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

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

AUGUST 2021

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Dr Rashidah Arsat, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Dr Zaharah Johari for her guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Kementerian Pengajian Tinggi (KPT) for funding my Ph.D study with Fundamental Research Grant Scheme (FRGS): 4F485 – Title: The characterization of Multifunction Flexible SAW device. Technicians and Lab assistants also deserve special thanks for their assistance in the laboratory machine utilization in UTM and IIUM.

My fellow postgraduate friends should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

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 μm, 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..

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFM - Atomic Force Microscope
AGNR - Graphene Nanoribbon
Al - Aluminum
AlN - Aluminum Nitride
Ar - Argon
AZO - Aluminum Doped Zinc
C - 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
$GaPO_4$ - 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
$LiNbO_3$ - Lithium Niobate

$LiTaO_3$ - Lithium Tantalate
MEMS - Microelectromechanical Systems
Mo - Molybdenum
MWCNT- MultiWalled Carbon Nanotubes
NEGF - Non-Equilibrium Green's Function
NH_3 - 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
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
y_0 - Characteristic admittance of the SAW transmission line
d - Thickness
r - Cylindrically bend to radius
$a_{1,2}$ - Triangular lattice unit vector
$b_{1,2}$ - 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
T - 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
P - Pressure
R - Gas constant
T - Air temperature

Δf - Frequency shift

U_L - Left displacement

U_R - Right displacement

φ_L - Left boundary potential

φ_R - Right boundary potential

Ea - Binding energy

$E_{(Graphene\ +\ Gas)}$ - Total energy of optimized graphene and gas molecule

$E_{(Graphene)}$ - Total energy of optimized graphene

$E_{(Gas)}$ - Total energy of optimized gas molecule

N - Charge transfer

Dij - Density matrix

Sij - Overlap matrix

P_3 - *c*-axis direction of polarization

e_{33} - Wurtzite piezoelectric stress coefficient

e_{31} - Wurtzite piezoelectric stress coefficient

$\varepsilon_{1,2}$ - Lattice constant on *a*-plane

ε_3 - Lattice constant from 002 plane

c - Lattice constant obtained from (002) plane

c_0 - Lattice constant obtained from (002) plane

a - The lattice constant along *a* plane

a_0 - The lattice constant along *a* plane

e - Piezoelectric constant

ε - Dielectric constant along the acoustic wave propagation

c_s - Effective elastic stiffness

v_s - The sound velocity for ZnO along *c*-axis

F - Force

k - Stiffness of the lever

D - Crystalline size

X_{rad} - FWHM of the (002) plane peak in radians

δ - Dislocation density

d_{hkl} - *d*-spacing

c - *c*-axis lattice constant

σ - Biaxial strain

ε - Film strain along (002) orientation

c_{film} - The lattice constants obtained from (002) plane

c_{ZnO} - Lattice constant of ideal ZnO

$I_{(bkg)}$ - Background intensity

$I_{(002)}$ - Intensity of the peak at plane of (002)

φ_A - The phase shift produced by the amplifier

φ_c - Phase shift produced by gas chamber electrical connections

T - Signal delay

φ_e - Constant if the amplifier is working at stable conditions

S - Sensitivity

R_{air} - Resistance of the sensor in air

R_{gas} - Resistance of the sensor in presence of gas

LIST OF APPENDICES

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_2) 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_2 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:

1. 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.

REFERENCES

[1] T. Hübert, L. Boon-Brett, V. Palmisano, and M. A. Bader, “Developments in gas sensor technology for hydrogen safety,” in *International Journal of Hydrogen Energy*, 2014, vol. 39, no. 35, pp. 20474–20483, doi: 10.1016/j.ijhydene.2014.05.042.

[2] O. Kassem, M. Saadaoui, M. Rieu, and J. P. Viricelle, “Fabrication of SnO2 Flexible Sensor by Inkjet Printing Technology,” *Proceedings*, vol. 2, no. 13, p. 907, 2018, doi: 10.3390/proceedings2130907.

[3] G. Manohar, “Investigation of Various Surface Acoustic Wave Design Configurations for Improved Sensitivity,” *Univ. South Florida*, no. January, pp. 1–112, 2012, [Online]. Available: http://scholarcommons.usf.edu/etd/4365/.

[4] W. P. Jakubik, “Surface acoustic wave-based gas sensors,” in *Thin Solid Films*, 2011, vol. 520, no. 3, pp. 986–993, doi: 10.1016/j.tsf.2011.04.174.

[5] S. Shiokawa and J. Kondoh, “Surface Acoustic Wave Sensors,” *Jpn. J. Appl. Phys.*, vol. 43, no. 5S, p. 2799, 2004, doi: 10.1143/JJAP.43.2799.

[6] S. Drewniak *et al.*, “Investigations of SAW structures with oxide graphene layer to detection of selected gases,” in *Acta Physica Polonica A*, 2013, vol. 124, no. 3, pp. 402–405, doi: 10.12693/APhysPolA.124.402.

[7] D. M. and K. K. Preethichandra, “Bending curvature measurement using a SAW sensor fabricated on a polyvinylidine difluoride (PVDF) substrate.,” 2005.

[8] D. M. G. Preethichandra and K. Kaneto, “SAW sensor network fabricated on a polyvinylidine difluoride (PVDF) substrate for dynamic surface profile sensing,” *IEEE Sens. J.*, vol. 7, no. 5, pp. 646–649, 2007, doi: 10.1109/JSEN.2007.894911.

[9] Z.-L. Tseng, Y.-C. Tsai, S. Wu, Y.-D. Juang, and S.-Y. Chu, “The Effect of Bending on the Electrical and Optical Characteristics of Aluminum-Doped ZnO Films Deposited on Flexible Substrates,” *ECS J. Solid State Sci. Technol.* , vol. 2, no. 1, pp. P16–P19, 2013, doi: 10.1149/2.018301jss.

[10] J. Park, J. Hong, J. Yang, J. Kim, S. Park, and H. Kim, “Bending Effects of

Indium-Zinc Oxide Thin Films Deposited on Polyethylene Terephthalate Substrate by Radio Frequency Magnetron Sputtering," *J. Korean Phys. Soc.*, vol. 48, no. 6, pp. 1530–1533, 2006.

[11] J. Liu, W. Wang, S. Li, M. Liu, and S. He, "Advances in saw gas sensors based on the condensate-adsorption effect," *Sensors*, vol. 11, no. 12, pp. 11871–11884, 2011, doi: 10.3390/s111211871.

[12] A. Marcu and C. Viespe, "Surface acoustic wave sensors for hydrogen and deuterium detection," *Sensors (Switzerland)*, vol. 17, no. 6, 2017, doi: 10.3390/s17061417.

