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A MEMS based Carbon Nanotube–Field Effect Transistor as a Gas Sensor

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Abstract. ***This paper deals with the sensing and detection of harmful and toxic industrial gases which are posing a huge threat to the existence of life on earth. In this paper, we hypothise the fabrication of a MEMS based Carbon Nanotubes (CNT)- Field Effect Transistor(FET) which will act as a gas sensor having almost threefold sensitivity and efficiency than the other metal oxide gas sensors such as Tin oxide (SnO2) sensors, which are available in the market.The Field effect transistor of (CNTs) are of great interest for various application including chemical and biological sensing.CNTs can be designed to have specific properties by changing the ratio of the diameters of linearly joined CNTs, which in turn can be used in the fabrication of FETs.The fabricated devices exhibit good lectrical characteristics showing high Transconductance even at low levels of Gate voltage.With the increasing demand of CNTs in many applications due to its unusual properties, we propose that the fabrication of these CNT- FETs will also be quite economical. In this respect, it is also estimated that with the advent of large scale synthesis methods like Chemical Vapor Deposition (CVD), Carbon Arc methods, Laser evaporation etc for CNTs, its cost is also expected to come down in future.***

Index terms----- CNT-FET, Economical, Gas sensor, MEMS, Transconductance

I. INTRODUCTION

Gases are the key measurand in many industrial or domestic activities. In the last decade the specific demands for gas detection and monitoring has emerged, particularly as the awareness of the need to protect the environment. In such a condition gas sensors find applications in numerous fields such as:

1. Detection of single gases (NO_X ,Cl_2 ,SO_X , NH_3 , CO etc).
2. Discrimination of odours or generally the monitoring of changes in the ambient conditions.
3. Single gas sensor can be used as fire detector, leakage detector, ventilation controllers in cars and planes, alarm devices, wherein it warns the overcoming threshold concentration values of hazardous gases in work places.

In general solid state gas sensors the semiconducting metal oxides materials deposited in the form of thick or thin films are used as active layers in gas sensing devices. Generally the read out of the measurand value is performed via electrodes, diodes, transistors, surface wave component, thickness mode transducer and optical arrangements. However here CNT is used as the active layer for sensing the gases, and the read- out of the measurand value is performed by the FET.

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II. DISADVANTAGES OF SOLID STATE GAS SENSORS

At this stage, it is very important to throw some light on the disadvantages of present-day solid state gas sensors, which would in turn justify further research in the field of CNT-FET gas sensors. The main disadvantages are as follows:-

1. They suffer from limited measurement accuracy.
2. Problems of long time durability.
3. Partial sensitivity varies with the aging of the sensor due to drift or contamination effect.
4. Usually these gas sensors are normally sensitive to more than one chemical species in air which shows cross sensitivity.
5. Due to temperature requirement they are not suited for wireless applications.
6. Less sensitive than a MEMS or Nano-based sensor.

Table 1: Types of solid states gas sensors with the corresponding physical change used as gas detection principle

	Type of devices	Physical change
1	Semiconductor gas sensors	Electrical conductivity
2	Field effect gas sensors: diodes, transistors, capacitors	Work function (electrical polarisation)
3	Piezoelectric sensors : Quartz crystal microbalances (QMB), surface acoustic wave (SAW), microcantilevers	Mass
4	Optical sensors (fibre optic or thin film)	Optical parameters: SPR, reflection, interferometry, absorption, fluorescence, refractive index or optical path length
5	Catalytic gas sensors: Seebeck effect, pellistors, semistors	Heat or temperature
6	Electrochemical gas sensors (potentiometric or amperometric)	Electromotive force or electrical current in a solid state electrochemical cell

III. CNT-FET GAS SENSOR

In both developed and rapidly industrializing countries, the major historic air pollution problem has typically been high levels of smoke and Sulphur dioxide arising from the combustion of Sulphur-containing fossil fuels such as coal for domestic and industrial purpose.

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The major threat to clean air is now posed by traffic emissions. Petrol and diesel-engine motor vehicles emit a wide variety of pollutants, principally carbon monoxide (CO), oxides of nitrogen (NOx), volatile organic compounds (VOCs) and particulates (PM10), which have an increasing impact on urban air quality. In addition, photochemical reactions resulting from the action of sunlight on nitrogen dioxide (NO_2) and VOCs from vehicles leads to the formation of ozone, a secondary long-range pollutant, which impacts in rural areas often far from the original emission site. Acid rain is another long-range pollutant influenced by vehicle NOx emissions.

