometric effects, the piezoresistive effect in silicon results from a change in resistivity and exhibits significantly higher sensitivities. Because of this and the easy fabrication of resistors in standard IC fabrication, piezoresistive detection is a widely applied sensing principle for mechanical microstructures for measurements using an electrical signal. The piezoresistive effect in silicon depends strongly on the crystal orientation, doping type, and concentration. Piezoresistive property of polysilicon is used as piezoresistor transducer in this research.

II. THEORY OF PEIZORESISTIVE TRANSDUCERS

The general relation between the relative changes of a resistance R, which equals to the change in resistivity ρ in Polysilicon applications, is given by [5]:

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Waddah Abdelbagi Talha, Department of Electronic Engineering, University of Gazira Sudan, Wad Madani, (Sudan) North Africa.
Mohammed A. A. Emaleeh, Department of Control Engineering, University of Khartoum, (Sudan) North Africa.
John Ojur Dennis, Departments of Electrical and Electronic Engineering, Universiti Teknologi Petronas, Perak, Malaysia.

$$\frac{dR}{R} = \frac{d\rho}{\rho} \tag{2}$$

The electrical resistance of a piece of any material depends on its dimensions, shape and the resistivity ρ. For example a metallic rod with cross-section A and length L the resistance R (Ω) is given by [ref]:

$$R = \frac{\rho l}{A} \tag{3}$$

Therefore the change of the resistance of a material (ΔR) is directly proportional to the change in its resistivity (Δρ).The simulation software will realize the results in percentage values of the unstressed resistance value of the Piezoresistor [5].

$$\Delta R\% = \frac{(stressed - unstressed)}{unstressed}\% \tag{4}$$

Where ΔR% is percent change in resistance.

Using equation 3, the value of the change of the resistance (in Ω) can be obtained by:

$$\Delta R_p = \frac{\Delta R\%}{100} \times R \tag{5}$$

where R is the original (unstressed) value of the resistance of the piezoresistive material. The change in resistivity of a piezoresistive material subject to a mechanical deformation is used to measure many physical quantities such as pressure, force, and acceleration. The advantages of piezoresistor technology implementation in circuits include low cost fabrication opportunity, mature processing technology, readout circuitry can either be on-chip or discrete, various sensitivities can be obtained, and different pressure levels can be achieved according to the application [6]. Piezoresistive pressure sensors are one of the very-first products of MEMS technology. Those products are widely used in automotive applications such as air pressure detection, in biomedical applications such as blood pressure measurement and in household appliance such as washing machines, dishwashers and vacuum cleaners.

III. DESIGN AND FABRICATIONOF PIEZORESISTOR FOR OUTPUT SIGNAL MEAUREMENT

Coventor Ware is used to perform finite element simulation (fabrication, design, analysis) of the micromachined U-shaped cantilever. The software is a versatile tool which can be used to quickly build models in micro scale of electromechanical system devices (MEMS) for different simulation model and system level optimization by simulating micromachined device with full control on device parameters. Fig.1 shows the piezoresistive material embedded in a U-shaped beam and Aluminum layer deposited as conductor layer at the top of the cantilever, while Fig.2 shows the cross-sectional view of the arm width and arm Length of the beam and a polysilicon piezoresistor embedded inside the *Si* beam of the U-shaped cantilever device. The value of the piezoresistor at (Ω) is depending on its dimensions to convert this result to electrical signals when from the Wheatstone bridge depend on the value of the change of the resistor of the piezoresistor ΔR_P.

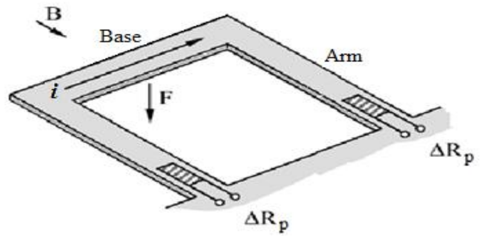
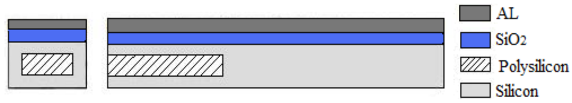


Fig1. U-shaped cantilever with incorporation of Piezoresistor



(a) (b)

Fig2. Cross-sectional view of a U-shaped Polysilicon-Piezoresistor Cantilever. (a) Arm width (b) Arm Length

To match process parameters, such as diffusion depth, the user may independently control the process-dependent geometry of each resistor. In a two-step solution, the software solves the beam mechanical problem and then applies the beam stress results to solve for the resultant piezoresistive change. Fig. 3 illustrates the set up of all boundary conditions for the separate beam and piezoresistor. It shows the cantilevered beam part, the Piezoresistor witch grown in the cantilever and the combined model for the geometry placement.