[13] A. Laposa, M. Husak, J. Kroutil, and R. Vrba, "Gas sensor with SAW structures," in *Technical Proceedings of the 2012 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2012*, 2012, pp. 574–577.

[14] J. T. Tsai, K. Y. Chiu, D. H. Wu, and J. H. Chou, "Modelling for SAW sensors," in *Conference Proceedings - 2014 International Conference on System Science and Engineering, ICSSE 2014*, 2014, pp. 74–75, doi: 10.1109/ICSSE.2014.6887908.

[15] D. T. S. Staline Johnson, "Design and Analysis of SAW Based MEMS Gas Sensor for the Detection of Volatile Organic Gases," *Int. J. Eng. Res. Appl.*, vol. 4, no. 3 (Version 1), pp. 254–258, 2014.

[16] Liu Bo; Chen Xio; Chai Hualin; Mohammad Ali Mohammad, "Surface acoustic wave device for sensor applications," *J. Semicond.*, vol. 37, no. 2, p. 9, 2016.

[17] S. Kurosawa, N. Kamo, D. Matsui, and Y. Kobatake, "Gas Sorption to Plasma-Polymerized Copper Phthalocyanine Film Formed on a Piezoelectric Crystal," *Anal. Chem.*, vol. 62, no. 4, pp. 353–359, 1990, doi: 10.1021/ac00203a009.

[18] M. H. Wohltjen, G. C. Frye, E. T. Zellers, Robert M. White, *Acoustic Wave Sensor Theory Designs and physio-chemical applications*. Academic Press, 1996.

[19] H. C. Hao *et al.*, "Improved Surface Acoustic Wave Sensor for Low Concentration Ammonia/Methane Mixture Gases Detection," in *17th International Conference on Miniaturized Systems for Chemistry and Life Sciences*, 2013, pp. 245–247.

[20] Y. Y. Chen, T. T. Wu, T. H. Chou, and F. C. Huang, "SAW Gas Sensor with

Nanostructured Sensing Materials," *Iutam Symp. Recent Adv. Acoust. Waves Solids*, vol. 26, pp. 397–402, 2010, doi: Doi 10.1007/978-90-481-9893-1_40.

[21] M.-C. Chiang *et al.*, "Gas sensor array based on surface acoustic wave devices for rapid multi-detection," 2012, doi: 10.1109/NMDC.2012.6527578.

[22] H. Wohltjen and R. Dessy, "Surface Acoustic Wave Probe for Chemical Analysis. I. Introduction and Instrument Description," *Anal. Chem.*, vol. 51, no. 9, pp. 1458–1464, 1979, doi: 10.1021/ac50045a024.

[23] J. A. Thiele and M. P. Da Cunha, "High temperature LGS SAW gas sensor," *Sensors Actuators, B Chem.*, vol. 113, no. 2, pp. 816–822, 2006, doi: 10.1016/j.snb.2005.03.071.

[24] et al. Talbi, A., "Zero TCF ZnO/Quartz SAW structure for gas sensing applications," 2004.

[25] et al Osugi, Y., "Single crystal FBAR with LiNbO3 and LiTaO3 piezoelectric substance layers," 2007.

[26] S. Datta, *Surface acoustic wave devices*. NJ, USA: Prentice-Hall Englewood Cliffs, 1986.

[27] M. Sayer, "Piezoelectric thin film devices," 1991.

[28] P. Sundriyal and S. Bhattacharya, "Inkjet-Printed Sensors on Flexible Substrates," 2018, pp. 89–113.

[29] P. H. Cole, L. H. Turner, Z. Hu, and D. C. Ranasinghe, "The next generation of RFID technology," in *Unique Radio Innovation for the 21st Century: Building Scalable and Global RFID Networks*, 2011, pp. 3–23.

[30] L. Shu *et al.*, "The Characterization of Surface Acoustic Wave Devices Based on AlN-Metal Structures," *Sensors*, vol. 16, no. 4, p. 526, 2016, doi: 10.3390/s16040526.

[31] C. K. Chen, D. T. W. Lin, Y. Der Juang, Y. C. Hu, Y. T. Kuo, and C. Y. Chen, "The innovated flexible surface acoustic wave devices on fully InkJet printing technology," *Smart Sci.*, vol. 1, no. 1, pp. 13–17, 2013, doi: 10.1080/23080477.2013.11665581.

[32] J. Zhou, S. Dong, H. Jin, B. Feng, and D. Wang, "Flexible surface acoustic wave device with AlN film on polymer substrate," *J. Control Sci. Eng.*, vol. 2012, 2012, doi: 10.1155/2012/610160.

[33] C.-H. Zhang *et al.*, "Wafer-Scale Flexible Surface Acoustic Wave Devices Based on an AlN/Si Structure," *Chinese Phys. Lett.*, vol. 30, no. 7, p. 77701,

Jul. 2013, doi: 10.1088/0256-307X/30/7/077701.

[34] H. Jin *et al.*, “Flexible surface acoustic wave resonators built on disposable plastic film for electronics and lab-on-a-chip applications,” *Sci. Rep.,* vol. 3, 2013, doi: 10.1038/srep02140.

[35] C.-K. Chen, D. T. W. Lin, Y. Juang, Y.-C. Hu, Y. T. Kuo, and C. Y. Chen, “The Innovated Flexible Surface Acoustic Wave Devices on Fully InkJet Printing Technology,” *Smart Science*, vol. 1, no. 1. pp. 13–17, 2013, doi: 10.6493/SmartSci.2013.109.

[36] C. H. Zhang *et al.*, “Wafer-scale flexible surface acoustic wave devices based on an Aln/Si structure,” *Chinese Phys. Lett.*, vol. 30, no. 7, 2013, doi: 10.1088/0256-307X/30/7/077701.

[37] W. S. Wong *et al.*, “Amorphous silicon thin-film transistors and arrays fabricated by jet printing,” *Appl. Phys. Lett.*, vol. 80, no. 4, pp. 610–612, 2002, doi: 10.1063/1.1436273.

[38] W. S. Wong, R. Lujan, J. H. Daniel, and S. Limb, “Digital lithography for large-area electronics on flexible substrates,” *J. Non. Cryst. Solids,* vol. 352, no. 9–20 SPEC. ISS., pp. 1981–1985, 2006, doi: 10.1016/j.jnoncrysol.2005.12.055.

[39] D. Kim, S. H. Lee, S. Jeong, and J. Moon, “All-ink-jet printed flexible organic thin-film transistors on plastic substrates,” *Electrochem. Solid-State Lett.*, vol. 12, no. 6, 2009, doi: 10.1149/1.3098962.