Nitrogen oxides are formed during high temperature combustion processes from the oxidation of nitrogen in the air or fuel. The principal source of nitrogen oxides - Nitric oxide (NO) and Nitrogen dioxide (NO_2), collectively known as NOx is road traffic, which is responsible for approximately half the emissions in whole world. C o n c e n t r a t i o n s o f NO and NO_2 therefore are greatest in urban areas where traffic is heaviest.Other important sources are power stations, heating plants and industrial processes.

NO_2 is a part of group of gaseous air pollutant produced as a result of road traffic and other fossil fuel combustion process. Its presence in air contributes to the formation and modification of various other pollutants like Ozone (O_3) particulates and acid rain.

Long term exposure to high levels of these toxic gases may decrease lung functions and increase the risk of respiratory symptoms such as acute bronchitis, cough and asthma, particularly in children. Several studies have shown that the exposure increases allergic responses to inhaled pollens.

The air pollution is mainly caused by motor vehicles and industries such as chemical and energy production. Though exposure to these gases depend mainly on local outdoor concentration, yet, it can also be affected by indoor pollution sources, such as tobacco smoking and unvented cooking or heating appliances using gas.

A technique similar to semiconductor or solid-state gas sensors is the use of a miniaturized MEMS based sensor. Currently, three of the most popular materials are nanobelts, nanowires and carbon nanotubes, which is the subject of this paper. Despite many difficulties ,the recent successes in the MEMS-based fabrication methods have shown significant trends towards the realization of CNT- FET gas sensors which will offer excellent promise in near future. Some of the background works worth mentioning would be the fabrication of MEMS based ionization gas sensors using CNTs. By Hou et.al in two of their works. Sayago et.al also proposed the fabrication of CNT gas sensors for Nitrogen dioxide (NO_2) detection. The idea of integrating the CNT with MEMS based fabrication methods was further reinstated by Hanein. Occhiuzzi et.al also proposed a method of fabricating RFID passive gas sensors integrated with CNTs. Hence, in this paper we are aiming to implement such a MEMS based gas sensor which will be able to sense the main groups of poisonous and harmful atmospheric gases. The sensor is projected to have the following advantages:-

1. Low costt
2. Low power consumption
3. High reliability
4. Designing of smart and miniaturized sensing devices
5. Greater portability
6. Short time constant

A. Physical Properties Of Carbon Nanotubes

Carbon nanotubes, which are long thin cylinders of carbon were discovered in 1991 by S.Lijima. They can be thought of as a sheet of graphite rolled into a cylinder. The nanotubes have very broad range of electronic, thermal and structural properties that depends on different kinds of nanotubes (defined by its diameter, length and chirality or twist).

The CNTs are very uniform in diameter, highly ordered and perfectly vertical with respect to the plane of the template. The characteristics of CNT can be varied by the process of joining. The pair of armchair zig-zag nanotubes joined linearly is expected to exhibit rectifying behavior. It has been reported that semiconducting multiwall nanotubes exhibit Field Effect Transistor (FET) like characteristics at room temperature.

A linear junction of two tubes with different diameter consists of five and seven member rings. These rings act as a defect and decrease the conductivity of the joined tube. T herefore by joining CNTs of different diameters we

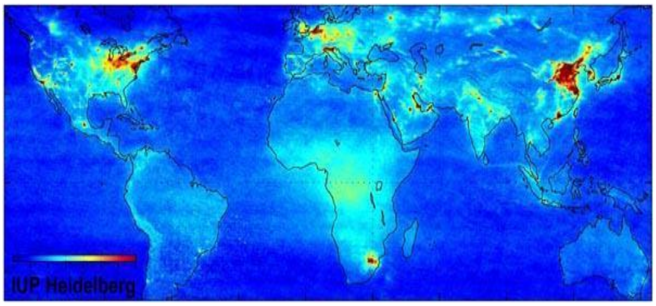

Figure 1 - The map illustrates regions where traffic and fuel combustion contribute to hazardous air pollution. It shows the mean ground level toxic gases' concentration as measured by Satellites