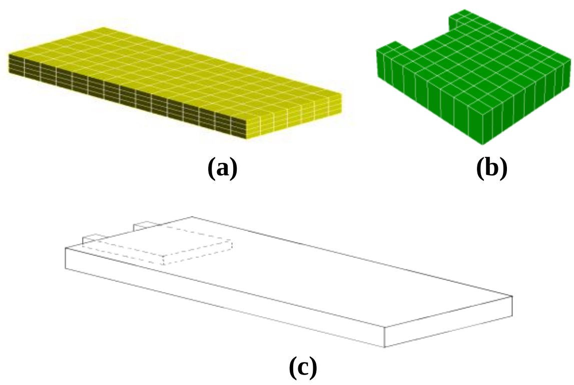


Fig 3. Pre-process view of (a) meshed cantilevered beam, (b) meshed piezoresistor and (c) combined geometry of beam and piezoresistor.

After the piezoresistor segment is designed, the original value of the resistor in (Ω) is determined by applying a voltage of 5 volt to the Piezoresistor model shown in Fig.4.

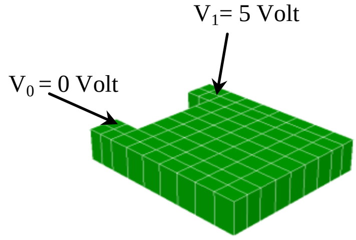


Fig4. Piezoresistor model

The CoventorWare software program finds out the percentage change in the current through the piezoresistor after applying the deflection of the cantilever. Accordingly the rate of change in Piezoresistance (ΔR_P) could be calculated. Initially an unstressed current through the Piezoresistor device is calculated and then compares the value with the stress solution number to compute the percentage difference. The resistance of the Piezoresistor depends on its dimensions. In order to convert the change in resistance to electrical signal, a well know technique called Wheatstone bridge configuration shown in Fig4. is used to measure the output voltage [7].

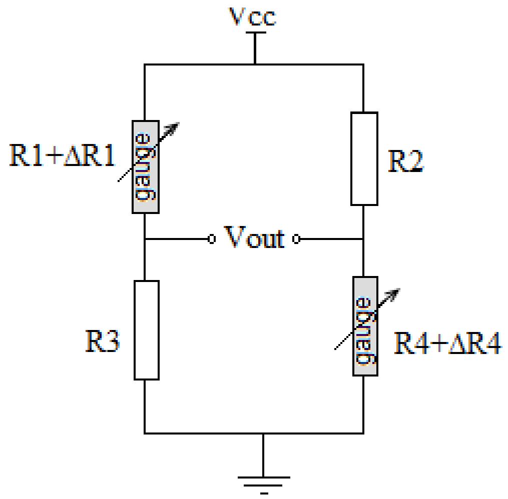


Fig.5 Wheatstone bridge configuration [7].

All the resistors constructing the bridge shown in Fig.5 are chosen to be equal. This results in getting zero output voltage. For the U-shaped cantilever shown in Fig.1, the mechanical strain generated by the bending translates into a change of gauge resistances placed closely to the anchor of the suspended "U-shape". The bridge configuration with voltage supply is the common interconnection of Piezoresistor. The two gauges named R1 and R4 are arranged in a Wheatstone bridge together with two reference resistors R2 and R3 deposited over the bulk [7]. In this study at least one of the resistors has to be dependent on the measured parameter. The change of the resistance is then used to transform the response of the cantilever into electrical signal. The differential output voltage (V_{out}) of the Wheatstone bridge is calculated using the expression:

$$V_{out} = V_{cc}\frac{R_2.R_3 - (R_1 + \Delta R_1).(R_4 + \Delta R_4)}{((R_1 + \Delta R_1) + R_3)(R_2 + (R_4 + \Delta R_4))} \qquad (6)$$

In the balance condition of the bridge the following arrangement will be true:

$$R_2.R_3 = R_1.R_4 \qquad (7)$$

And there is no change occurs in the Piezoresistors R1 and R4 (ΔR_P = zero) and the output voltage is null. Otherwise the output voltage can be measured [8-9]. As previously noticed, the measurement of low magnetic flux of the earth magnetic field is obtained by using the piezoresistive gauges. Due to the low signal level measured across the gauges, an amplifier with a very high voltage gain and low noise is required to use at the output of the bridge configuration [8-9].

