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Heavy Metal Ion Detection in Water using MEMS Based Sensor

Dinesh Rotake[a] , A. D. Darji[a]

[a] *Department of Electronics Engineering, S. V. National Institute of Technology, Surat-395007, Gujarat, India*

Abstract

Today most of the countries facing many environmental problems out of which water pollution are extremely hazards and world's most of the countries facing enormous challenges to solve this. Water pollution due to Heavy Metal Ions (HMIs) is a global issue which requires proper attention to maintain the water quality demands. A portable system made of MEMS sensors capable of detecting multiple analytes simultaneously is highly demanded. The HMI detection in vapour phase can be a solution for laboratory based detection, but for the field instrument using MEMS the temperature cannot be raised beyond certain limit. Hence, the microfluidic detection is the only option which required high sensitivity. Accordingly, our main objective is to develop a microfluidic platform that can be used for sensing HMIs using a capacitive microcantilever beam fabricated by using MEMS technology. The proposed system is divided into two parts; the first one includes microfluidic chamber or tub and polydimethylsiloxane (PDMS) based microfluidic channel for handling water and second one uses the array of microcantilever beams surface modified with different protein for selective detection of HMIs. In this work, we try to investigate the cantilever based capacitive sensor for different pressure due to HMIs and sensitivity enhancement. Sensitivity optimization is very much essential and it is improved by using different shape, stress concentration region (SCR) and changing the dimension of microcantilever for HMI detection in water environment. It is found that in case of rectangular beam with SCR improves deflection up to 33% and in case of triangular beam this improvement is up to 73%.

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Keywords: FEA; HMIs; MEMS; Microcantilever; Capacitive Sensor; Microfluidic; SCR.

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1. Introduction

Environmental issues causing enormous effect on the human life all around the world out of which water contamination is proven to be very hazardous according to many health organization and required urgent solution.

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* Dinesh Rotake Tel.: +919423407088; fax: 2201551.
E-mail address: d15ec003@eced.svnit.ac.in

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According to experts, 15 million children die each year under the age of five because of diseases caused by drinking water. We have investigated the research done in the field of HMIs detection such as, The fabrication and evaluation of a DNAzyme functionalized capacitive type micromechanical sensor array for the detection of Pb2+ ions presented by [1] and Shear horizontal surface acoustic wave (SH-SAW) sensor is discussed in [2] but both the approaches require the experimental setup which cannot solve the problem of portability and cost. A graphene nanodots-encaged porous gold electrode via ion beam sputtering deposition (IBSD) for electrochemical sensing for targeted heavy metal ions Cu2+ and Pb2+ by Osteryoung square wave voltammetry (OSWV) is presented by [3] ; Disposable Au nanoparticles (AuNPs) based electrodes are used for the monitoring of Cd2^{+} ions in real water samples with a low detection limit of 2.6 ppb [4]; A glutathione stabilized silver nanoparticles (GSH-AgNPs) modified screen printed electrode [5] and Shark-inspired MEMS chemical sensor [6] was proposed to determine the trace levels of Pb2^{+} with a low detection limit using cyclic voltammetry. All these approaches use the electrochemical workstation and complex experimental setup which leads to non portable device.

Microcantilevers functionalized with metal-binding protein "AgNt84-6" are demonstrated as good sensors for the detection of heavy metal ions like Hg2^{+} and Zn2^{+} by [7]. SAMs (self-assembled monolayer's) modified microcantilevers used for detection of Ca2^{+} ions is presented in [8]. Arrays of microcantilever sensors encapsulated in fluidic wells and fluidic channel are discussed in [9] and [10], respectively. A Chitosan (CS)-graphene oxide (GO) Surface Plasmon resonance (SPR) sensor is explained in [11] while, simple microcantilever beam based detection is given in [12-14]. Since all of these methods use optical readout, require heavy setup and costly lab equipment. The analysis of different shapes and stress concentration region (SCR) to improve the sensitivity of microcantilever beam has been very well explained in [15-18] but for microfluidic application these dimension are not suitable and need to be investigated.