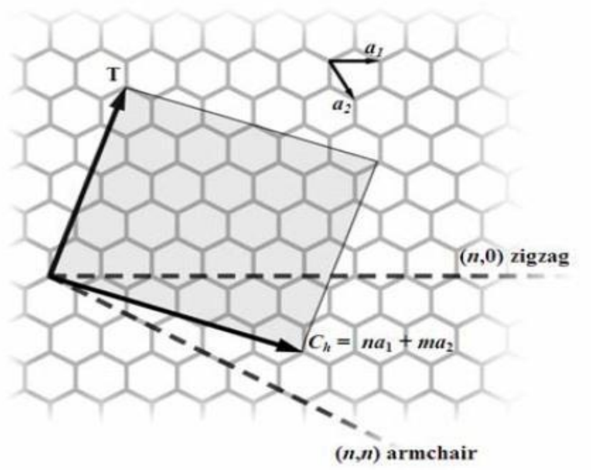

Figure 2 - Schematic Cross section of CNT

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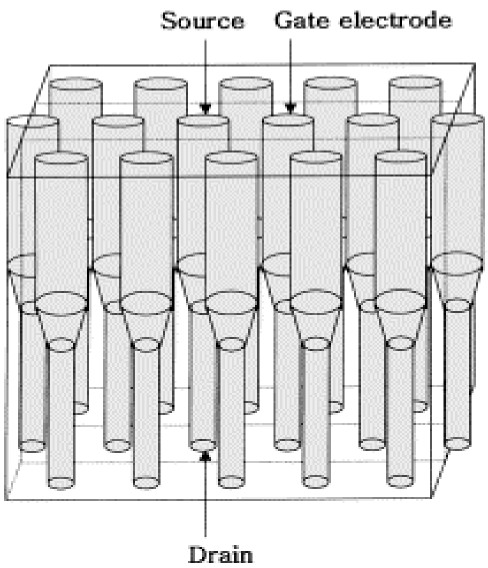

Figure 3 – FET like behaviour and mechanism for Gas Sensing

can modify the electronic characteristics of CNTs.A linear junction of two tubes with different diameter consists of five and seven member rings. These rings act as a defect and decrease the conductivity of the joined tube. T herefore by joining CNTs of different diameters we can modify the electronic characteristics of CNTs.

B. Fabrication of the CNT-FET

The well ordered CNTs can be used in the fabrication of FET. In these structures, one end of Carbon Nanotubes could work as source and the other end as drain. One or some of the six neighbors can be used as the gate electrode. This is basically the same structure as the insulated gate CNT fabricated on a substrate. These structures are always well ordered and almost fit perfectly with respect to the template plane and have a high density.

The electronic properties of linearly joined CNTs could be controlled by changing ratio of the diameters. These linearly joined tubes can be used in fabrication of Micro/Nano scale electronic devices like FET. The CNT-FET sensor exhibit excellent sensing and recovery properties in detecting the poisonous gases at ambient conditions.

A MEMS based fabrication procedure is followed to fabricate the device. The CNT field effect transistor can be fabricated on a 3 inch Polyimide substrate. The reason for selecting Polyimide as a substrate material is due to features like high thermal stability, good chemical resistance, excellent mechanical properties, high tensile strength and heat resistance, etc. A 0.5 micron thick Noble metal (here, Gold) electrodes were lithographically patterned atop an oxide layer. The Gold electrodes serve as the drain and the source, and a 0.3 micron CNT layer as the active conduction channel.

The diameter of the CNTs. was in the range of 45 nm. The doped substrate serves as the gate electrode, separated from the CNT layer by the 0.7 micron thick insulating Silicon dioxide layer, which acts as a stress relief between the substrate and the upper layers. These devices displayed clear p-type transistor action, with gate voltage modulation of gate current over several orders of magnitude. A schematic of the device to be fabricated is given below:-

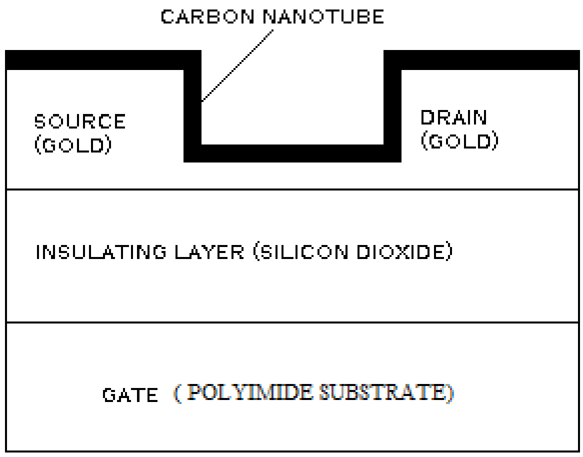

Figure 4 – Cross-sectional schematic of a FET made from Carbon Nanotubes.

