DEVELOPMENT OF SURFACE ACOUSTIC WAVE SENSOR FOR FEMALE AEDES MOSQUITO DETECTION

by

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LIST OF SYMBOLS

K^2	Electromechanical coupling coefficient
Hz	Hertz
Å	Angstrom
Kh	Film thickness
λ	SAW wavelength
v_p	Phase velocity
ω	Angular velocity
k	Wave vector
f_o	Operational frequency
Λ	IDT periodicity
e	Piezoelectric coefficient
E	Electric field
S	Strain
ε	Electrical permittivity
C^E	Elasticity matrix
v_f	Free surface velocity
v_m	Metalized surface velocity
T	Stress vector
D	Electrical displacement
V	Electric potential
ρ	Rho
∂	Partial deferential

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S	Sum
t_s	Time step
h	Maximum mesh element size
F	Lorentz force
q	Particle charge
B	Magnetic field
d	Crystal grain size
β	Full width at half maximum
θ	Diffraction Bragg's angle
c	Lattice constant
ε_{zz}	Film strain
R	Reflectance
eV	Electron volt
G	Radiation conductance
b	Susceptance
dB	Decibel
N	Number of electrode finger pairs

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LIST OF ABBREVIATIONS

DF	Dengue fever
SAW	Surface acoustic wave
IDT	Interdigital transducer
SPL	Sound pressure level
RNA	Ribonucleic acid
DEN	Dengue virus serotype
DHF	Dengue hemorrhagic fever
DSS	Dengue shock syndrome
WHO	World health organization
Ae	Aedes
BAW	Bulk acoustic wave
TSM	Thickness shear mode
SH-APM	Shear horizontal acoustic bulk mode
SH-SAW	Shear horizontal surface acoustic wave
STW	Surface transverse wave
FPW	Flexural plate wave
SSBW	Surface skimming bulk wave
TCF	Temperature coefficient of frequency
TCD	Temperature coefficient of delay
ppm	Part per million
FEM	Finite element method
MEMS	Micro-electromechanical system

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VHF	Very high frequency
CFL	Friedrichs Lewy condition
FFT	Fast Fourier transaction
RF	Radio Frequency
XRD	X-ray Diffraction
FESEM	Field emission scanning electron microscope
AFM	Atomic force microscope
PL	Photoluminescence
UV	Ultraviolet
PR	Positive resist
HMDS	Hexametyldisilazane
Ra	Roughness average
RMS	Root mean square
Eg	Energy gap

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Pembangunan Sensor Gelombang Akustik Permukaan untuk Pengesanan Nyamuk Aedes Betina