[40] H. Jin *et al.*, “Flexible surface acoustic wave respiration sensor for monitoring obstructive sleep apnea syndrome,” *J. Micromechanics Microengineering*, vol. 27, no. 11, 2017, doi: 10.1088/1361-6439/aa8ae0.

[41] W. Xuan *et al.*, “High sensitivity flexible Lamb-wave humidity sensors with a graphene oxide sensing layer,” *Nanoscale,* vol. 7, no. 16, pp. 7430–7436, 2015, doi: 10.1039/c5nr00040h.

[42] S. Wang, C. Xu, X. Pan, and B. Wei, “Design and application of high precision differential SAW sensor,” in *Proceedings - 2017 International Conference on Computer Technology, Electronics and Communication, ICCTEC 2017*, 2017, pp. 890–893, doi: 10.1109/ICCTEC.2017.00197.

[43] X. L. He *et al.*, “High sensitivity humidity sensors using flexible surface acoustic wave devices made on nanocrystalline ZnO/polyimide substrates,” *J. Mater. Chem. C,* vol. 1, no. 39, pp. 6210–6215, 2013, doi:

10.1039/c3tc31126k.

[44] W. Xuan, J. Chen, X. He, W. Wang, S. Dong, and J. Luo, “Flexible surface acoustic wave humidity sensor with on chip temperature compensation,” in *Procedia Engineering*, 2015, vol. 120, pp. 364–367, doi: 10.1016/j.proeng.2015.08.639.

[45] X. L. He *et al.*, “High performance dual-wave mode flexible surface acoustic wave resonators for UV light sensing,” *J. Micromechanics Microengineering*, vol. 24, no. 5, 2014, doi: 10.1088/0960-1317/24/5/055014.

[46] et al. He, X., “High sensitivity humidity sensors using flexible surface acoustic wave devices made on nanocrystalline ZnO/polyimide substrates,” *J. Mater. Chem. C*, vol. 1, no. 39, 2013.

[47] P. Zheng *et al.*, “Langasite SAW device with gas-sensitive layer,” in *2010 IEEE International Ultrasonics Symposium*, 2010, pp. 1462–1465, doi: 10.1109/ULTSYM.2010.5935779.

[48] C. Dagdeviren *et al.*, “Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation,” *Extreme Mechanics Letters*, vol. 9. pp. 269–281, 2016, doi: 10.1016/j.eml.2016.05.015.

[49] W. Jakubik, M. Urbańczyk, and E. Maciak, “SAW hydrogen gas sensor based on WO3 and Pd nanostructures,” in *Procedia Chemistry*, 2009, vol. 1, no. 1, pp. 200–203, doi: 10.1016/j.proche.2009.07.050.

[50] Z. Yunusa *et al.*, “Development of a hydrogen gas sensor using a double saw resonator system at room temperature,” *Sensors (Switzerland)*, vol. 15, no. 3, pp. 4749–4765, 2015, doi: 10.3390/s150304749.

[51] X. Y. Zhang, R. H. Ma, L. S. Li, L. Fan, Y. T. Yang, and S. Y. Zhang, “A room-temperature ultrasonic hydrogen sensor based on a sensitive layer of reduced graphene oxide,” *Sci. Rep.*, vol. 11, no. 1, 2021, doi: 10.1038/s41598-020-80875-0.

[52] W. P. Jakubik, M. Urbańczyk, E. Maciak, and T. Pustelny, “Surface acoustic wave hydrogen gas sensor based on layered structure of palladium/metal-free phthalocyanine,” *Bull. Polish Acad. Sci. Tech. Sci.*, vol. 56, no. 2, pp. 133–138, 2008.

[53] D. Li, W. Y. Lai, Y. Z. Zhang, and W. Huang, “Printable Transparent Conductive Films for Flexible Electronics,” *Advanced Materials*, vol. 30, no. 10. 2018, doi: 10.1002/adma.201704738.

[54] M. V. Kulkarni, S. K. Apte, S. D. Naik, J. D. Ambekar, and B. B. Kale, “Ink-jet printed conducting polyaniline based flexible humidity sensor,” *Sensors Actuators, B Chem.*, vol. 178, pp. 140–143, 2013, doi: 10.1016/j.snb.2012.12.046.

[55] H. Menon, R. Aiswarya, and K. P. Surendran, “Screen printable MWCNT inks for printed electronics,” *RSC Adv.*, vol. 7, no. 70, pp. 44076–44081, 2017, doi: 10.1039/c7ra06260e.

[56] R. R. Søndergaard, M. Hösel, and F. C. Krebs, “Roll-to-Roll fabrication of large area functional organic materials,” *Journal of Polymer Science, Part B: Polymer Physics*, vol. 51, no. 1. pp. 16–34, 2013, doi: 10.1002/polb.23192.

[57] R. F. Pease and S. Y. Chou, “Lithography and other patterning techniques for future electronics,” *Proc. IEEE*, vol. 96, no. 2, pp. 248–270, 2008, doi: 10.1109/JPROC.2007.911853.

[58] A. Nathan *et al.*, “Flexible electronics: The next ubiquitous platform,” in *Proceedings of the IEEE*, 2012, vol. 100, no. SPL CONTENT, pp. 1486–1517, doi: 10.1109/JPROC.2012.2190168.

[59] M. A. Bissett, S. Konabe, S. Okada, M. Tsuji, and H. Ago, “Enhanced chemical reactivity of graphene induced by mechanical strain,” *ACS Nano*, vol. 7, no. 11, pp. 10335–10343, 2013, doi: 10.1021/nn404746h.

[60] A. K. Geim and K. S. Novoselov, “The rise of graphene,” *Nat. Mater.*, vol. 6, no. 3, pp. 183–191, 2007, doi: 10.1038/nmat1849.

[61] H. Okimoto *et al.*, “Low-voltage operation of ink-jet-printed single-walled carbon nanotube thin film transistors,” *Jpn. J. Appl. Phys.*, vol. 49, no. 2 PART 2, 2010, doi: 10.1143/JJAP.49.02BD09.

[62] Z. Fan *et al.*, “Toward the Development of Printable Nanowire Electronics and Sensors,” *Adv. Mater.*, vol. 21, no. 37, pp. 3730–3743, 2009, doi: 10.1002/adma.200900860.

[63] M. A. M. Leenen, V. Arning, H. Thiem, J. Steiger, and R. Anselmann, “Printable electronics: Flexibility for the future,” *Phys. Status Solidi Appl. Mater. Sci.*, vol. 206, no. 4, pp. 588–597, 2009, doi: 10.1002/pssa.200824428.

[64] F. C. Krebs, “Fabrication and processing of polymer solar cells: A review of printing and coating techniques,” *Solar Energy Materials and Solar Cells*, vol. 93, no. 4. pp. 394–412, 2009, doi: 10.1016/j.solmat.2008.10.004.