The sensitivity (S) of all magnetic field sensors is defined as the ratio between the voltage output of the measurement circuit and the magnetic flux density detected and is given by:

$$S = \frac{V_{out}}{B_{ext}} \qquad (7)$$

There are two sensitivities of the system: static sensitivity S_{stat} for the static mode of the cantilever and resonant sensitivity S_{reso} for the dynamic mode at the resonant frequency of vibration. The maximum deflection in the static mode is too small if the output voltage and sensitivity are compared to that in dynamic resonance response.

IV. RESULTS AND DISCUSSION

(a) Cantilever deflection against Lorentz force.

Two conditions could be realized: when the DC current carrying U-shaped cantilever is placed in an orthogonal static external magnetic field the Lorentz force acts on it. The magnitude of this force is calculated using equation 1. It produces various deflections on the arms of the current-carrying U-shaped cantilever shown in Fig.1. According to the cantilever beam tolerate of the strain a current of 100 mA assumed, an external static magnetic field of 12 mT for the cantilever of length of the base (b) and arms (l) of 760 µm and 1000 µm, respectively, Using equation-1 a value of 0.9 µN is calculated for the force acting on the base of the cantilever. This force represents the Lorentz force due to the constant DC current in a static magnetic field that is perpendicular to the base. Fig. 6 shows the result of the cantilever deflection, it shows a maximum displacement of 9.1 µm on the base when the constant force of 0.9 µN is applied on the base in the negative z-direction (down). Secondly: when a periodic force representing the force due to an alternating current in the device placed in an external static magnetic field, is applied to the cantilever in order to realize the dynamic mode. In this case, if the cantilever is driven by a periodic Lorentz force near it is natural frequency, the resonance occurs and a considerably large displacement results. It increases the sensitivity of the device.

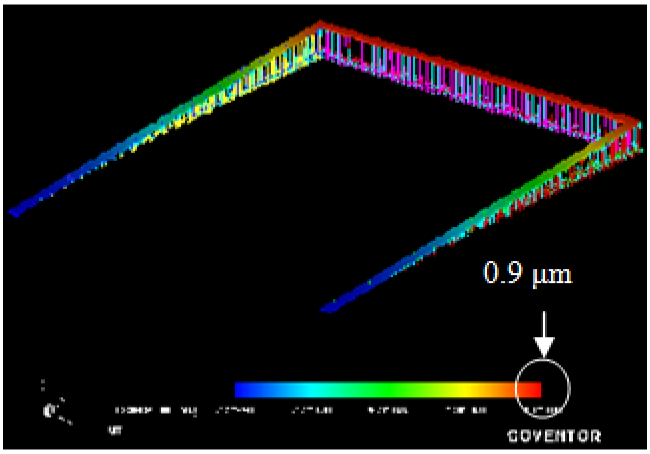


Fig 6. 3D simulation of constant applied force 0.9 µN downward on the base of the cantilever.

Therefore, the displacement of the cantilever observed is significantly large. It is about 45 µm when a periodic force is applied at 3.019 kHz (natural frequency or resonant frequency) for the vibration mode as compared to a constant force (static case).

Table1 compares the maximum displacement and sensitivity of the cantilever for the static and dynamic modes at the same applied Lorentz force on the arms and base produced. The current value is assumed 100 mA and external static magnetic field is 12 mT.

Table-1 the Maximum displacement and sensitivity of the cantilever in the three modes of vibration for static and dynamic cases

Static displacement (µm)	Resonant displacement (µm)	Static senstivty (µm/µN)	Resonant senstivty (µm/µN)
9.10	45.20	10.1	50.2

(b) Piezoresistor Value calculations.

To investigate the change in the resistance of the piezoresistor, the constant force applied to the cantilever is varied and the corresponding deflections were measured. The percent change in resistance (ΔR*p*%) from the original value of Piezoresistor resistance Rp named unstressed position of the Piezoresistor is then obtained. The value of R*p* from the simulation results is1709.83 Ω. Fig.7 shows the results of ΔR*p* % for different values of the cantilever deflections. It is observed that the change in resistance of the piezoresistor increases nonlinearly with increase in the displacement of the cantilever.