ABSTRAK

Kes demam denggi (DF) dan demam denggi berdarah telah menunjukkan peningkatan dalam masa sedekad yang lalu di seluruh dunia. Keadaan ini membawa kepada kerugian besar sesebuah ekonomi dan komplikasi kesihatan yang serius. Setakat ini, penawar yang mampu menyembuhkan DF dan peranti yang berkesan untuk mengawal dan mengesan nyamuk *Aedes* yang menjadi punca DF masih belum dihasilkan. Oleh itu, pembikinan peranti untuk pencegahan virus denggi sangat diperlukan. Dalam kajian ini, rekabentuk dan pembikinan peranti gelombang akustik permukaan (SAW) untuk mengesan nyamuk *aedes* betina akan dibentangkan. Kajian ini adalah yang pertama melaporkan tentang pengesanan nyamuk *Aedes* betina di dalam penempatan manusia menggunakan peranti SAW. Teknologi SAW boleh diaplikasikan untuk menghasilkan peranti yang amat peka kerana kepekaan usikan permukaan yang tinggi. Lapisan peranti SAW adalah terdiri daripada bahan zink oksida (ZnO)/pemindaharuh antara digit (IDT)/128˚ YX litium niobate ($LiNbO_3$), komposisi struktur ini telah direka, dibikin, dan dicirikan di dalam tesis ini. Pertama sekali, peranti ini telah dicirikan secara teori menggunakan kaedah elemen terhingga didalam perisian "COMSOL Muliphysics" 4.3b. Menggunakan perisian tersebut, respon frekuensi, mod perambatan SAW, kecekapan sesaran SAW, dan pekali gandingan elektromekanik akan dicirikan secara teori. Ketebalan ZnO yang pelbagai digunakan untuk mendapatkan kondisi yang unggul. Keputusan berangka akan disahkan menggunakan peranti yang sudah dihasilkan dan perkaitan yang baik diantara simulasi dan eksperimen telah diperolehi. Peranti SAW telah dihasilkan setelah penyelarasan terakhir parameter rekaan dilakukan, proses photolithografi lazim telah digunakan untuk menghasilkan dua IDT diatas substrat 128° YX $LiNbO_3$ untuk memancar dan menerima SAW. Proses terakhir melibatkan enapan ZnO yang setebal 1.5 µm menggunakan teknik pemercitan RF magnetron. Ciri-ciri struktur lapisan ZnO dikaji menggunakan pembelauan sinar-X. Struktur nano ZnO telah dienap secara sempurna diatas sampel dan diindeks kepada fasa heksagon yang mempunyai struktur "wurtzite". Dua puncak pada (002) dan (201) satah pembelauan juga dilihat. Ciri morfologi struktur juga dikaji menggunakan daya atomic dan pancaran medan kemikroskopan elektron imbasan. Gambar yang diperbesar mendedahkan kepingan nano-siratan dan struktur bentuk cuping yang tumbuh secara rawak diatas substrat $LiNbO_3$ yang menunjukkan keseragaman yang baik. Teknik foto pendarkilau dan Uv-vis digunakan untuk pencirian secara optikal. Tiga jenis sela jalur tenaga didedahkan, sela jalur tenaga yang kecil, sederhana dan besar yang wujud masing-masing berkait rapat dengan kepingan nano ZnO, nano siratan dan substrat $LiNbO_3$. Peranti SAW juga dicirikan secara elektrik menggunakan penganalisa dua birai rangkaian vector. Respon frekuensi yang diperolehi ialah 158.8 MHz, manakala nilai K^2 yang dikira ialah 10.1 %, dan factor kualiti ialah 1,323. Respon peranti SAW diperoleh dengan signal nyamuk simulasi dan yang sebenar. Peranti ini mampu mengesan dan membezakan nyamuk *Aedes* jantan dan betina. Magnitud S_{11} dikurangkan kepada 0.6 dan 1.25 dB masing-masing dengan nyamuk *Aedes* jantan dan betina. Tambahan pula, peranti SAW mempamerkan kepekaan yang baik pada suasana tekanan bunyi yang

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rendah pada jarak diantara 40-55 dB, oleh itu, peranti ini sesuai digunakan di penempatan manusia.

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Development of Surface Acoustic Wave Sensor for Female Aedes Mosquito Detection

ABSTRACT

The cases of dengue fever (DF) and dengue hemorrhagic fever have been increasing worldwide in the last decade. These conditions lead to large economic losses and health complications. To date, a direct cure for DF and an efficient device to control or detect *Aedes* mosquitoes causing DF are unavailable. Therefore, the fabrication of a device to prevent dengue virus infection is necessary. In this study, the design and the fabrication of a surface acoustic wave (SAW) sensor for female *Aedes* mosquito detection are presented. This study is the first to report the detection of female *Aedes* mosquitoes in human habitations using a SAW sensor. SAW technology can be applied to create highly sensitive sensors because of its extreme sensitivity to surface perturbation. A layered SAW device based on the ZnO/interdigital transducer (IDT)/128° YX lithium niobate ($LiNbO_3$) structure was designed, fabricated, and characterized in this thesis study. First, the device was characterized theoretically using the finite element method in COMSOL Multiphysics 4.3b. The frequency response, SAW propagation mode(s), SAW displacement efficiency, and electromechanical coupling coefficient were theoretically investigated. Various ZnO layer thicknesses were used to obtain the ideal conditions. Numerical results were verified with a fabricated device. A good correlation was obtained between the simulation and experimental results. The SAW device was fabricated after setting the final design parameters, and conventional photolithography was used to produce two IDTs on 128° YX $LiNbO_3$ substrate to transmit and receive SAWs. Finally, a 1.5 μm ZnO layer was coated using the RF magnetron sputtering technique. The structural properties of the ZnO layer were studied using the X-ray diffraction technique. The ZnO nanostructure was grown successfully on the sample and indexed to the hexagonal phase with a wurtzite structure. Two peaks on the (002) and (201) diffraction planes were also observed. The morphological properties of the structure were investigated using the atomic force and field emission scanning electron microscopes. The high-magnification images revealed a nanoflake–corolla lobe-like structure randomly grown on the $LiNbO_3$ substrate that was uniform in all substrate dimensions. Photoluminescence and Uv-vis techniques were used to study the optical properties. Three energy band gaps were revealed, and the small, medium, and large energy band gaps were related to the nanoflake ZnO, nanocorolla lobe, and $LiNbO_3$ substrate, respectively. The SAW device was characterized electrically using a two-port vector network analyzer. The frequency response was 158.8 MHz, the measured K^2 value was 10.1%, and the quality factor was 1,323. The SAW device response was investigated with simulated and actual mosquito signals. This device could detect and distinguish between male and female *Aedes* mosquitoes. The S_{11} magnitude was reduced by 0.6 and 1.25 dB with female and male *Aedes* mosquitoes, respectively. Furthermore, the SAW sensor exhibited good sensitivity in low sound pressure environments in the range of 40–55 dB, thereby making it suitable for human habitations.

