# FLEXIBLE ZINC OXIDE SURFACE ACOUSTIC HYDROGEN GAS SENSOR BASED ON GRAPHENE OXIDE SENSING LAYER

FATINI SIDEK

UNIVERSITI TEKNOLOGI MALAYSIA

# FLEXIBLE ZINC OXIDE SURFACE ACOUSTIC HYDROGEN GAS SENSOR BASED ON GRAPHENE OXIDE SENSING LAYER

FATINI BINTI SIDEK

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy

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#### ABSTRACT

This thesis presents the design and development a flexible surface acoustic wave (SAW) gas sensor. Fabrication and characterization of SAW device, nanostructure material, and the gas sensing performance were examined. The flexibility of the SAW substrate is highly essential due to the uneven and curved surface. The investigated structure was based on three basic conditions of the device, which are flat, bend in, and bend out. Based on the conditions, the devices were tested for the electrical and gas sensing performances to hydrogen (H2) gas. The design of the flexible SAW gas sensor was completed using a simulation process prior to fabrication. The SAW propagation and properties were investigated using finite element method (FEM) simulation. It was observed that at bending inward radius of 1.5  $\mu$ m, the total displacement and frequency shift increased by 24.5% and 89%, respectively. The simulated nanostructure sensing elements have improved the sensitivity of the gas sensor by 85.5%. For the sensing element, simulation was conducted to investigate the graphene oxide effect on bending (warping) surface towards gas. From this study, a further increase of warping angle from 180° to 270° has enhanced the binding energy. The sensor was fabricated by depositing a piezoelectric layer, interdigitated electrodes, and nanostructured material. Zinc oxide (ZnO) was deposited as the piezoelectric layer using radio frequency (RF) magnetron sputtering with different parameters and characterised using atomic force microscopic (AFM), field emission scanning electron microscopy (FESEM), and x-ray diffraction (XRD). Based on the investigation of material characteristics and surface morphology of ZnO sputtered on polyimide (PI), higher RF power increased the deposition rate at 38% from 150 to 200 W, meanwhile at 300 W, the deposition rate spiked to 67%. The S21 measurement provided insertion loss (IL) and frequency response of the SAW device. The thickness of piezoelectric thin film significantly affected the frequency response and phase velocity of the acoustic wave. The measured response of graphene nanosheet flexible SAW sensor at room temperature was taken. The radii of curvature were defined as 10 mm for bend in and bend out. The frequency shift increased in the bend in condition compared to bend out and flat conditions. The graphene oxide nanosheet sensitive element conductivity increased when electron was injected into the device surface since H2 is a reducing gas. Therefore, the centre frequency of the acoustic wave velocity decreases significantly when the sensor exposed to the H2 gas. The SAW gas sensing performance of the investigated nanostructure materials provides a way for further investigation to future commercialisation of these types of sensors for different types of flexible substrates