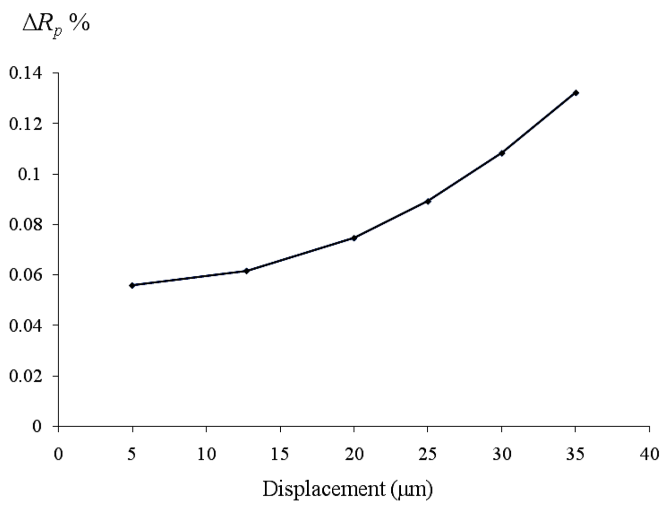


Fig 7. ΔR*p* % various cantilever deflections

The values of ΔR*p* % obtain by simulation are used to deduce the values for ΔR*p* in Ω mathematically and then to apply this change in the resistance on the Wheatstone bridge circuit to achieve the voltage output measurements. The simulation software will realize the output as percent values of the original (unstressed) value of the piezoresistor as given in equation 4. The value obtained is then used to calculate the change in the resistance in Ω by using equation 5. As an example, at 5 µm deflection of the cantilever in negative z direction, the value of ΔR*p*% is 0.056. The unstressed resistance value is calculated to be equal to 1709.83 Ω and thus ΔRp is calculated to be 0.96 Ω. Wheatstone bridge is shown in Figure 8.

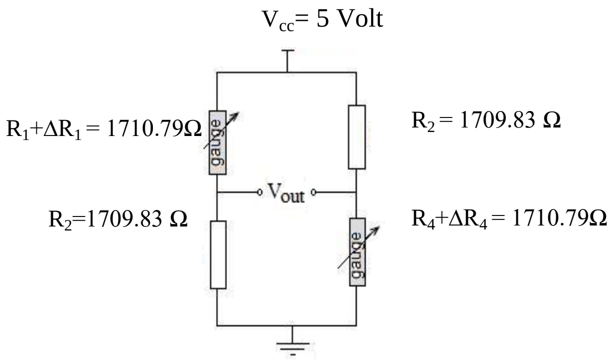


Fig 8. Conditioning circuit for strain gauges at 5 µm deflection of the cantilever in –z direction

The simulation results for the circuit shown in Fig.8 show the value of 1.405 mV at the output V_{out}. And by applying these resistors values in equation 6 the calculated output voltage is found 1. 4033 mV, which shows a good agreement with that obtained from simulation.

Fig.9 shows the calculated values of ΔR*p* and the estimated output voltage (mV) of the measurement circuit for different values of the cantilever deflection.

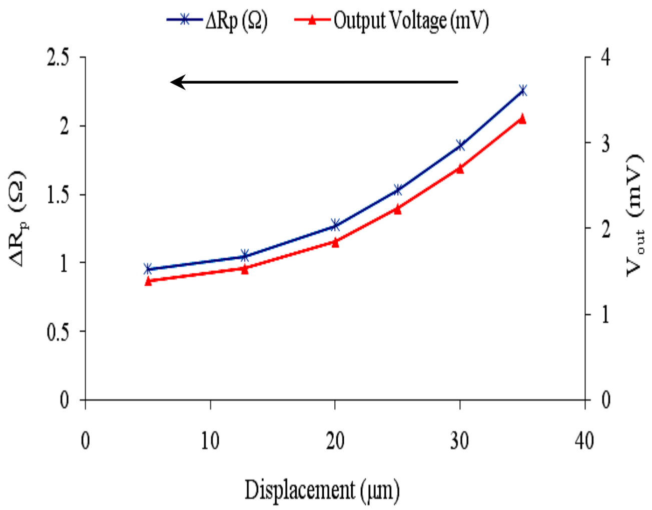


Fig9. Calculated values of ΔRp and estimated output voltage (mV) versus cantilever deflection

The signal output of 1.545 mV is induced by the Lorentz force due to an external static magnetic field of 10 mT the results in a sensitivity that is estimated from equation 7 to be 0.155 mV/mT. The output voltage (V_{out}) calculated in this study is obtained directly from the Wheatstone bridge. However, due to the low signal level available across the gauges, on-chip amplification with very high gain of up to 1000 times and low noise is required. The different values of the ΔR*p* % and sensitivity are compared in Fig.10 for three different values of the piezoresistor thickness based on the thickness of the cantilever beam [10, 11].