Nomenclature

MEMS	Micro-Electro-Mechanical System
FEA	Finite Element Analysis
WHO	World Health Organization

2. Proposed HMIs Detection System

We proposed a portable, cost effective, low power, highly sensitive, easy to use, continuous and fast HMIs detection system, which can be accessible to remote areas because most of the remote areas across the country face the saviour water pollution problem. Microfluidic platform can be used for sensing HMIs using a capacitive microcantilever sensor. This type of sensor is called as surface stress-based biosensors (SSBS) used for effectively solve the problem of HMIs detection in groundwater and industrial waste water. It is one of the new technologies of micro-level and label-free design and have great potential to satisfy the demand for best sensor quality. This technology has been investigated by different researchers over the recent years. The block diagram of proposed system shown using Fig.1. The function of each and every block in detail has been explained as following.

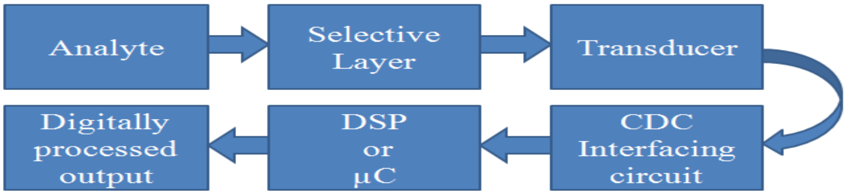


Fig.1: Block Diagram of Proposed system

2.1. Analyte

The analytes in microfluidic system is input which needs to be detected and they consume very low energy with micro-scale effects. In our case, highly toxic heavy metals such as Lead ($Pb2^{+}$), Mercury ($Hg2^{+}$), Cadmium ($Cd2^{+}$), Arsenic ($As2^{+}$) and Copper ($Cu2^{+}$) can be consider as analytes.

2.2. Selective layer

The selective layer can be designed to detect the analytes in biomaterial recognition. Antigen-antibody binding, DNA-Enzymes, functionalized nucleic acids etc. are some of the examples of biomaterial recognition. Recently, self-assembled monolayer’s (SAMs) is used for better surface selectivity [18]. The protein is used as a selective layer to bind the HMIs for this research work to achieve higher sensitivity.

2.3. Transducer

Microcantilever beam is used as transducer which converts mechanical energy to desired capacitance. A surface stress-based transducer structure is made by silicon nitride or polysilicon and a contact layer i.e., gold layer on cantilever surface is used to get sufficient bending stiffness for the selective layer.

2.4. CDC (Capacitance to Digital Converter) circuit

The most challenging task is to design the CDC circuit for femto Farads (fF) range because most of the MEMS microcantilever beams designers require about part per trillion ranges of detection rather than part per billion. The output signal produced by a sensor is usually not suitable to be processed directly in the digital domain. Therefore CDC interfacing circuit is required to condition sensor output before giving to the DSP or Microcontroller as input.

3. Capacitive Sensor design

Capacitive sensor shown in Fig.2 has numerous advantages as compared to others sensing circuits such as non-contact measurements, simple to design, compatible with MOS technology and easy fabrication. The requirement of interfacing circuit is the only disadvantage to convert capacitance in the digital domain.

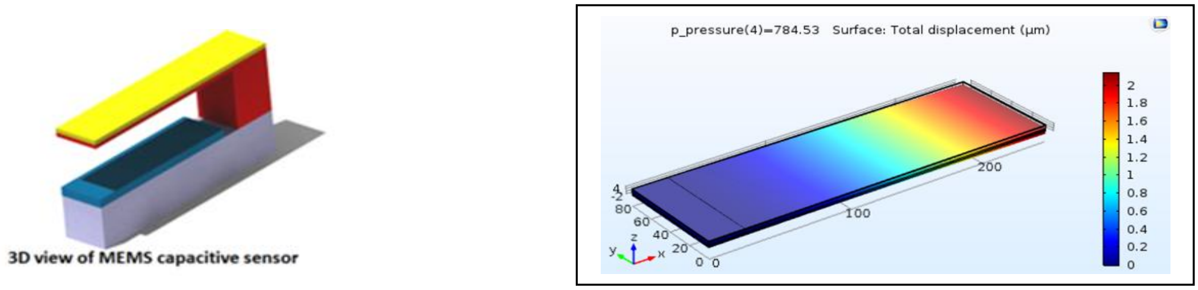


Fig. 2: Capacitive Sensor (Polysilicon)