#### ABSTRAK

Dalam tesis ini, kajian adalah berkisar tentang penderia gas gelombang permukaan akustik (SAW) yang fleksibel. Pembikinan dan pencirian peranti SAW, bahan struktur nano serta prestasi tindak balas gas telah diperiksa. Kebolehlenturan substrat SAW sangat penting kerana permukaan yang tidak rata dan melengkung. Struktur yang dikaji adalah berdasarkan tiga keadaan asas peranti iaitu rata, membengkok masuk, dan membengkok keluar. Berdasarkan keadaan tersebut, prestasi elektrik dan tindak balas gas penderia diuji terhadap gas hydrogen (H2). Reka bentuk penderia SAW gas yang fleksibel dilengkapkan menggunakan proses simulasi sebelum pembikinan. Perambatan dan sifat gelombang penderia kemudian dikaji dengan menggunakan simulasi FEM. Didapati bahawa pada radius membengkok masuk sebanyak 1.5 µm, jumlah anjakan dan perbezaan frekuensi masing-masing meningkat sebanyak 24.5% dan 89%. Elemen tindak balas struktur nano telah meningkatkan kepekaan penderia gas sebanyak 85.5%. Untuk unsur deria, simulasi dilakukan untuk menyiasat kesan grafena oksida pada lengkungan (lenturan) permukaan terhadap gas. Dari kajian ini, peningkatan lebih lanjut dalam sudut melengkung dari 180° hingga 270° telah meningkatkan tenaga pengikat. Penderia dibikin dengan mendeposit lapisan piezoelektrik, elektrod terpadu dan bahan berstruktur nano. Zink oksida (ZnO) didepositkan sebagai lapisan piezoelektrik menggunakan percikan magnetron frekuensi radio (RF) dengan parameter yang berbeza dan dicirikan menggunakan mikroskopik daya atom (AFM), mikroskop elektron pengimbas pancaran medan (FESEM) dan pembelauan sinar-x (XRD). Berdasarkan penyiasatan ciri-ciri bahan dan morfologi permukaan ZnO terhadap poliimida (PI), daya RF yang lebih tinggi meningkatkan kadar pemendapan pada 38% dari 150 hingga 200 W, manakala pada 300 W kadar pemendapan melonjak menjadi 67%. Pengukuran S21 memberikan kehilangan sisipan (IL) dan tindak balas frekuensi terhadap peranti SAW. Ketebalan filem piezoelektrik memberi kesan terhadap tindak balas frekuensi dan halaju fasa gelombang akustik. Tindak balas yang diukur pada suhu bilik penderia SAW fleksibel kepingan nano diambil. Jejari kelengkungan didefinisikan sebagai 10 mm untuk membengkok masuk dan membengkok keluar. Peralihan frekuensi meningkat dalam keadaan membengkok masuk berbanding keadaan membengkok keluar dan rata. Kekonduksian elemen sensitif grafena oksida meningkat apabila elektron disuntik ke permukaan peranti kerana H2 adalah gas pengurang. Oleh itu, frekuensi pusat halaju gelombang akustik menurun dengan ketara apabila penderia didedahkan dengan gas H2. Prestasi penderia gas SAW berkaitan bahan struktur nano yang dikaji membuka ruang untuk kajian lanjut untuk pengkomersialan jenis penderia berbeza terhadap substrat kebolehlenturan berbeza.

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# LIST OF ABBREVIATIONS

AFM	-	Atomic Force Microscope
AGNR	-	Graphene Nanoribbon
Al	-	Aluminum
AlN	-	Aluminum Nitride
Ar	-	Argon
AZO	-	Aluminum Doped Zinc
С	-	Carbon
CMOS	-	Complementary Metal-Oxide-Semiconductor
$CO_2$	-	Carbon Dioxide
CSA	-	Camphor Sulfonic Acid
DFT	-	Density Functional Theory
DFT	-	Density Functional Theory
DI	-	Dionized
DOF	-	Degree of Freedom
EDA	-	Electronic Design Automation
FEM	-	Finite Element Method
FESEM	-	Field Emission Scanning Electron Microscopy
FWHM	-	Full Width at Half Maximum
GaPO <sub>4</sub>	-	Gallium Phosphate
GO	-	Grapheme Oxide
$H_2$	-	Hydrogen
$H_2S$	-	Hydrogen Sulphide
IDT	-	Interdigitated Transducer
IL	-	Insertion Loss
IoT	-	Internet of Things
ISS	-	Impedance Standard Substrate
LCD	-	Liquid Crystal Display
LGS	-	Langasite
LiNbO <sub>3</sub>		Lithium Niobate

LiTaO <sub>3</sub>	-	Lithium Tantalate
MEMS	-	Microelectromechanical Systems
Мо	-	Molybdenum
MWCN	Γ-	MultiWalled Carbon Nanotubes
NEGF	-	Non-Equilibrium Green's Function
NH <sub>3</sub>	-	Ammonia
NO	-	Nitrogen Oxide
$O_2$	-	Oxygen
PANI	-	Polyaniline
PCB	-	Printed Circuit Board
PI	-	Polyimide
PNVP	-	Poly-N-inylphyrolidone
PVDF	-	Polyvinylidine Diflouride
PZT	-	Lead Zirconate Titanate
RF	-	Radio Frequency
RH	-	Relative Humidity
RMS	-	Root Mean Square
SAW	-	Surface Acoustic Wave
Si	-	Silicon
$SO_2$	-	Sulphur Dioxide
VNA	-	Vector Network Analyzer
XRD	-	X-Ray Diffraction
7.0		