The sensor design was done in the 3-D builder module of Intellisuite MEMS CAD tool. The various steps are shown below:-

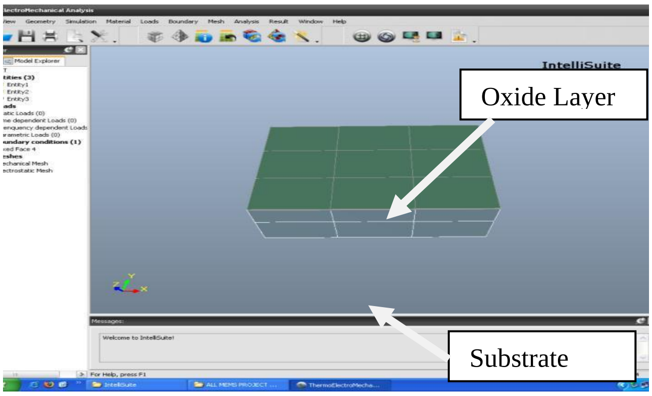

Figure 5 – Sensor with the Silicon dioxide layer over the Polyimide substrate

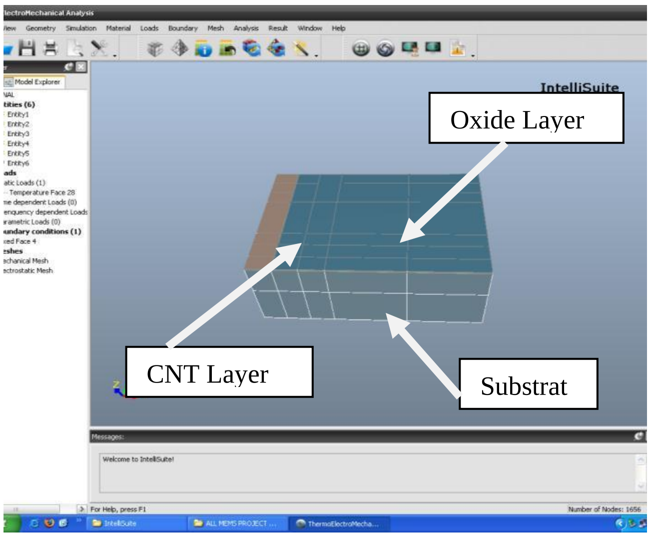

Figure 6 – Sensor with the CNT layer over the oxide layer

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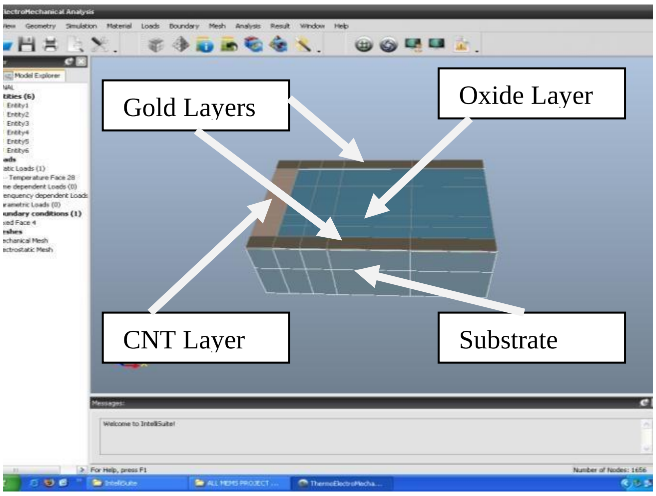

Figure 7 – The Gold layers are patterned as the Source and the Drain

C. Sensing Mechanism

A field effect transistor made of the chiral semi onducting carbon nanotubes can be used as a sensitive detector of various gases, such as NOx, Cl_2 and SOx etc. The transistor is placed in a 500ml flask having electrical feed through and inlet and outlet valves to allow gases to flow over the carbon nanotubes of the FET. Two to 200 parts per million of the gas flowing at a rate of 700ml/min for 10 min should cause a threefold increase in the conductance of the carbon nanotubes and current–voltage relationship before and after exposure to the gases can be obtained. The effect occurs because when the gas molecules bond to the carbon nanotubes, charge is ransferred from the nanotubes to the gas molecules, increasing the hole concentration in the carbon nanotubes and enhancing the conductance..

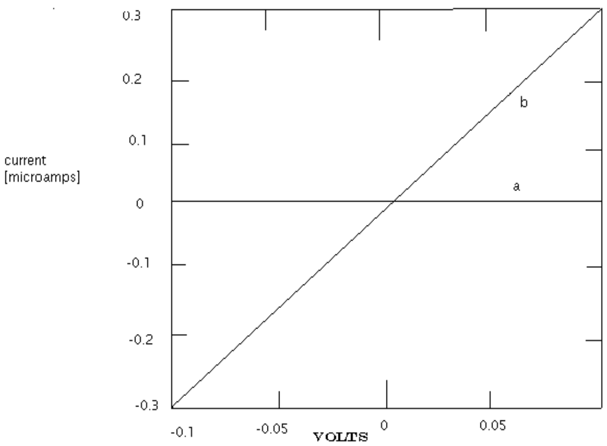

Figure 8 – Expected plot of current v/s voltage for the FET before (line a) and after (line b) exposure to the gas. The data is to be taken for 4V gate voltage