[65] R. A. Street, T. N. Ng, S. E. Ready, and G. L. Whiting, “Printing,” in

Handbook of Visual Display Technology, 2016, pp. 1289–1303.

[66] I.-C. Cheng, *Flexible and printed electronics*. 2016.

[67] J. Suikkola *et al.*, “Screen-Printing Fabrication and Characterization of Stretchable Electronics,” *Sci. Rep.*, vol. 6, 2016, doi: 10.1038/srep25784.

[68] R. Mannerbro and M. Ranlöf, “Inkjet and Screen Printed Electrochemical Organic Electronics,” 2007.

[69] B. Andò, S. Baglio, A. R. Bulsara, T. Emery, V. Marletta, and A. Pistorio, “Low-cost inkjet printing technology for the rapid prototyping of transducers,” *Sensors (Switzerland)*, vol. 17, no. 4. 2017, doi: 10.3390/s17040748.

[70] S. Jung, S. D. Hoath, G. D. Martin, and I. M. Hutchings, *Inkjet Printing Process for Large Area Electronics*. 2015.

[71] M. Gao, L. Li, and Y. Song, “Inkjet printing wearable electronic devices,” *Journal of Materials Chemistry C*, vol. 5, no. 12. pp. 2971–2993, 2017, doi: 10.1039/c7tc00038c.

[72] F. Torrisi *et al.*, “Inkjet-printed graphene electronics,” *ACS Nano*, vol. 6, no. 4, pp. 2992–3006, 2012, doi: 10.1021/nn2044609.

[73] V. B. Mohan, K. tak Lau, D. Hui, and D. Bhattacharyya, “Graphene-based materials and their composites: A review on production, applications and product limitations,” *Composites Part B: Engineering*, vol. 142. pp. 200–220, 2018, doi: 10.1016/j.compositesb.2018.01.013.

[74] M. Assar and R. Karimzadeh, “Enhancement of methane gas sensing characteristics of graphene oxide sensor by heat treatment and laser irradiation,” *J. Colloid Interface Sci.*, vol. 483, pp. 275–280, 2016, doi: 10.1016/j.jcis.2016.08.045.

[75] D. Sun, Y. Luo, M. Debliquy, and C. Zhang, “Graphene-enhanced metal oxide gas sensors at room temperature: A review,” *Beilstein Journal of Nanotechnology*, vol. 9, no. 1. pp. 2832–2844, 2018, doi: 10.3762/bjnano.9.264.

[76] F. Perrozzi, S. Prezioso, and L. Ottaviano, “Graphene oxide: From fundamentals to applications,” *Journal of Physics Condensed Matter*, vol. 27, no. 1. 2015, doi: 10.1088/0953-8984/27/1/013002.

[77] N. Sharma, V. Sharma, S. K. Sharma, and K. Sachdev, “Gas sensing behaviour of green synthesized reduced graphene oxide (rGO) for H2 and NO,” *Mater. Lett.*, vol. 236, pp. 444–447, 2019, doi:

10.1016/j.matlet.2018.10.145.

[78] Y. Yang, N. Wan, and H. Yu, “The Preparation of Modified Graphene Oxide and Gas Sensitivity Study,” in *Proceedings of IEEE Sensors*, 2018, vol. 2018–Octob, doi: 10.1109/ICSENS.2018.8589718.

[79] J. Song, X. Wang, and C. T. Chang, “Preparation and characterization of graphene oxide,” *J. Nanomater.*, vol. 2014, 2014, doi: 10.1155/2014/276143.

[80] A. Omidvar and A. Mohajeri, “Edge-functionalized graphene nanoflakes as selective gas sensors,” *Sensors Actuators, B Chem.*, vol. 202, pp. 622–630, 2014, doi: 10.1016/j.snb.2014.05.136.

[81] Y. Peng and J. Li, “Ammonia adsorption on graphene and graphene oxide: A first-principles study,” *Front. Environ. Sci. Eng.*, vol. 7, no. 3, pp. 403–411, 2013, doi: 10.1007/s11783-013-0491-6.

[82] A. Pavithra, R. A. Rakkesh, D. Durgalakshmi, and S. Balakumar, “Room Temperature Detection of Hydrogen Gas Using Graphene Based Conductometric Gas Sensor,” *J. Nanosci. Nanotechnol.*, vol. 17, no. 5, pp. 3449–3453, 2017, doi: 10.1166/jnn.2017.13054.

[83] J. S. Arellano, L. M. Molina, A. Rubio, and J. A. Alonso, “Density functional study of adsorption of molecular hydrogen on graphene layers,” *J. Chem. Phys.*, vol. 112, no. 18, pp. 8114–8119, 2000, doi: 10.1063/1.481411.

[84] O. Leenaerts, B. Partoens, and F. M. Peeters, “Adsorption of H2O,NH3,CO, and NO on graphene: A first-principles study,” *Phys. Rev. B*, vol. 77, no. 12, p. 125416, 2008, doi: 10.1103/PhysRevB.77.125416.

[85] P.-G. Su, C.-H. Wei, and W.-L. Shiu, “Fabrication of Sno2/Reduced Graphene Oxide Nanocomposite Films for Sensing No2 Gas at Room-Temperature,” *Int. J. Sci. Eng. Technol.*, vol. 4, no. 4, pp. 268–272, 2015, doi: 10.17950/ijset/v4s4/411.

[86] S. Liu, B. Yu, H. Zhang, T. Fei, and T. Zhang, “Enhancing NO2 gas sensing performances at room temperature based on reduced graphene oxide-ZnO nanoparticles hybrids,” *Sensors Actuators, B Chem.*, vol. 202, pp. 272–278, 2014, doi: 10.1016/j.snb.2014.05.086.

[87] E. C. Mattson, K. Pande, S. Cui, M. Weinert, J. H. Chen, and C. J. Hirschmugl, “Investigation of NO2 adsorption on reduced graphene oxide,” *Chem. Phys. Lett.*, vol. 622, pp. 86–91, 2015, doi: 10.1016/j.cplett.2015.01.018.

[88] C. W. Na *et al.*, “Highly selective and sensitive detection of NO2 using rGO-In2O3 structure on flexible substrate at low temperature,” *Sensors Actuators, B Chem.*, vol. 255, pp. 1671–1679, 2018, doi: 10.1016/j.snb.2017.08.172.

[89] S. M. Mortazavi Zanjani, M. M. Sadeghi, M. Holt, S. F. Chowdhury, L. Tao, and D. Akinwande, “Enhanced sensitivity of graphene ammonia gas sensors using molecular doping,” *Appl. Phys. Lett.*, vol. 108, no. 3, 2016, doi: 10.1063/1.4940128.