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CHAPTER 1

INTRODUCTION

1.1 Overview

The presents of female *Aedes* mosquito in or around human habitation can cause fatal diseases. Most commonly, dengue fever (DF) is one of the dangerous diseases transmitted to human through a bite caused by the females of this mosquito genus. The focus of this thesis work is to develop a surface acoustic wave (SAW) sensor for the detection of female *Aedes* mosquito in human habitation.

It is entrenched that SAW devices show a high sensitivity towards various physical and chemical phenomena. As sensors, they can offer innovative solutions for a wide range of applications (Borrero, Bravo, Mora, Velásquez, & Segura-Quijano, 2013). These devices are simple, inherently robust and competitively priced. Furthermore, they can be passive (no power source) and wireless (can be operated remotely) which make it suitable to operate in extreme conditions and harsh environments (Elhosni et al., 2015). Recently, a large number of applications has been reported in the literature of SAW devices such as SAW chemical, pressure, temperature sensors as well as many other commercial applications (Flewitt et al., 2015; Li, Dhagat, & Jander, 2012; Raj, Nimal, Parmar, Sharma, & Gupta, 2012; Rodriguez-Madrid, Iriarte, Williams, & Calle, 2013; Wei et al., 2010; Xuan et al., 2013) which makes it a very promising approach for developing a SAW sensor for the detecting of female *Aedes* mosquito.

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1.2 Research scope

The scope of this work focuses on developing a high performance SAW sensor for the detection of female *Aedes* mosquito using wing beat frequency as sensing mechanisms. This includes the following:

1. Explore previous studies to identify the necessary properties, characteristics and parameter that can affect the device performance.
2. Theoretical study by modeling and simulation to investigate the critical parameters and identify the best conditions.
3. Utilizing different characterization techniques to validate and test the device electrically.

1.3 Problem statement

Aedes mosquito genus are the main vectors for transmitting the viruses that cause dengue fever, yellow fever, West Nile fever, chikungunya, and Eastern equine encephalitis along with many other less harmful diseases. At present, there is no device to control or detect the present of *Aedes* mosquito around humans. Furthermore, current control methods have not stopped the spread of *Aedes* mosquito worldwide. There is no effective vaccine or specific treatment for dengue fever with *Aedes* female mosquitoes depends on humans to get a blood meal in order to lay fertile eggs. According to the last ten years statistics there is a significant increase in the incidence of dengue fever (Mudin, 2015).

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1.4 Research objectives

The aim of this research is to develop a novel surface acoustic wave sensor for the detection of female *Aedes* mosquito based on the mosquito's wing beat frequency as a sensing mechanism which is in the range between 400-500 Hz. This objective will be accomplished by achieve the following:

1. To determine the wing beat frequency range of *Aedes* mosquito and other common mosquito species.
2. To design and fabricate a high performance SAW device for detecting signals in the mosquito's wing beat frequency range.
3. To examine the performance of the fabricated SAW device under lab and field conditions.