3.1. FEA Analysis of Capacitive Sensor with COMSOL 5.2

Finite element analysis (FEA) of different polysilicon capacitive sensor has been performed using COMSOL software. The analysis is carried out for different lengths and thickness of microcantilever with Polysilicon and

Silicon Nitride materials. The proposed design uses Polysilicon for cantilever because it acts as one of the plates of capacitor so that the coating of any metallic material is avoided. So the analysis of capacitance variation with respect to length is carried out to decode the optimum length of cantilever in the proposed design as shown in Fig. 3. At the same time it is also important to see the use of Polysilicon must not change the sensitivity as compared to normally used Silicon Nitride material for cantilever.

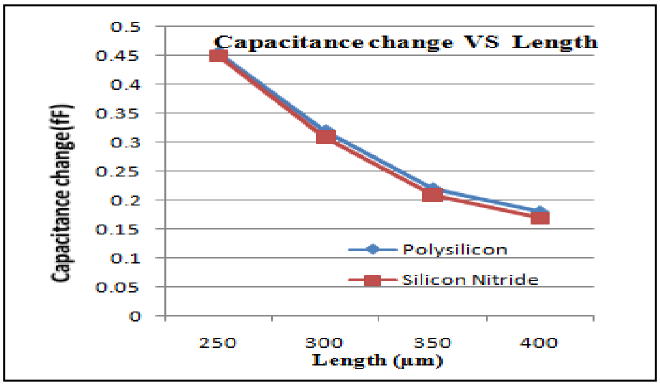


Fig. 3: Graph: Capacitance change Vs Length

The maximum change in capacitance is observed as 0.455fF for L=250 µm with maximum displacement of 2.15 µm for polysilicon and Silicon Nitride as shown in Fig. 3. It is also observed that the increase in length of cantilever leads to lower capacitance for both the materials. Moreover, the same value of capacitance is observed for L = 250 µm for both the materials which, proves that the Polysilicon can be used in place of Silicon Nitride. After deciding length, it is also important to decide the width of the cantilever to have better sensitivity without breaking of cantilever. So the maximum displacement and capacitance variation is analyzed with respect to thickness keeping length L = 250 µm and cavity as 2.5 µm as constant parameter as shown in Fig. 4 (a) and (b).

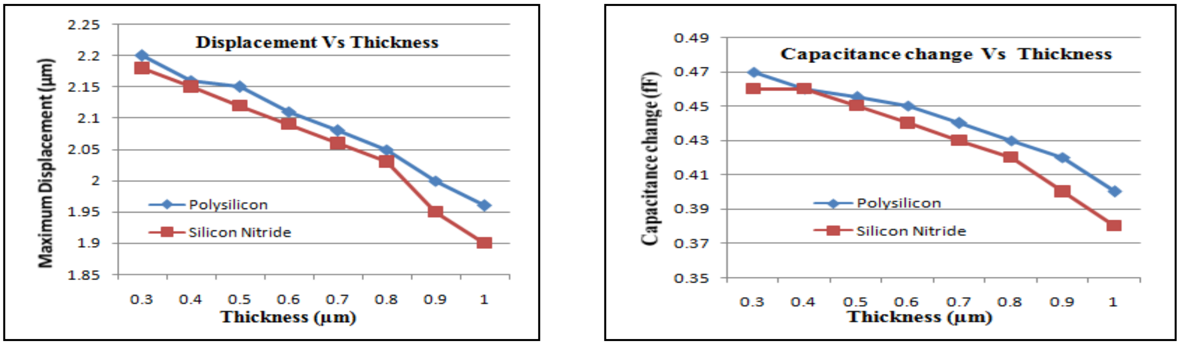


Fig. 4: Graph (a) Maximum Displacement Vs Thickness (b) Capacitance change Vs Thickness

So from all these analysis, we have decided to have Polysilicon cantilever with *L=250µm, W=80 µm, T=0.5µm* for the capacitive sensor so get higher capacitance variation with enough strength of cantilever beam so that it can take the load of heavy metal ion.