[90] L. Bao *et al.*, “3D Graphene Frameworks/Co3O4 Composites Electrode for High-Performance Supercapacitor and Enzymeless Glucose Detection,” *Small*, vol. 13, no. 5, 2017, doi: 10.1002/smll.201602077.

[91] J. Wang, S. Rathi, B. Singh, I. Lee, H. I. Joh, and G. H. Kim, “Alternating Current Dielectrophoresis Optimization of Pt-Decorated Graphene Oxide Nanostructures for Proficient Hydrogen Gas Sensor,” *ACS Appl. Mater. Interfaces*, vol. 7, no. 25, pp. 13768–13775, 2015, doi: 10.1021/acsami.5b01329.

[92] A. Venkatesan *et al.*, “Molybdenum disulfide nanoparticles decorated reduced graphene oxide: Highly sensitive and selective hydrogen sensor,” *Nanotechnology*, vol. 28, no. 36, 2017, doi: 10.1088/1361-6528/aa7d66.

[93] K. Wasa, S. Hayakawa, Kiyotaka Wasa; Shigeru Hayakawa, K. Wasa, S. Hayakawa, and Kiyotaka Wasa; Shigeru Hayakawa, *Handbook of Sputter Deposition Technology: Principles, Technology, and Applications*. 1992.

[94] D. A. Powell, K. Kalantar-zadeh, and W. Wlodarski, “Optimum sensitive area of surface acoustic wave resonator chemical and bio-sensors,” in *Proceedings of IEEE Sensors*, 2005, vol. 2005, pp. 1229–1232, doi: 10.1109/ICSENS.2005.1597928.

[95] P. Prepelita, R. Medianu, B. Sbarcea, F. Garoi, and M. Filipescu, “The influence of using different substrates on the structural and optical characteristics of ZnO thin films,” *Appl. Surf. Sci.*, vol. 256, no. 6, pp. 1807–1811, 2010, doi: 10.1016/j.apsusc.2009.10.011.

[96] G. Scholl, F. Schmidt, and U. Wolff, “Surface Acoustic Wave Devices for Sensor Applications,” *Phys. Status Solidi Appl. Res.*, vol. 185, no. 1, pp. 47–58, 2001, doi: 10.1002/1521-396X(200105)185:1<47::AID-PSSA47>3.0.CO;2-Q.

[97] P. Zhao, S. Kim, S. Yoon, and P. Song, “Characteristics of indium zinc

oxide/silver/indium zinc oxide multilayer thin films prepared by magnetron sputtering as flexible transparent film heaters," *Thin Solid Films*, vol. 665, pp. 137–142, 2018, doi: 10.1016/j.tsf.2018.09.018.

[98] Y. Wang *et al.*, "Flexible gas sensors with assembled carbon nanotube thin films for DMMP vapor detection," *Sensors Actuators, B Chem.*, vol. 150, no. 2, pp. 708–714, 2010, doi: 10.1016/j.snb.2010.08.011.

[99] Y. Q. Fu *et al.*, "Recent developments on ZnO films for acoustic wave based bio-sensing and microfluidic applications: a review," *Sensors Actuators, B Chem.*, vol. 143, no. 2, pp. 606–619, 2010, doi: 10.1016/j.snb.2009.10.010.

[100] A. Laposa, M. Husák, Kroutil J., and R. Vrba, "Gas sensor with SAW structures," in *Technical Proceedings of the 2012 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2012*, 2012, pp. 574–577.

[101] H. Morkoç and Ü. Özgür, *ZnO Growth*. 2009.

[102] D. P. Norton *et al.*, "Charge carrier and spin doping in ZnO thin films," in *Thin Solid Films*, 2006, vol. 496, no. 1, pp. 160–168, doi: 10.1016/j.tsf.2005.08.246.

[103] T. Yamamoto, T. Shiosaki, and A. Kawabata, "Characterization of ZnO piezoelectric films prepared by rf planarmagnetron sputtering Characterization of ZnO piezoelectric films prepared by rf planar-magnetron sputtering," *J. Appl. Phys. J. Appl. Phys. Appl. Phys. Lett. Diode Sputtering J. Vac. Sci. Technol*, vol. 51, no. 87, 1980, doi: 10.1116/1.1316694.

[104] M. Godlewski *et al.*, *Zinc oxide for electronic, photovoltaic and optoelectronic applications*, vol. 37, no. 3. 2011.

[105] and J. G. C. F. Klingshirn, A. Waag, A. Hoffmann, *Zinc Oxide*. Springer Science & Business Medi, 2010.

[106] C. Campbell, *Surface acoustic wave devices for mobile and wireless communications*. 1998.

[107] C. K. Campbell, *Surface Acoustic Wave Devices for Mobile and Wireless Communication*. 1998.

[108] A. N. Nordin, "Design and Implementation, Characterization of Temperature Compensated SAW Resonator in CMOS Technology for RF Oscillator," George Washington University, 2008.

[109] A. Stelzer, G. Schimetta, L. Reindl, A. Springer, and R. Weigel, "Wireless SAW sensors for surface and subsurface sensing applications," in *Subsurface*

and Surface Sensing Technologies and Applications Iii, 2001, vol. 4491, p. 358–366\r400, doi: 10.1117/12.450181.

[110] T. Kannan, “Finite Element Analysis of Surface Acoustic Wave Resonator,” University of Saskatcehwan, 2006.

[111] X. Y. Du *et al.*, “ZnO film thickness effect on surface acoustic wave modes and acoustic streaming,” *Appl. Phys. Lett.*, vol. 93, no. 9, 2008, doi: 10.1063/1.2970960.

[112] T. Hoang, “SAW Parameter Analysis and Equivalent Circuit of SAW Device,” In Tech, 2008.

[113] W. Soluch, “Design of SAW delay lines for sensors,” *Sensors Actuators, A Phys.*, vol. 67, no. 1–3, pp. 60–64, 1998, doi: 10.1016/S0924-4247(97)01737-8.

[114] L. Haofeng, J. Rui, L. Weilong, C. Chen, and L. Xinyu, “Surface Acoustic Wave Sensors of Delay Lines Based on MEMS,” *J. Nanosci. Nanotechnol.*, vol. 10, no. 11, pp. 7258–7261, 2010, doi: 10.1166/jnn.2010.2817.

[115] T. . Staline Johnson, “Design and Analysis of SAW Based MEMS Gas Sensor for the Detection of Volatile Organic Gases,” *Int. J. Eng. Res. Appl.*, vol. 4, no. 3, pp. 4–10, 2014.

[116] N. Standard, “IEEE Standard on Piezoelectricity,” *East*, p. 74, 1988, doi: 10.1109/IEEESTD.1988.79638.