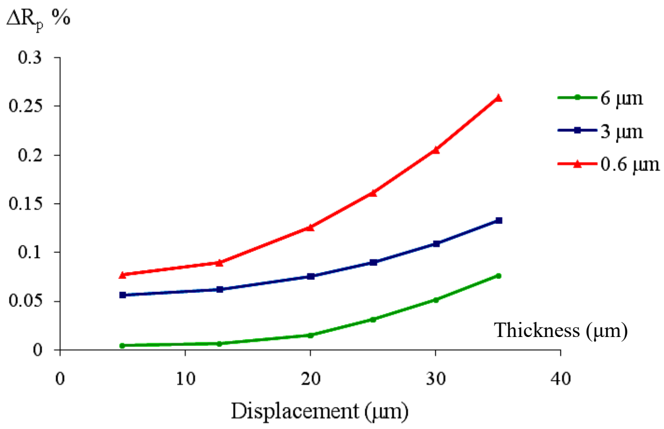


Fig 10. Simulated values of ΔR*p*% various cantilever deflections for various beam thickness

It is noted that the graph is not linear indicating highest sensitivity for small thicknesses. Table 2 presents the comparison of piezoresistor resistance and resonant displacement and the percentage change of the resistance for three different thicknesses of the U-shaped cantilever and the embedded piezoresistor when the same force is applied to the cantilever corresponding to Lorentz force at the 10 mT of the external magnetic flux. Table 3 shows the theoretically determined sensitivities.

Table2. The simulation results showing the changes in various parameters for different thicknesses of the Piezoresistor

Thickness of Si beam (µm)	Thickness of Piezoresistor (µm)	resistance (Ω)	Resonant Frequency (kHz)	Maximum displacement (µm)	ΔR_p %
2	0.6	5557	2.117	117.6	2.50
5	3	1710	4.55	12.74	6.17E-2
9	6	570	8	2.5	1.9E-2

Table3.The calculated values of the voltage output and the sensitivity for difference thickness of Piezoresistor

Thickness of piezoresistor (µm)	voltage output (mv)	Sensitivity (mV/mT)
0.6	6.35	64
3	0.155	0.16
6	0.634×10^{-3}	0.06

V. CONCLUSION

Analytical model describing vibration mode for U-shaped cantilever devices that are actuated by the Lorentz force and their verification by simulation is discussed. It is shown that when the cantilever is driven at or near its natural frequency by a periodic force, a large displacement is realized as compared to a static force. The Piezoresistor is very good and a simple sensing element which used to transduce this response into voltage output signal. The graph of displacement as a function of the applied force is shown to be perfectly linear in both the static and dynamic situations. The percentage change in resistance, ΔR%, of a polysilicon Piezoresistor is found to be proportion to the cantilever deflections. The estimated sensitivity from the output voltage of a Wheatstone bridge circuit setup for thicknesses of the cantilever of 6, 3, and 0.6 µm is found to be about 0.06, 0.16, and 64 mV/mT, respectively. The highest value of the percent change in resistance (ΔR*p*) % is obtained at the highest displacement of the cantilever when the cantilever is driven at the resonant frequency.

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AUTHORS PROFILE

Waddah Abdelbagi Talha Mohammed, received his BSc degree from the Faculty of Engineering (Telecommunication and Control), University of Gezira in. 2006 Mr. Waddah was appointed as a teaching assistant in the department of electronic engineering, university of Gezira. In 2010 he received his MSc degree from the department of electrical and electronic engineering, Universiti Tek nologi PETRONAS, Malaysia. Since then he was promoted as lecture in the department of electronic engineering, university of Gezira. Mr. Waddah participated in many IEEE conferences. His research interest includes Nano technology, modeling and simulation of electronic devices and electronic engineering.

Mohammed Elmaleeh, received his BSc degree from University of Gezira (Sudan), Faculty of Engineering and Technology (Communication and Control Engineering). In 1998 Elmaleeh received his MSc in Electrical and Electronic Engineering, University of Khartoum, Sudan. From 1994-1998 Mr. Elmaleeh worked as a researcher in Sudan Atomic Energy Commission. In 1999 he worked as automation engineer, QAPCO, Qatar. In 2009 Elmaleeh received his PhD degree in Electrical and Electronic Engineering, University Technology PETRONAS, Malaysia. Currently Elmaleeh works as Associate Professor at Tabuk University, Saudi Arabia. Dr Elmaleeh published many papers in the field of electronic engineering. He supervised many post graduate and undergraduate students in their research projects. Elmaleeh is assigned as a reviewer for several IEEE conferences and international journals. His research interest includes electronic engineering; industrial automation, control engineering, fiber optics, wireless communication and computer engineering.