ZnO - Zinc Oxide

# LIST OF SYMBOLS

f	-	Frequency
V	-	Acoustic wave velocity
λ	-	Acoustic wave wavelength
$k^2$	-	Electromechanical coupling coefficient
$C_s$	-	Dielectric constant
уо	-	Characteristic admittance of the SAW transmission line
d	-	Thickness
r	-	Cylindrically bend to radius
<i>a</i> <sub>1,2</sub>	-	Triangular lattice unit vector
<i>b</i> <sub>1,2</sub>	-	Reciprocal triangular lattice
$E_k$	-	Tight binding structure of graphene
$E_F$	-	Fermi energy
K'	-	Dirac point
t	-	nearest neighbour hoping integral
h	-	Bending radius
Т	-	Stress tensor
$c^E$	-	Elasticity matrix
S	-	Strain tensor
e	-	Piezoelectric coupling constants
$E_k$	-	Electric field intensity
$W_e$	-	Width of electrodes
$W_{sp}$	-	Space between each electrode
$f_0$	-	Operating frequency
$v_0$	-	Velocity of wave propagation
ρ	-	Partial density
Р	-	Pressure
R	-	Gas constant
Т	-	Air temperature

UL-Ieff displacementUR-Right displacementφL-Right displacementφL-Right boundary potentialØR-Right boundary potentialEa-Total energy of optimized graphene and gas moleculeE (Graphene)-Total energy of optimized grapheneE (Graphene)-Total energy of optimized gas moleculeF (Graphene)-Total energy of optimized gas moleculeR (Graphene)-Total energy of optimized gas moleculeN-Charge transferDij-Overlap matrixSij-C-axis direction of polarizatione33-C-axis direction of polarizatione34-Lattice constant on a-planee37-Lattice constant on a-planec-Lattice constant ofram (002) planec-The lattice constant oltained from (002) planea-Piezoelectric constante-Piezoelectric constante-Frective elastic stiffnessvs-Stiffness of the leverD-Frective elastic stiffnessvs-Stiffness of the leverD-Silocation densitydhal-G-spacingc-Silocation densitydhal-Silocation densityf-Silocation densityf-Silocation densityf-Silocation density <td< th=""><th><math>\Delta f</math></th><th>-</th><th>Frequency shift</th></td<>	$\Delta f$	-	Frequency shift
φ <sub>L</sub> -Icfl boundary potentialφ <sub>R</sub> -Right boundary potentialEa-Binding energyE (Graphene + Gas)-Total energy of optimized graphene and gas moleculeE (Graphene)-Total energy of optimized grapheneE (Graphene)-Total energy of optimized gas moleculeN-Charge transferDij-Density matrixSij-Overlap matrixP3-C-axis direction of polarizatione33-Wurtzite piezoelectric stress coefficiente34-Vurtzite piezoelectric stress coefficiente33-Lattice constant on a-planee33-Lattice constant from 002 planec-Statice constant obtained from (002) planec-The lattice constant along a planea0-Piezoelectric constante3-Fiective clastic stiffnessvs-Stiffness of the leverc-Stiffness of the leverc-Stiffness of the leverb-Stiffness of the leverc-Stiffness of the leverc-Stiffness of the leverc-Stiffness of the leverb-Stiffness of the leverc-Stiffness of the lev	$U_L$	-	Left displacement
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δ-Dislocation density $d_{hkl}$ - $d$ -spacingc- $c$ -axis lattice constant $\sigma$ -Biaxial strain	D	-	Crystalline size
$d_{hkl}$ - $d$ -spacing $c$ - $c$ -axis lattice constant $\sigma$ -Biaxial strain	$X_{rad}$	-	FWHM of the (002) plane peak in radians
$c$ - $c$ -axis lattice constant $\sigma$ -Biaxial strain	δ	-	Dislocation density
$\sigma$ - Biaxial strain	$d_{hkl}$	-	d-spacing
	С	-	<i>c</i> -axis lattice constant
$\varepsilon$ - Film strain along (002) orientation	σ	-	Biaxial strain
	З	-	Film strain along (002) orientation