[117] C. K. Ho, E. R. Lindgren, K. S. Rawlinson, L. K. McGrath, and J. L. Wright, “Development of a Surface Acoustic Wave Sensor for In-Situ Monitoring of Volatile Organic Compounds,” *Sensors*, vol. 3, pp. 236–247, 2003.

[118] X. Y. Du, “Design and fabrication of a prototype aluminum nitride-based pressure sensor with finite element analysis and validation,” Wayne State University, 2012.

[119] M. Buchner, W. Ruile, A. Dietz, and R. Dill, “FEM analysis of the reflection coefficient of SAWs in an infinite\nperiodic array,” *IEEE 1991 Ultrason. Symp.*, pp. 371–376, 1991, doi: 10.1109/ULTSYM.1991.234189.

[120] M. a Bissett, M. Tsuji, and H. Ago, “Strain engineering the properties of graphene and other two-dimensional crystals.,” *Phys. Chem. Chem. Phys.*, vol. 16, no. 23, pp. 11124–38, 2014, doi: 10.1039/c3cp55443k.

[121] A. Mitrushchenkov, R. Linguerri, and G. Chambaud, “Piezoelectric properties of AlN, ZnO, and HgxZn1-xO nanowires by first-principles calculations,” *J.*

Phys. Chem. C, vol. 113, no. 17, pp. 6883–6886, 2009, doi: 10.1021/jp9007015.

[122] G. Substrates, M. Kadota, and M. Minakata, “Piezoelectric Properties of Zinc Oxide Films on,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 42, no. 3, pp. 345–350, 1995.

[123] Y. Zaatar *et al.*, “Fabrication and characterization of stacked ZnO and ZnOGa2O3layers for the realization of bulk acoustic wave resonated membranes,” *Microelectronics J.*, vol. 38, no. 4–5, pp. 538–546, 2007, doi: 10.1016/j.mejo.2007.03.010.

[124] R. Ondo-Ndong, G. Ferblantier, M. Al Kalfioui, A. Boyer, and A. Foucaran, “Properties of RF magnetron sputtered zinc oxide thin films,” *J. Cryst. Growth*, vol. 255, no. 1–2, pp. 130–135, 2003, doi: 10.1016/S0022-0248(03)01243-0.

[125] W. LIN, R. MA, W. SHAO, B. KANG, and Z. WU, “Properties of doped ZnO transparent conductive thin films deposited by RF magnetron sputtering using a series of high quality ceramic targets,” *Rare Met.*, vol. 27, no. 1, pp. 32–35, 2008, doi: 10.1016/S1001-0521(08)60025-X.

[126] K. B. Sundaram and A. Khan, “Characterization and optimization of zinc oxide films by r.f. magnetron sputtering,” *Thin Solid Films*, vol. 295, no. 1–2, pp. 87–91, 1997, doi: 10.1016/S0040-6090(96)09274-7.

[127] W. Li and H. Hao, “Effect of temperature on the properties of Al:ZnO films deposited by magnetron sputtering with inborn surface texture,” *J. Mater. Sci.*, vol. 47, no. 8, pp. 3516–3521, 2012, doi: 10.1007/s10853-011-6196-y.

[128] W. Y. Chang, T. H. Fang, S. H. Yeh, and Y. C. Lin, “Flexible electronics sensors for tactile multi-touching,” *Sensors*, vol. 9, no. 2, pp. 1188–1203, 2009, doi: 10.3390/s9021188.

[129] I. C. Cheng, “Flexible and printed electronics,” in *Materials for Advanced Packaging, Second Edition*, 2016, pp. 813–854.

[130] F. C. Krebs *et al.*, “A complete process for production of flexible large area polymer solar cells entirely using screen printing-First public demonstration,” *Sol. Energy Mater. Sol. Cells*, vol. 93, no. 4, pp. 422–441, 2009, doi: 10.1016/j.solmat.2008.12.001.

[131] J. A. Rather, S. Pilehvar, and K. De Wael, “A graphene oxide amplification platform tagged with tyrosinase-zinc oxide quantum dot hybrids for the

electrochemical sensing of hydroxylated polychlorobiphenyls," *Sensors Actuators, B Chem.*, vol. 190, pp. 612–620, 2014, doi: 10.1016/j.snb.2013.09.018.

[132] A. A. F. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, "Electric Field Effect in Atomically Thin Carbon Films," *Electr. F. Eff. At. thin carbon Film.*, vol. 306, no. 5696, pp. 666–669, 2013, doi: 10.1126/science.1102896.

[133] E. B. Bahadir and M. K. Sezgintürk, "Applications of graphene in electrochemical sensing and biosensing," *TrAC - Trends in Analytical Chemistry*, vol. 76. pp. 1–14, 2016, doi: 10.1016/j.trac.2015.07.008.

[134] H. Graphenes *et al.*, "Highly sensitive and selective gas sensor using hydrophilic and hydrophobic graphenes.," *Sci. Rep.*, vol. 3, p. 1868, 2013, doi: 10.1038/srep01868.

[135] F. Schedin *et al.*, "Detection of individual gas molecules adsorbed on graphene," *Nat. Mater.*, vol. 6, no. 9, pp. 652–655, 2007, doi: 10.1038/nmatXXXX.

[136] B.-C. Yao, Y. Wu, Y. Chen, X.-P. Liu, Y. Gong, and Y.-J. Rao, "Graphene-based microfiber gas sensor," in *OFS2012 22nd International Conference on Optical Fiber Sensors*, 2012, vol. 8421, p. 8421CD, doi: 10.1117/12.2013416.

[137] Q. Tang, Z. Zhou, and Z. Chen, "Graphene-related nanomaterials: Tuning properties by functionalization," *Nanoscale*, vol. 5, no. 11. pp. 4541–4583, 2013, doi: 10.1039/c3nr33218g.

[138] C. N. R. Rao, U. Maitra, and H. S. S. R. Matte, "Synthesis, characterization, and selected properties of graphene.," *Graphene*, pp. 1–47, 2013, doi: 10.1002/9783527651122.ch1.

[139] D. A. Graphene Oxide: Synthesis, Characterization, Electronic Structure, and ApplicationsStewart and K. A. Mkhoyan, "Graphene Oxide: Synthesis, Characterization, Electronic Structure, and Applications," *Graphene Nanoelectron.*, 2012, doi: 10.1109/ISDRS.2009.5378331.

[140] B. H. Lee, S. H. Park, H. Back, and K. Lee, "Novel film-casting method for high-performance flexible polymer electrodes," *Adv. Funct. Mater.*, vol. 21, no. 3, pp. 487–493, 2011, doi: 10.1002/adfm.201000589.