IV. ELECTRONIC CIRCUIT OF THE SENSOR

A typical application consists of measuring the tube gas level indoors close to gas generating sources or outdoor to detect disturbing or harmful concentration of the gases in the atmosphere. The sensor is usually placed inside a housing to protect the sensing element from water and dust projections. Ambient air containing the gases reaches the sensing element by gas diffusion. A change of electrical conductance of the sensing layer can be converted into a corresponding voltage change. This voltage change can then be used to calculate an equivalent concentration of the sensed gas by using a microcontroller or simply to display or sound an alarm by comparing a voltage from the sensor with a preset threshold voltage, showing the safe limits of the gas concentration.

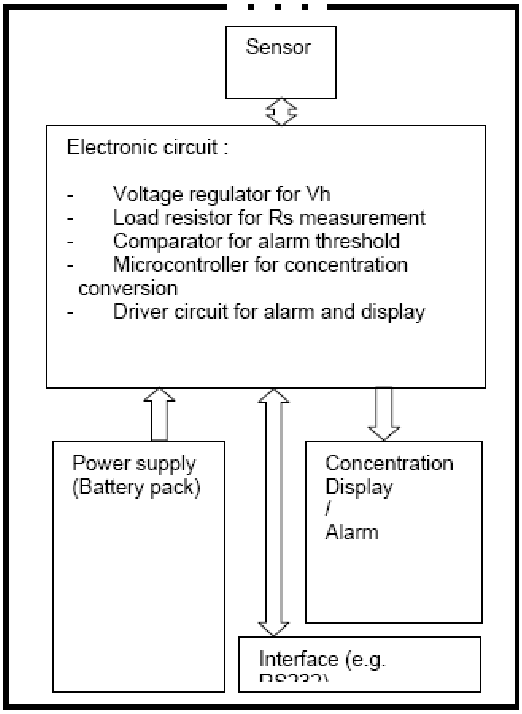

Figure 9 - Schematic of a CNT-FET gas detection system with built- in alarm

The sensor should essentially be placed in a filtered package that will protect it against liquid water or dust projection. To protect the sensor a convenient solution is to be placed in a shield plastic housing. Sensor element is placed near a hole that is closed with a breather membrane (polyester coated) such as those used to avoid contamination of electronic devices.

V. CONCLUSION

Hence the CNT-FET can be a promising device for future applications, having numerous advantages. It can also be utilized as a device which will be helpful to monitor the air quality and the emerging hazardous factor Global Warming by measuring the concentration of the various atmospheric gases responsible for it.

Once this technology gets commercialized it will be broadly implemented. Due to the enormous application potential, it might be reasonable to hope that the large scale fabrication methods of CNT-FETs would be developed, resulting in the decrease of the cost.

There is another problem with the CNT-FETs, which is the problem of its selectivity. Once the FET is used to sense & measure the concentration of a particular group of gas (say NO_2), it becomes selective to the group. At that time, it gives very low or inaccurate results with the other groups of gases (like SO_2, CO_2, Cl_2, etc.). Modern research has been in this direction to solve this problem and it is to be seen, whether we can achieve the same amount of accuracy of sensing for all the groups of the hazardous gases, which will make the sensor versatile.

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REFERENCES

1. Charles P.Poole Jr, Frank J.Owens, "Introduction to nanotechnology", Wiley India Pvt. Ltd.
2. Morinubo Endo,Sumio Lijima,MildredS.Dresselhaus,"Introduction to carbon nanotubes"
3. J.kong *et al*, "Science Journal"
4. Hou *et al*, "A MEMS-Based Ionization Gas Sensor Using Carbon Nanotubes", IEEE Transactions on Electron Devices, VOL 54, No.6,June 2007
5. Hou *et al*, "MEMS-based microelectrode system incorporating carbon nanotubes for ionization gas sensing ", Elsevier, ScienceDirect
6. [6] Sayago *et al*, "Carbon nanotube networks as gas sensors for NO_2 detection", Elsevier, ScienceDirect, Talanta
7. Yael Hanein, "Carbon nanotube integration into MEMS devices", physica status solidi b
8. Occhiuzzi *et al*, "RFID Passive Gas Sensor Integrating Carbon Nanotubes", IEEE Transactions on Microwave Theory and Techniques, VOL.59, NO.10, October 2011. Gas Passive Gas Sensor *al*,
9. http://www.esa.int, Source: European Space Agency
10. http://www.intellisensesoftware.com