3.2. FEA Analysis of Microcantilever Beam using ANSYS Software

In case of capacitive sensor, the change in capacitance is directly proportional to mass of HMIs detected with very high sensitivity. So to improve sensitivity is one of the major challenges for microfluidic application.

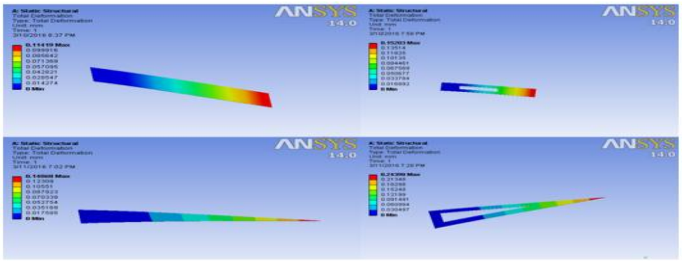


Fig.5: Simulation results in ANSYS for polysilicon cantilever (L=250µm, W=80 µm, T=0.5µm)

Finite element analysis (FEA) of different Polysilicon microcantilever shapes is performed using ANSYS software. In order to improve the sensitivity, two types of SCR are used as shown in Fig.5. The comparison of deflection with respect to force is shown in Fig.6 and values are listed in Table-1. The proposed application assumes variation in HMIs mass between 1 µg to 1000 µg per litter range as per the World Health Organization (WHO) data.

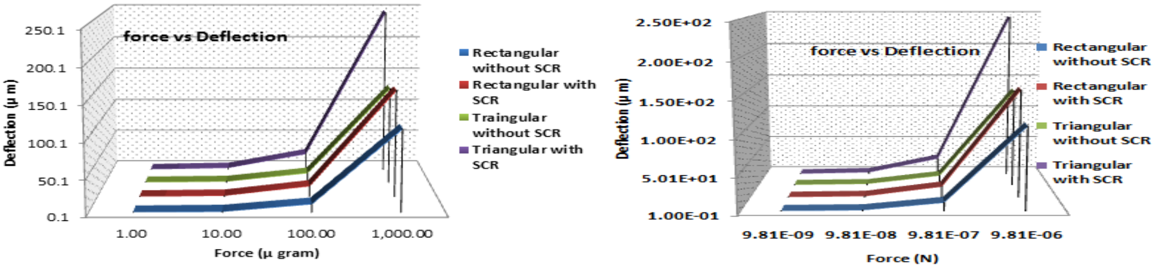


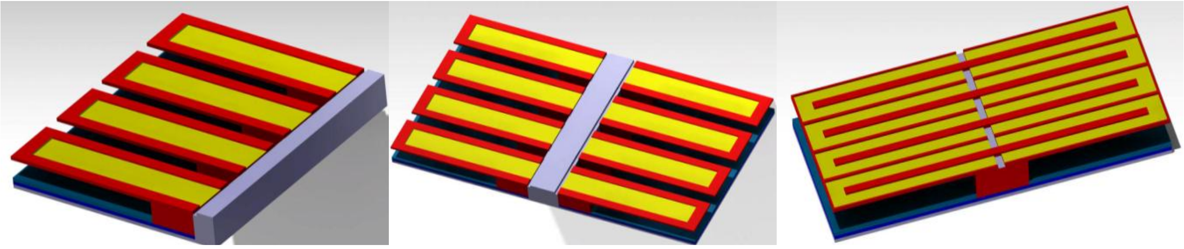
Fig.6: Graph of Force Vs Deflection in (µm)

Table.1. Comparison for different SCR

Force(N)	Deflection				
	Rectangular cantilever with different SCR				
	circular	**Hexagon**	**Square**	**Triangular**	**Rectangular**
9.81E-09	0.12	0.12	0.12	0.119	0.152
9.81E-08	1.21	1.22	1.22	1.19	1.52
9.81E-07	12.1	12.05	12.2	11.9	15.2
9.81E-06	121	120.5	123	119	152.