Cfilm	-	The lattice constants obtained from (002) plane
CZnO	-	Lattice constant of ideal ZnO
I <sub>(bkg)</sub>	-	Background intensity
<b>I</b> (002)	-	Intensity of the peak at plane of (002)
$\varphi_A$	-	The phase shift produced by the amplifier
$\varphi_c$	-	Phase shift produced by gas chamber electrical connections
Т	-	Signal delay
$\varphi_e$	-	Constant if the amplifier is working at stable conditions
S	-	Sensitivity
Rair	-	Resistance of the sensor in air
Rgas	-	Resistance of the sensor in presence of gas

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#### **CHAPTER 1**

### **INTRODUCTION**

### 1.1 Introduction

The purpose of this chapter is to provide a general overview and introduction for the research presented in this PhD thesis. This chapter addresses the research motivations, problem statement, objectives, scopes and the significance to knowledge.

### 1.2 Problem Background

One of the most significant sources of air pollution is electricity generation, which is caused by the fossil fuels used by power plants. Since hydrogen (H<sub>2</sub>) is renewable, plentiful, and reliable, as well as having zero emissions, interest in using it as a clean energy source or a fuel gas has risen dramatically in order to reduce fossil fuel usage. H<sub>2</sub> is also widely used in a variety of industries for instance industries to make ammonia, methanol and rocket fuel and also as a replacement for natural gas in warming homes and powering hot water heaters.

However, the explosive nature of  $H_2$  gas above 4% concentration makes it highly dangerous to store, transport and use [1]. Further, the small size gas molecules of  $H_2$  are prone to leak through the smallest possible holes and cracks. Hence, the detection of  $H_2$  gas becomes essential even at trace levels.

Gas sensors are applied for facilitating the safe use of  $H_2$  in, for example, fuel cell and  $H_2$  fueled vehicles. New sensor developments, aimed at meeting the increasingly stringent performance requirements in emerging applications are presented. Flexible and wearable sensor application potential has been great field of interest for the past several decades. The development of flexible gas sensing systems is raising a high interest among the scientific community due to their potential applications in wear-able and portable electronic products, in RFID tags. Moreover, the techniques used in the flexible gas sensing industry, such as screen and inkjet printing, enable the large-scale fabrication of low-cost effective systems [2]. Many reports have been published regarding the growth of gas sensor market.

#### **1.3 Problem Statement**

There are various methods of gas detection types can be found in several papers. In the past 20 years, there was vast development of Surface Acoustic Wave (SAW) as a sensor with numerous applications ranging from very basic home appliances, advanced medical devices, automotive industry to space vehicles [3]–[5].

 $H_2$  gas is used as reducing agent and as a carrier gas in the process of manufacturing semiconductors. It has been increasingly known as a clean source of energy or a fuel gas. Based on [6] leaking of hydrogen gas must be avoided as it will lead to explosion if mixed with air in ratio of 4.65-93.9 vol.%. Therefore, fast response and accurate hydrogen detector before the explosive concentration and room temperature still a great problem.

SAW gas sensors are very attractive based on their excellent sensitivity due to changes of boundary conditions for propagating acoustic Rayleigh waves. Change in physical and chemical properties can be easily detected as long as the thickness of sensitive layer is less than the wavelength of the surface wave.

Most of the SAW sensor are made on rigid substrates are not suitable for curved surface which are essential for flexible sensing devices. In 2005, before the flexible SAW sensors were proven to be utilized as temperature and humidity sensor, Preethichandra et. al [7], [8] have shown that flexible SAW sensor has an ability to measure bending curvature. Preethichandra et. al have fabricated SAW sensor on a flexible Polyvinylidine Diflouride (PVDF) substrate in order to obtain bending curvature which will be use in a high-accuracy tele-operational robotic hand. They found that the output voltage of the SAW sensor is proportional to the curvature. Based on this ability, they suggests the possibility of devising a dynamic surface profile sensor in which has a lot of scope in biomedical applications.