[141] "Field Emission Scanning Electron Microscopy (FESEM)," *PhotoMetric, Inc, The Material Characterization Lab*. http://photometrics.net/field-emission-

scanning-electron-microscopy-fesem/ (accessed Jul. 11, 2018).

[142] G.-J. Janssen, “Information on the FESEM (Field-emission Scanning Electron Microscope),” *Radboud Univ. Nijmegen*, pp. 1–5, 2015, [Online]. Available: http://www.vcbio.science.ru.nl/public/pdf/fesem_info_eng.pdf.

[143] N. S. Muhamad Sauki, S. H. Herman, M. H. Ani, and M. R. Mahmood, “Electrical Properties Dependence on Substrate Temperature of Sputtered ZnO Nanoparticles Thin Films on Teflon Substrates,” *Adv. Mater. Res.*, vol. 795, pp. 403–406, 2013, doi: 10.4028/www.scientific.net/AMR.795.403.

[144] A. Cassetta, “X-Ray Diffraction (XRD),” in *Encyclopedia of Membranes*, 2014, pp. 1–3.

[145] X. Wang, Q. Lei, J. Yuan, W. Zhou, and J. Yu, *Effects of power on properties of ZnO:Al films deposited on flexible substrates by RF magnetron sputtering*, vol. 650. 2010.

[146] J. Kim, H. Kim, and D. K. Kim, “Effect of RF Power on an Al-doped ZnO Thin Film Deposited by RF Magnetron Sputtering,” *J. Korean Phys. Soc.*, vol. 59, no. 3, pp. 2349–2353, 2011, [Online]. Available: papers://fa062ed5-ee69-40ff-be78-790de8fae533/Paper/p5924.

[147] H. Wang *et al.*, “High performance AZO thin films deposited by RF magnetron sputtering at low temperature,” *Recent Patents Mater. Sci.*, vol. 8, no. 3, 2015, doi: 10.2174/1874464808666151014213229.

[148] M. Saad and A. Kassis, “Effect of rf power on the properties of rf magnetron sputtered ZnO:Al thin films,” *Mater. Chem. Phys.*, vol. 136, no. 1, pp. 205–209, 2012, doi: 10.1016/j.matchemphys.2012.06.053.

[149] I. Nikolaou *et al.*, “Novel SAW gas sensor based on graphene,” 2015, doi: 10.1109/SBMicro.2015.7298140.

[150] V. Kumar *et al.*, “The role of growth atmosphere on the structural and optical quality of defect free ZnO films for strong ultraviolet emission,” *Laser Phys.*, vol. 24, no. 10, 2014, doi: 10.1088/1054-660X/24/10/105704.

[151] S. Ahmad *et al.*, “Influence of substrate materials on the structural properties of ZnO thin films prepared by RF magnetron sputtering,” *J. Teknol.*, vol. 76, no. 9, 2015, doi: 10.11113/jt.v76.5650.

[152] D. D. Han *et al.*, “Influence of sputtering power on properties of ZnO thin films fabricated by RF sputtering in room temperature,” *Sci. China Inf. Sci.*, vol. 55, no. 4, pp. 951–955, 2012, doi: 10.1007/s11432-011-4347-z.

[153] A. Samavati, H. Nur, A. F. Ismail, and Z. Othaman, “Radio frequency magnetron sputtered ZnO/SiO2/glass thin film: Role of ZnO thickness on structural and optical properties,” *J. Alloys Compd.*, vol. 671, pp. 170–176, 2016, doi: 10.1016/j.jallcom.2016.02.099.

[154] W. C. Shih, T. L. Wang, and Y. K. Pen, “Enhancement of characteristics of ZnO thin film surface acoustic wave device on glass substrate by introducing an alumina film interlayer,” *Appl. Surf. Sci.*, vol. 258, no. 14, pp. 5424–5428, 2012, doi: 10.1016/j.apsusc.2012.02.028.

[155] H. Morkoc and Ü. Özgür, “General Properties of ZnO,” in *Zinc Oxide*, 2009, pp. 1–76.

[156] J. H. Park *et al.*, “Structural, optical, and electrical properties of semiconducting ZnO nanosheets,” *J Nanosci Nanotechnol*, vol. 8, no. 9, pp. 4658–4661, 2008, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/19049079.

[157] P. Wang, N. Chen, Z. Yin, F. Yang, and C. Peng, “Fabrication and properties of Sb-doped ZnO thin films grown by radio frequency (RF) magnetron sputtering,” *J. Cryst. Growth*, vol. 290, no. 1, pp. 56–60, 2006, doi: 10.1016/j.jcrysgro.2006.01.022.

[158] J. Vinoth Kumar, Y. Matsumoto, A. Maldonado, and M. L. De La Olvera, “Effect of substrate position on Structural, Morphological, and optical properties of reactively sputtered ZnO thin films,” 2016, doi: 10.1109/ICEEE.2016.7751209.

[159] R. S. Gonçalves, P. Barrozo, and F. Cunha, “Optical and structural properties of ZnO thin films grown by magnetron sputtering: Effect of the radio frequency power,” *Thin Solid Films*, vol. 616, pp. 265–269, 2016, doi: 10.1016/j.tsf.2016.08.040.

[160] S. O’Brien *et al.*, “Zinc oxide thin films: Characterization and potential applications,” in *Thin Solid Films*, 2010, vol. 518, no. 16, pp. 4515–4519, doi: 10.1016/j.tsf.2009.12.020.

[161] M. Suchea, S. Christoulakis, K. Moschovis, N. Katsarakis, and G. Kiriakidis, “ZnO transparent thin films for gas sensor applications,” *Thin Solid Films*, vol. 515, no. 2 SPEC. ISS., pp. 551–554, 2006, doi: 10.1016/j.tsf.2005.12.295.

[162] H. Yu *et al.*, “ZnO thin films produced by the RF magnetron sputtering,” in *Proceedings of 2011 International Conference on Electronic and Mechanical*

Engineering and Information Technology, EMEIT 2011, 2011, vol. 5, pp. 2486–2489, doi: 10.1109/EMEIT.2011.6023604.

[163] A. A. M. Ralib, A. N. Nordin, N. A. Malik, and R. Othman, “Dependence of preferred c-axis orientation on RF magnetron sputtering power for AZO/Si acoustic wave devices,” 2015, doi: 10.1109/DTIP.2015.7160990.

[164] K. Miandal, M. L. Lam, F. L. Shain, A. Manie, K. A. Mohamad, and A. Alias, “RF Power Dependence of ZnO Thin Film Deposited by RF Powered Magnetron Sputtering System,” *J. Adv. Res. Mater. Sci. ISSN*, vol. 20, no. 1, pp. 6–13, 2016, [Online]. Available: http://www.akademiabaru.com/doc/ARMSV20_N1_P6_13.pdf.