3.3. Microfluidic Design and Simulation

Microfluidic platform basically design to operate the sample volumes in Micro-litters to Nano-litters range which effectively address the problem of large sample volumes. We have proposed three different geometry approaches for microfluidic platform. In first approach, four-microcantilevers are used with single channel shown in Fig.7 (a). The channels feed with sample water using syringe pump. Sample water is spread on the microcantilever which has a gold coating with different protein layer. This protein binds the HMIs and cantilever start bending depending on the mass of HMIs attached to the surface. If more than one sample is required to test simultaneously, then second approach is best suited but it required two syringe pumps to feed the sample as shown in Fig.7 (b). The third approach includes eight-microcantilever with single channel as shown in Fig.7 (c). In all three approaches the other end of channel is closed until sample water spread on the cantilever surface and one cantilever can treat as a reference.



(a) (b) (c)

Fig. 7: Different geometries for microfluidic design platform

If the channel is very small i.e., of the order of micro/nano metres, the flow may be laminar. This is mostly true in case of microfluidic devices. Reynolds number (*Re*) is key factor to decide flow is laminar or turbulent.

$$Re=\frac{Diameter\ of\ channel \times Velocity}{Kinematic\ Viscosity}$$

If ($Re > 2200$), then the flow is turbulent otherwise laminar. Here the FEA analysis is done with COMSOL 5.2 for second approach shown Fig.7 (b) with normal inflow velocity (v=30 m/s), T=27 ^{0}C, dynamic Viscosity (μ) $=0.8509\times10^{-3}$ (Pa-s), density (ϱ) = 996.59 (Kg/m^3). The calculated value of *Re is* 1410 which indicates that flow is laminar. Plot for velocity magnitude and pressure is shown in Fig.8 for microfluidic array.

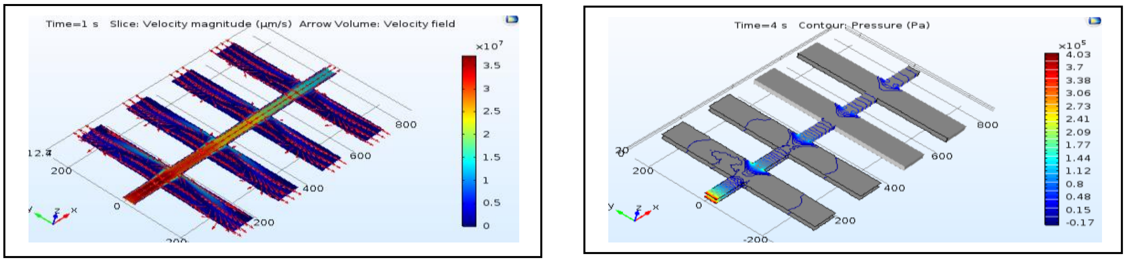


Fig. 8: Microfluidic array (a) Velocity magnitude plot (b) Pressure magnitude plot

4. Conclusion

We have proposed protein-fictionalized capacitive microcantilever sensor for HMIs detection. Most of the microcantilever based systems studied for HMIs detection require costly equipment for characterization, processing and heavy experimental setup led to non-portable system. The proposed capacitive method overcomes all above problems with additional cost of interfacing circuit. The FEA analysis for capacitive sensor shows the maximum capacitance variation 0.455 fF for HMIs mass between 1 µg to 1000 µg per litter range according to WHO. FEA analysis shows that triangular shape gives better sensitivity than the rectangular shape. The analysis results clearly show that the triangular beam improves sensitivity up to 27% as compared with rectangular beam. Moreover, the SCR improves the deflection up to 33% and 73% for rectangular and triangular beam, respectively depending on dimensions of SCR. Our future work will be focused on fabrication of capacitive sensor and microfluidic platform.

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