Moreover, studies investigated by Tseng et al. and Ad Park et al. [9], [10] show the effect of bending on the electrical and optical characteristics of ZnO thin film. The result shows the durability of the thin film on flexible polymer produces good electrical stability and resistivity changes gradually depends on bending radius. However, there are not many research found for flexible SAW gas sensor due to difficulties in achieving high quality of piezoelectric thin film.

This is due dimension of a flexible substrate with various surface adhesion which possess low surface energies, this will cause difficulties in achieving the growth of high quality piezoelectric thin film. Most critical part is when the fabricate of flexible SAW devices are it is challenging to obtain high c-axis oriented, low surface roughness piezoelectric films with a good piezoelectric constant and this may cause by several factors. An effective approach of manufacture flexible SAW is lack causes complications in exploitation of flexible devices. Therefore, the main goal of this research is to fabricate sensor with improved quality of piezoelectric thin film.

#### 1.4 Research Objectives

The objectives of this research are:

- To study the propagation and analyse the properties of SAW gas sensor with graphene thin film and nano-structure sensing element via simulation using Finite Element Method.
- 2. To investigate the material characteristics and surface morphology of ZnO thin film that sputtered on polyimide with different sputtering parameters.
- 3. To investigate in detail the basic behaviour (such as electrical performance, reflection  $(S_{11})$  and transmission  $(S_{21})$  of SAW device on flexible substrate.
- 4. To examine the effect of bending towards the performance of SAW gas sensor.

## 1.5 Research Scopes

In this project, a flexible Surface Acoustic Wave hydrogen gas sensor is fabricated. The design of flexible SAW gas sensor completed using simulation process prior to fabrication via COMSOL Multiphysics. Based on simulation, there are several analyses which include eigenfrequency analysis, total displacement velocity and frequency shift. The analysis is important to relate performance with the fabricated sensor. Next, the fabrication of the sensor realized by depositing piezoelectric layer using RF sputtering. Interdigitated electrodes for the sensor were deposited using print screen technique. While sensing material realized by drop casting method. All of the fabricated materials have been characterized the morphology, crystallography, orientation and film thickness using based on XRD, AFM and FESEM to observe the quality and performance. The nanostructured material deposited onto the active area of SAW device to increase the volume to surface ratio, subsequently will improve the sensor's sensitivity. The flexibility of the SAW substrate is highly essential due to the uneven and curved surface. Experimental investigation and data evaluation will be carried out to proof the ability a flexible SAW sensor for hydrogen gas sensing performance.

#### 1.6 Significance and Original Contribution of This Study

This study significantly contributes to the optimizing the growth of zinc oxide (ZnO) and its role as a piezoelectric on the flexible substrate. It also to study about the deposition morphology, crystallography, orientation and film thickness of ZnO effect on the SAW transmission characteristics. Furthermore, implementing the print screen method for IDT and effect of bending the SAW gas sensor.

### 1.7 Thesis Structure and Organization

The thesis is primarily devoted to this topic and is divided as follow:

• Chapter 2 presents the literature review on flexible SAW gas sensor, operating principles and mechanisms. This chapter also includes the

past studies on rigid and flexible sensors.

- Chapter 3 discusses in detail the simulation of flexible SAW gas sensor using COMSOL Multiphysics to provide the preliminary results on the sensor functionality.
- Chapter 4 explains the fabrication steps for flexible SAW gas sensor which involving the deposition of piezoelectric thin film, the metallization layer deposition and the implementation of the sensing element.
- Chapter 5 characterizes the flexible SAW gas sensor piezoelectric thin film, metallization and sensing element by employing X-Ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FESEM).
- Chapter 6 focuses on the experimental gas sensing system design which presents the testing of the flexible SAW gas sensor on bending position and measuring the response of the sensor toward the gas.
- Chapter 7 concludes the project work based on the results drawn and future works that may be applied.

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## LIST OF PUBLICATIONS

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