1.5 Significance of research

The significance of this study includes, firstly, the modeling and simulation of two port SAW device based on ZnO/IDT/128º YX $LiNbO_3$ as a pre-fabrication step to obtain a high performance and sensitivity. During this theoretical analysis, the influence of the ZnO layer thickness to the SAW device frequency response, SAW displacement and coupling coefficient was investigated. Secondly, wing beat frequency produced by the mosquito's flight tone was measured with the sound pressure level (SPL). Finally, the sensor was characterized electrically, and the sensor's performance was investigated with simulated and real mosquito signals. To the best of our knowledge, this is the first attempt toward fabricating a device for the detection of female *Aedes* mosquito.

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1.6 Thesis outline

This thesis consists of five chapters.

Chapter 1 presents a short introduction about SAW sensors and *Aedes* mosquito. Also present the research scope, problem statement, objectives and significant of the research.

Chapter 2 reviews the literature and scientific background of *Aedes* mosquito and dengue fever and their incidents worldwide. Furthermore, it reports a brief overview about acoustic wave devices and technology along with the theory of piezoelectricity and its applications.

Chapter 3 details the methodology includes the FEM model description for non-layered and layered SAW devices, the experimental work and techniques performed in order to fabricate and characterize both the SAW device and the coting.

Chapter 4 presents the measured wing beat frequency and SPL of *Aedes* mosquito and two other mosquito species. The theoretical results obtained by the FEM modeling and simulation. The structural, morphological and optical properties of the coated layer are illustrated in this chapter. Finally, the electrical characteristics of the SAW device along with the sensitivity toward simulated and real mosquito signals are detailed.

Chapter 5 provides the study conclusions and future work.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, firstly, a literature review of dengue fever and virus is presented along with the incident of *Aedes* mosquito worldwide. Furthermore, the theory and application of piezoelectricity is described. The most common acoustic wave devices and acoustic wave propagation modes is summarized. Finally, this chapter is ended with a brief overview about the modeling and simulation of layered SAW devices.

2.2 Dengue fever and Aedes mosquito

2.2.1 Dengue fever

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Dengue fever is one of the most dangerous mosquito-borne diseases that become a serious health concern (Gubler, 2002). In the period between the 18th and 19th centuries, sailing ships were the main factor that helped expanding both the mosquito vector (genus *Aedes*) and the virus responsible for dengue fever worldwide. By using the water stored in the ships, the mosquitoes were able to complete their life cycle and spread to new areas when it reaches a new port (Murray, Quam, & Wilder-Smith, 2013). Dengue virus mature particle is spherical with a diameter of 50 nm containing a multiple copies of three structural proteins (host-derived membrane bilayer, single-standard RNA genome and seven nonstructural proteins) (X. Zhang et al., 2013) as illustrated in figure 2.1.

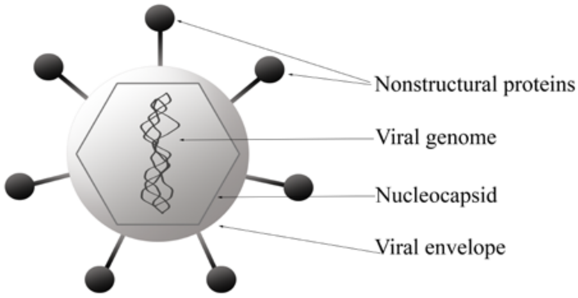

Figure 2.1: Dengue virus structure.

Dengue virus can be classified into four serotypes (DEN-1, DEN-2, DEN-3 and DEN-4) and a new surprising serotype (DEN-5) is discovered recently (Normile, 2013). These serotypes return from the genus *Flavivirus*, and the family *Flaviviridae* (Calisher & Gould, 2003). The Symptomatic infections of dengue virus include three categories: undifferentiated fever, dengue fever (DF) and dengue hemorrhagic fever (DHF). Furthermore DHF was classified into four grades of severity, with grades three and four DHF develops into dengue shock syndrome (DSS) (Ranjit & Kissoon, 2011). A large number of mosquito species are responsible for transmitting many types of diseases to humans and animals.

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2.2.2 Aedes mosquito

The genus *Aedes* considered the main vector for numerous fatal diseases. The most prominent species in this genus are *Aedes Aegypte* and *Aedes Albopictus* (Añez & Rios, 2013). This species are responsible for transmitting dengue fever, West Nile fever, chikungunya and Eastern equine encephalitis viruses and many other less harmful diseases to humans (Tolle, 2009). The females of this species can transmit all serotypes