[165] K. Yamanaka *et al.*, “Noncontact characterization of crystal surface and thin films by the phase velocity scanning of laser interference fringes,” in *Proceedings of the IEEE Ultrasonics Symposium*, 1994, vol. 2, pp. 1211–1214.

[166] D. W. Galipeau, P. R. Story, K. A. Vetelino, and R. D. Mileham, “Surface acoustic wave microsensors and applications,” *Smart Mater. Struct.*, vol. 6, no. 6, pp. 658–667, 1997, doi: 10.1088/0964-1726/6/6/002.

[167] R. Arsat, X. F. Yu, Y. X. Li, W. Wlodarski, and K. Kalantar-zadeh, “Hydrogen gas sensor based on highly ordered polyaniline nanofibers,” *Sensors Actuators, B Chem.*, vol. 137, no. 2, pp. 529–532, 2009, doi: 10.1016/j.snb.2009.01.028.

[168] M. Z. Atashbar, K. Kalantar-zadeh, S. J. Ippolitto, and W. Wlodarski, “Palladium nanowire hydrogen sensor based on a SAW transducer,” in *IEEE Sensors, 2005.*, 2005, pp. 1363–1365, doi: 10.1109/ICSENS.2005.1597961.

[169] M. F. Lewis, “Surface acoustic wave devices and applications. 6. Oscillators - the next successful surface acoustic wave device?,” *Ultrasonics*, vol. 12, no. 3, pp. 115–123, 1974, doi: 10.1016/0041-624X(74)90068-7.

[170] A. Bryant, M. Poirier, G. Riley, D. L. Lee, and J. F. Vetelino, “Gas detection using surface acoustic wave delay lines,” *Sensors and Actuators*, vol. 4, no. C, pp. 105–111, 1983, doi: 10.1016/0250-6874(83)85014-8.

[171] A. Z. M. Sadek, “Investigation of Nanostructured Semiconducting Metal Oxide and Conducting Polymer Thin Films fo gas sensing Applications,” University of Melbourne Australia, 2008.

[172] G. K. Montress, T. E. Parker, and D. Andres, *Review of SAW oscillator*

performance, vol. 1. 1994.

[173] S. . Ippolito, “Investigation Of Multilayered Surface Acoustic Wave Devices For Gas Sensing Applications- Employing Piezoelectric Intermediate And Nanocrystalline Metal Oxide Sensitive Layers,” RMIT University, 2006.

[174] Y. Sun and H. H. Wang, “High-performance, flexible hydrogen sensors that use carbon nanotubes decorated with palladium nanoparticles,” *Adv. Mater.*, vol. 19, no. 19, pp. 2818–2823, 2007, doi: 10.1002/adma.200602975.

[175] A. A. B. M. R. M. Raghib and A. N. Nordin, “Analysis of electromechanical coupling coefficient of surface acoustic wave resonator in ZnO piezoelectric thin film structure,” 2014, doi: 10.1109/DTIP.2014.7056641.

[176] J. P. Jung, J. B. Lee, J. S. Kim, and J. S. Park, “Fabrication and characterization of high frequency SAW device with IDT/ZnO/AlN/Si configuration: Role of AlN buffer,” in *Thin Solid Films,* 2004, vol. 447–448, pp. 605–609, doi: 10.1016/j.tsf.2003.07.022.

[177] A. N. Nordin and M. E. Zaghloul, “Modeling and fabrication of CMOS surface acoustic wave resonators,” *IEEE Trans. Microw. Theory Tech.,* vol. 55, no. 5, pp. 992–1001, 2007, doi: 10.1109/TMTT.2007.895408.

[178] A. B.A., *Acoustic fields and waves in solids,* vol. 8. 1990.

[179] R. Bogue, “Nanomaterials for gas sensing: A review of recent research,” *Sensor Review,* vol. 34, no. 1. pp. 1–8, 2014, doi: 10.1108/SR-03-2013-637.

[180] K. I. Bolotin *et al.*, “Ultrahigh electron mobility in suspended graphene,” *Solid State Commun.*, vol. 146, no. 9–10, pp. 351–355, 2008, doi: 10.1016/j.ssc.2008.02.024.

[181] K. S. Novoselov *et al.*, “Two-dimensional gas of massless Dirac fermions in graphene,” *Nature,* vol. 438, no. 7065, pp. 197–200, 2005, doi: 10.1038/nature04233.

[182] I. Banerjee *et al.*, “Graphene films printable on flexible substrates for sensor applications,” *2D Mater.*, vol. 4, no. 1, 2017, doi: 10.1088/2053-1583/aa50f0.

[183] Y. H. Lee and Y. J. Kim, “Electrical and lattice vibrational behaviors of graphene devices on flexible substrate under small mechanical strain,” *Appl. Phys. Lett.,* vol. 101, no. 8, 2012, doi: 10.1063/1.4746285.

[184] M. A. S. Mohammad Haniff *et al.*, “Piezoresistive effects in controllable defective HFTCVD graphene-based flexible pressure sensor,” *Sci. Rep.,* vol. 5, 2015, doi: 10.1038/srep14751.

LIST OF PUBLICATIONS

Journal

1. Fatini, S., Rashidah, A., Zaharah, J., Aizat, A. M. I., and Mahyuddin, A. (2017). Performance Enhancement by Implementation of Nano structure Sensing Element for Bendable SAW Gas Sensor: Simulation. International Journal of Applied Engineering Research (Scopus) (online special issue) (ISSN: 0973-4562).

Conference Proceeding

1. **Fatini, S**., Rashidah, A., Rafidah, I., Aizzat, A. M. I., Zaharah, J., and Leow, P. L. (2017). A Comparative Study on Simulation Performances of Rigid and Bendable SAW for Gas Sensor. In AIP Conference Proceedings 1808, 020048 (2017); doi: 10.1063/1.4975281.

2. **Fatini, S**., Nurul, I., M. I., Rashidah, A., Leow, P. L., and Mahyuddin A. (2018). Intermediate Layer of Love Mode Surface Acoustic Wave Device Modelling. In Nanotech Malaysia 2018.

3. Aizzat A. M. I.,Rashidah A., **Fatini S**., Pei L. L., Zaharah J., and Mahyuddin A. (2019). Bending Effect on Flexible Surface Acoustic Wave Device towards Resonant Frequency. In 2019 IEEE International Conference on Sensors and Nanotechnology.

4. **Fatini S**., Aizzat A. M. I., and Rashidah A., Flexible Surface Acoustic Wave Device for Gas Sensing Application (2020). In The 6th International Symposium toward the Future of Advanced Researches in Shizuoka University (ISFAR- SU2020).